Fabrication of Micro and Nano Structures in Glass using Ultrafast Lasers

Denise M. Krol
University of California, Davis

IMI Glass Workshop
Washington DC
April 15-17, 2007
Femtosecond laser modification of glass: questions

■ Interaction of glass with sub-bandgap, focused, 100 fs laser pulses
  what is special?

■ Which glass properties can be modified?
  what can this be used for?

■ What is the influence of laser parameters and glass composition?
  pulse energy, rep rate, wavelength and spot size of the laser
  writing geometry
  glass composition

■ What are the atomic scale structural changes after modification?
  what is the mechanism?

■ Summary
  key challenges and issues
Femtosecond laser modification of glass: questions

- Interaction of glass with sub-bandgap, focused, 100 fs laser pulses
  what is special?

- Which glass properties can be modified?
  what can this be used for?

- What is the influence of laser parameters and glass composition?
  pulse energy, rep rate, wavelength and spot size of the laser
  writing geometry
  glass composition

- What are the atomic scale structural changes after modification?
  what is the mechanism?

- Summary
  key challenges and issues
Interaction of glass with sub-bandgap, focused, fs laser pulses

- cw laser at 800 nm
- silica glass
- sub-bandgap light is transmitted
- photon energy
- Light-matter Interaction is localized in time and space -> 3-D control of modification
- ultrashort (100fs) pulses and tight focusing (μm-size spot)
- deposition of laser energy into glass
- permanent modification

at low to moderate intensities
- sub-bandgap light is transmitted
- photon energy
How does the material change on an atomic scale?

1) Multiphoton absorption
2) Avalanche photoionization
3) Plasma formation
4) Proposed mechanism:
   - Shockwave propagation (microexplosion)
   - Fast heating and cooling
5) Modified spot

Femtosecond laser modification of glass: questions

- Interaction of glass with sub-bandgap, focused, 100 fs laser pulses
  what is special?

- Which glass properties can be modified?
  what can this be used for?

- What is the influence of laser parameters and glass composition?
  pulse energy, rep rate, wavelength and spot size of the laser
  writing geometry
  glass composition

- What are the atomic scale structural changes after modification?
  what is the mechanism?

- Summary
  key challenges and issues
Femtosecond laser pulses can modify various glass properties

Properties:

- Refractive index
- Absorption
- Composition (phase separation)
- Valence state (Sm$^3+$ -> Sm$^2+$)
- Crystal nucleation (Ag and Au colloids in glass)

Applications:

- Photonic devices
- Lab-on-chip
- Data storage
- Optical switching

Foturan glass:
Lithium alumino silicate glass doped with Ce$^{3+}$ and Ag$^+$ ions

Fs laser fabrication involves 4-step process:
(1) direct writing of latent images in the sample (Ce$^{3+}$ + Ag$^+$ $\rightarrow$ Ce$^{4+}$ and Ag)
(2) heat treatment of the sample induces crystallization of metasilicate phase in exposed regions
(3) etching of the sample in HF solution for selective removal of the modified regions,
(4) postbaking of the etched sample for further smoothing of the internal surfaces

Fs laser fabrication of microfluidic reactor in Foturan glass

Schematic diagram of valve operation

Fs laser fabrication procedure

Actual device

Fs laser fabrication of microfluidic dye laser in Foturan glass

Integration of microfluidics and microoptics

Femtosecond laser fabrication of microchannels and nanogratings in BK7

Fig. 6. SEM images of xy-sections of nanostructures with linear polarization (a) parallel; (b) perpendicular to S, 65 µm subsurface with NA = 0.65, \( \tau_p = 150 \, \text{fs} \), \( E_p = 300 \, \text{nJ} \), repetition rate \( f = 100 \, \text{kHz} \), writing speed \( v = 30 \, \mu\text{m/s} \); the samples were etched 20 min in 0.5% HF; (c) optical images of etched channels (480 min in 2.5% HF); top channel corresponds to (a), bottom channel-to (b), middle channel-to 45° linear polarization.

Fig. 7. Etch rates due to nanostructures [2]. Writing parameters as in Fig. 6.

Fs laser micro-welding

conventional laser joining

fs laser joining

Fs laser micro-welding

Welding of 2 borosilicate samples:

Laser parameters:
- \( \lambda = 1558 \text{ nm} \)
- \( E = 0.8 \mu\text{J} \)
- Rep rate = 500 kHz
- \( \tau = 950 \text{ fs} \)

Also possible with dissimilar materials:
- borosilicate glass-fused silica
- phosphate glass (Schott IOG-1)-fused silica
- borosilicate glass-polymer
- borosilicate glass and silicon

Joint strength
- 9.87 MPa
- 6.81 MPa
Fs pulses have been used for spatially selective crystallization of metal nanoparticles in glass.

- **(a)** Irradiation with fs laser
- **(c)** Subsequent heat treatment at 520 C
- **(d)** Re-irradiation with fs laser
- **(e)** Further heating at 300 C

Fs laser fabrication of components for integrated optics

- Integration of functionalities
  - example: waveguide laser
  - Bragg gratings ($n_2$)
  - rare-earth doped glass substrate ($n_0$)
  - waveguide region ($n_1$)
  - $n_2 > n_1 > n_0$

- Component arrays
  - waveguides
  - $\lambda_1$, $\lambda_2$, $\lambda_3$

- Ability to fabricate 3D structures
Fs laser pulses have been used to fabricate optical splitters

Fs laser pulses have been used to write fiber Bragg gratings


Fig. 4. Photographic image of photoinduced index modulation as seen through an optical microscope. The spacing between lines in the image corresponds to the 3.213-μm period of the phase mask.
Fs laser pulses have been used to fabricate waveguide lasers

Erbium:Yb-doped phosphate glass waveguide

$$\Delta n = 10^{-2}$$
Loss < 0.4 dB/cm
Single mode at 1600 nm
25 mW output power

Laser parameters:
Cavity dumped ML Yb: glass
$$\lambda=1 \ \mu m$$
270 nJ
685 KHz
100 $$\mu m/s$$

Femtosecond laser modification of glass: questions

- Interaction of glass with sub-bandgap, focused, 100 fs laser pulses
  what is special?

- Which glass properties can be modified?
  what can this be used for?

- What is the influence of laser parameters and glass composition?
  pulse energy, rep rate, wavelength and spot size of the laser
  writing geometry
  glass composition

- What are the atomic scale structural changes after modification?
  what is the mechanism?

- Summary
  key challenges and issues
Experimental parameters in fs-laser writing

- writing geometry:

- pulse energy: 0.1-10 \( \mu \text{J} \):
Dependence on fs laser pulse energy in fused silica

**laser parameters:** 800 nm, 130 fs, 1 kHz

**scan speed:** 40 µm/s  
**MO:** 50x, 0.55 NA

Distance: 5 µm

**degree of modification:**
- Slight modification
- Damage

**fs energy (µJ):**
- 0.00
- 0.15
- 0.25
- 0.7
- 1.3
- 2.0
- 2.7
- 5.9

**Good waveguides**
Experimental parameters in fs-laser writing

- Writing geometry:
  - Longitudinal writing
  - Transverse writing

- Pulse energy: 0.1-10 µJ
- Laser wavelength: 800 nm
- Pulse repetition rate

- 1 kHz
- 25 MHz
Difference between high and low pulse repetition rate

E. Mazur et al., Harvard Univ.
Modification in IOG-1 is different from fused silica

White light transmission images of:

- **800 nm, 130 fs, 1 kHz**

10x, NA = 0.25

One pass

20 µm/s

- **fused silica**
- **IOG-1 glass (phosphate glass)**

High index region

Low index region
Femtosecond laser modification of glass: questions

- Interaction of glass with sub-bandgap, focused, 100 fs laser pulses
  what is special?

- Which glass properties can be modified?
  what can this be used for?

- What is the influence of laser parameters and glass composition?
  pulse energy, rep rate, wavelength and spot size of the laser
  writing geometry
  glass composition

- What are the atomic scale structural changes after modification?
  what is the mechanism?

- Summary
  key challenges and issues
We can probe the fs-modified glass with high spatial resolution using confocal fluorescence and Raman microscopy.

- **Fluorescence spectroscopy reveals**
  - color center defect formation
  - photobleaching of color centers upon exposure to laser light

- **Raman spectroscopy shows**
  - permanent structural reconfiguration of the glass network
  - in fused silica glass densification occurs
  - in fused silica densification is main contributor to induced index change of $10^{-4}$
Comparison between fused silica and phosphate glass IOG-1

- **Fused Silica**
  - White light images
  - NO color centers in w.g. regions
  - W.g. regions not directly exposed to fs pulses

- **Phosphate Glass**
  - White light images
  - Fluorescence images
  - High index region
  - Low index region

**04/17/2007**
IMI Glass Workshop
Comparison between fused silica and IOG-1

Deposition of femtosecond laser energy results in “fast heating and cooling” of material so that the exposed glass is similar to glass which is rapidly quenched from a high melting temperature (higher $T_f$)

Refractive index of glass depends on quenching rate ($T_f$)

- $n$ increases with quenching rate
- $n$ decreases with quenching rate

high index (guiding) regions
low index regions

Fused silica
Phosphate glass
Femtosecond laser modification of glass: questions

- Interaction of glass with sub-bandgap, focused, 100 fs laser pulses
  what is special?

- Which glass properties can be modified?
  what can this be used for?

- What are the atomic scale structural changes after modification?
  what is the mechanism?

- What is the influence of laser parameters and glass composition?
  pulse energy, rep rate, wavelength and spot size of the laser
  writing geometry
  glass composition

- Summary
  key challenges and issues
Fs laser structuring of glass: summary

- Ultrafast lasers can be used to fabricate micro and nanostructures in glass with high spatial selectivity

- This techniques has applications for:
  - Lab-on-chip devices
  - Integrated optics
  - Micro-welding
  - ??
Fs laser structuring in glass: issues and challenges

- Fs laser fabrication is fairly new technology—still many more applications to be explored.
- 3D capability, high device density.
- Amorphous nature of glass crucial for many applications, e.g., photonics.
- Integration of different device components in one fabrication process.
- Different experimental parameters and materials needed for different types of microstructures.
- Process scaling?
- Excellent method for fabrication of prototypes.
- Fs lasers are (not yet) cheap.

Further exploration of devices and optimization of processing conditions needed.
Fs laser structuring: scientific questions

Still many aspects not well understood:

➢ Interplay between glass composition and laser parameters
   rep rate
   pulse duration
   scan speed

➢ Detailed structural modification, dynamics and mechanism

➢ Photonics
   - Refractive index profile and loss have complex dependence on laser processing parameters—not well understood
   - Materials issues, passive vs active vs nonlinear glasses
   - Integration of functions, e.g., waveguides and Bragg gratings

➢ Lab-on-chip devices
   - Foturan developed for UV laser fabrication, other glass compositions?

➢ Nanogratings and nanocrystals
   - Reproducibility
   - Size control
Ultrafast Lasers in Materials Research

David G. Cahill and Steve M. Yalisove, Guest Editors

Abstract

With the availability of off-the-shelf commercial ultrafast lasers, a small revolution in materials research is underway, as it is now possible to use these tools without being an expert in the development of the tools themselves. Lasers with short-duration optical pulses—in the sub-picosecond (less than one-trillionth of a second) range—are finding a variety of applications, from basic research on fast processes in materials to new methods for microfabrication by direct writing. A huge range of pulse energies are being used in these applications, from less than 1 nJ (a billionth of a joule) to many joules.

Keywords: laser, ablation.