Ultrafast-laser materials processing uncovers new anisotropy effects

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Ultrafast-laser materials processing, including modification of transparent matter, has become an attractive and rapidly developing area of research, which (at first glance) might look like it is predominantly industrially targeted. However, recent results have revealed purely scientific richness as well. One example is the discovery of light-induced, self-assembled nanogratings in the bulk silica-glass orientation, which can be controlled by varying the polarization of femtosecond-laser beams. These nanostructures, which can withstand heat of up to 1000°C, have been used to create birefringent Fresnel-zone plates, embedded microreflectors, rewritable optical memory, and nanofluidic channels. In Figure 1, the polarization encoding is demonstrated by imprinting the image of a rose in silica glass. Form birefringence, resulting from the subwavelength pattern, colors the rose when placed in cross-polarized light. One could imagine printing family color photos that remain unchanged for a thousand years, when images produced by conventional methods will vanish. In addition, complex 3D diffractive elements enabling full control of a light beam, including of its phase, amplitude, and polarization, can also be constructed.

While analyzing the conditions for nanograting formation, we noticed that moving a sample from left to right and vice versa produces different modifications in glass (see Figure 2). For instance, nanogratings and related form birefringence could be formed only in one scanning direction. This is related to the pulse-front tilt, an intrinsic property of ultrashort laser beams that normally does not reveal itself in interactions of light with matter. The presence of a pulse-front tilt means that the arrival time of an ultrashort pulse varies across the beam profile, making the laser beam behave like a quill pen. Thus, the observed effect is referred to as ‘quill writing.’ Moreover, we observed a new type of light-induced modification in a solid (anisotropic cavitation) near the focus at high fluencies (see Figure 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 pulse-front tilt. More recently, we demonstrated experimentally that this tilt can be used to control material modifications, in particular as a new tool for laser processing and optical manipulation or to achieve calligraphy-style laser writing, where the appearance of a ‘stroke’ varies with direction.

It has also been a common belief that in a homogeneous medium the photosensitivity and corresponding light-induced material modifications do not change with the reversal of the light’s propagation direction. We have demonstrated, in collaboration with Yuri Svirko (University of Joensuu, Finland), that when the propagation direction of the femtosecond-laser beam is reversed from $+Z$ to $-Z$ (see Figure 4), structures written in

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lithium niobate crystals are mirror images when translating the beam along $+Y$ and $-Y$ (see Figure 5). In contrast to glass, the directional dependence of writing in lithium niobate depends on the crystal’s orientation with respect to the beam-movement and light-propagation directions. The nonreciprocity is attributed to the interplay of the crystal’s anisotropy with light-induced heat flow. In the lithium niobate, nonreciprocal photosensitivity is manifested as a change in the sign of the light-induced heat current upon reversal of the light-propagation direction. Therefore, in a noncentrosymmetric medium, material modifications can be different when light propagates in opposite directions. This is a new nonreciprocity effect (known as the ‘KaYaSo effect’).

Nonreciprocity is produced by magnetic fields (Faraday effect) and movement of the medium with respect to the direction of light propagation, either parallel (Sagnac effect) or perpendicular (KaYaSo effect). The latter can lead to development of a new type of optical isolator, where transmission of the signal can be controlled by the direction of motion. We are currently trying to understand the mechanisms responsible for the observed phenomena while simultaneously extending our analysis of these effects to other optical materials.

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References