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Writing of refractive-index gratings in germanosilicate fibres by near-UV radiation

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Abstract. A refractive-index grating was formed for the first time in a germanosilicate fibre by cw Ar^+ laser radiation in the near-UV range (333 – 364 nm). The refractive index change induced in a fibre with 10 mol.% GeO_2 in the core was 1.9×10^{-4} when the radiation power density was 1.7×10^5 W cm^{-2}. The gratings formed in this way were as thermally stable as those formed by KrF laser (248 nm) radiation.

1. Introduction

The photosensitivity of germanosilicate optical fibres is attracting much interest recently since this property can be used to form refractive-index (RI) gratings in the fibre core and such gratings have extensive applications in various fibre-optic devices [1]. As a rule, these gratings are formed by high-power UV radiation of wavelength which excites a singlet – singlet ($S_0 - S_1$) absorption band of germanium oxygen-deficient (GOD) centres with its maximum at 242 nm [2]. The mechanism by which RI changes are induced is under active investigation, but it is not yet fully understood. However, there is no doubt that photoexcitation of the GOD centres is the initial stage of this process.

In addition to the singlet – singlet transition, allowed by the selection rules, the GOD centres have an absorption band with a maximum at 330 nm [3] attributed to a forbidden singlet – triplet ($S_0 - T_1$) transition. Since, as a rule, the latter absorption band is three orders of magnitude weaker than the singlet – singlet band, it is difficult to use the singlet – triplet absorption in the formation of photoinduced structures. Nevertheless, the processes that occur as a result of direct excitation of the triplet state of the GOD centres represent a topical subject, since these processes can provide new information on the mechanism responsible for induced RI change and to determine whether other wavelengths (and, consequently, other radiation sources) can be used in practical applications.

In our earlier experiments [4] we demonstrated efficient photobleaching of the triplet – singlet luminescence by direct photoexcitation of the triplet state of the GOD centres by near-UV radiation. For example, 35% luminescence bleaching was observed in a glass with 8 mol.% of GeO_2 when this glass was exposed to cw Ar^+ laser radiation of 3.5×10^3 W cm^{-2} intensity. We also found that similar excitation induced an additional RI change in the core of a germanosilicate fibre as demonstrated by partial photoerasure of a long period grating [5]. In these experiments the RI change reached 3×10^{-5}, suggesting that near-UV radiation could be used to form in-fibre RI gratings.

Convenient objects for checking this possibility would be long-period ($\Lambda = 100$ μm – 1 cm) RI gratings coupling two fibre modes propagating in the same direction. Such gratings are used widely as intermode converters [6], narrow-band optical pass filters [7], various fibre sensors [8], etc. It is much simpler to form such gratings than the Bragg gratings, because of considerable relaxation of the requirements in respect of the coherence and intensity of the UV radiation, and in respect of the mechanical stability of the grating-formation system.

We shall report the first-ever formation of long-period cladding-mode-coupled gratings in a germanosilicate fibre. These gratings were induced by cw Ar^+ laser radiation, resulting in direct photoexcitation of the triplet state of the GOD centres.

2. Experiments

The gratings were formed by radiation from a cw Ar^+ laser (Coherent Innova 200 model) emitting simultaneously several near-UV lines (333 – 364 nm). We used the apparatus shown schematically in Fig. 1. A grating was formed by consecutive formation of each 'groove'. The UV radiation was focused in the core of a fibre by a spherical silica lens with a focal length of 1 cm. The diameter of the focal waist of the laser beam was $\sim$20 μm. The focusing was monitored with the aid of an optical microscope by measuring the longitudinal size of the luminescing region of the fibre core.

A fibre with 10 mol.% GeO_2 in the core and with the cutoff wavelength 0.92 μm was placed on a computer-controlled moving stage (translator) capable of displacing the fibre along one coordinate (fibre axis) in steps of 3 μm minimum size. The largest possible displacement was 40 mm. The grating period, $\Lambda = 200$ μm, was selected to ensure that the resonance wavelengths responsible for the $HE_{11} - HE_{1m}$ mode coupling, where $2 < m < 9$, were in the spectral range (1200 – 1600 nm) convenient for measurements.

A grating 'groove', 100 μm long, consisted of a discrete set of points in space separated by a distance governed by the minimum translator step. The irradiation time at each point was 1 s. After the formation of such a 'groove', the UV

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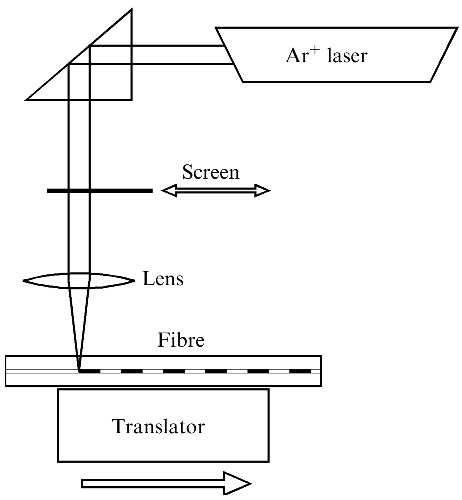

Figure 1. Schematic diagram of the apparatus used to form long-period refractive-index gratings.

radiation was interrupted and the translator moved the fibre to form the next grating period. In this way we were able to produce a practically rectangular grating profile along the fibre axis, where the region of the transition between the irradiated and unirradiated regions was of the order of the diameter (20 μm) of the focal waist. The total length of the grating was $L = 40$ mm.

The overall UV radiation intensity was varied in the range 20 – 170 kW cm^{-2} by introducing wide-band optical filters into the laser beam. This ensured a constant ratio of the laser line intensities and, consequently, a constant ratio of their contributions to the induced RI. The absorption spectrum of the grating was measured with an optical spectral analyser and the radiation source was a tungsten halogen lamp.

Fig. 2 shows the transmission spectrum of a long-period grating formed by this method when the UV radiation intensity was 1.7×10^5 W cm^{-2}. The amplitude of the strongest peak, corresponding to the $HE_{11} - HE_{19}$ mode coupling, was in excess of 3 dB. The full width at half-maximum of the peak was 6 nm, in good agreement with theoretical predictions; this confirmed that the recorded grating was uniform.

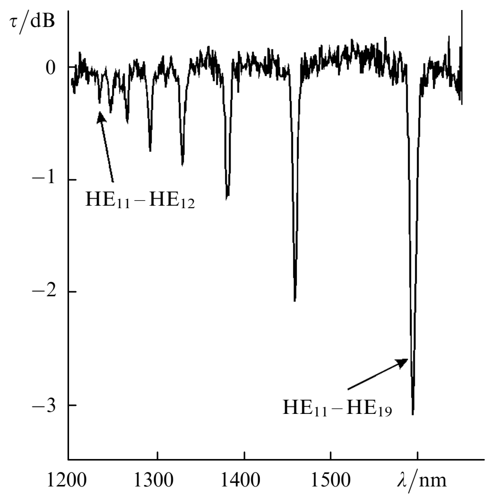

Figure 2. Transmission spectrum of a grating 40 mm long, formed in a fibre with 10 mol.% of GeO_2 in the core (grating period 200 μm).

It follows from the theory of coupled modes [9] that the losses S at a resonance of a long-period grating with a rectangular index profile are

$$S = \sin^2 \frac{4\Delta n I L}{\lambda_r}, \qquad (1)$$

where Δn is the amplitude of a periodic perturbation in the fibre core; I is the overlap integral of the fundamental (HE_{11}) and cladding (HE_{1m}, $m > 1$) modes in the region of the UV-induced RI change (in the fibre core); λ_r is the resonance wavelength. For our fibre the integral representing the overlap of the HE_{11} and HE_{19} modes was $I = 0.0765$. Therefore, the grating with the spectrum shown in Fig. 2 induced the RI change $\Delta n_{ind} = 2\Delta n \approx 1.9 \times 10^{-4}$.

The dependence of Δn_{ind} on the UV radiation intensity is plotted in Fig. 3. As in the singlet – singlet excitation case [10], this dependence tended to saturation.

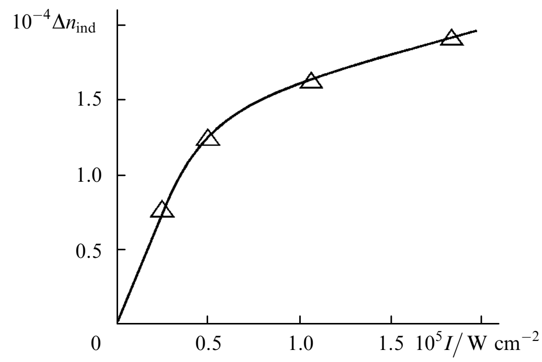

Figure 3. Dependence of the change in the refractive index, induced in the core, on the UV radiation intensity.

The spectral dependence of the induced RI change was determined by forming long-period gratings using separate Ar$^+$ laser emission lines. The intensities of these lines were selected to be inversely proportional to the singlet – triplet absorption of the GOD centres at these wavelengths. Therefore, the power absorbed in the core was kept constant. The spectral efficiency of the induced RI change agreed well with the absorption spectrum of the GOD centres (Fig. 4), thus providing unambiguous evidence of the dominant role of the triplet state of the GOD centres in the investigated process.

Fig. 5 gives the dependences of the relative RI change in the gratings formed by radiations with the wavelengths 333 – 364 nm (curve *1*) and 248 nm (KrF laser, curve *2*) on the temperature during isochronous annealing of the gratings lasting 2 min at each temperature. The defect centres formed as a result of direct photoexcitation of the triplet state of the GOD centres had almost the same thermal stability as the centres formed by excitation in the region of the 242 nm absorption band (some discrepancy between the curves in Fig. 5 was evidently associated with the different initial values of the induced RI change Δn_{init}). This allowed us to draw the conclusion that all the mechanisms of the photoinduced RI changes were similar, apart from the band of the GOD centres used in photoexcitation. Moreover, such a comparison confirmed the hypothesis of a considerable role of the long-lived triplet state T_1 in the photorefractive effect [4].

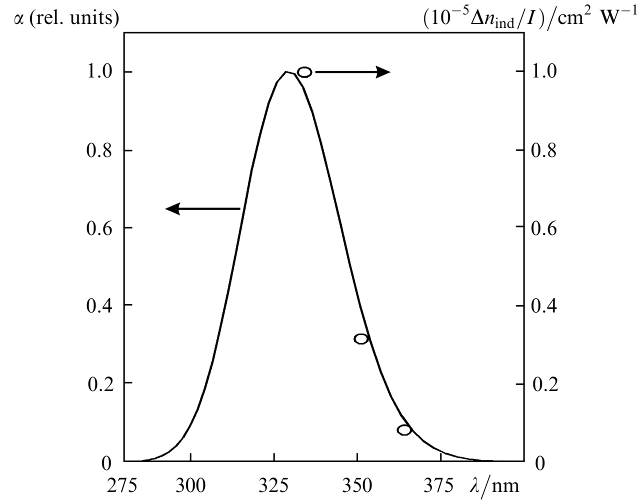

Figure 4. Comparison of the spectral efficiency of the change in the refractive index (experimental points) and the singlet – triplet absorption spectrum of the germanium oxygen-deficient centres [3] (continuous curve).

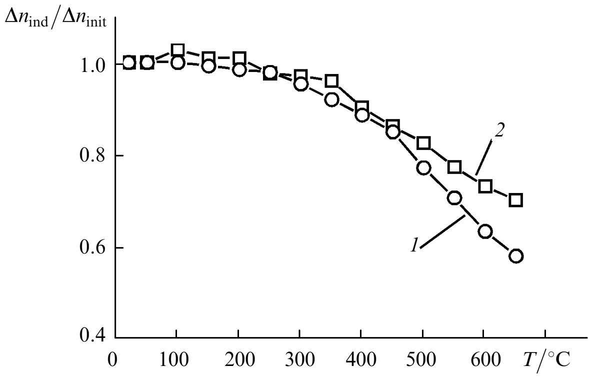

Figure 5. Dependences of the relative change in the refractive index on the temperature of annealing of gratings formed by radiation with the wavelengths 333 – 364 nm (*1*) and 248 nm (*2*).

3. Conclusions

Our results demonstrate that near-UV radiation can be used to 'write' long-period gratings in germanosilicate optical fibres. The maximum RI change induced in the fibre core was 1.9×10^{-4}. Therefore, the readily available and widely used Ar^+ laser can be used (without frequency doubling) to form various types of long-period photoinduced gratings.

The method for the excitation of the GOD centres described above can also be used to 'write' Bragg gratings, but it is then necessary to select one laser line in order to increase the coherence of the UV radiation. This reduces considerably the UV radiation intensity and, consequently, the efficiency of inducing an RI change. As found in our experiments, even a considerable increase in the irradiation time cannot compensate for the reduction in the intensity of the 'writing' radiation.

Further investigations are needed in order to gain full understanding of the mechanisms of the observed photorefractive effect in direct triplet excitation and its correlation with other photoinduced processes activated by the singlet – triplet absorption in the GOD centres. It is worth mentioning that the method of formation of long-period gratings described above can be used also to measure the induced RI change.

References

1. Kashyap R *Opt. Fiber Technol.* **1** 17 (1994)
2. Williams D L, Ainslie B J, Kashyap R, Maxwell G D, Armitage J R, Campbell R J, Wyatt R *Proc. SPIE Int. Soc. Opt. Eng.* **2044** 55 (1993)
3. Neustruev V B *J. Phys. Condens. Matter* **6** 6901 (1994)
4. Dianov E M, Staradubov D S *Opt. Lett.* **21** 635 (1996)
5. Dianov E M, Staradubov D S *Proc. SPIE Int. Soc. Opt. Eng.* **2777** 60 (1995)
6. Kanellopoulos S E, Handerek V A, Rogers A J *Proc. SPIE Int. Soc. Opt. Eng.* **2044** 261 (1993)
7. Dianov E M, Karpov V I, Kurkov A S, Medvedkov O I, Prokhorov A M, Protopopov V N, Vasiliev S A *Paper presented at the Conference on the Photosensitivity and Quadratic Nonlinearity in Glass Waveguides: Fundamental and Applications, Portland, OR, 1995* (OSA Technical Digest Vol. 22) (Washington, DC: Optical Society of America, 1995) p. 14
8. Dianov E M, Kurkov A S, Medvedkov O I, Vasiliev S A *Papers presented at the Eurosensors X Conference, Leuven, Belgium, 1996* p. 308
9. Tamir T (Ed.) *Integrated Optics* (Berlin: Springer, 1975)
10. Patrick H, Gilbert S L *Opt. Lett.* **18** 1484 (1993)