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Photosensitivity of a tin doped multicomponent silicate glass: direct UV writing of channel waveguides

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Abstract

In this paper the fabrication of channel waveguides by direct UV writing into a bulk tin doped multicomponent silicate glass is presented. Different laser powers and scan rates were employed and optimized to avoid surface ablation. The best results were obtained at a laser power of 95 mW and at a scan speed of 10 mm/min, where a refractive index change of 1.5×10^{-3} was estimated and an attenuation loss of 3.3 dB/cm was measured using the cutback method. A morphological investigation of the glass end facets was performed in order to assess the surface effect of the laser exposure.

For several years photosensitive glasses have attracted attention as a potential route towards low-cost integrated optical devices [1]. The localised change in refractive index induced in photosensitive materials when exposed to short-wavelength radiation has traditionally been used to fabricate fiber Bragg gratings, which are key components for mirrors, filters and other wavelength selective devices for telecom and sensor applications. Since the discovery of photosensitivity by Hill et. al. in 1978 [2], most research has been focused on commercially available silicate glass hosts where the photosensitive element is Ge [1] and the maximum UV-induced refractive index changes is around 10^{-3}. Further studies towards enhancing the photosensitive response of such glasses led to the introduction of Sn^{4+}, at first as a codopant to germanium [3], and later as the only photosensitive ion [4]. With the introduction of tin providing an improved UV-induced refractive index change, Na_2O was then added to increase the solubility above 1 mol % of SnO_2 in the silicate glass host, allowing fiber Bragg gratings with an induced refractive index change of 6×10^{-4} and a remarkable temperature stability (up to 680°C) to be produced [5].

Recently, photosensitivity in glasses has been extended towards planar device fabrication by UV laser direct writing, a process in which a laser beam is scanned along the surface of a photosensitive substrate in order to induce a local refractive index change suitable for waveguiding. This technique eliminates the development time and costs associated with repeated photolithographic steps, providing a rapid and potentially inexpensive route towards device prototyping and small lot production. Direct UV writing was first employed on Chemical Vapor Deposition (CVD) photosensitive thin films, where GeO_2 doped silicate glasses were used to produce channel waveguides [6]. More recent experiments in direct UV writing have led to the fabrication of channel waveguides in GeO_2 doped sodium silicate bulk glass samples, with different results depending on the photosensitive element concentration: at lower Ge content (6 mol %) vertical slab waveguides were obtained with a refractive index change all the way through the material, while at higher Ge content (20 mol %) an increased absorption provided channel waveguides in the surface of the material [7]. The surface effect associated to such waveguide types was negligible in the case of vertical slab waveguides, whereas for the 20 mol % GeO_2 doped glass a photothermal expansion was detected by means of surface profilometry. In both cases however, low numerical apertures (NA = 0.05) were obtained.

In this letter we present the first example of channel waveguides obtained by direct UV writing into a bulk tin doped multicomponent silicate glass. For this experiment, our glass was designed to incorporate at least 5 mol % tin oxide to provide photosensitive behavior and therefore to increase its solubility sodium oxide had to be added into the material [8]. The composition chosen for our glass was $85SiO_2{:}5SnO_2{:}10Na_2O$, a composition similar to that used in our previous fiber Bragg grating fabrication, but containing half the amount of Na_2O to provide a higher glass transition temperature for better high temperature properties and thus a higher laser induced damage threshold for direct-UV-written waveguide fabrication [5]. It is hoped that this new glass type will provide a potential route towards integrating direct-written channel waveguides and Bragg gratings in bulk photosensitive glasses [9], and is expected to exhibit much higher photosensitivity than commercially available germanosilicate glasses.

The glasses used during this experiment were fabricated by melting high purity batch oxide and carbonate powders at 1700 °C in Pt-crucibles in a chamber furnace in air. After annealing at the glass transition temperature for 2 hours, followed by slow furnace cooling, the glasses were drilled out of the crucibles. The samples were then cut using a precision saw, polished to optical quality and then characterized in terms of physical and optical properties. By differential scanning calorimetry a Tg value of 658°C was measured. Optical characterization was carried out using UV spectroscopy on the prepared glass and on sodium doped germanosilicate glass having approximately the same quantity of photosensitive ions (6 mol % GeO_2) and the measured loss values at 244 nm were 0.2268 and 0.0154 dB/μm, respectively. This data was used to plot the transmittance vs. depth curves of Figure 1, where half of the UV beam is absorbed within a 12 μm depth in the tin doped glass and within a 200 μm depth for the germanium doped glass. These results show that tin oxide incorporation produces a much higher absorption at 244 nm than a silicate glass containing the same amount of germanium oxide.

Direct UV writing was performed using a frequency doubled Ar-ion laser operating at an emission wavelength of 244 nm and focused to a 7 μm diameter spot. The sample was set up on a computer controlled translation stage [7] and, after a preliminary focusing of the beam on the sample surface, laser scanning was operated by moving the sample in a direction perpendicular to the laser beam.

A preliminary study was conducted in order to determine the best power conditions to be used to photo-write the glass. Laser powers ranging from 90 to 250 mW and scan speeds from 3 to 3000 mm/min were tested. The existence of waveguides was checked by launching a Helium:Neon laser beam into the polished end of the glass and analyzing the far field image. Guiding structures have been observed only for laser powers of <150 mW. Further optimization of the channel waveguide geometry was then performed by fine adjustment of the writing intensity and translation speed of the focused UV beam. For this experiment, a beam power of 95mW provided the best wave guiding results, leading to the formation of channel waveguides. A series of waveguides were then photo-written at this power with scan rates ranging from 10 to 2000 mm/min.

Optical characterization of the channel waveguides was performed by near field microscopy using laser sources at 633 nm, 980 nm and 1550 nm. All waveguides written at speeds up to 1500 mm/min showed mode guiding at 633 and 980 nm, whereas none of them supported mode confinement at 1550 nm.

UV-induced refractive index changes were estimated by fitting the measured near field profiles with the ones calculated assuming an exponential decay of Δn (an assumption based on our observation of exponential UV absorption in these glass types), as depicted in Figure 1. The recovered values for Δn are those that correspond to a difference between measured and computed field intensities below the incertitude of the measurement. An example of field fitting for the waveguides written at 10 mm/min is shown in Figure 2, where both the measured and the computed depth cut of the near field intensity profiles are compared. Previous tests of this method were performed for the analysis of ion-exchanged silicate glasses (in this case a Gaussian profile must be considered), and good results were achieved [10]. Although this approach does not take into account thermal effects or partial ablations due to the UV beam, it leads to a useful correlation between the writing speed and the capability of changing the refractive index. Improvements in index profile measurement are going to be performed by using other techniques such as the refractive near field method [11], which may lead to accuracy in index profiling up to 10^{-5}.

Results of field-fitting index recover are reported in Figure 3. It can be seen that higher Δn are obtained at lower speeds, where the refractive index change ranges from 1.5×10^{-3} to 0.5×10^{-3}. It must be pointed out that the near field intensity profiles for channel waveguides written at scan speeds above 400 mm/min included a significant amount of background noise, and as such the recovered values for the index variation are assumed to be less accurate.

Propagation losses in the channel waveguides were measured using the cutback method. The light was coupled both at the input and output ends of the waveguide by optical fibers, detected using a photodiode and then measured on a power meter. The strongest channel waveguides, written at scan speeds below 700 mm/min and possessing a well-confined mode, featured an average propagation loss of 3.4 dB/cm, whereas the weaker waveguides written at speeds above 700 mm/min presented an increasing loss due to poorer mode confinement, as reported in Figure 3.

The analysis of Figure 3 would suggest that the best results in terms of maximum refractive index and low attenuation loss are to be found at speeds lower than 10 mm/min. Such scan speeds are, however, too low for practical applications, as the fabrication of an integrated optical circuit would require too much time. An improvement of the waveguide properties is then to be pursued by tailoring the glass composition, for example by finding methods to increase the SnO_2 concentration without increasing the Na_2O concentration at too high levels, where ablation at low laser powers would occur.

In order to assess the effect of the laser beam on the sample surface a morphological topography investigation was performed using Scanning Electron Microscopy. In Figures 4a and b the micrograph of waveguides written at 50 mm/min and at 500 mm/min are shown, respectively. At the higher speed no physical change was detected at the surface of the glass, whereas at lower scan speeds a depression, featuring side lobes, was seen to occur in the UV-induced waveguide region. An investigation of the refractive index change mechanism is to be pursued in a future work.

In conclusion, we have demonstrated the fabrication of the first direct written channel waveguides in a bulk tin doped sodium silicate glass using a frequency doubled Ar ion laser source, operating at 244 nm. Characterization of waveguides written at different scan speeds led to a maximum index variation of 1.5×10^{-3} at 10 mm/min writing speed. Channel waveguides written using these conditions were optimized and characterized for operation at wavelengths below 1um. Attenuation measurements using the cutback method revealed a propagation loss of 3.3 dB/cm for all channel waveguides fabricated using the same writing speed. These results represent a first step towards optimized bulk photosensitive tin-silicate materials and direct writing conditions which could lead to low cost optical integrated devices for mass production requirements.

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Figure captions.

FIG. 1: Transmittance vs. thickness plot of glass $85SiO_2:5SnO_2:10Na_2O$ and of glass $84SiO_2:6GeO_2:10Na_2O$ at $\lambda = 244$ nm.

FIG. 2: Comparison of the depth cut of the measured (solid line) and computed (dash line) field intensity profile for the waveguide written at 10 mm/min (laser power was 95 mW).

FIG. 3: Maximum index change and loss per unit length against UV-beam speed.

FIG. 4: SEM micrograph showing the end facets of a waveguide written at (a) scan rate of 50 mm/min and (b) at 500 mm/min.

Figure 1 Daniel Milanese Applied Physics Letters

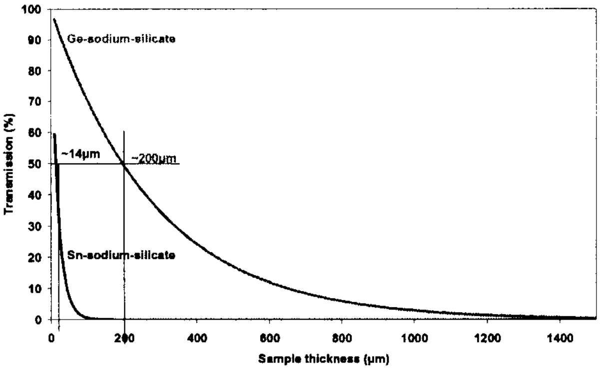
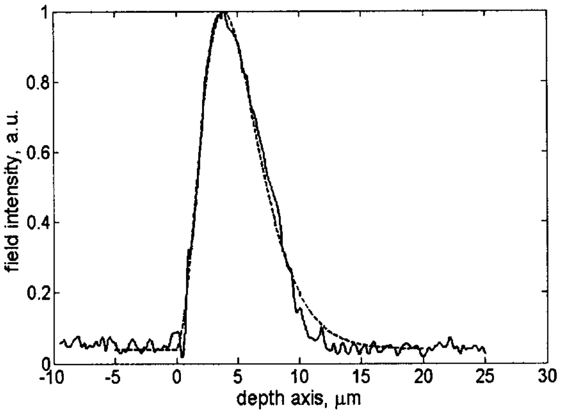


Figure 2 Daniel Milanese Applied Physics Letters



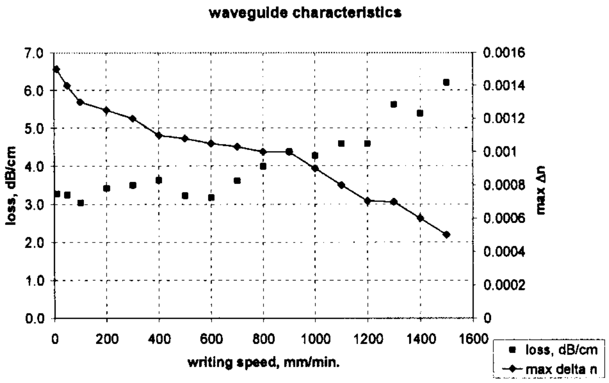
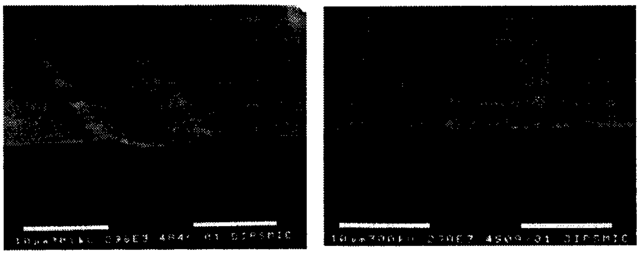

waveguide characteristics
loss, dB/cm
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
200
400
600
800
1000
1200
1400
1600
writing speed, mm/min.
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
max Δn
■ loss, dB/cm
◆ max delta n

Figure 4 Daniel Milanese Applied Physics Letters



(a) (b)