Ultrafast Laser Calligraphy

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Abstract: Control of structural modifications inside transparent materials by varying the direction of pulse front tilt is demonstrated, achieving a calligraphic style of writing. Anisotropic ultrafast laser cavitation in the irradiated region is observed.

Recently it has been suggested to add a tilt of intensity front of ultrashort pulse to the list of parameters which affect light-induced material transformations [1]. Here we provide experimental evidence that indeed the pulse front tilt can be used to control material modifications and in particular as a new tool for laser processing and optical manipulation, e.g. for achieving calligraphic style of laser writing, when the appearance of a “stroke” varies in relation to its direction. Moreover, a new type of light-induced modification in a solid, namely the formation of an anisotropic cavitation is observed in the vicinity of focus at high irradiation fluencies. The bubbles can be trapped and manipulated in the plane perpendicular to the light propagation direction by controlling laser writing direction relative to the tilt of pulse front.

The experiments were carried out using a regeneratively amplified mode-locked Ti: Sapphire laser system (Coherent RegA 9000) generating 150 fs pulses with a maximum energy of 2.4 µJ at a wavelength of 800 nm and a repetition rate of 250 kHz. A linearly polarized Gaussian laser beam was focused via a 50X objective (NA=0.55) at a depth of 130 µm below fused silica sample. The spot size at the focus was estimated to be ~ 2 µm, producing light intensity of \( \text{5} \times 10^{14} \text{W/cm}^2 \) at the maximum pulse energy.

Groups of lines were written with various pulse energies ranging from 0.2 µJ to 2.4 µJ and 50 µm/s speed. For each group, four lines were imprinted with alternating directions (Fig. 1). Lines imprinted with low pulse energies from 0.2 µJ to 1 µJ reveal modifications with form birefringence (type 2) and no difference in the lines written in opposite directions. Form birefringence is explained by the formation of nanogratings in the irradiated region [2,3].

![Fig. 1](image-url) Bright field images (light part) and images in crossed polarizers (dark part) of the line structures imprinted with 1.4 µJ pulse energy using (a) two mirrors or (b) three mirrors setup. The pulse front is shown as tilted red line.
However, with an increase of energy the directional dependence in the written lines was observed, which was strongest at 1.4 μJ (Fig. 1a). The lines written in one direction reveal void formation (type 3), in contrast the lines written in the opposite direction still maintain type 2 modification. This remarkable directional dependence is explained by anisotropic trapping of electron plasma by a tilted front of the ultrashort laser pulse resulting in anisotropic heat flow.

For the interpretation of the experimental results the measurements of the pulse front tilt in the focus of the beam are necessary [4]. However, such measurements are difficult to realize due to small spot size and high light intensity in the focus of the beam.

An unambiguous experiment, without involving the direct measurement of the pulse front tilt, was carried out in order to prove the mechanism of the directional dependence. We added one more mirror in the path of the writing beam in order to reverse the direction of the pulse front tilt (Fig. 1b). Then, another group of four lines with alternating writing directions was imprinted with the pulse energy of 1.4 μJ. It is observed that the structural modifications in the lines of group 1 and 2 are mirrored. This result clearly demonstrates that the directional dependence in ultrafast laser writing is produced by the pulse front tilt.

Another intriguing result is the demonstration of anisotropic directional cavitation in the irradiated region when the pulse energy was increased to the level of 2.4 μJ (Fig. 2). Bubbles with diameters of about 1-2 μm were observed on the sides of irradiated line structures and about 10 μm upstream from the focus of the beam towards the laser (Fig. 2a). When the writing direction was reversed the bubbles were shifted towards one side from the center of the beam (Fig. 2b). The formation of multiple bubbles in the plane perpendicular to writing direction is difficult to explain by the micro-explosion mechanism [5]. One should expect a micro-explosion to take place only in the region of highest intensity, which is in the centre of the Gaussian beam. It is likely that the bubbles are created as the result of glass melting followed by cavitation.

The observation of the shift of the bubble formation from the centre of the beam can be explained by the fact that a particle with a refractive index lower than the surrounding medium, such as void or bubble is repulsed from the region of high intensity in the focus of a Gaussian beam. The component of the tilt, which is orthogonal to the directions of writing and the light propagation, will trap and shift the bubbles towards one side of the imprinted line structure, in a kind of a “snow plough” effect. It should be noted that this effect provides the first evidence of a possibility of manipulation of microscopic objects using pulses with tiled intensity front.

References