Analysis and applications of femtosecond-laser-induced nanogratings from UV to telecom wavelength

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Abstract: Nanostructures induced by femtosecond laser beam are characterized over the visible. Permanent refractive index increase with subpicosecond pulses is achieved. Feasibility of using induced anisotropy for spatial mode conversion to 1.5 μm is shown.

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Femtosecond-laser-induced nanogratings in fused silica, with their ability to locally control polarization state of transmitted light, have proven to be a successful tool for numerous applications ranging from polarization Fresnel zone plates and holograms [1,2] to multi-dimensional optical memory and polarization converters [3,4]. It is well known that periodic dielectric layered medium is effectively homogeneous and uniaxial birefringent for optical waves with the wavelength much larger than the layer period. One of the most important parameters characterizing anisotropic optical properties of nanogratings is retardance defined as optical path difference along slow and fast axis. Previous studies of nanogratings in fused silica were mainly concentrated on structural properties such as grating period [5], its dependence on wavelength and inner structure [6]. However, numerous applications involve broadband or multiple wavelength light sources and require spectral characterization of such parameters as retardance and absorption. In this paper, we use a simple optical setup to characterize laser-induced birefringence. Additionally, we investigate transmission the induced structures. As a result of this study we were able to demonstrate a mode converter for 1550 nm, which proves the concept of using light-induced nanostructures in telecommunication devices.

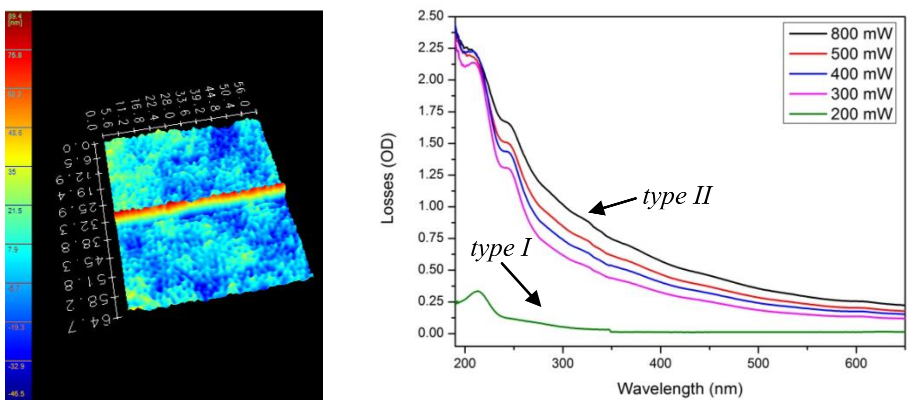

Fig. 1. (Left) Positive phase change induced in fused silica with 320 fs laser pulses. Measurements were performed with digital holography microscope (Lyncee Tech). (Right) Losses measured for a group of samples written with 2nd harmonics at 5 mm/s translation speed. The legend indicates the range of average power used during writing procedure. The large difference in absorption spectra of the structures written at 200 mW (green) and 300-800 mW indicates presence of I (isotropic refractive index increase) and II type (nanograting) modifications.

A regeneratively amplified, mode-locked Yb:KGW (Yb-doped potassium gadolinium tungstate)-based femtosecond laser system PHAROS (Light Conversion Ltd.) was used in the experiments. Repetition rate was set at 200 kHz and pulse duration was adjusted from 270 to 800 fs. For comparison we used two sets of aspheric lenses with the same parameters designed for the visible and near-infrared. The laser beam was polarized perpendicular or parallel to the writing direction. The pulse energy was varied from 1 μJ to 4 μJ and the scanning speed was 2, 5, and 10 mm/s. During the experiments a series of uniform 2 × 2 mm square regions were written in fused silica (Viosil, OH content 1200 ppm) with fundamental (1030 nm) and second (515 nm) harmonics.

After the laser irradiation, the samples were analyzed with a custom polarization measurements set-up enabling retardance measurements in the range from 450 to 1500 nm. Spectral intensity modified by birefringent structures was characterized with a fiber coupled spectrometer. Complimentary characterization and calibration was performed with the quantitative birefringence measurement system Abrio (CRi. Inc.) operating at 515 nm. The losses (180 – 650 nm) on the laser-induced permanent material modification were measured with the spectrometer.

Depending on the fluence, two distinctive types of material modification were obtained. At low pulse energies (<1 μJ) and high scanning speeds (>2 mm/s) isotropic refractive index increase (type I modification) was induced (Fig. 1, left). This type of modification does not exhibit birefringence and has negligible losses over the whole visible region. According to the previous studies, isotropic refractive index increase could not be achieved with pulse durations longer than 150 fs [7]; however, in our experiments we noticed that this modification can be induced even with 400 fs pulse trains if the pulse energy and number is relatively small (few hundreds of pulses) or, in other words if writing speed is high enough (at least 2 mm/s). This observation indicates that waveguiding structures can be written in fused silica even with relatively long sub-picosecond laser pulses: the duration which is typical for amplified diode pumped solid state or fibre laser systems.

The type II modification was induced at higher pulse energies and it exhibited strong anisotropy (which is related to self-assembled nanograting) and high scattering losses at short wavelength side (Fig. 1, right). The retardance value was constant from 500 to 1500 nm (not shown here). The main part of losses is contributed to the Rayleigh scattering caused by the inhomogeneous structure and it follows $1/\lambda^4$ dependence. Additionally, two absorption bands can be distinguished at short wavelength, which are attributed to Si E' centers (210 nm), an unpaired electron in a silicon atom bound to three oxygen atoms, and ODC(II) (245 nm), a divalent silicon atom, defects induced by ultrashort light pulses [8]. On the contrary, structures with induced isotropic refractive index increase showed negligible scattering and curiously only E' centers related absorption band is observed (Fig. 1, right).

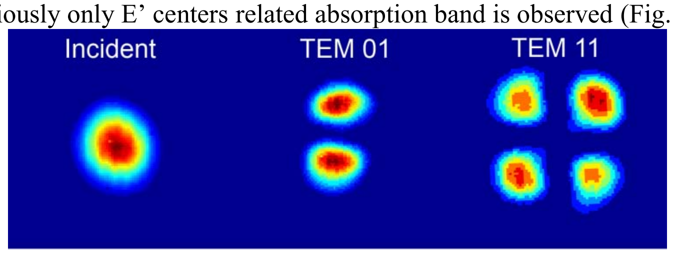

Fig. 2. Measured beam profiles of incident circularly polarized Gaussian mode (1550 nm) and higher TEM modes generated using birefringent mode converters.

The low losses at the near infrared (80% and 90% transmission for 1030 nm and 1550 nm respectively) allowed fabricating birefringent mode converters for 1550 nm. A sufficient phase retardation was reached with a converter comprised of three birefringent layers. As a result of $\pi/2$ retardance, the phase of the incident circularly polarized beam is spatially altered. Two different mode converters were fabricated for TEM01 and TEM11 mode generation. This method could be explored for higher mode generation and phase control by polarization manipulation. Optical properties of the mode converters were characterized with InGaAs camera (Fig. 2). One can see that generated modes are symmetric with no apparent presence of the incident beam, indicating good conversion of the Gaussian beam into high transverse modes.

References

1. E. Bricchi, J. D. Mills, P. G. Kazansky, B. G. Klappauf, and J. J. Baumberg, "Birefringent Fresnel zone plates in silica fabricated by femtosecond laser machining.," Optics letters **27**, 2200-2 (2002).
2. W. Cai, A. R. Libertun, and R. Piestun, "Polarization selective computer-generated holograms realized in glass by femtosecond laser induced nanogratings.," Optics express **14**, 3785-91 (2006).
3. M. Beresna, M. Gecevičius, P. G. Kazansky, and T. Gertus, "Radially polarized optical vortex converter created by femtosecond laser nanostructuring of glass," Applied Physics Letters **98**, 201101 (2011).
4. Y. Shimotsuma, M. Sakakura, P. G. Kazansky, M. Beresna, J. Qiu, J. Qiu, K. Miura, and K. Hirao, "Ultrafast manipulation of self-assembled form birefringence in glass.," Advanced materials **22**, 4039-43 (2010).
5. W. Yang, E. Bricchi, P. G. Kazansky, J. Bovatsek, and A. Y. Arai, "Self-assembled periodic sub-wavelength structures by femtosecond laser direct writing," Optics Express **14**, 10117 (2006).
6. Y. Bellouard, E. Barthel, A. A. Said, M. Dugan, and P. Bado, "Scanning thermal microscopy and Raman analysis of bulk fused silica exposed to lowenergy femtosecond laser pulses," Optics Express **16**, 19520 (2008).
7. C. Hnatovsky, R. S. Taylor, P. P. Rajeev, E. Simova, V. R. Bhardwaj, D. M. Rayner, and P. B. Corkum, "Pulse duration dependence of femtosecond-laser-fabricated nanogratings in fused silica," Applied Physics Letters **87**, 014104 (2005).
8. A. Zoubir, C. Rivero, R. Grodsky, K. Richardson, M. Richardson, T. Cardinal, and M. Couzi, "Laser-induced defects in fused silica by femtosecond IR irradiation," Physical Review B **73**, 1-5 (2006).