Recent advances in ultrafast laser nanostructuring of transparent materials

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In ultrafast laser writing, it has been widely accepted that higher energy density leads to stronger material changes unless thermal effects are involved. We challenge this belief by demonstrating that decreased energy density—achieved through increased scanning speed and without thermal accumulation—leads to more significant modifications in silica glass. This phenomenon is attributed to the nonlocality of light-matter interaction at tight focusing, where the intensity gradient and charge carrier diffusion play a critical role in enhancing material modification. We observed a tenfold increase in the writing speed of polarization multiplexed data storage, achieving MB/s rates using high transmission nanopore-based modification.

The temporal contrast of femtosecond pulses is also crucial in laser writing. Anisotropic nanopores in silica glass are produced by high-contrast (107) femtosecond Yb laser pulses, rather than low-contrast (103) Yb fiber laser pulses. The difference arises from the fiber laser storing a third of its energy in a post-pulse of up to 200 ps duration. This low-intensity fraction is absorbed by laser-induced transient defects with long lifetimes and low excitation energy, such as self-trapped holes, altering the energy deposition kinetics and the type of material modification. Low-contrast pulses effectively create lamellar birefringent structures, potentially driven by a quadrupole nonlinear current.

Differential interference contrast (DIC) microscopy benefits from femtosecond laser writing, which enables the creation of anisotropic nanopores with ultrahigh transmittance (>99%), producing negative form birefringence, comparable to the positive birefringence of quartz crystal.

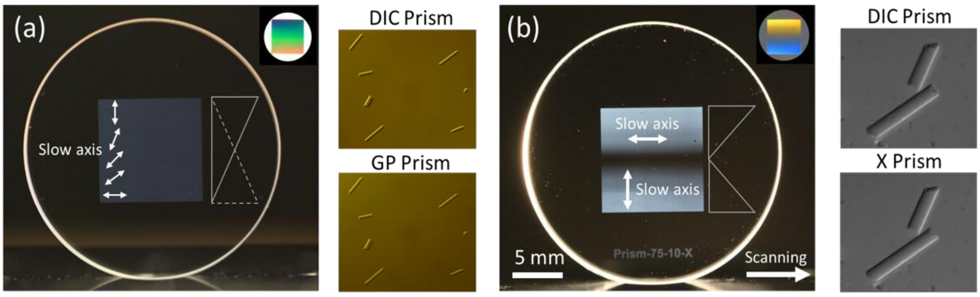

Fig. 1 (a) A 10 mm geometric phase prism (GP Prism) and (b) a 10 mm X prism written by ultrafast laser writing in silica glass. The double arrow represents the direction of the slow axis. The inset on the upper right is their image taken by polychromatic polarization microscope. The image performance of prisms was compared with a commercially available DIC prism (Olympus U-DIC20HR).

High-performance birefringent elements, such as geometric phase prism (GP prism) and retardance gradient prism (X prism), were fabricated by modulating the slow axis or retardance of the birefringent modification (Fig.1). These elements can replace standard DIC prisms without losing image quality, increase resolution, field of view and advantage of design flexibility.

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[3] Y. Lei, P. Kazansky, and M. Shribak, "Birefringent elements for optical microscopy by ultrafast laser writing," in CLEO/Europe 2023, Technical Digest Series (Optica Publishing Group, 2023), paper ch_7_4.