# Beyond Conventional 3D Ultrafast Laser Material Processing

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Material processing with ultrafast lasers has attracted considerable interest due to a wide range of applications from laser surgery and integrated optics to optical data storage, 3D micro- and nano-structuring [1,2]. A decade ago it has been discovered that under certain irradiation conditions ordered sub-wavelength structures with features smaller than 20 nm can be formed in the volume of silica glass [3]. The effect of nanograting formation has attracted considerable interest with proposals of applications ranging from nanofluidics [4,5] to polarization control devices [6].

More recently, the self-assembled sub-wavelength nanostructuring have been proposed for fabrication of vortex polarization converters and rewritable polarization multiplexed optical memory [7], where the information encoding is realized by means of two birefringence parameters, i.e. the slow axis orientation (4th dimension) and retardance (5th dimension), in addition to three spatial coordinates (Fig.1).

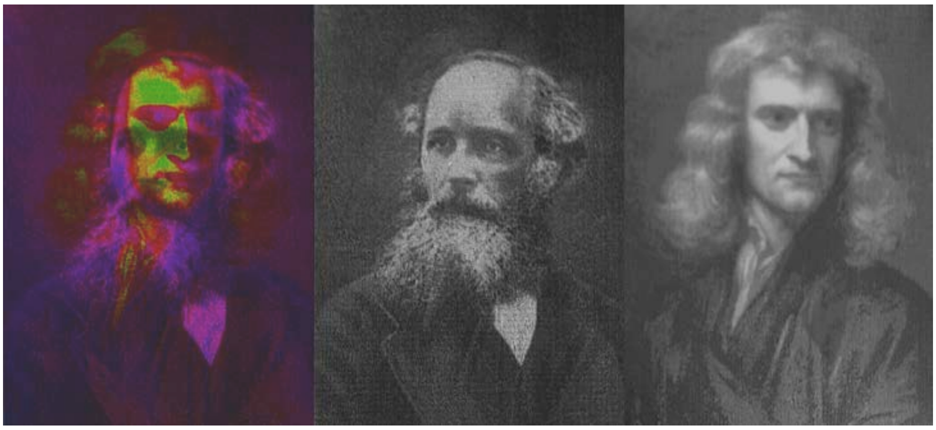

**Fig. 1 |** Ultrafast optical recording via self-assembled nanograting induced birefringence in fused silica. Maxwell and Newton are recorded in one image (left, in pseudo colours), however, they can be easily decoupled as Maxwell is recorded in strength of retardance (centre) and Newton in azimuth of the slow axis (right). Size is 1.5 × 2 mm.

A remarkable effect has also been discovered, referred to as quill or calligraphic laser writing, which reveals strong dependence of the material modification, in particular the self-assembled sub-wavelength structures in glass, on orientation of the writing direction relative to direction of the pulse front tilt [8-10]. Moreover, evidence of the first order phase transition associated with self-assembled nanostructures formation was revealed and supercooled state of laser damage was observed using pulses with tilted intensity front. More recently it has been demonstrated that the tip of an ultrafast laser quill has a property that is very different from an ordinary quill [11]. Specifically, the modification of glass can be controlled even in stationary conditions by the mutual orientation of light polarization azimuth and the pulse front tilt. Figuratively, the polarization can be used as a sharpening blade for the ultrafast light quill. The demonstrations of self-assembled nano-structuring and employing mutual orientations of beam movement or the light polarization plane and pulse front tilt to control interaction of matter with ultrashort light pulses, open new opportunities in material processing.

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