Refractive-index gratings written by near-ultraviolet radiation

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Received August 13, 1996

This is the first report, to our knowledge, of refractive-index grating side writing in 10 mol. % GeO_2-doped fiber by the near-UV light of a cw Ar^+ laser (333–364 nm). An induced-index magnitude as large as 1.9×10^{-4} at 1.7×10^5 W/cm^2 UV power density has been achieved. The observed gratings have exhibited the same temperature stability as gratings written by a KrF excimer laser (248 nm). © 1997 Optical Society of America

The photosensitivity of germanosilicate optical fibers has attracted considerable interest because it allows one to imprint index gratings in the fiber core. Such gratings can be written by UV radiation with the excitation of a singlet–singlet (S_0–S_1) transition band (242 nm) of a germanium–oxygen-deficient center (GODC).[1] The mechanism of the index change has been actively debated, but this phenomenon has not been completely clarified to date. Nevertheless, the GODC photoexcitation is certainly an initial stage of this process.

It is well known that a GODC has a weak forbidden absorption band with its maximum at 330 nm ascribed to the singlet–triplet (S_0–T_1) transition.[2] In our previous experiments a strong photobleaching of GODC triplet–singlet luminescence by direct excitation of the triplet state with near-UV light has been demonstrated.[3] Also, partial erasure of an index grating by homogeneous exposure of cw 333–364-nm radiation has been reported.[4] These results have shown that direct photoexcitation of the GODC triplet state can induce changes in germanosilicate glass structure similar to those induced by 242-nm band excitation and can therefore lead to the index change. But the absorbance of the S_0–T_1 band is 3 orders of magnitude smaller than that in the singlet–singlet transition. This fact can limit the practical utilization of this band for the fabrication of photoinduced structures. However, it is obvious that investigation of the processes induced by direct triplet excitation also stirs scientific interest because it gives additional information concerning the microscopic mechanisms responsible for the refractive-index change.

A suitable object for the investigation of near-UV photorefractivity is long-period ($\Lambda = 100$ μm–1 cm) index gratings that couple two copropagating fiber modes and successfully work as mode converters,[5] narrow-band optical filters,[6] various sensors,[7] etc. The preparation of such a grating type is easier than that of a Bragg grating, because there are no strict limitations on UV light coherence or on the mechanical stability of the writing scheme.

This is the first report, to our knowledge, of fabrication of a long-period cladding-mode-coupled grating in germanosilicate fiber by the cw light of an Ar^+ laser directly exciting the GODC triplet state.

In our experiments we used a Coherent Innova 200 Ar^+ laser operating in the 333–364-nm multiline regime. The gratings were written in step-index profile fiber with 10 mol. % GeO_2 in the core, with a cutoff wavelength of 0.92 μm, by a step-by-step technique. The UV light was focused at the fiber core by a 1-cm-focus spherical silica lens. A typical diameter of a focal spot measured by the optical microscope was ~20 μm. The fiber was placed upon a computer-controlled translation stage that had a minimum step of 3 μm. The grating period of 200 μm to place the resonance wavelengths corresponding to the coupling of HE_{11}–HE_{1m} ($2 \leq m \leq 9$) modes in the working spectral range of 1200–1600 nm. The irradiated part of the grating period $\Lambda/2 = 100$ μm consisted of a discrete set of points separated by the minimum translation step. A typical irradiation time of each point was 1 s. After the irradiation of a half-period region the UV light was blocked by a shutter, and we moved the fiber to write the next grating period. In the scheme described here we formed an approximately rectangular grating profile along the fiber axis. The total grating length L was 40 mm. We varied the total (333–364-nm) UV intensity in the 20–170 kW/cm^2 range by inserting broadband optical filters in the laser beam, keeping a constant relation between the intensities of the laser lines and therefore between their contributions to the induced refractive index. The grating spectrum measurements were performed by an optical spectral analyzer simultaneously with the grating preparation. A halogen lamp was used as a white-light source.

Figure 1 demonstrates a transmission spectrum of a grating written by the technique described herein with a UV intensity of 1.7×10^5 W/cm^2. The fiber was not sensitized by hydrogen loading. As one can see, the depth of our strongest loss peak corresponding to HE_{11}–HE_{19} mode coupling was more than 3 dB. In accordance with the theoretical estimation, the full width at half-maximum of the peak was 6 nm, which testifies to good grating uniformity.

Using coupled-mode theory,[8] we obtained the following relation for loss value S at the resonance wavelength λ_r of the long-period grating:

$$S = \sin^2\left(\frac{4\Delta nIL}{\lambda_r}\right), \tag{1}$$

where Δn is the amplitude of the periodic perturbation of the UV-induced refractive index in the fiber core and I is the overlap integral of the fundamental and the cladding modes in the fiber core. Here we have assumed a rectangular grating profile. For

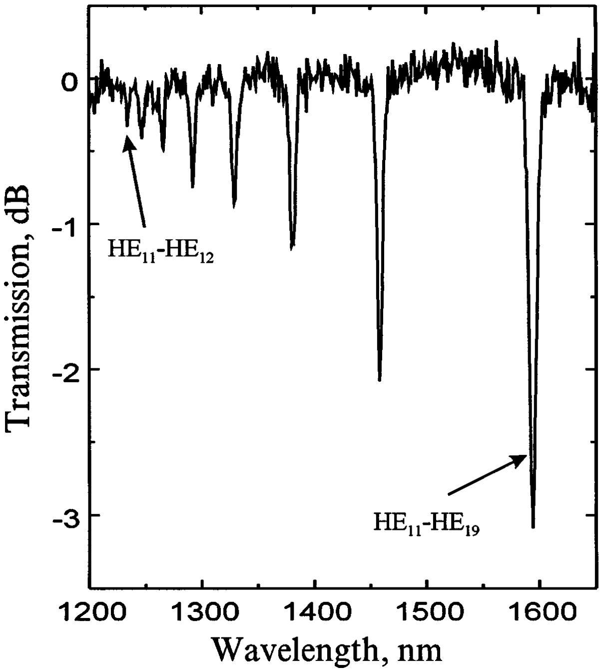

Fig. 1. Transmission spectrum of a 40-mm long-period cladding-mode-coupled grating written in 10 mol. % GeO_2-doped fiber. The grating period is 200 μm.

our fiber the calculated magnitude of the overlap integral was 0.0765. Substituting this value into Eq. (1), we determined the induced refractive-index change $\Delta n_{\mathrm{ind}} = 2 \times \Delta n$ caused by UV radiation. The obtained Δn_{ind} for the grating shown in Fig. 1 was 1.9×10^{-4}.

Figure 2 represents the dependence of the induced refractive index on the UV power density. As in the case of singlet–singlet excitation,[9] this dependence has a saturable behavior.

The grating fabrication with different near-UV lines of an Ar^+ laser, selected by an external prism, shows (Fig. 3) that the spectral efficiency of the refractive-index change (ovals) is similar to the spectral shape of the singlet–triplet absorption of a GODC (curve[2]). In other words, the induced index change is directly proportional to UV power absorbed in the fiber core. Thus near-UV photorefractivity is caused by GODC triplet-state absorption rather than by other secondary processes.

The dependencies of the relative change of the induced index on the temperature at the isochronal annealing of long-period gratings, written by 333–364-nm (curve 1) and by 248-nm (curve 2) light, are shown in Fig. 4. The annealing time at every given temperature was 2 min. Figure 4 demonstrates that the defect centers accumulated under direct triplet excitation have approximately the same temperature stability as those under singlet excitation (some discrepancy between the curves shown in Fig. 4 can be explained by the different initial values of the induced refractive index Δn_{in} in the tested gratings). This set of circumstances allows us to make a conclusion about the analogous mechanisms of index inducing in these two cases of GODC photoexcitation and confirms an our assumption of the important role played by the long-lived triplet state T_1 in GODC photodestruction.[4]

In summary, the experimental results obtained in this study show that the near-UV radiation that directly excites the triplet state of the GODC center can be used for preparation of long-period index gratings. In these experiments we achieved a maximum value of induced refractive index in the 10 mol. % GeO_2-doped fiber core that was as large as 1.9×10^{-4}. Therefore an accessible, widespread Ar^+ laser without frequency doubling can be successfully used for fabrication of a long-period grating.

Note that the method of GODC photoexcitation described here can be used for fabrication of a Bragg grating; there it is necessary to select only one laser spectral line to increase light coherence. However, in this case the UV power and the efficiency of index change are considerably decreased. As we observed in our experiments, even a strong increase of writing time

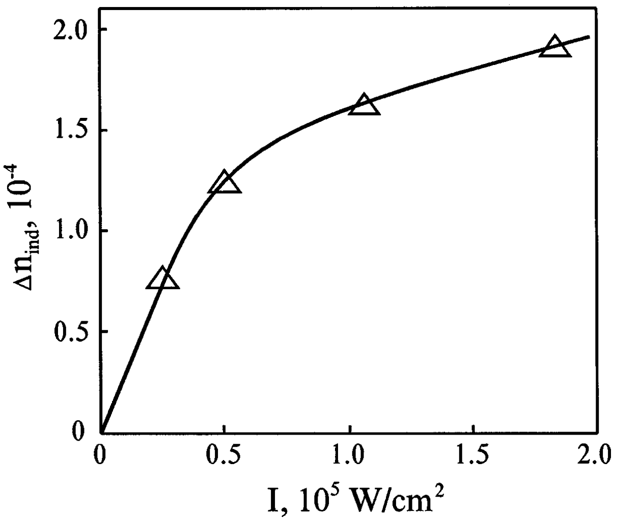

Fig. 2. Dependence of induced refractive index on near-UV power density.

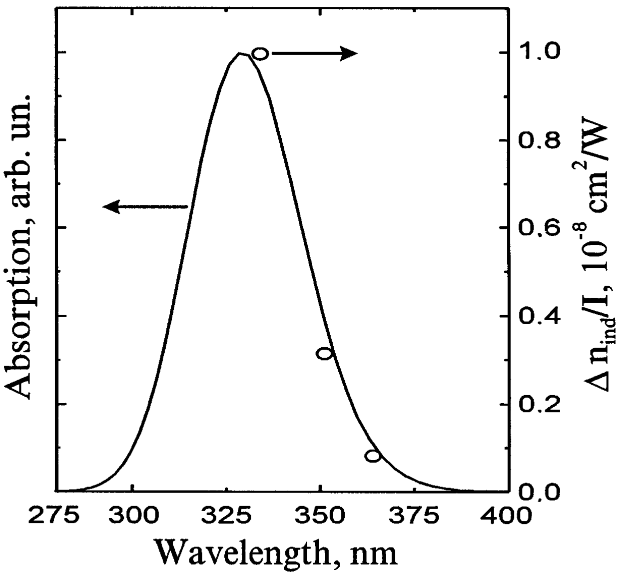

Fig. 3. Spectral efficiency of refractive-index change (circles) in comparison with the spectrum of singlet–triplet absorption of a GODC (curve[2]).

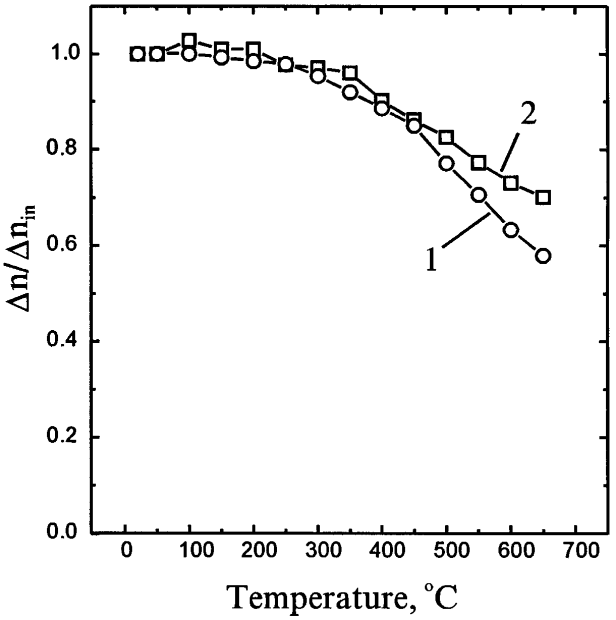

Fig. 4. Dependencies of relative changes of induced index on the temperature at the isochronal annealing of long-period gratings, written by 333–364-nm (curve 1) and 248-nm (curve 2) radiation.

cannot compensate for the power shortage. Therefore we believe that to write an in-fiber Bragg grating one should use a more powerful near-UV laser, and (or) fiber with increased photosensitivity.

The authors thank V. B. Neustruev for stimulating discussions.

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