

# Spatio-temporally Focused Femtosecond Laser Pulses for Anisotropic Writing in Optically Transparent Materials

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**Abstract:** Simultaneous spatial and temporal focusing provides precise control of the pulse front tilt necessary for anisotropic writing and maintains this behavior over a large range of focal positions and at low numerical aperture and fluence.

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Femtosecond laser material processing has yielded structures with remarkable properties that, when combined, can produce devices with spectroscopic, fluidic and mechanical microscale functionalities. Depending on the substrate and the laser parameters, the modification may appear as a change in the refractive index, a void or a birefringent feature [1]. Birefringent features have been, thus far, less frequently applied in microscale functionalities, but they were recently demonstrated for use in unique applications including a polarization-selective optical router [2] and a polarization diffraction grating [3]. Under some conditions these birefringent features have the additional quality of dependence upon the sample's scanning direction in that the characteristics of the modification change when the scan direction is reversed. This phenomenon is due to pulse front tilt (PFT) [1,4]. In practice, PFT may be imposed on the laser beam by tuning the laser's grating compressor [1]. However, any adjustment to the parallelism of the gratings produces angular dispersion that necessarily results in spatial and temporal distortions at focus. Consequently, the conditions for generating PFT are not easily translated between systems so that deciphering the effect of PFT on anisotropic writing is confounded.

We present a method to obtain the conditions necessary for anisotropic writing in a controlled and reproducible manner by exploiting the PFT inherent to a simultaneous spatial and temporal focusing (SSTF) arrangement [5]. In SSTF lateral spatial chirping is used to form a frequency-distributed array of low numerical aperture (NA) beamlets. A feature of SSTF is that out-of-focus nonlinear interactions are suppressed, facilitating femtosecond material modification in the bulk of transparent substrates [6]. Importantly, at focus, the frequencies overlap spatially and temporally, and the pulse is transform-limited in time as well as diffraction-limited in space. Thus, the PFT generated in an SSTF system does not suffer from the distortions associated with misaligning the compressor. The striking contrast generated by PFT is shown in Fig. 1. Anisotropic writing is observed for writing directions parallel to the axis of PFT (Fig. 1(c)-(e)) but not for directions perpendicular to the axis of PFT (Fig. 1(b)).

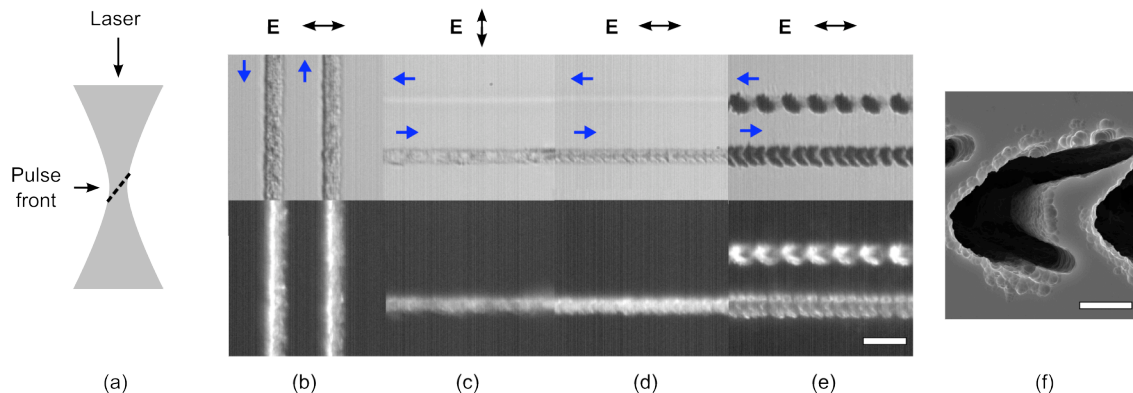


Fig. 1. (a) The orientation of the pulse front tilt at the focal plane (dashed line). The pulse arrives first on the left hand side of the focal spot. In (b)-(e) blue arrows indicate the lateral scanning direction for the laser beam with respect to the sample. In (b) the scanning directions were

perpendicular to the PFT. In (c)-(e) the scanning directions were parallel to the axis of PFT. Each set of anti-parallel lines was imaged with bright field (top) and cross-polarized illumination (bottom). The orientation of the electric field,  $\mathbf{E}$ , is marked with black arrows. In (b)-(d) the scanning rate was  $10 \mu\text{m/s}$ , and the location of the axial focal position was in the bulk of the sample,  $284 \mu\text{m}$  beneath the front surface. In (e) the scanning rate was  $5 \mu\text{m/s}$  and the focal position was  $40 \mu\text{m}$  beyond the back surface of the sample. Scale bar,  $50 \mu\text{m}$ . (f) A scanning electron microscope image of a Chevron-shaped structure. Scale bar,  $10 \mu\text{m}$ .

The magnitude of PFT in an SSTF system is readily adjusted by changing the beam aspect ratio (BAR), i.e., the ratio of the beam width in the spatially chirped dimension to the beam width in the unchirped dimension. Fourier beam propagation simulations predicted that the PFT changed proportionally with the BAR (Fig. 2(b)). We examined anisotropic writing for a PFT value of  $16,000 \text{ fs/mm}$  (Fig. 2(a)), which was five orders of magnitude more PFT than employed in a study by Yang *et al.* [1]. Notably, our experiments showed a reduced dependence on the axial focal position in the sample compared to Yang *et al.*, who reported that  $5 \mu\text{m}$  movement away from the optimum focal position eliminated the appearance of anisotropic writing [1]. Under our experimental conditions ( $0.88 \text{ J/cm}^2$ ,  $0.03 \text{ NA}$ ), we observed anisotropic writing over a range of axial focal positions from  $230 \mu\text{m}$  to  $500 \mu\text{m}$  beneath the surface of a  $500 \mu\text{m}$  thick fused quartz sample. Additionally, anisotropic void formation was revealed on the back surface of the sample (Fig. 1(e), (f)) where either circular wells or Chevron shapes (the shape of a ‘V’ character) were ablated, depending on the scanning direction.

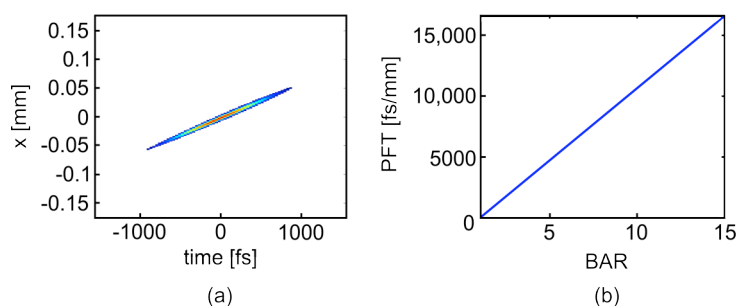


Fig. 2. (a) The simulated spatio-temporal intensity profile of the pulse at the focal plane where  $x$  is the spatial dimension along the direction of spatial chirp. (b) The predicted relationship between the pulse front tilt (PFT) and the beam aspect ratio (BAR) for our system.

In summary, with an SSTF system, the PFT necessary in anisotropic writing is achieved in a calculable and reproducible manner and without the need to misalign the laser’s grating or prism compressor. The SSTF system, having several orders of magnitude larger PFT and much lower NA, maintained anisotropic writing over a greater range of focal depths ( $230 \mu\text{m}$  to  $500 \mu\text{m}$ ), including the back surface of a  $500 \mu\text{m}$  thick sample, and at more than two orders of magnitude less fluence than reported by previous work. We anticipate that the anisotropic surface patterning possible with SSTF will broaden applications for femtosecond laser fabrication. Notably, the structures we have created here are of sufficient extent that Chevron-patterned channels can be created in a single pass for particle alignment in microfluidic devices [7]. Thus, devices can be fabricated quickly and efficiently.

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