Oscillator-only micromachining of transparent materials

Chris B. Schaffer
Andre Brodeur
Jose F. Garcia
Alan Jamison
Eric Mazur

Photonics West
January, 2000

Harvard University
Department of Physics
high intensity at focus

100 fs

objective

transparent material
causes nonlinear ionization
producing microscopic bulk damage
producing microscopic bulk damage

with only tens of nanojoules!
producing microscopic bulk damage

with only tens of nanojoules!
why bulk?
why bulk?

three-dimensional micromachining
why bulk?

three-dimensional micromachining

why nanojoules?
why bulk?

three-dimensional micromachining

why nanojoules?

non-amplified micromachining
Amplifier micromachining
Amplifier micromachining

Oscillator micromachining
Amplifier micromachining
Oscillator micromachining
Summary
AMPLIFIER MICROMACHINING

40 nJ
100 fs
800 nm
0.65 NA
Corning 0211

top view
40 nJ
100 fs
800 nm
0.65 NA
Corning 0211

**top view**
40 nJ
100 fs
800 nm
0.65 NA
Corning 0211
40 nJ
100 fs
800 nm
0.65 NA
Corning 0211
100 fs
800 nm
0.45 NA
Corning 0211

side view SEM, 140 nJ
100 fs
800 nm
0.45 NA
Corning 0211

side view SEM, 250 nJ
side view SEM, 540 nJ

100 fs
800 nm
0.45 NA
Corning 0211
AMPLIFIER MICROMACHINING

transition in damage mechanism and morphology

thermal mechanism  explosive mechanism
shot number and energy dependence at 1 kHz

- Shot number and energy dependence
- Energy (nJ): 6.6, 8.3, 10, 13, 17, 26, 33, 41, 52, 66
- Number of shots: 2, 5, 10, 30, 100, 500, 1000, 5000
- Parameters: 100 fs, 800 nm, 1.4 NA, Corning 0211

10 µm
only 6.6 nJ; can we use only an oscillator?
energy threshold vs. NA for 100-fs pulses in Corning 0211
can we micromachine with an un-amplified laser?
to deliver 5 nJ to the sample

5-W DPSS laser at 532 nm

after losses in the objective and prism compressor...
... extend cavity of standard Ti:Sapph oscillator

laser specs: 20 nJ, 25 MHz, 20 fs

scale model of 1.4 NA focusing geometry

fs pulse  1.4 NA objective
scale model of 1.4 NA focusing geometry
actual 1.4 NA focusing geometry

plasma spark
damage made with 25-MHz oscillator: 5 nJ; 25,000 shots
5 nJ; 25,000 shots
OSCILLATOR MICROMACHINING

5 nJ; 25,000 shots

10 nJ; single shot
OSCILLATOR MICROMACHINING

5 nJ; 25,000 shots

cumulative heating by successive pulses melts the glass

10 nJ; single shot

explosive or small-scale melting mechanism
number of laser shots

$2.5 \times 10^4$ $2.5 \times 10^5$ $2.5 \times 10^6$ $2.5 \times 10^7$

more shots melt larger volumes

30 µm
how can we use this new femtosecond thermal micromachining?

write waveguides!
waveguide morphology: 20 mm/s machining speed
waveguide mode analysis

He:Ne
image of near field mode
line-out of near field waveguide mode for 633 nm
### Summary of Damage Morphologies and Mechanisms

<table>
<thead>
<tr>
<th>Single Shot</th>
<th>Low Energy</th>
<th>High Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-m $\Delta n$ small melt</td>
<td>$\downarrow$</td>
<td>Sub-m voids explosive</td>
</tr>
<tr>
<td>Multiple Shot</td>
<td>Larger $\Delta n$ accumulated melt</td>
<td>High contrast voids cumulative drilling</td>
</tr>
<tr>
<td>Slow Rep. Rate</td>
<td>M-sized $\Delta n$ cumulative melting</td>
<td>CAN'T AFFORD! $\downarrow$</td>
</tr>
</tbody>
</table>
Damage morphology

- Conneting morphology to damage mechanisms
- Need work on ionization mechanisms

Oscillator only machining

- Combining thermal and single-shot micromachining, we hope to create a variety of photonic structures using only a low-cost femtosecond laser oscillator.
ACKNOWLEDGEMENTS

W. Leight
Prof. N. Bloembergen
National Science Foundation

For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu/
pump sample with femtosecond pulse
block probe beam
detect light scattered by damage
THRESHOLDS

Vary NA, material, pump wavelength