Peter R. Herman  
Dept. of Electrical and Computer Engineering, Institute for Optical Sciences  
University of Toronto  
http://photonics.light.utoronto.ca/laserphotronics/

ECE 1473 Advance Laser Processing

Ultrashort Laser Interactions in Fabrication of Optofluidic MicroSystems

-- Herman Group
- Femtosecond MicroFabrication
- Burst Effects – heat accumulation physics
- Optical Circuits & Microfluidics: $\rightarrow$ 3D OPTOFLUIDICS
- 5-D Spectroscopy:
  - 3-D imaging, time-resolved imaging, and time-resolved spectroscopy
  - physical insights & intelligent laser processing
PULSED LASER MACHINING: nanosecond vs femtosecond laser pulses

Ultrafast Laser Processing – Handbook by Clark MXR


Simplified view of physical interactions and applications for ultrafast lasers

Nanosecond Laser Machining; Clark MXR view
Femtosecond Laser Machining; Clark MXR view
Pulsetrain 'burst' ultrafast (1ps) machining: Fused Silica low vs. high repetition rate

Fluence: 93 J/cm²
4 shots x 1 Hz

Temperature cycling leads to cracks

Fluence: 100 J/cm²
430 shots x 133 MHz

No Cracks!

Burst Laser Machining Method
US Pat: 6,552,301
Ultrafast Laser Burst Micromachining

- ‘Serendipitous discovery’

*High repetition rate offers two advantages*

- Minimum pulse-to-pulse separation avoids plasma shielding
- Minimum repetition rate heats surrounding glass

<table>
<thead>
<tr>
<th>Heat diffusion scale length in 7.5-ns $(4D_t\tau)^{1/2}$</th>
<th>Effective optical absorption depth $1/\alpha_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17 µm [Brittle $\Rightarrow$ Ductile]</td>
<td>0.25 µm</td>
</tr>
</tbody>
</table>

*Ultrafast Bursts* offer a new means of laser material processing that controls thermal relaxation between pulses

P.R. Herman, R.S. Marjoribanks, A. Oettl, Burst-ultrafast laser machining method, US patent (6,552,301)
Laser-Burst Micromachining

Ultrafast Laser Pulses

Sample

Microhole
Laser-Burst Micromachining

Ultrafast Laser Pulses

Plume

Heat Affected Zone
Laser-Burst Micromachining

Ultrafast Laser Pulses
for ideal Burst Effect

Plume is gone

Heat Affected Zone has not dissipated

Next laser pulse interacts with thin heated sheath of substrate
Laser-Burst Micromachining

Ultrafast Laser Pulses
for ideal Burst Effect

Burst Benefits:
• laser heated interaction zone avoids inbuilt stresses from thermal cycling
• annealing of laser interaction zone
• improved ductility avoids micro-crack generation
• long-enough pulse separation to avoid plume shielding
• maintain merits of ultrafast laser interaction benefits

Next laser pulse interacts with thin heated sheath of substrate

Heat Affected Zone has not dissipated
Burst Femotosecond Laser

Compact Imra Fiber Laser (0.1-5 MHz, 450fs)

Spitfire (1kHz, 45fs)

Burst Resonator

opa

Aerotech XYZ Air-bearing Motion Stages (100nm)

5D Microscopy System Setup

1 kHz laser-Spitfire
- 800nm, 3mJ, 1 kHz
- 40fs to 5 ps
- Modified burst 37MHz

Fiber-amplified MHz laser (Imra America uJewel)
- 1044/522nm, 300fs, 0.5 W, 0.1-5 MHz

High resolution processing station
- 100-nm precision air-bearing xyz stages
ULTRAFAST BURST GENERATOR

S. Abbas Hosseini and PR Herman
Burst Train Profiles

- Variable # pulses
- Variable Time Separation (26ns x n)
- Variable Energy Profile
BK7 glass: Top view

Single Pulse – NOT BURST
1 kHz mode
1000 pulse
115 µJ/pulse
BK7: Side view

Burst mode
7 pulse in each burst
115 µJ/burst
Conclusion: Optofluidics, MicroReactors, Microsystems on a chip, lab on a fibre

Start dreaming in 3D

Drilling holes in SMF-28 Fiber Burst mode, Jacket is not removed
**BURST** Ultrafast Laser Processing

- Toronto Discovery of Heat Accumulation Effects from purpose built *burst* picosecond laser
- Develop new *burst ultrafast* laser technology at UofT
- Today: Novel recipes, numerous patents, and IP on drilling, dicing, writing photonic and lab-on-chip microsystems.

Damage without burst laser
Writing Optics Circuits in GLASS

Waveguides at the same Net exposure:

Thermal Diffusion
→ lowest loss waveguide: 0.2 dB/cm

Heat Accumulation

5-D Microscopy
Time + Spectrum + Space

→ Unravel underlying physics
→ Image: diagnostic and positioning
→ Feedback Control
→ lower waveguide loss?
Burst Ultrafast Laser Refractive Index Modification: Cumulative heating effect

**AF45 borosilicate**

- 450-nJ pulse energy, 1045-nm ultrafast laser, static exposure
- 1.5 μm beam dia.
- Small changes in repetition rate have dramatic effect on thermal modification zone

<table>
<thead>
<tr>
<th>Repetition Rate (pulses)</th>
<th>Beam Diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4 \times 10^7$</td>
<td>1.0</td>
</tr>
<tr>
<td>$4 \times 10^6$</td>
<td>0.1 MJ/cm²</td>
</tr>
<tr>
<td>$4 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>$4 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>$4 \times 10^3$</td>
<td></td>
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</tbody>
</table>

Small changes in repetition rate have dramatic effect on thermal modification zone.
Temperature evolution during waveguide writing

200 nJ absorbed energy, 1.6-μm spot size, 985°C softening point

Heat Accumulation Here!
High Repetition Rate Laser Waveguide Writing:
Constant Laser Power by Energy x Speed = constant
Refractive Index Profile (RNF) → Corning Eagle2000 borosilicate

- Lowest loss waveguides (~0.2 – 0.5 dB/cm) at each repetition rate
- Both Diffusion and Heat Accumulation → large elliptical heat zone
- Thermal effects precluded Bragg grating formation at λ ~ 0.5 μm
  - Try lower repetition rate & higher pulse energy
Effect of repetition rate on insertion loss

- At all repetition rates, minimum insertion loss occurs at 200 mW, 10-25 mm/s
  - The minimum insertion loss occurs at 1.5-MHz repetition rate
  - At 2 MHz, energy too low
  - Mode field diameter best matched to SMF at 1-2 MHz
Threshold energy for heat accumulation

Heat Accumulation Threshold: minimum pulse energy for 2-fold expansion over single-pulse thermal diffusion size

Diffusion-only processing

Diffusion & Heat Accumulation processing
Devices
fs-laser writing of Optical Circuits
Directional Couplers - Eagle2000 Herman Group

In Progress: Birefringent Waveguide Polarization Splitters

WDM SYMMETRIC COUPLERS
Tailor designed Add/Drop spectrum

BROAD BAND ASYMMETRIC COUPLERS
Tailor designed Coupling ratio
fs-lasers: Optical Circuits - Herman Group Bragg grating waveguides (BGWs)

wavelength tuning, chirping, apodization

At high scan speed of ~0.5mm/s

Spotsize: ~1μm

Eagle 2000 Glass

Laser rep rate
Scan speed
1-kHz Single Pulse Voxel Writing

**EAGLE2000 Borosilicate**

Mode Profile: Gaussian

\[ 10 \text{ mm} \times 11 \text{ mm} \]

\[ \rightarrow 0.1 \text{ dB Facet loss} \]

Laser Modification: \( \sim 2 \text{ um core} \)

MODE Solutions software (Lumerical)

\[ \rightarrow \Delta n_{DC} = \sim 0.01 \]

Propagation Loss

\[ \rightarrow 0.5 \text{ dB/cm} \]

(0.2 dB/cm possible)

\[ \Delta n_{AC} = \frac{\lambda}{\pi L \eta} \tanh^{-1} \left( \sqrt{R} \right) \]

\[ \rightarrow \Delta n_{AC} = \sim 4 \times 10^{-3} \ (40\%) \]

\[ 11/17/2009 \]

CLEO CThG1 Tut - Herman - UofT 29
Bragg Grating Application Directions

- **Wavelength tuning**
- **Chirping**
- **Cascading**
- **Sensing**
- **Telecom**

BGW fabrication methods:

06/13/2007

PHD thesis defense -- Haibin Zhang

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3D BGW sensor network
Measurement of the thermal optic property

![Diagram showing hot plate, glass, conduction, convection, ASE, OSA, and BGW.]
Measurement of the thermal optic property

- 10.4 pm/°C, close to SMF 28 FBGs
Sensor strain response

(a)
Sensor strain response

...temperature compensated

- 1.38 pm/µε and -1.27 pm/µε
- 1.15 pm/µε for SMF28 FBGs for 1550-nm radiation [119]
Surface Texturing: holographic and coloured logos
Herman Group, UofT

- Macro, Micro, & Nano-structuring of grating relief on polished steel ( stamping templates)

MACRO

- laser: 50 fs, 800nm,10uJ
- 7 pulse burst train (38 MHz)
- 0.25 NA; 1.1 um dia.
- ~10 mm/s raster scan

2 – 20 um MACRO grating patterns controlled by line-by-line spacing
Surface Texturing: holographic and coloured logos
Herman Group, UofT

MICRO & NANO
- Laser-induced periodic surface structures (LIPSS)
  - Perpendicular to polarization; sub-wavelength: 0.65 \( \lambda \) to 0.86 \( \lambda \)
- New: nano rippled gratings
  - \( \sim \)70 to 100 nm period that were aligned parallel to the laser polarization.

MACRO, MICRO & NANO:
Self-organized and direct-write gratings enable Holographic Logos and metal colouring.
Microfluidic Channels

- Laser exposure
  - generate nanogratings
- HF (5%) etching
  - direction selective
- Polarization control
  - enhance/inhibit etching

How to stop waveguides from being etched?
1\textsuperscript{st} Step: Laser Patterning (multi-scan)

IMRA Fiber-Amplified Ultrafast Laser:
- Wavelength: 522-nm
- Repetition Rate: 1 MHz
- Pulse Duration: 220 fs (Lorentzian)
- Power: up to ~200 nJ pulse energy
- Objective Lens: 40x 0.55-NA Aspherical Lens

$\text{d}_S \rightarrow 75 \, \mu\text{m} \text{ to } 210 \, \mu\text{m}$
$\text{d}_T \rightarrow 1 \, \mu\text{m} \text{ to } 3 \, \mu\text{m}$
$\text{d}_L \rightarrow 1 \, \mu\text{m} \text{ to } >4 \, \mu\text{m}$
Cross-sectional Shaping

- Processing Parameters
  - Scan speed = 0.5 mm/s
  - 5% HF etching
Integrated Optofluidic Device

- Single scan routine
- Reservoirs (L x W x H): 0.5 x 0.5 x 0.3 mm³
- Channel: 5 x 5 array with $d_T = 2 \, \mu m$, $d_L = 3 \, \mu m$
- Depth: ~75 \, \mu m deep

- Waveguide: single track
- Speed: 0.5 mm/s
- Power: 125 mW
- 3.5 hrs @ 5% HF
- Evanescent field probe of fluid
- Temperature/Strain Gauges
- 3D Optofluidic integration

BGWs depth beneath glass surface = 75 \( \mu \text{m} \)
SUN
Radiation spectrum from surface temperature
- cannot see inner core

“Laser Sun”:
- 1 MHz → heat accumulation
- laser heated core – opaque?
- Radiative shells of decreasing temperature and decreasing opacity
Intelligent Laser Processing

- Modified burst-mode kHz laser (Spitfire)

- Compact fiber-amplified MHz laser (Imra America)

- High resolution optical processing station with 100-nm precision air-bearing xyz stages
Schematic Diagram of 5D Microscopy System

Glass Target:
- Alkaline Earth Boro-Aluminosilicate glass (EAGLE2000™)

Air-bearing stages Aerotech

Aspherical / Objective Lens NA ~ 0.55
internal focus ~ 0.8 μm
DOF: ~2.5 μm

2w lens

2w filter

2w crystal

IMRA fs laser

Imra (μJewel) fiber Laser
~450 fs 1045nm/522nm
1 MHz Rep Rate
v_{scan} ~ 100 μm/s to 20 mm/s

2D Time-Resolved Imaging
time-gated ICCD Andor (2 ns)

3D Multiphoton Laser Scanning Microscopy

Fiber Bundle

Delay Generator

Becker&Hickl TCSPC Board

Spectrograph

Becker&Hickl TCSPC Board

Time-Resolved Spectroscopy

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3-D Multi-photon Laser Scanning Microscopy

- 2-D Time-resolved Imaging
- Time-resolved Spectroscopy
Multiphoton UF Laser Scanning Microscopy Image of UF Laser Written Waveguides

Borosilicate: Eagle2000

WG Writing Parameters:
--1045nm/450fs/170nJ
--1MHz Rep Rate
--15mm/s scan speed

Imaging Parameters:
--1045nm/450fs/40nJ
--1MHz Rep Rate
--10mm/s scan speed
--(X) Pixel size: 0.5μm
--(Y) Line separation: 0.5μm
3-D Multi-photon Laser Scanning Microscopy

- 2-D Time-resolved Imaging
- Time-resolved Spectroscopy
Time-Resolved 2D Images of Borosilicate Glass

Gate Delay: 0ns  200ns  500ns  900ns

0ns  12ns  22ns  62ns

1 MHz: >500ns decay!
100 kHz: <100ns decay!
Not Photoluminescence!
- 3-D Multi-photon Laser Scanning Microscopy
- 2-D Time-resolved Imaging
- Time-resolved Spectroscopy
Time-resolved Spectra of Borosilicate Glass

Gate Delay: 0ns  80ns  380ns  880ns

Long decay: ~500ns (1MHz)

0ns  40ns  80ns  140ns

Short decay: ~60ns (100kHz)

1MHz / 1045nm / 180nJ / 15mm/s

100kHz / 1045nm / 180nJ / 1.5mm/s

Emission is >2 times stronger for 1MHz!

Laser Power absorption:
~66% @1MHz
~36% @100kHz
Correlation: Real-time Spectra & Waveguide Loss

Strongest emission associated with lowest waveguide loss:
→ new direction for real time feedback for controlling waveguide writing?
Laser Material Processing – is highly successful application of laser, and essential to manufacturing today
Ultrafast Laser Interactions
- exciting new science events → fundamental investigation
- advantages to break open new commercially important applications

CONCLUSION and Thanks!