Dynamic control of directional asymmetry observed in ultrafast laser direct writing

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A liquid crystal spatial light modulator (SLM) is used to control the focal symmetry and the associated directional "quill" effect encountered when using a femtosecond laser for direct laser writing of fused silica. Applying a blazed grating to the SLM effectively introduces pulse front tilt to the fabrication beam and a spatiotemporal asymmetry at the focus. As a result different fabricated features are generated when moving the substrate in opposite directions relative to the tilt. It is additionally shown that inhomogeneous pupil illumination can cause similar directionality in the fabrication via a spatial asymmetry in the focus. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4756904]

Ultrafast laser material processing permits three dimensional fabrication inside transparent substrates. The nonlinearity of any absorption coupled with the ultrashort nature of the pulse allows the generation of embedded features confined to the focal volume, without any damage to surrounding regions or the surface. The technique is of increasing interest in the fabrication of a range of devices, such as artificial bandgap materials, microfluidic devices, and photonic waveguide circuits.[1,2]

When writing continuous subsurface features, there are typically three regimes of fabrication dependent on several factors related to the substrate material, the ultrashort pulse train and the experimental setup. When machining fused silica, if the pulse energy is increased and all other experimental parameters remain constant, the fabricated features range from a smooth isotropic refractive index modification[3] (type 1) to a birefringent nanograting[4] (type 2) and to void formation[5] (type 3). Interestingly, the fabrication regime encountered is often additionally found to be dependent on the direction the sample is translated perpendicular to the optic axis ("quill writing"[6]). This occurs despite the homogeneity of the sample and without any change to the experimental conditions. The effect has been attributed to a tilt of the pulse front relative to the phase front in the incident fabrication beam.[6–9] When transformed by an objective lens, a pulse front tilt (PFT) is considered to generate an asymmetry in the focal intensity distribution, which gives rise to directionally dependent writing.[6]

Previously, it has been shown that directional effects in laser writing may be reversed by tuning the grating compressor of the laser to adjust the PFT of the system[7] or that spatio-temporal focusing with a low numerical aperture can generate very large amounts of PFT and introduce directionality.[9] In this letter, we demonstrate how the degree of pulse front tilt in a system can be adjusted using a liquid crystal phase-only spatial light modulator (SLM), enabling the control of directional fabrication effects. Furthermore, we find that similar directionality in the fabrication process is observed when there is an asymmetric illumination of the objective lens. Here the asymmetry arises from the spatial rather than the temporal distribution of intensity at the focus. This can also be dynamically manipulated using an SLM.

Fig. 1 shows a schematic of the experimental layout. The pulses emitted from the regeneratively amplified titanium sapphire laser (Solstice, Newport/Spectra Physics, pulse length 150 fs, repetition rate 1 kHz, central wavelength 790 nm) were attenuated using a rotatable half-wave plate and a Glan-Laser polariser. The expanded beam was directed onto a reflective liquid crystal phase-only SLM (X10468-02, Hamamatsu Photonics). The SLM and the pupil plane of the objective were imaged onto one another by a 4f system, composed of two achromatic doublet lenses. A 500 μm diameter pinhole on an adjustable mount was inserted into the Fourier plane of the SLM. The beam fully illuminated the back aperture of a Zeiss Plan Neofluar 0.3 NA 10× objective, with internal correction for a 170 μm coverglass. The effective pupil size on the SLM was 12 mm in diameter (600 pixels). The substrate was mounted on a three axis air-bearing translation stage, (Aerotech ABL10100 (x,y) and ANT95-3 -V (z)). An LED illuminated transmission brightfield microscope allowed viewing of the specimen during fabrication.

Initially a phase pattern was assigned to the SLM which compensated any existing system aberrations, including nonuniformities across the SLM itself. Lines were written 170 μm beneath the surface of high grade fused silica (Schott Lithosil Q1). Each line was written by a single pass of the focused beam. The incident power was adjusted to be close to the transition from a type 1 to type 2 material modification. The beam was polarized parallel to the direction of motion. There was found to be an initial directionality present in the fabrication, whereby the modifications were of type 1 moving in one direction while type 2 when moving antiparallel, as can be seen in Fig. 2(a). The tracks shown in brightfield and crossed polariser images in Fig. 2(a) were written at a speed of 10 μm/s with a pulse energy of 0.5 μJ. The difference in fabrication in each direction is particularly

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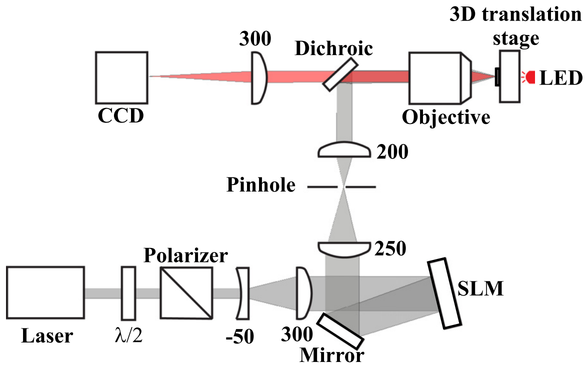

FIG. 1. The experimental configuration. All the tube lenses were achromatic doublets; focal lengths are in mm.

pronounced when viewed between crossed polarizers, with a strong birefringence related to type 2 modifications only found in one track.

The directional dependence to the fabrication could be removed by applying an appropriate blazed phase grating to the SLM. The grating generates angular dispersion in the ultrashort beam and an associated PFT.[10,11] The grating used had a period of 2.4 lines per mm (l/mm) on the SLM and modulus 2π radians for a wavelength of 790 nm. A grating with this periodicity adds a PFT of 6.3 fs/mm to the beam following the SLM, neglecting any dispersion from the liquid crystal layer.[10] A pinhole in the Fourier plane of the SLM blocked all light other than that in the first diffracted order. In the focal plane, the associated writing focus was shifted laterally in the opposite direction to that which produced the type 2 modification without any grating (to the left in Fig. 2). This effect on the fabrication is illustrated by the images in Fig. 2(b). The fabrication speed is $10\,\mu\text{m/s}$ and the pulse energy is raised to $0.95\,\mu$J. In both directions, the power is on the threshold between type 1 and type 2 fabrication, with each track displaying regions belonging to each regime. This shows that the blazed grating displayed on the SLM generates sufficient PFT to cancel any focal asymmetry present in the system and effectively remove the directional dependence to the fabrication threshold.

The degree of PFT introduced to the ultrashort beam by the grating can be tuned by adjusting the grating period. This is easily achieved with the reconfigurable SLM. If the grating is reversed or the period reduced we are able to create a large amount of PFT and reintroduce a directional dependence to the fabrication. The tracks shown in the images of Figs. 2(c) and 2(d) were written with a blazed grating periodicity of -2.4 l/mm and $+7.2$ l/mm, respectively, both at a speed of $10\,\mu\text{m/s}$ and with a pulse energy of $1.95\,\mu$J. It is clear that the directional dependence to the fabrication is reintroduced, and when the grating direction is reversed (thus reversing the induced PFT) so is the directionality. If there is assumed to be an initial PFT to the system of 6.3 fs/mm, then these tracks were written with a net PFT of $\pm$ 12.6 fs/mm in the beam. The control over the fabrication provided thus was consistent over the range of speeds ($1\,\mu\text{m/s}$ to $20\,\mu\text{m/s}$) and depths ($50\,\mu$m to $200\,\mu$m) tested. Reversing the direction of the PFT by reversing the grating on the SLM had no effect on the fabrication in the direction perpendicular to the tilt, as expected.

In order to ascertain the nature of the asymmetry in our system, we calculated the time dependent focal intensity for an ultrashort beam with PFT, following a Fourier optics approach described in Ref. 12. We assume a Gaussian spectral distribution for the pulse corresponding to a $1/e$ pulse duration of 150 fs. The SLM is conjugate to the back focal

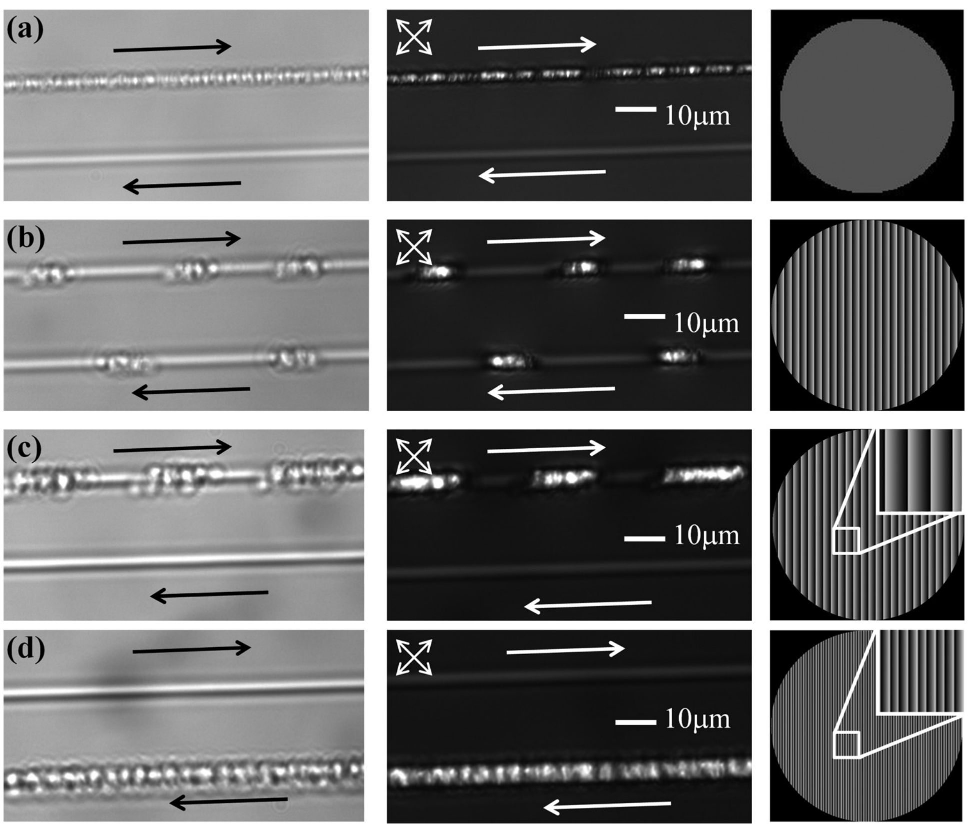

FIG. 2. Tracks written at a depth of $170\,\mu$m in fused silica at a speed of $10\,\mu\text{m/s}$. For each set of tracks a bright-field (left) and a crossed polarizer (centre) image are shown, as well as the phase pattern displayed on the SLM during fabrication (right). The grating period used was (a) 0, (b) 2.4, (c) -2.4, and (d) 7.2 lines per mm. Single headed arrows denote the direction of motion of the substrate for each track.

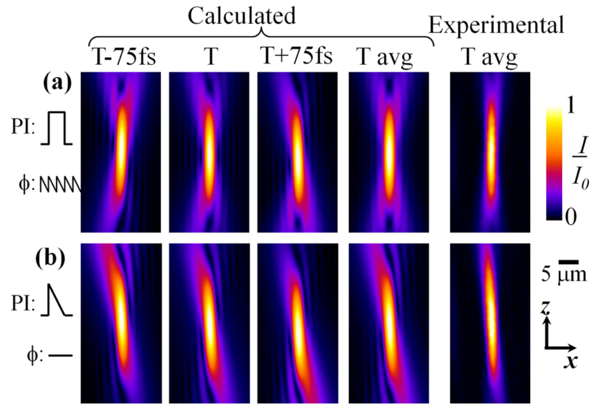

FIG. 3. Calculated and experimental focal intensity distributions for a 150 fs pulse with (a) a "top-hat" pupil illumination (PI) with a blazed phase grating (ϕ) introducing a PFT of 12.6 fs/mm and (b) a gradient in the PI with a flat phase distribution ($\phi = 0$, no PFT). The focal intensity is shown at time T corresponding to the centre of the pulse, and at T$\pm$75 fs. Each image is individually normalized. The corresponding time averaged intensity is shown both from calculation and experimental measurements. The optical axis is along z.

plane of the objective, within which we neglect any dispersion effects.[13] The focal intensity distribution is shown in Fig. 3(a) for a uniform "top-hat" illumination of the objective pupil and a blazed grating phase, for times T and T $\pm$ 75 fs, where T corresponds to the centre of the pulse. The period of the blazed grating was set to introduce a PFT of 12.6 fs/mm, as in the experiments described above. There is an instantaneous asymmetry in the intensity distribution, which can be clearly seen at times $T \pm 75$ fs. However, the form of the asymmetry shows a strong temporal dependence and is reversed for times before and after T to result in a time average which is symmetric. The theoretical prediction corresponds well to the experimental measurement of the time averaged focal intensity which is equally symmetric. The experimental data were taken by inserting a mirror specimen into the focal region of the objective and imaging the reflected light on to the CCD shown in Fig. 1. Even though the time averaged focal intensity is symmetric, it is the temporally advanced portion of the pulse which undergoes non-linear absorption and establishes an energetic plasma at focus, which is subsequently augmented through avalanche ionization. Thus, the initial asymmetry in the focal intensity may be sufficient to generate an asymmetry in the plasma distribution and explain the directional dependence to the fabrication.[6]

It is interesting to consider other potential sources of asymmetry in the focal intensity and whether these lead to similar directionality in fabrication. One such case is an asymmetric illumination of the objective pupil, which might occur if the beam were not perfectly centred in the pupil. We consider here a linear gradient in intensity across the objective pupil with a flat phase distribution (no PFT), giving rise to a focal intensity distribution as shown in Fig. 3(b). Here, there is a clear asymmetry at the focus which is not temporally dependent (it persists after time averaging). In experiment, such an asymmetry in the illumination of the objective pupil was generated using the SLM as indicated in Figs. 4(a) and 4(c). A blazed grating was again placed onto the SLM, but the modulation depth varied from $0 \rightarrow 2\pi$ radians as a function of position across the SLM. A grating modulation

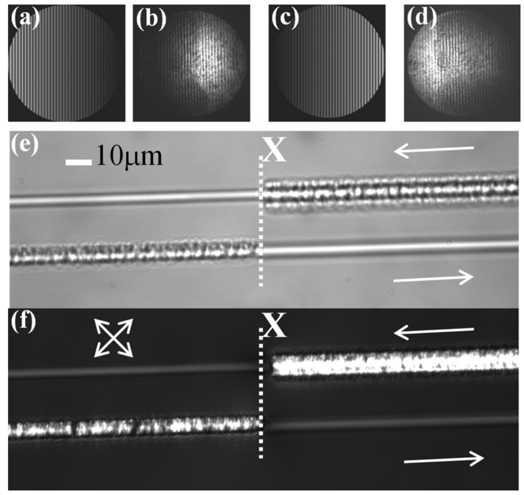

FIG. 4. Control of the pupil illumination using the SLM. (a) and (c) SLM phase distributions used to generate an intensity gradient in the pupil illumination by the zero order beam, as shown in (b) and (d). Brightfield (e) and crossed polarizer (f) images of tracks written where the SLM phase distribution is switched from (a) to (c) at point X during fabrication. Single headed arrows denote the direction of motion of the substrate for each track.

depth of 2π rad corresponds to the diffraction of light into the first order with maximum efficiency, while the light is unperturbed as the modulation depth drops to zero and remains in the zero order. In the Fourier plane of the SLM the pinhole was moved to block all incident light except that in the *zero order*, such that there was an approximately linear spatial modulation of the beam intensity illuminating the pupil of the objective, as can be seen in Figs. 4(b) and 4(d). In all subsequent fabrication, the *zero order* beam was used to ensure that the SLM phase pattern introduced *no* PFT, in contrast to the results described previously. Taking a time averaged image of the resultant focal intensity distribution revealed a strong spatial asymmetry as shown in Fig. 3(b), which is in good agreement with the theoretical prediction.

Tracks were generated by moving the sample at a speed of 10 μm/s at a depth of 100 μm with a pulse energy of 2.2 μJ. The polarization was parallel to the direction of motion. The asymmetric illumination of the objective lens was found to have a pronounced effect on the fabrication directionality as can be seen in Figs. 4(e) and 4(f). The pupil illumination asymmetry was reversed at point X during fabrication and a clear transition can be seen from a type 1 to type 2 modification. The transition is opposite in nature for movement in opposite directions. There was no change to the fabrication when moving the substrate in a direction perpendicular to the induced gradient in the pupil illumination. The effect was prevalent across a range of depths and speeds. If the laser beam was manually misplaced to either side of the objective while displaying a flat phase shape on the SLM, there was a consistent directionality present in the fabrication, confirming that it is related to an asymmetry in the pupil illumination.

We have shown that two different forms of focal asymmetry may give rise to similar directional affects during direct laser writing (DLW) of continuous subsurface structures. The focal asymmetry may be either spatio-temporal in nature, when arising from PFT, or time-invariant, when due to an inhomogeneous illumination of the objective pupil. In most experimental scenarios it is not straightforward to decipher which of these factors is driving any observed directionality in fabrication. We have shown that dynamic control of both the PFT and the intensity profile of the beam using a SLM can introduce or remove directional effects. These results are particularly relevant to ultrafast DLW of continuous structures, such as photonic circuits, using dynamic diffractive optics.[14–16] In these systems, PFT is inherent in the diffracted orders and can introduce directionality in the fabrication effects. Adaptive control of the PFT and/or intensity profile could be applied to regulate these effects.

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