Writing optical waveguides in fused silica using 1 kHz femtosecond infrared pulses

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We have investigated the writing of waveguides in bulk pure fused silica glass with femtosecond Ti:Sapphire laser at 1 kHz repetition rate. The photoinduced tracks were characterized in terms of writing geometry (parallel and perpendicular), pulse duration (45 fs, 140 fs, and 200 fs), pulse energy (1–10 μJ), and translation speed (5–150 μm/s) of the sample. Under specific writing conditions, uniform buried waveguides with circular cross section, core diameter of 3–4 μm, and refractive-index change as large as 5×10^{-3} between core and cladding were achieved. © 2003 American Institute of Physics. [DOI: 10.1063/1.1557777]

In recent years, there is a growing interest in glass micromachining by Ti:Sapphire laser. A lot of studies were conducted on finding the damage threshold of glass in different regimes, on improving the glass surface ablation in femtosecond regime, on having three-dimensional (3D) optical storage in transparent materials, and on creating photonic crystals for light guiding. It was demonstrated that a focused Ti:Sapphire laser pulse can induce a change in the refractive index inside glass network without damage. Using this technique, it is possible to write directly 3D structures such as waveguides inside different kinds of transparent glasses, pure and doped fused silica glass, and chalcogenide glass, by translating the sample through the focal point of the beam. For example, Homoelle et al. reported buried waveguides written in pure fused silica with index changes as large as 3×10^{-3} using a 1 kHz laser beam. In addition, it has been shown that this method allows the writing of more complex structures such as couplers, and diffraction gratings. Furthermore, it was demonstrated recently that waveguides can be written inside glass using only a Ti:Sapphire oscillator with nanojoule energy per pulse.

We report experimental results on the writing and characterization of buried waveguides in pure fused silica using 1 kHz Ti:Sapphire laser. We found that under a restricted range of writing conditions, index changes as large as 5×10^{-3} can be achieved. Plasma formation through multiphoton excitation (MPE) of electrons from the valence to the conduction bands seems to be the major contribution in the formation of our waveguides. Such a study is important for determining the optimal conditions for producing the requisite refractive-index changes for fabricating practical photonic devices in bulk optical materials.

Two regeneratively amplified 810 nm Ti:Sapphire lasers (Spectra-Physics and Clark-MXR Inc.) at a 1 kHz repetition rate were used. A vacuum spatial filter was used to produce a Gaussian beam profile. The beam was subsequently focused with a Nikon microscope objective lens (NA: 0.3, f: 20.8 mm, aperture size: 12.5 mm) and injected into the polished surface of the silica glass. The energy per pulse before the lens was varied between 0.5 and 10 μJ by using a half-wave plate placed before the compressor. An autocorrelator was used to measure pulse duration before the focusing lens with a ±5 fs uncertainty. Three pulse durations were used in this experiment, i.e., 45, 200, and 140 fs. The first and the second pulse durations are nearly transform limited while the third one (140 fs) corresponds to a chirped pulse. The input beam diameter (1/e^2 intensity) before the focusing lens was measured to be about 4.6 mm with a charge coupled device (CCD) camera. The beam spot size and confocal parameter in the glass were estimated to be 2w_0≈2.94 μm and b = 2πnw_0^2/λ = 24.4 μm, where n≈1.46 and λ are the index of refraction of fused silica and wavelength in a vacuum, respectively. The sample was moved at a speed ranging between 5 and 150 μm/s parallel and perpendicular to the incident beam by using a motorized translation stage with a resolution of 1 μm. As a result, visible tracks inside the glass were created. The effects of pulse energy, translation speed,
and pulse duration, on the refractive index change and homogeneity of the guiding tracks were investigated. Figure 1 shows the schematic of the experimental setup. The tracks and their cross sections were subsequently examined under a 100×–400× magnifying optical microscope. For all energies used, some photoinduced modifications took place in the sample. This was manifested by a weak continuous scattered light observed in the transverse direction perpendicular to the laser beam. In addition, sometimes during scanning the sample, we observed both by the naked eye and with an infrared viewer a relatively strong scattered light when using the longer pulse durations and/or sufficiently higher energies.

The tracks appear to be either homogeneous or inhomogeneous. That is, their characteristics depend strongly on pulse duration and scan speed. In perpendicular writing, almost all of the visible tracks were homogeneous for both 140 fs (pulse energy <8 μJ, scan speed ≥20 μm/s) and 45 fs (pulse energy <10 μJ, scan speed ≥10 μm/s) pulse duration, as shown in Figs. 2(a) and 2(b). However, in parallel writing all the tracks written with 140 fs and 200 fs pulses were inhomogeneous similar to the ones written perpendicular at 8 and 10 μJ shown in Fig. 2(a); whereas those written with 45 fs pulse were homogeneous, up to the maximum power used (7 mW). The inhomogeneous tracks are similar to those observed by other groups and are known as voidlike structures, which are not efficient for guiding light. The tracks written with 45 fs pulse within the range of energy used (1–10 μJ) showed relatively good uniformity, performing as efficient waveguides (as tested later) with the apparent absence of scattering centers [Fig. 2(b)].

We looked at the cross section of the track after polishing the glass using an optical microscope. The cross sections of those written perpendicular to the laser beam appeared to be strongly elliptical for all the pulse durations [Fig. 2(c)], similar to the ones reported in Ref. 10. In contrast, the cross sections of those written parallel to the laser beam were almost circular (∼3–4 μm in diameter) when probing both at the surface and inside the glass [Fig. 2(d)]. In addition, one could note that the tracks written with 140 fs pulse appear to be larger and darker for 4 and 7 μJ compared with those written by 45 fs pulse.

In perpendicular writing, the length of the major axis of the elongated elliptical cross section varied with pulse energy. That is, it became longer with higher pulse energy, varying from 40 to 180 μm. The length of the minor axis, however, varied only from 3 to 4 μm. More importantly, we
noticed that the length of the major axis was always larger than the depth of focus of the laser beam. This is an indication of self-focusing and filamentation of the laser pulses inside the glass.\textsuperscript{21,22}

To investigate the possibility of guiding light through the tracks with circular cross sections, we coupled a He–Ne laser beam at 632.8 nm into the polished surface of the glass using a 16\times microscope objective, and looked at both the near- and far-field patterns of the output beam with the CCD camera and a white screen. It appeared that all the homogeneous tracks written in the parallel configuration with 45 fs pulse resulted in a clear interference pattern in the form of concentric rings together with a bright central disk in the far field. This ring pattern is associated with the interference of guided light with the light passing through the surrounding unexposed region of the glass. Moreover, we observed no scattered red light alongside such tracks during the light coupling. The intensity profile of the light coupled out of some of the waveguides was nearly Gaussian (similar to fundamental LP\textsubscript{01} mode of a fiber) as shown in Figs. 3(a) and 3(b), suggesting the single-mode propagation at 633 nm. The inhomogeneous tracks written in parallel with 140 fs and 200 fs pulses strongly scattered the red light during propagation and no interference pattern was observed in the far field.

The induced refractive-index changes were estimated by measuring the numerical aperture \[ NA = (n_1^2 - n_2^2)^{1/2} \] \( n_1 \) and \( n_2 \) are core and cladding refractive indices, respectively] of the cone of light emerging from the end facet of the waveguides. By measuring the radii (at two far and near distances from the sample) at which the rings fade, we estimated (for small \( \Delta n \) and assuming a step index waveguide) the refractive index change between core and cladding using \( \Delta n \sim NA^2/2n_2 \). It appeared that for pulse energies higher than about 3 \( \mu \)J (at 20 \( \mu \)m/s), both the size and the intensity of the central bright disk start decreasing, while the width and the intensity of the first ring gradually increase up to the formation of a larger but less bright disk at a higher pulse energy of about 6 \( \mu \)J, as illustrated in Figs. 3(c) and 3(d).

This could be due to a complicated output intensity distribution resulted from the overlap of several guided modes that simultaneously propagate through the multimode waveguides. Besides, the phase variation of the guided light with pulse energy may also contribute to the interference conditions and observed changes in the far-field pattern. The results of \( \Delta n \) measurements are summarized in Fig. 4. An estimated experimental error of 30\% is associated with this technique mostly due to the uncertainty in measuring the ring radius. The index change has a saturation behavior versus pulse energy for two scan speeds of 10 and 20 \( \text{m/s} \), where values up to 5\times10\textsuperscript{-3} have been obtained. Compared to a recent work, the waveguides written by Homoelle et al.\textsuperscript{14} were damaged for pulse energies higher than 4 \( \mu \)J, whereas we could achieve uniform waveguides using writing energies up to 8 \( \mu \)J per pulse.

Furthermore, by measuring the guided light intensity profile (with a CCD camera) of different waveguides written with 2 \( \mu \)J pulse energy and pulse duration of 45 fs (at the position of the sample) at different translation speeds between 20 \( \mu \)m and 150 \( \mu \)m, we observed that the waveguides written at higher speeds show both smaller core size and less
confinement of light in the core region. This might be due to the fact that the total exposure energy received by each point of these waveguides is less than that for those written at lower speeds (less energy accumulation effect), and thus the refractive index change would be smaller. Therefore, these observations together with the data shown in Fig. 4 suggest a nonmonotonic variation of index change with scan speed. Attempts to achieve waveguides with higher index changes by scanning the sample at lower speeds led to damaged waveguides as observed in the case of long pulse excitation.

In order to describe the observed experimental results, we need to point out the two following physical mechanisms involved in our experiments. Intense ultrashort near IR or visible laser pulses propagating through glass (or any optical medium) can self-transform into a broadband pulse that appears white to the naked eye.21 This phenomenon, popularly called supercontinuum generation, occurs during filamentation,22–23 that in turn results from the dynamical balance between two effects: Self-focusing due to the nonlinear Kerr effect, and self-defocusing associated with the plasma formation in the self-focus, mainly through MPE of electrons from the valence band to the conduction band in glass.

The second mechanism, optical breakdown, is an accumulative process in time which is based on strong plasma formation at (near) the geometrical focus, caused by inverse Bremsstrahlung, impact ionization, and electron avalanche, with a time scale of a few hundred femtoseconds (note that in glass compared to gases, the required buildup time for such a plasma would be shorter). The optical breakdown is usually accompanied by an isotropic white radiation (plasma emission) due to electron recombination, as well as by partial scattering, reflection, and absorption of the input laser beam.

The relative contribution of these two mechanisms mostly depends on pulse duration and external focusing condition. That is, a tight focusing and/or irradiation by sufficiently long pulse favors the occurrence of optical breakdown earlier than filamentation. For tighter focusing, this is due to an increase in impact ionization rate,2 and for long pulse excitation, there is sufficient time for electron avalanche to develop and create the plasma with a high density of \(10^{19} - 10^{21} \text{ cm}^{-3}\). On the other hand, filamentation can take place earlier than optical breakdown when focusing by sufficiently long focal length lenses using femtosecond pulses.23

We were able to detect the weak scattered light, mentioned earlier, as a manifestation of optical breakdown, by using an appropriate bandpass filter, and a lens (\(f = 60 \text{ mm}\)) to focus the diverging light onto a photomultiplier tube. The measured threshold energy (~0.3 \(\mu\text{J}\)) was lower than all of the input energies used for the waveguide writing. Thus, the strong plasma formation via MPE and partially through avalanche ionization, followed by transferring its energy to the glass lattice, could be at the origin of the index changes.

On the other hand, we estimated the length of filaments, approximated as the distance between the first self-focal position and the geometrical focus, in terms of pulse energy using the relations \([1 - 3]\) in Ref. 22; the nonlinear index of refraction of fused silica being \(n_2 \approx 3 \times 10^{-16} \text{ cm}^2/\text{W}\). They were found to be very close to those experimentally obtained through measuring the major axis of the elliptical waveguides under a microscope [Fig. 2(c)]. It should be emphasized, however, that although such beam filamentation can extend the region of refractive index change in the glass compared to sufficiently tight external focusing for which almost no filamentation occurs, the plasma formation should always be considered as responsible for the index changes.

The higher refractive index in the irradiated region can be interpreted as follows: The free electrons created by excitation from the valence to conduction band (via multiphoton excitation,22 and a partial avalanche ionization because the pulse is very short) transfer their energy to the glass structure following their relaxation, leading to local heating and melting the glass. The molten glass is subsequently rapidly cooled. This leads to densification in the irradiated region which contributes to the measured refractive index changes. Presently, we have no clear evidence for this assumption while further investigations are underway via studying the observed birefringence in our waveguides. Such local heating and melting the glass is also in agreement with the observation of ejected amorphous glass as well as crystalline particles from fused silica surface when irradiated by similar laser pulses.24

In summary, we have presented results on writing waveguides in pure fused silica glass with a Ti:Sapphire laser (810 nm, 1 kHz, and 45 fs). The waveguides written both in parallel and perpendicular geometries were characterized in terms of pulse energy between 0.5 and 10 \(\mu\text{J}\), and under translation speeds from 10 to 150 \(\mu\text{m}/\text{s}\). The dependence of refractive index change on pulse energy and scan speed was investigated, where index changes up to \(5 \times 10^{-3}\) were achieved for scan speed of 20 \(\mu\text{m}/\text{s}\). The plasma formation via MPE and partially through avalanche ionization followed by its energy transfer to the glass lattice is supposed to be responsible for the waveguide formation. However, more investigations need to be done to elucidate the complete physical mechanisms underlying the observed index changes.

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