Simultaneous space-time focusing
femtosecond micromachining

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The challenge - ablation inside transparent materials

Spatially chirped pulses for low NA, high aspect ratio backside femtosecond laser ablation

This work was inspired by:

Micromachining with space-time focusing

Simultaneous spatial and temporal focusing (SSTF)

• Spatially separate spectrum at lens
• Concentrate and overlap spectrum at focus
Micromachining with space-time focusing

Amplified, low NA beams have reduced sectioning as shown in the TPEF images above. SSTF retains axial localization.


Beam aspect ratio

Amount of spatial chirp impacts effectiveness of temporal focusing.
Reduce the out of focus intensity.

\[ \frac{7.4 \text{mm}}{0.69 \text{mm}} \approx 11 \]
We can achieve a diffraction limited spot with SSTF

Energy starts at 104 μJ, increased by ~3.5 times to 358 μJ

Focus axially shifted ~200μm toward the lens

Self-focusing present with conventional pulses.
SSTF focus

Energy starts at 104 µJ, increased by ~9 times to 900 µJ (3x more than conventional)

No shift in axial position

No distortion

Self focusing is suppressed with SSTF pulses.

SSTF vs Standard focus - efficiency can be an issue

358 µJ is best we can do for standard focus - 900 µJ is possible with SSTF
SSTF vs Standard focus - effects of dispersion

Standard focus - images of plasma breakdown in air

Focus moves toward lens as dispersion is optimized. ~16000 fs$^2$ steps per panel

SSTF vs Standard focus - effects of dispersion

SSTF - images of plasma breakdown in air

Focus moves across paraxial focus. ~8000 fs$^2$ steps per panel
Impact of dispersion in SSTF

GDD shifts focus & lowers peak intensity
TOD lengthens pulse duration & lowers peak intensity

Results

Craniotomy in mouse skull - performed under 5 mm of water!

500 µm³ per 130 µJ pulse

Writing in transparent materials - in bulk

380 µm beneath the surface of a fused silica microscope slide. 22 µJ/pulse; 0.03 NA; 50 µm/s.

Writing in transparent materials - on surface

Focused on the back surface of a fused silica microscope slide. 27 µJ/pulse; 0.03 NA; 15 µm/s.
Impact of pulse front tilt - the Quill effect

This work was inspired by:

Molded structures

Anisotropic Writing - Specimen 1 - Dawn - Moulded PDMS
**Molded structures - manipulation in microfluidic devices**

Fluorescence streak image

Microvortex particle sorting
C. Hsu et al., Lab Chip 8, 2128 (2008).

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**Conventional focusing**

Ablation of ocular tissue (extracted porcine lens)

~4 x above the ablation threshold for a 100 fs pulse in ocular tissue*, 0.6mm/s

- Nonlinear effects visible with focus 1 cm outside of sample
- Widespread damage
- Damage to delivery system

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Bubble formation with non-SSTF

- Precise targeted delivery
- Axial intensity localization/confined ablation
- No damage to delivery system

Ablation of ocular tissue (extracted porcine lens) ~4 above the ablation threshold for a 100 fs pulse in ocular tissue*, 0.6mm/s

Analysis

Histology of ablated porcine lens

With Conventional Focus:
- No control over damage zone
- Damage up to ~1 mm in depth

With SSTF:
- Precise targeted ablation
- Ablation confined to ~200 µm in depth

Same settings but dramatically different results

What do we expect?

- Black - Fluence contour of SSTF Plot
- Red - Ablation threshold fluence (pulsewidth dependent)
- Blue - Standard focus, fluence contour
- Black - SSTF focus, fluence contour
- Red - Ablation threshold fluence (pulsewidth independent)
A micromachining system optimized for SSTF

(a) Back surface ablation through 1 mm thick borosilicate sample. Translation speed was 1 mm/s. (b) Through focus series of front surface ablation for identical conditions. Scale is same in all photos.

Dark field images of channels cut at different rates. Starting from left, 1 mm/s, 5 mm/s, and 11 mm/s.
• Spatio-temporal focusing is a unique modality for micromachining.

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