Materials Processing using Ultrashort Laser Pulses

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Colby Sawyer, New London, NH
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Introduction

- microstructuring of transparent materials
Introduction

- microstructuring of transparent materials
- laser surgery
Introduction

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- laser surgery
- electronic and structural transitions
Introduction

- microstructuring of transparent materials
- laser surgery
- electronic and structural transitions
- laser assisted chemistry
Introduction

5 mm
Introduction
focus laser beam inside material…

100 fs

objective

transparent material
Introduction

high intensity at focus...

100 fs

objective

transparent material
Introduction

... causes nonlinear ionization...
Introduction

and microscopic bulk damage

objective

transparent material
Introduction

laser field ionization

multiphoton...
Introduction

laser field ionization

...or tunneling
Introduction

avalanche ionization

free carrier absorption…
Introduction

avalanche ionization

...and impact ionization
Introduction

Damage mechanisms:

- explosive
- thermal
- defect forming
Introduction

Applications:

- data storage
Introduction

Applications:

- data storage
Introduction

Applications:

- data storage
- photonic devices
Applications:

- data storage
- photonic devices
- internal micromachining
Damage morphology

40 nJ, 120 fs
0.65 NA
Corning 0211
Damage morphology

3 µm distance (µm)

0 6 2 4 6

top view

0 100 200 300

intensity

distance (µm)

250 nm
Damage morphology

3 µm

40 nJ, 120 fs
0.65 NA
Corning 0211
Damage morphology

3 µm distance (µm)

intensity

0 6 2 4 5 7

side view

2 µm

300

200

100

0

distance (µm)

intensity
Damage morphology

more shots → more energy

100 fs
1.4 NA
Corning 0211
Damage morphology

25,000 shots at 25 MHz
4.5 nJ, <100 fs
1.4 NA
Corning 0211
Damage morphology

Electron Microscopy:
explosive damage forms voids

100 fs, 500 nJ
0.65 NA
fused silica
**Damage morphology**

**summary of damage mechanisms**

<table>
<thead>
<tr>
<th></th>
<th>single shot</th>
<th>multiple shot (25 MHz)</th>
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# Damage morphology

## Summary of damage mechanisms

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## Damage morphology

**summary of damage mechanisms**

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### Damage morphology

**Summary of damage mechanisms**

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Outline

- Damage morphology
- Energy deposition
- Dynamics
Energy deposition

Determine threshold for damage:

- Optical microscopy
- Transmission
- Dark field scattering
Energy deposition

optical microscopy
Energy deposition

optical microscopy

6.6 nJ
Energy deposition

transmission of pump beam in fused silica

![Graph showing energy deposition with laser energy and transmission on a log-log scale. The graph indicates critical self-focusing and damage points.]
Energy deposition

Dark-field scattering

objective

sample
Energy deposition

block probe beam...
Energy deposition

...bring in pump beam...
Energy deposition

...damage scatters probe beam
Energy deposition

![Graph showing energy deposition over time for fused silica with 1.0 µJ of signal in arbitrary units (a.u.).]
Energy deposition

vary numerical aperture in Corning 0211
minimal self focusing, so spot size determined by:

\[ I = \frac{E}{\tau A} = \frac{E}{\tau} (\text{NA})^2 \]

and thus

\[ E = \frac{I \tau}{(\text{NA})^2} \]
Energy deposition

fit gives threshold intensity: $I_{th} = 2.5 \times 10^{17} \text{ W/m}^2$
Energy deposition

vary material...

![Energy deposition graph](image)

- Bandgap (eV)
- Threshold intensity (10^17 W/m^2)
- Threshold fluence (kJ/m^2)

Materials:
- CaF$_2$
- Fused silica
- 0211
- SF11
Energy deposition

threshold increases with bandgap...

![Graph showing energy deposition with bandgap](image)
Energy deposition

...but not very much

![Graph showing energy deposition thresholds for different materials.](image-url)
Energy deposition

same trend at 400 nm

<table>
<thead>
<tr>
<th>bandgap (eV)</th>
<th>threshold intensity ($10^{17}$ W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
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<th>threshold fluence (kJ/m²)</th>
</tr>
</thead>
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<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.6</td>
</tr>
</tbody>
</table>

800 nm

400 nm
Dynamics

imaging setup

sample

objective
Dynamics

imaging setup

- Sample
- Objective
- Pump
Dynamics

imaging setup

sample

objective
Dynamics

imaging setup

probe → sample → objective → CCD
Sapphire

3 µJ pulse

3.8 ns delay

40 µm radius
Dynamics

water ("self-healing")

1.0 µJ pulse

35 ns delay

58 µm radius
Dynamics

![Graph showing the dynamics of sapphire radius over time. The graph includes a line with a slope of 11.4 µm/ns and a label indicating the energy input as 3 µJ.]
Dynamics

<table>
<thead>
<tr>
<th>water</th>
<th>1.48 µm/ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (ns)</td>
<td>radius (µm)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
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</table>
Dynamics

![Graph showing the dynamics of water radius over time](image-url)
Dynamics

![Graph showing the dynamics of water with time and radius as variables.]
time-resolved scattering setup
Dynamics

time-resolved scattering setup
Dynamics

time-resolved scattering setup

objective

sample

detector
Dynamics

time-resolved scattering setup
Dynamics

time-resolved scattering setup

signal proportional to area of scatterer
Dynamics

Water

1 μJ

radius (μm)

time (ps)

0.1 1 10 100 1000

0 2 4 6 8 10
Dynamics

Water

1 \mu J

radius (\mu m)

time (ps)

100 \mu m/ns!
Conclusions

- submicron-scale bulk micromachining
- weak bandgap and wavelength dependence
- only a few nanojoules required
Laser micromachining simplified

5-nJ threshold: unamplified micromachining
Laser micromachining simplified

5-nJ threshold: unamplified micromachining
Laser micromachining simplified

waveguide machining
Laser micromachining simplified

waveguide machining
Future applications

- Photonic devices
Future applications

- Photonic devices
- Wavelength-selective splitter
Future applications

wavelength selective splitter
Future applications

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wavelength selective splitter
Future applications

- Photonic devices
- Wavelength-selective splitter
- Photonic bandgap materials
Open questions

- Propagation of pulses
- Mechanisms
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For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu