# New Science and Art of Femtosecond Laser Writing

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**Abstract:** Common beliefs that laser writing does not change when reversing beam scan or propagation direction are challenged. Recently discovered phenomena of quill and non-reciprocal femtosecond laser writing in glasses and crystals are reviewed.

Modification of transparent materials with ultrafast lasers has attracted considerable interest due to a wide range of applications including laser surgery, integrated optics, optical data storage, 3D micro- and nano-structuring [1].Three different types of material modifications can be induced with ultrafast laser irradiation in the bulk of a transparent material, silica glass in particular: an isotropic refractive index change (type 1); a form birefringence associated with self-assembled nanogratings and negative refractive index change (type 2) [2,3]; and a void (type 3). In fused silica the transition from type 1 to type 2 and finally to type 3 modification is observed with an increase of fluence.

Recently, a remarkable phenomenon in ultrafast laser processing of transparent materials has been reported manifesting itself as a change in material modification by reversing the writing direction

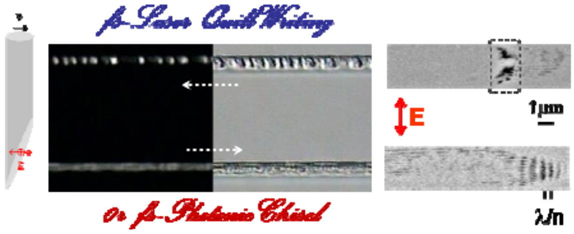


Fig. 1 (centre) Bright field images (light part) and images in crossed polarizers (dark part) of the lines written in opposite directions with amplified Yb fiber laser at 500 kHz repetition rate, writing speed 250 µm/s and pulse energy 0.9 µJ. (left)The tilted front of the pulse along writing direction is shown. (right) SEM images of cross sections of lines written with polarization perpendicular to writing direction are also shown. The nanograting of about 300 nm period, which is responsible for the form birefringence of irradiated regions, can be seen only in the initial part of cross sections of lines written in one of two directions. The region of collateral damage is marked with dashed line.

(Fig.1) [4]. The phenomenon has been interpreted in terms of anisotropic plasma trapping and heating by a tilted front of the ultrashort laser pulse.

More recently, we have experimentally demonstrated that indeed the pulse front tilt [5] 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 laser writing, when the appearance of a "stroke" varies in relation to its direction (Fig. 2) [6].

Moreover, a new type of light-induced modification in a solid, namely an anisotropic cavitation, was observed in the vicinity of the focus at high fluences (Fig. 3). The bubbles can be trapped and manipulated in the plane perpendicular to the light propagation direction by controlling the laser writing direction relative to the tilt of the pulse front. It should be pointed out that since the discovery of lasers, it has been believed that interactions of a Gaussian laser beam with an isotropic medium can produce only centrosymmetric material modifications. Our experiments provide the evidence that it is not always true.

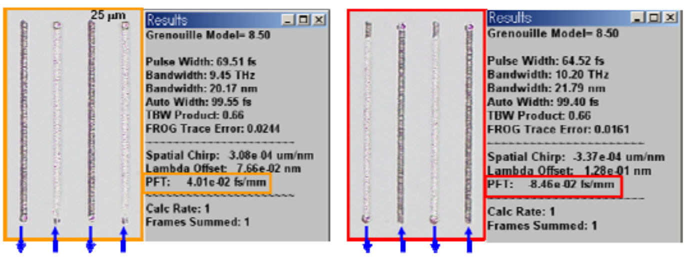


Fig. 2 Microscope bright-field image of the line structures written with a Ti:sapphire laser at 800 nm, 250 kHz , 50 µm/s using pulses with (left) positive pulse front tilt or (right) negative pulse front tilt. The writing direction is shown by the arrows. The corresponding screen shots containing measured laser pulse parameters by a GRENOUILLE device are shown.

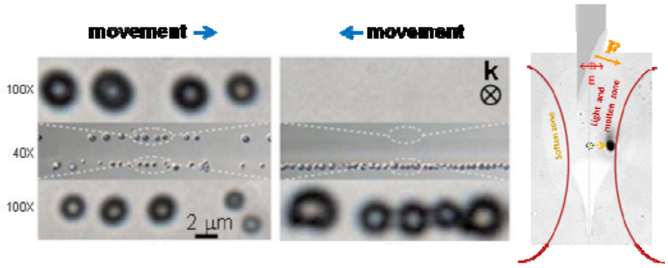


Fig. 3 Microscope images with different magnifications of the line structures fabricated in opposite directions with 2.4 μJ pulse energy and scan speed of 50 μm/ s (left and center) and a cross-section of the line structure (right).

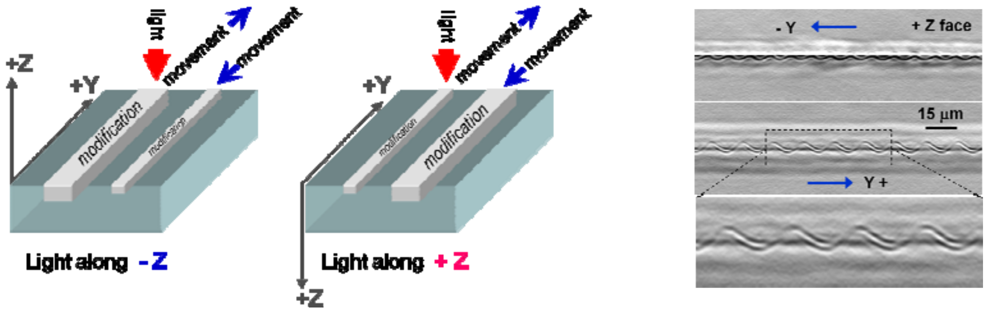


Fig. 4 The illustration of non-reciprocal laser writing - KaYaSo effect ((left and centre) and DIC images of wavy self-organized structures created when writing along the -Y axis and the + Y axis in lithium niobate (right).

It has also been a common belief that in a homogeneous medium, the photosensitivity and corresponding light-induced material modifications do not change on the reversal of light propagation direction. Recently, we have demonstrated that when the direction of the femtosecond laser beam is reversed from +Z to – Z directions, the structures written in a lithium niobate crystal are mirror images

when translating the beam along the +Y and –Y directions (Fig. 4) [7]. In contrast to glass, the directional dependence of writing in lithium niobate depends on the orientation of the crystal with respect to the direction of the beam movement and the light propagation direction. We demonstrate theoretically that interplay of the crystal anisotropy and light-induced heat flow gives rise to a new non-reciprocal nonlinear optical phenomenon, nonreciprocal photosensitivity. In the lithium niobate, the nonreciprocal photosensitivity manifests itself as a changing the sign of the light-induced current when the light propagation direction is reversed. Therefore, in a non-centrosymmetric medium, modification of the material can be different when light propagates in opposite directions. Non-reciprocity is produced by magnetic field (Faraday effect) and movement of the medium with respect to the direction of light propagation: parallel (Sagnac effect) or perpendicular (KaYaSo effect).

We anticipate that the observed phenomena will open new opportunities in laser material processing, laser surgery, optical manipulation and data storage.

## References


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**Peter G. Kazansky** received a M.Sc. degree in Physics from Moscow State University in 1979 and a Ph.D. under supervision of Nobel Laureate for the invention of laser A.M. Prokhorov from the General Physics Institute in 1985. He was awarded the Leninskii Komsomol Prize in 1989 for the pioneering work on "Circular photogalvanic effect in crystals" (which concerns conversion of photon angular momentum to charge carrier momentum). From 1989 to 1993 he led a group in the GPI which unravelled the mystery of a new optical phenomenon – light-induced frequency doubling in solid state centosymmetric media. In 1992 he joined the Optoelectronics Research Centre at the University of Southampton where since 2001 he is a chair leading “Physical Optics” group and pursuing his interests in new optical materials, photosensitivity, ultrafast material processing, nanotechnology and quantum information research. He is Vice-Chair of the TC-20 Technical Committee on Glasses for Optoelectronics of ICG, the International Commission on Glass.


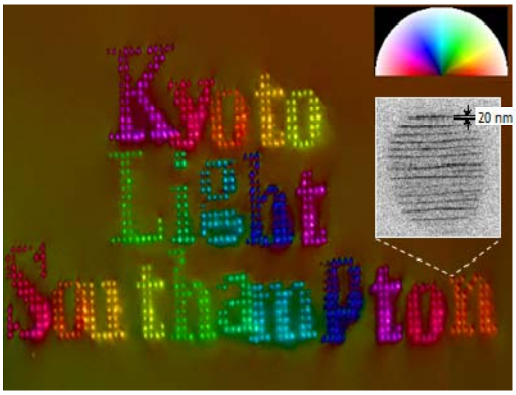


Image produced by femtosecond laser writing of self-assembled form birefringence in silica glass. Courtesy of M. Sakakura, K. Miura and K. Hirao.