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Refractive index variations induced by femtosecond laser direct writing in the bulk of As_2S_3 glass at high repetition rate

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ABSTRACT

This paper deals with the refractive index variation (Δn) induced by femtosecond laser irradiation in the bulk of As_2S_3 glass in a high repetition rate regime. Extensive measurements of spatially resolved Δn profiles of photowritten channels are reported for various values of the pulse energy. Nearly Gaussian profiles are obtained for energy slightly above the threshold whereas at higher energies the structure of Δn is more complex with a negative core surrounded by a positive ring. A thermal model is applied to reproduce the behaviour of the overall structure diameter.

1. Introduction

Chalcogenide glasses (ChG) exhibit particular properties including a wide IR transparency window, high linear and nonlinear refractive indexes, and a capability to be synthesized in a wide range of compositions so that properties can be engineered as needed [1]. The intensive investigations of ChG have shown that they are very promising optical materials over oxide glasses and single crystals because of high application potential in optical communications [2,3], infrared sensing [4–6] high density optical recording [7].

Optical waveguides in ChG can be fabricated by several techniques such as photo-lithography, ion implantation, and laser beam writing. Since the pioneering work of Hirao [8], femtosecond laser micromachining of photonic devices has received a growing interest and has demonstrated its ability to produce both passive and active elements [9,10] with performances comparable to those elaborated by more usual techniques [11]. Due to the high peak power of femtosecond pulse, nonlinear light-matter interaction with transparent media is effective, and because of this nonlinear character, the interaction and the resulting material modifications are very localized around the focus of the laser beam. Laser beam can then be used as a pen to modify the material properties, and consequently to design 3-dimensional structures what is considered as one of the most interesting potential of this technique [12,13].

Photowriting has already been demonstrated in different ChG [14,15]. In particular case of As_2S_3 ChG, literature reports a few works about the fabrication of waveguides in bulk using femtosecond laser pulses at $\lambda = 800$ nm [16,17]. At the best of our knowledge, no investigation relative to the influence of the pulse energy at a high repetition rate over spatially resolved refractive index variations (Δn) has been reported so far although the guiding properties are directly correlated.

The aim of this study is to underline the influence of the deposited pulse energy level at high repetition rate over the generated Δn. We report the inscription of straight lines in the bulk of As_2S_3 glass for different values of the deposited pulse energy. Spatially resolved Δn reconstruction demonstrates that the structure of the variation can be complex with a positive or negative core. Particular attention is paid on the low energy level. A simple thermal model is shown to reproduce the overall diameter of Δn but differs from what could be expected to be the guiding region.

2. Sample preparation and experiments

To optimise the optical properties of the As_2S_3 glass, the amount of absorbing impurities is minimised throughout two purification steps. The starting arsenic (CERAC, 99.9999%) is introduced into a silica tube and the high vapour pressure contaminants such as oxides are removed by evaporation under vacuum ($T = 290$ °C). The starting sulfur (CERAC, 99.999%) is beforehand heated at 120 °C for 12 h and introduced in the experimental set-up. Then, the

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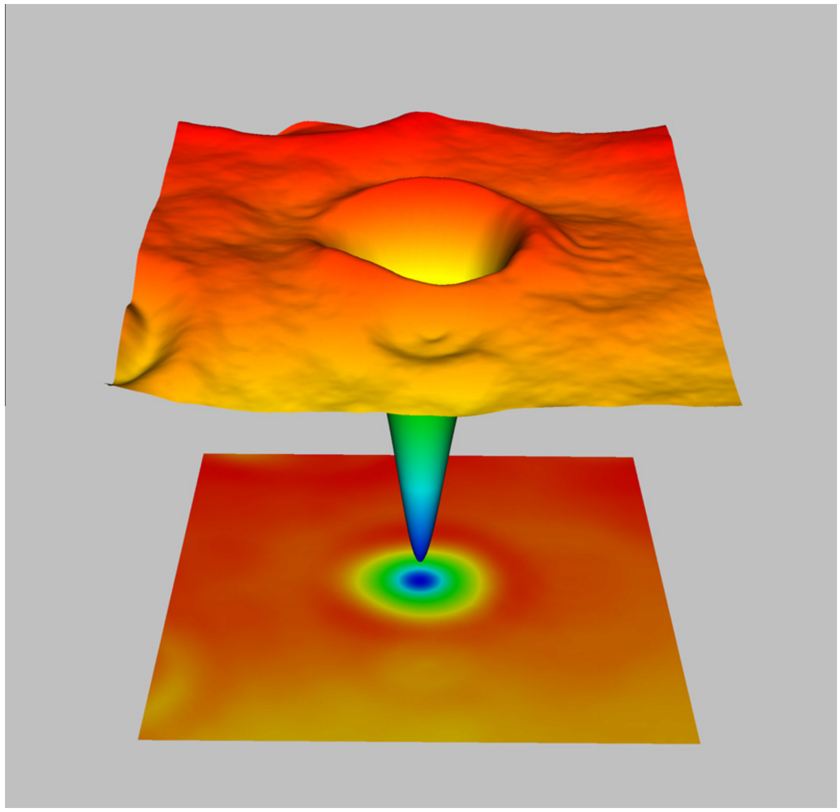

Fig. 1. Images of the spatially resolved profile of the phase induced by the irradiation of the As_2S_3 glass by femtosecond laser. The planar projection of the 3D image of the phase (in the top) is shown in the bottom to underline the circular profile of the inscription.

low vapour pressure contaminants such as carbon are separated by distilling the melt in a double chamber silica tube within a temperature gradient furnace. The resulting melt is then homogenised in a rocking furnace at 800 °C for 24 h. The quench is operated from 500 °C in a room temperature water. Finally, an annealing is processed around the glass transition temperature T_g.

The photoinscription is performed on samples shaped to parallelepipeds and polished down to optical quality. During the writing process, they are translated, across the focal point, parallel to the laser beam. This longitudinal geometry ensures axial symmetry of Δn profile. It is permitted since the low photosensitivity of ChG does not require strong focusing and allows to use long working distance microscope objective. Here a X5 one with numerical aperture equal to 0.1 was used. The translation is done at a constant speed of 1 mm s^{-1} for all the lines. Femtosecond pulses were generated with titane sapphire oscillator (Coherent Inc., Mira) of high repetition rate (76 MHz). Pulses have a central wavelength of 800 nm and their duration is measured to be on the order of 120 fs. Pulse energy adjustment is done by use of two crossed polarizers. The second one is kept in a fixed position to ensure a constant polarization for all the experiments.

3. Results and discussion

The reconstruction of Δn is carried out in two steps. First the transverse image of the photowritten structure is observed with a standard microscope equipped with Leica DFC320 camera. The phase of the optical wave that forms the image is determined by Quantitative Optical Phase Microscopy [18]. The transverse profile given in Fig. 1 clearly shows that the phase profile is axially symmetric as expected from the writing procedure. Consequently, an Abel inversion can be applied to the phase to get spatially resolved

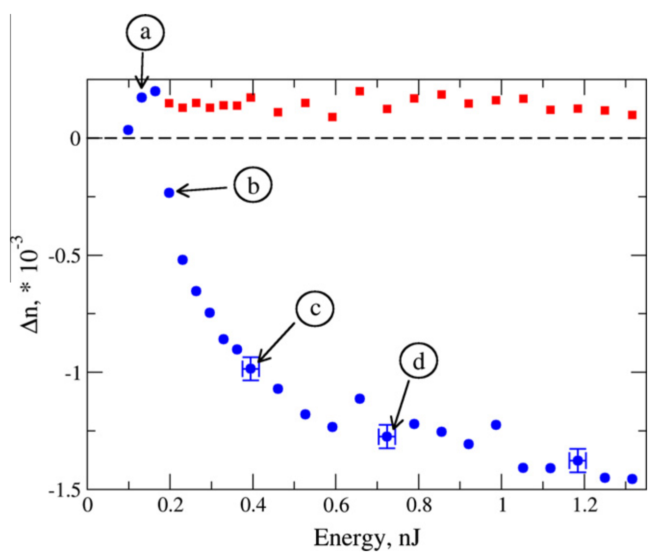

Fig. 2. Magnitude of Δn. Blue circles represent the magnitude of the core of the profile. Red squares correspond to the amplitude of the positive ring that surrounds the core (when exists). See Fig. 3. Horizontal error bars are related to the resolution of the powermeter. Vertical ones represent statistical variations for repeated writing experiments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$\Delta n(r)$ [19,20]. We point out that the obtained values are circularly averaged around the symmetry axis. The Abel inversion is performed according to the Nestor–Olsen algorithm [21,22]. All measurements are carried out with a wavelength around 630 nm. This Δn recovering method offers many advantages: (i) it does not require expensive equipment, (ii) it is sensitive and the sign of Δn