An IMI Video Reproduction of Invited Lectures from the 17th University Glass Conference

Using Ultrafast Lasers to Add New Functionality to Glass

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New Functionality in Glasses
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Adding new functionalities to glass

Usually the functionality of glass is determined by

➢ **composition**	**oxides, chalcogenides, fluorides** **continuous variation**
➢ **doping**	**SiO_2 (passive optical components)** **vs SiO_2:Er^{3+} (active components)**
➢ **processing**	**bulk glass** **vs optical fiber, microspheres**

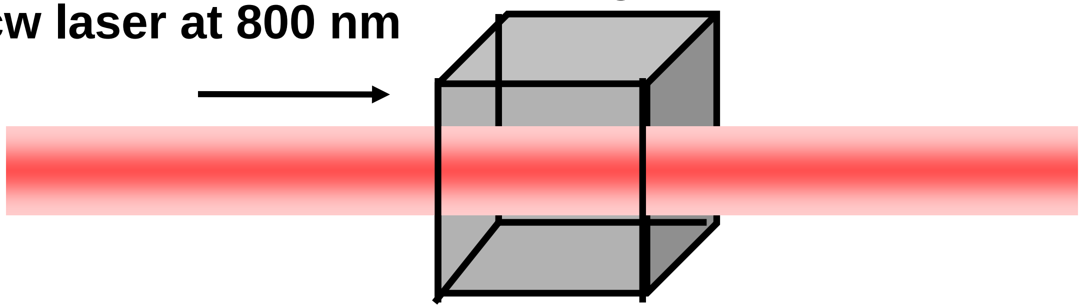
But functionality can also be modified by

➢ **light**	**UV inscription of Bragg gratings** **in SiO_2:Ge optical fibers**
➢ **electric field**	**thermal poling to induce $\chi^{(2)}$**

Femtosecond laser modification in glass

silica glass

cw laser at 800 nm

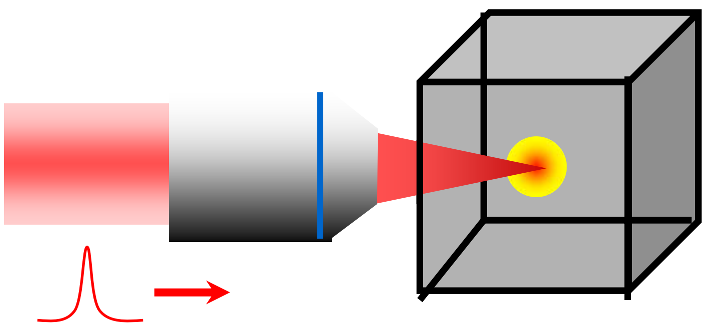


At low to moderate intensities below-bandgap light is transmitted

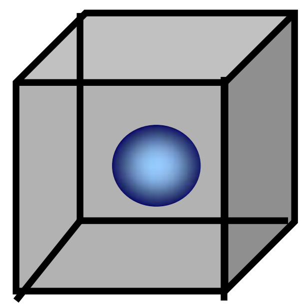
Light-matter Interaction is localized in time and space -> 3-D control of modification

ultrashort (100fs) pulses

and tight focusing (μm-size spot)



deposition of laser energy into glass

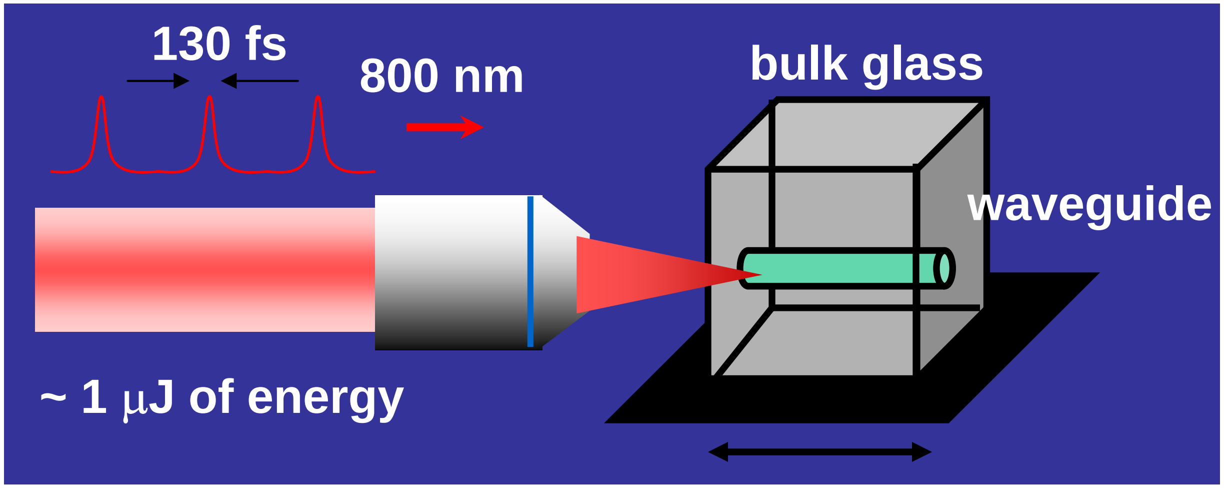


permanent modification

Femtosecond laser pulses can modify various glass properties

Properties that can be modified:

- **Refractive index**
- **Absorption**
- **Composition** — **phase separation**
- **Valence state** — **Sm3+ -> Sm2+**
- **Crystal nucleation** — **Ag and Au colloids in glass**

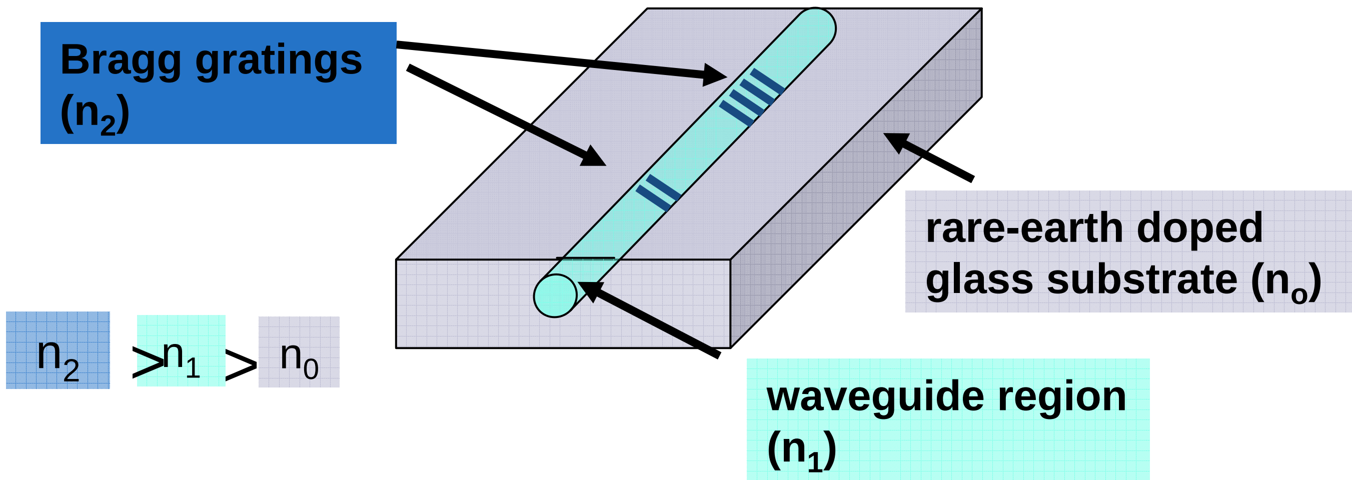


Davis *et. al*, Opt. Lett., 21, 1729 (1996)
Homoelle *et. al*, Opt. Lett., 24, 1311 (1999)

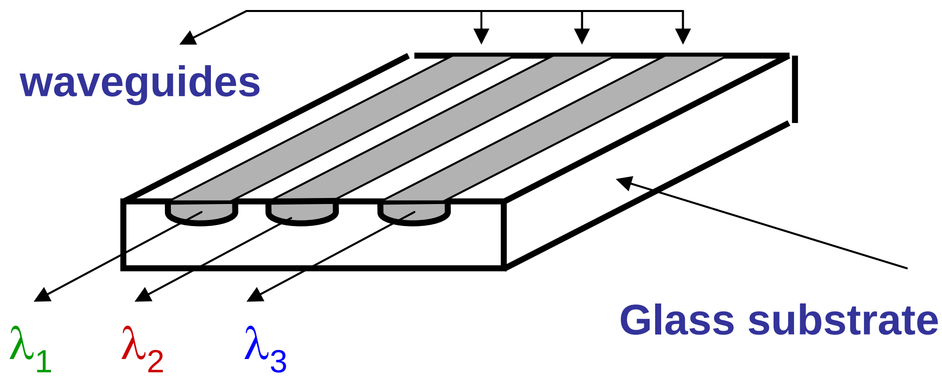
Femtosecond laser fabrication of components for integrated optics

– **Integration of functionalities**

example: waveguide laser



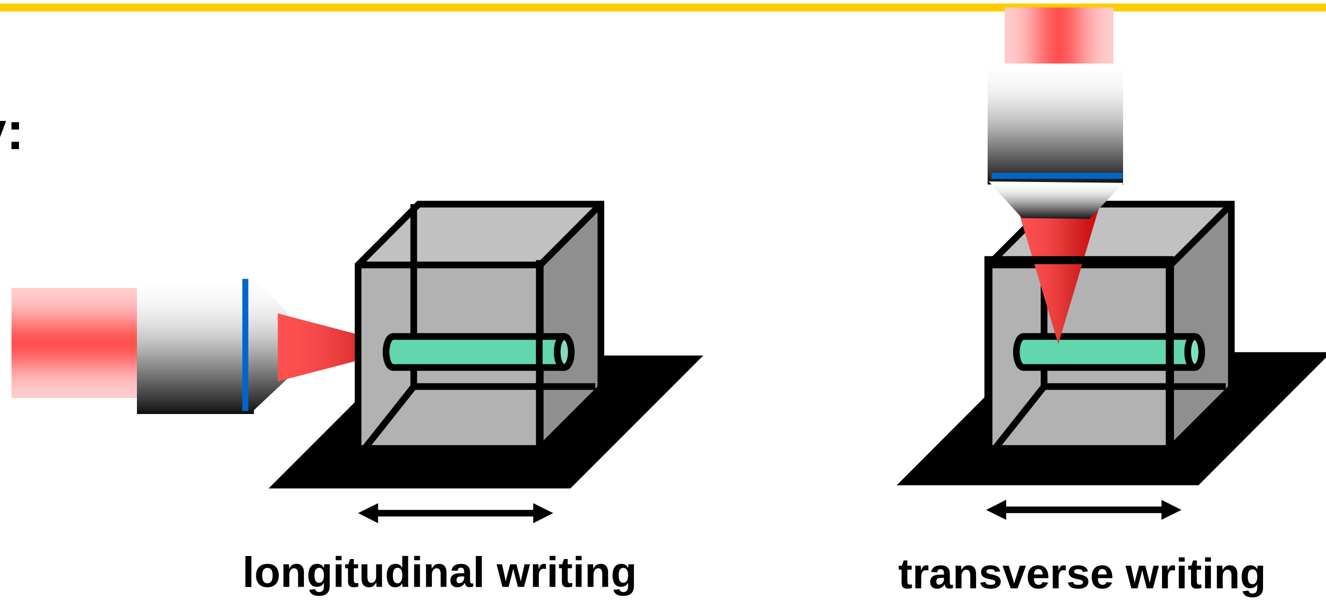
– **Component arrays**



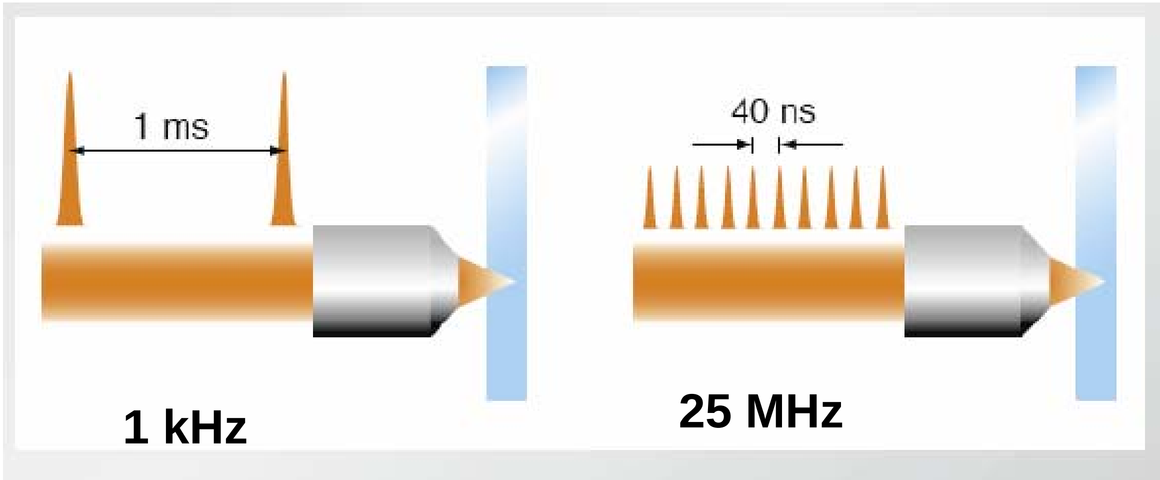
– **Ability to fabricate 3D structures**

Experimental parameters in fs-laser writing

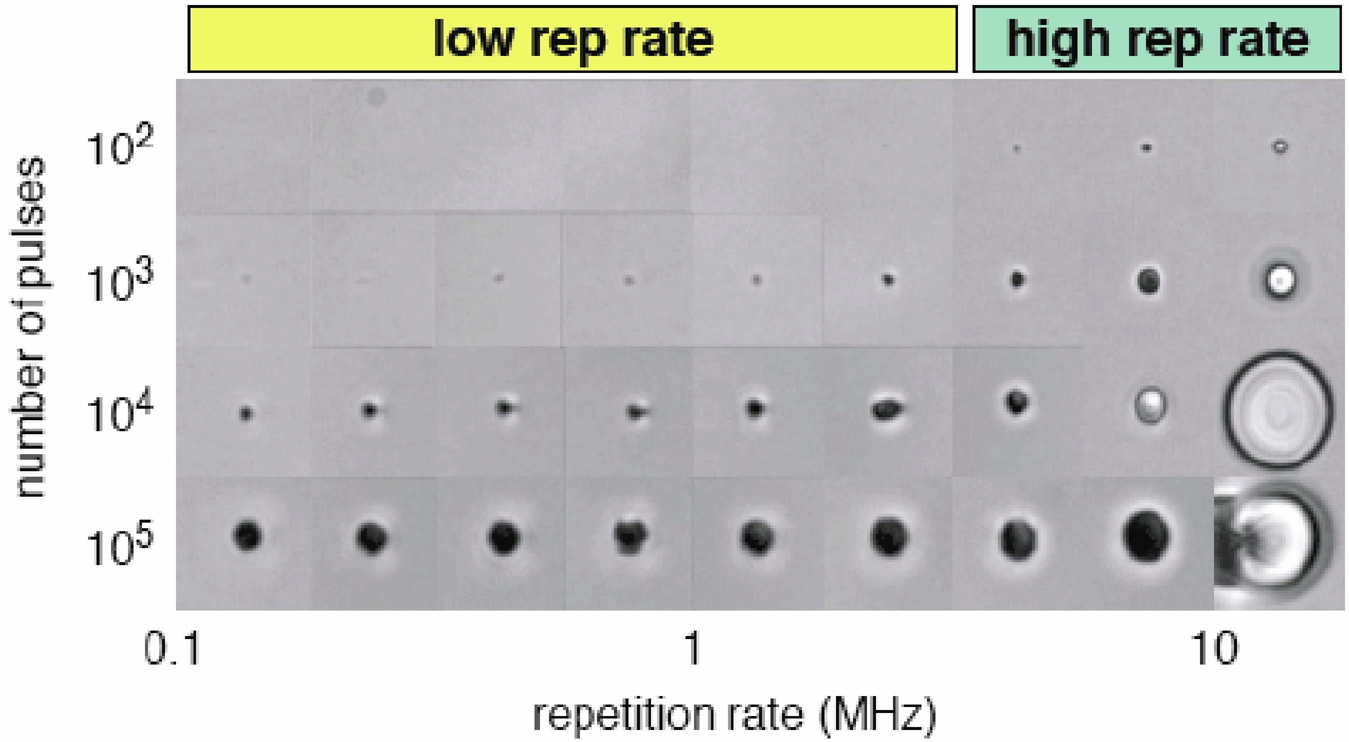
- **writing geometry:**



- **pulse energy: 0.1-10 μJ:**
- **laser wavelength: 800 nm**
- **pulse repetition rate**



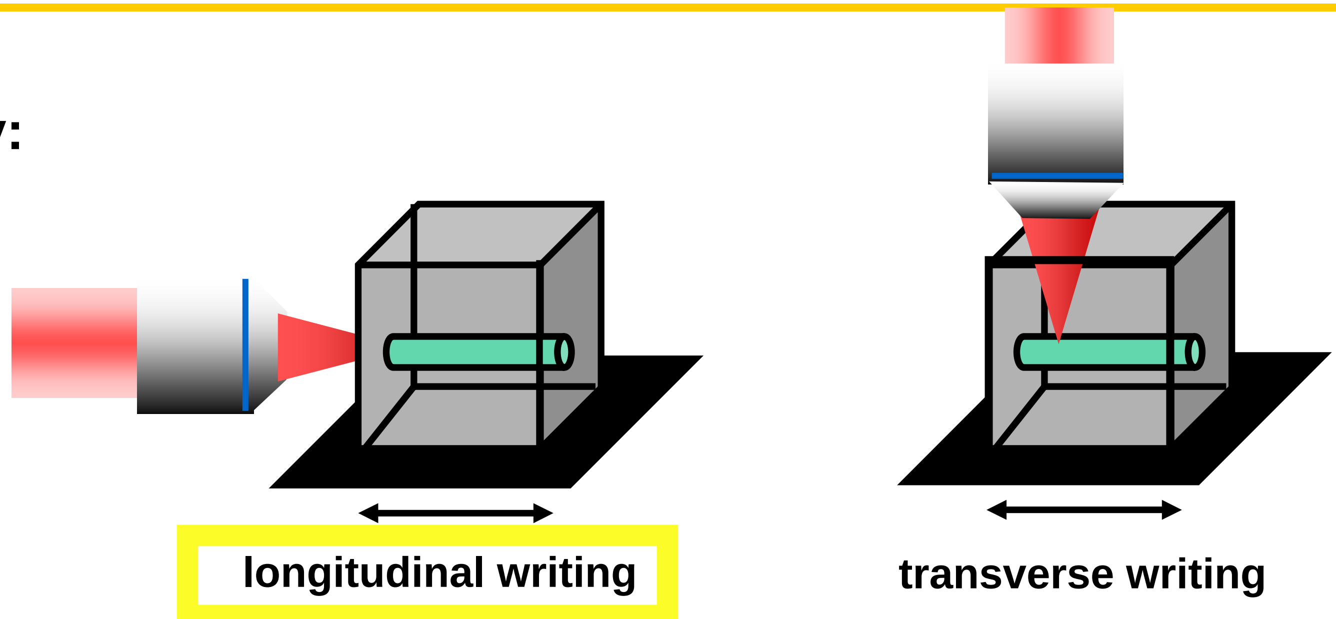
Difference between high and low pulse repetition rate



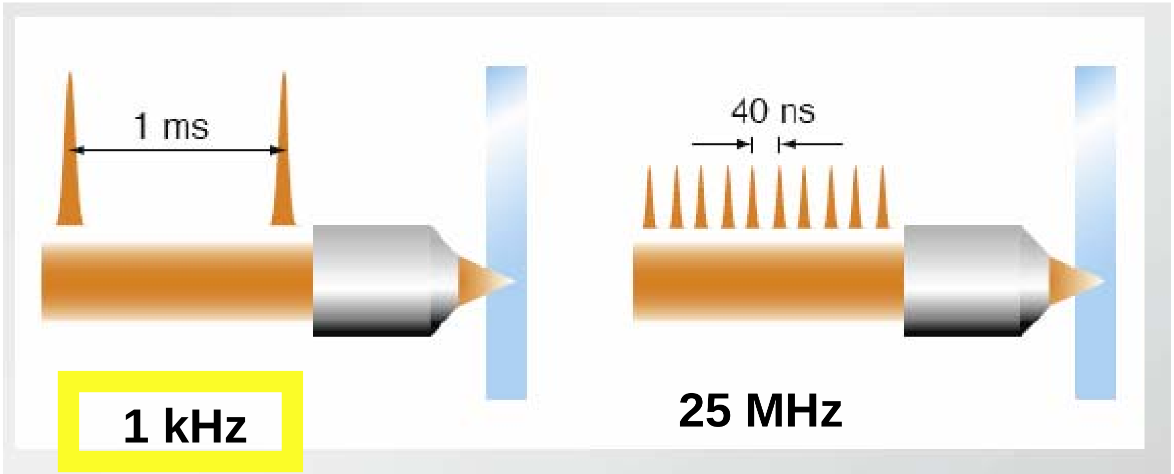
Is the structure of the modified material different for the low and high rep rate regimes ?

Experimental parameters used in our experiments

- writing geometry:



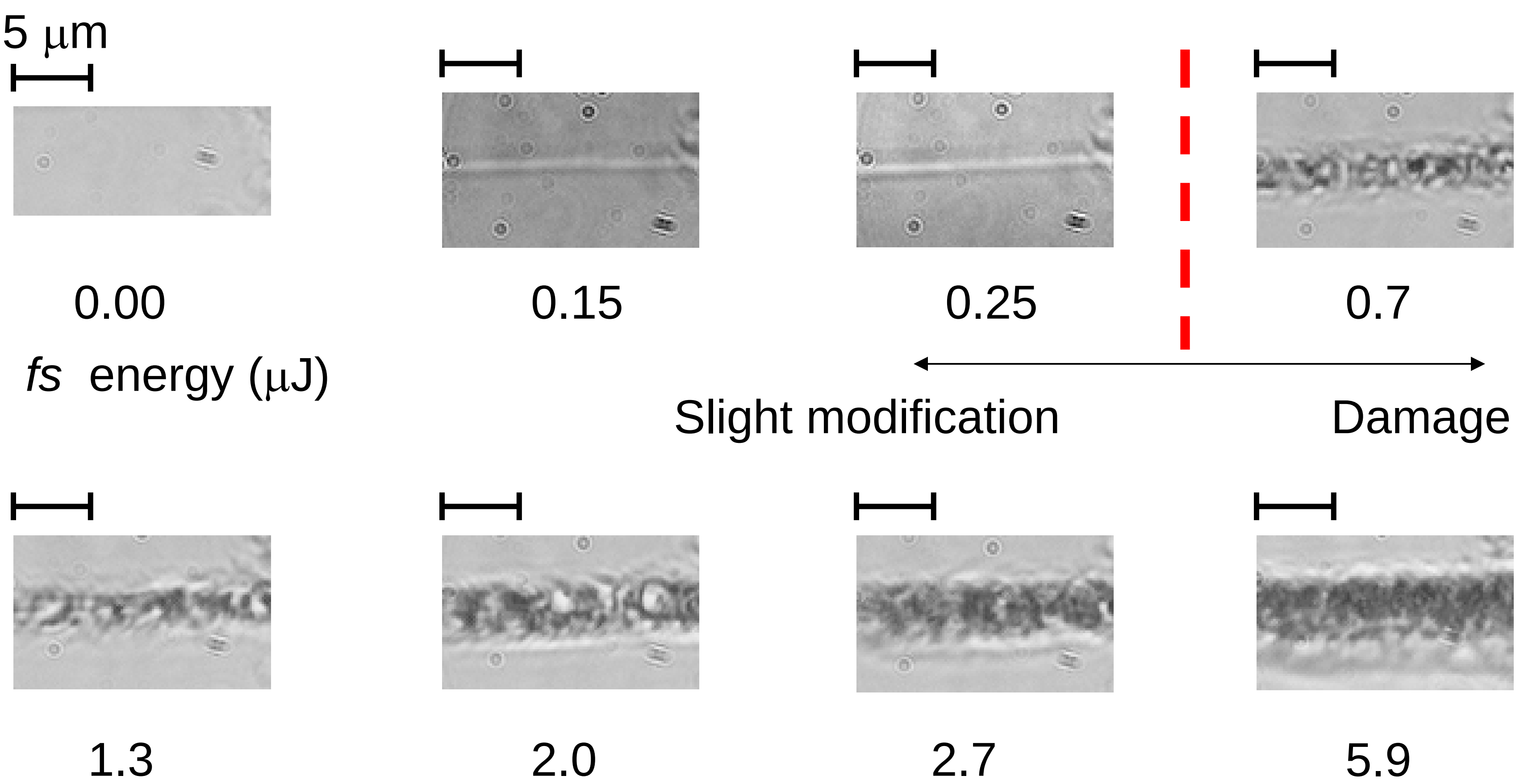
- pulse energy: 0.1-10 μJ:
- laser wavelength: 800 nm
- pulse repetition rate



White light micrographs of lines written with different fs pulse energies in fused silica

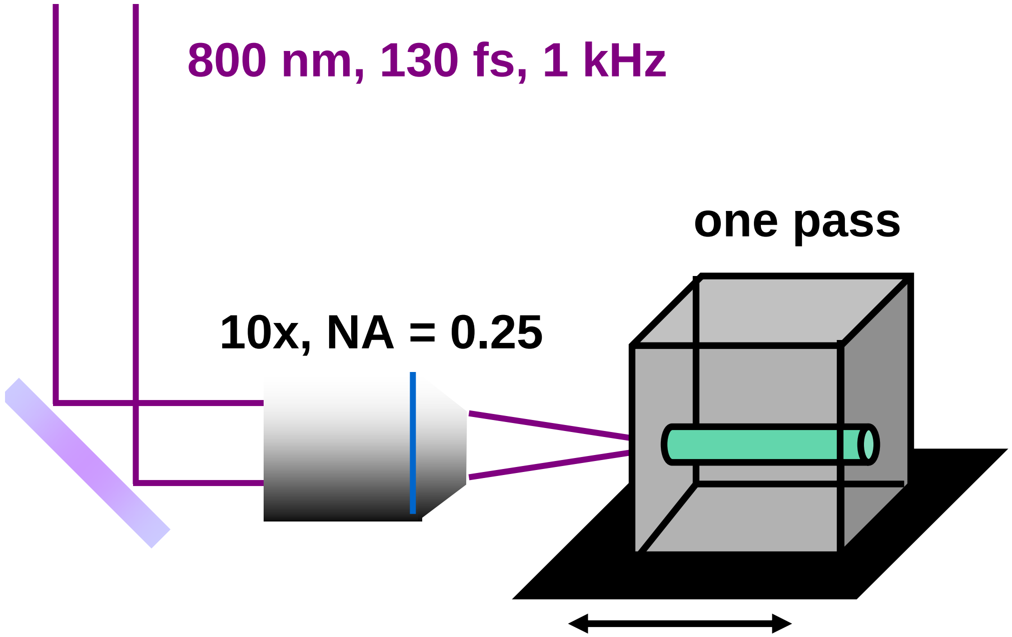
laser parameters: 800 nm, 130 fs, 1 kHz

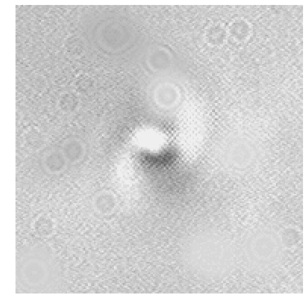
scan speed: 40 μm/s MO: 50x, 0.55 NA



Waveguides are written with 1 μJ of pulse energy

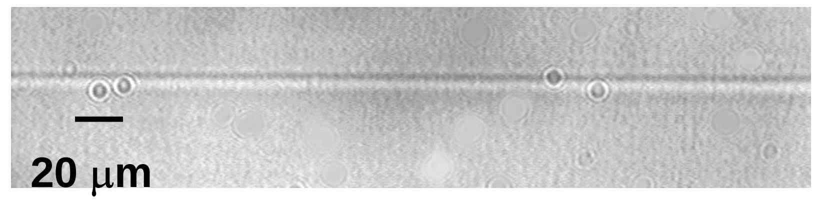
800 nm, 130 fs, 1 kHz



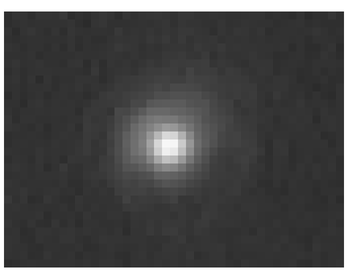


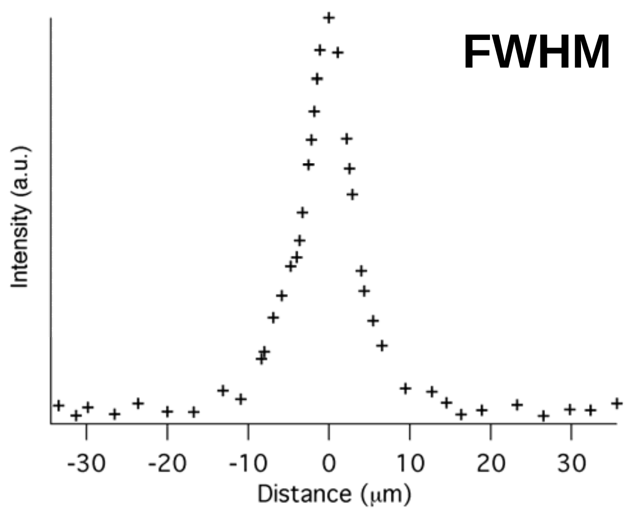
white light images

9 μm



Near field profile at 633 nm





FWHM = 8 μm

Far field profile

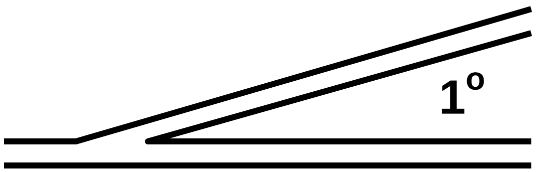
$$NA \sim \tan\theta$$

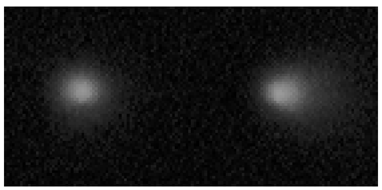
$$NA = \sqrt{2 n_o \Delta n}$$

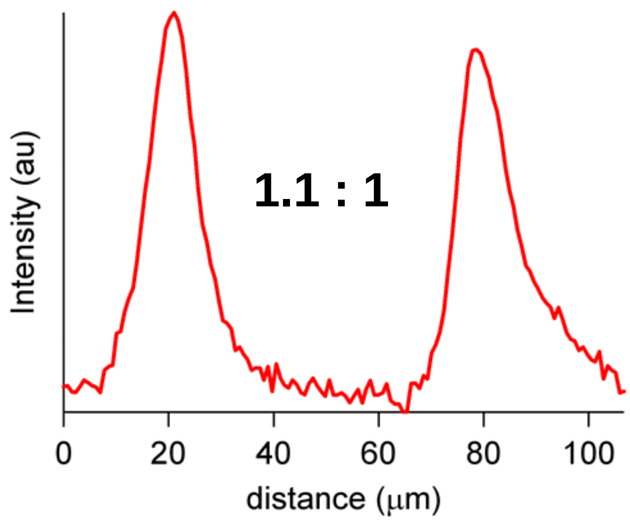
$\Delta n \approx 10^{-4}$

Splitters are made by scanning along multiple axes

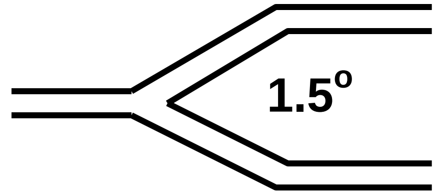
Asymmetric splitter

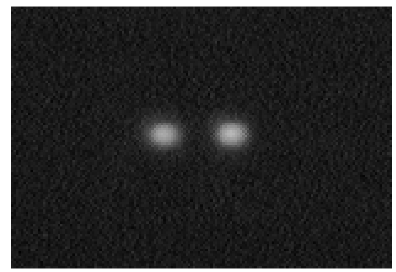


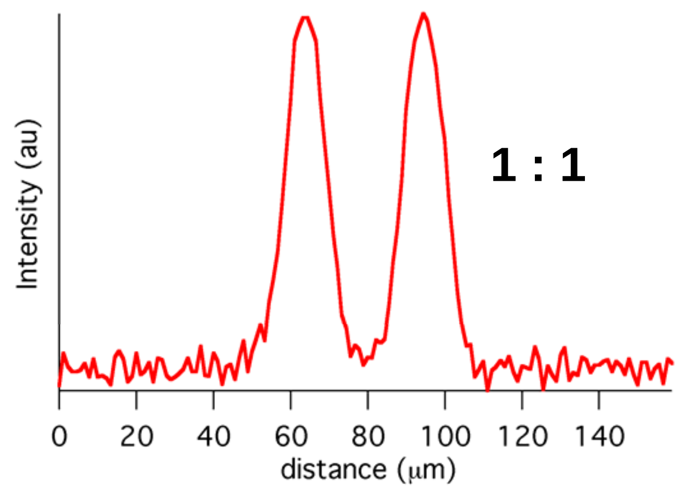




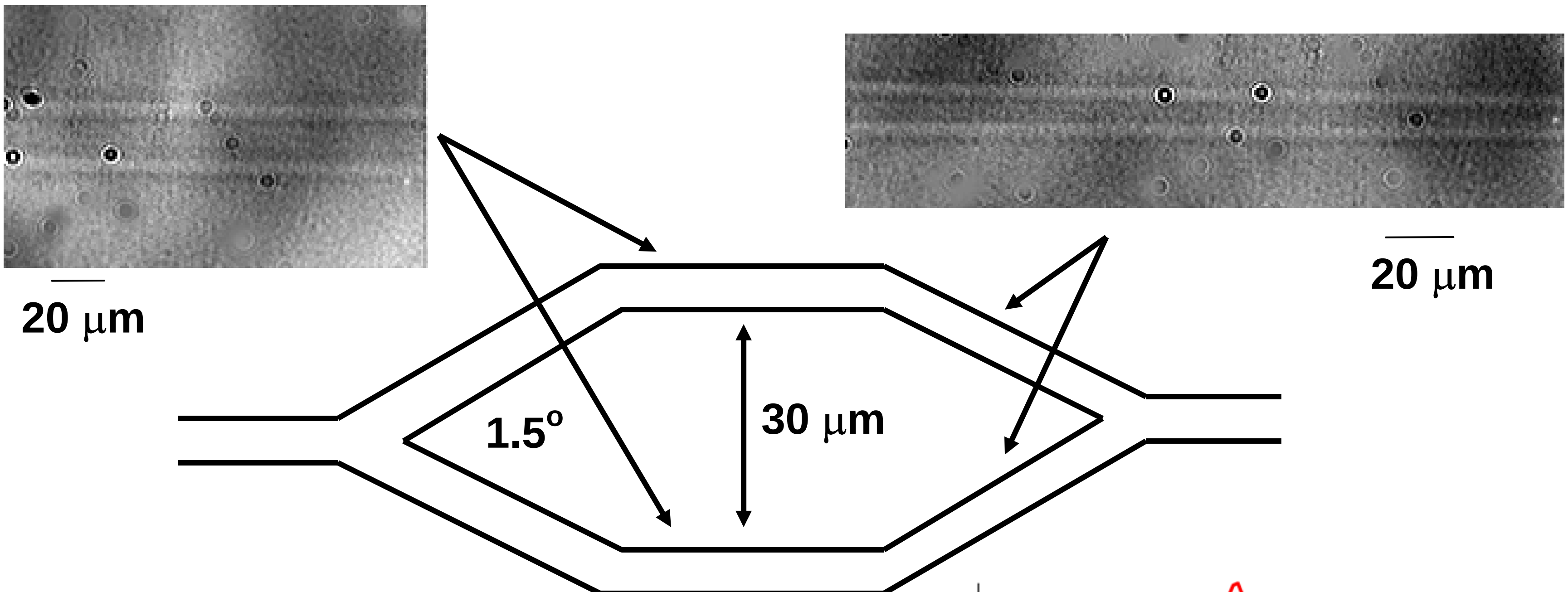
Y-branch splitter

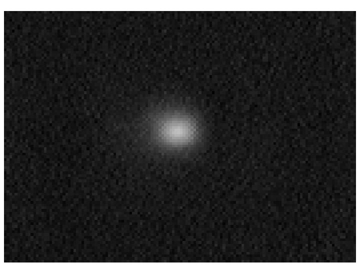




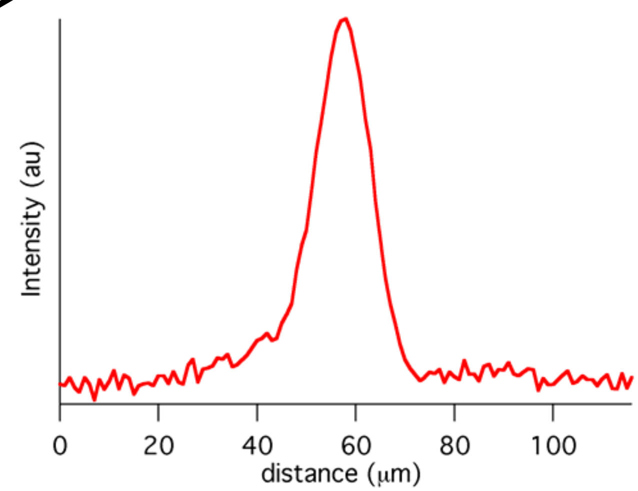


Mach-Zehnder interferometer inside fused silica





Near field profile at 633 nm



Fs pulses have been used to write fiber Bragg gratings

Mihailov et al., Opt. Lett. 28, 995 (2003)

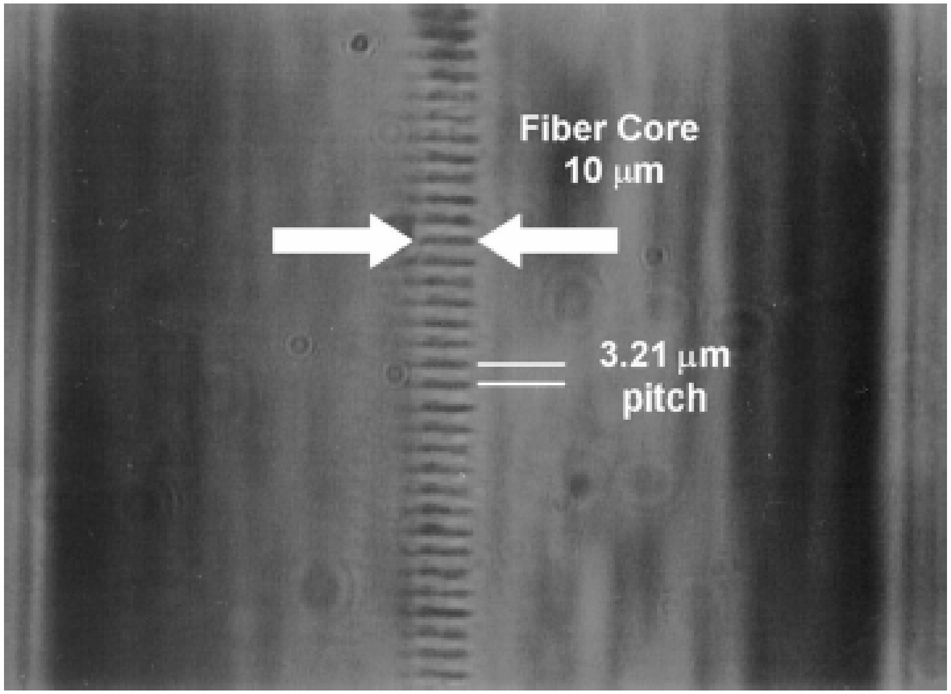


Fig. 4. Photographic image of photoinduced index modulation as seen through an optical microscope. The spacing between lines in the image corresponds to the 3.213-μm period of the phase mask.

Fs pulses have been used to write Er:Yb doped waveguide laser

Taccheo et al., Opt. Lett. 29, 2626 (2004)

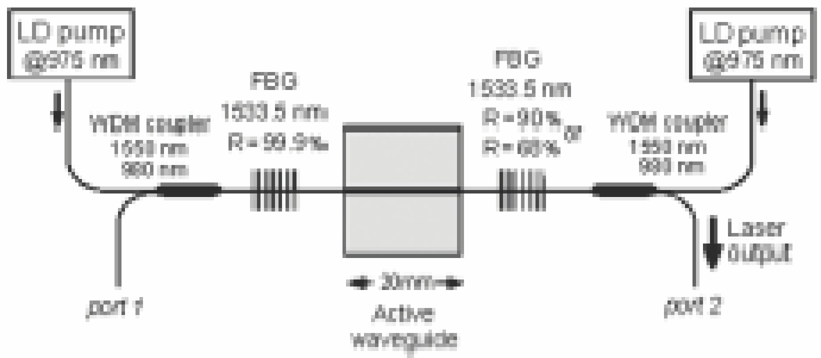


Fig. 3. Waveguide laser cavity configuration. Waveguide characterization was performed by removing the FBGs and coupling a tunable laser source throughout port 1. LD, laser diode; R, reflectivity.

Er:Yb-doped phosphate glass
Lasing wavelength: 1533.5 nm
Output power: 1.7 mW

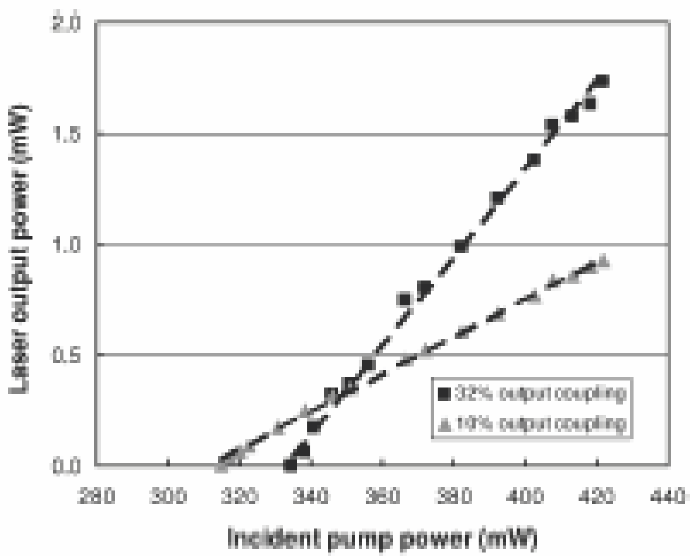


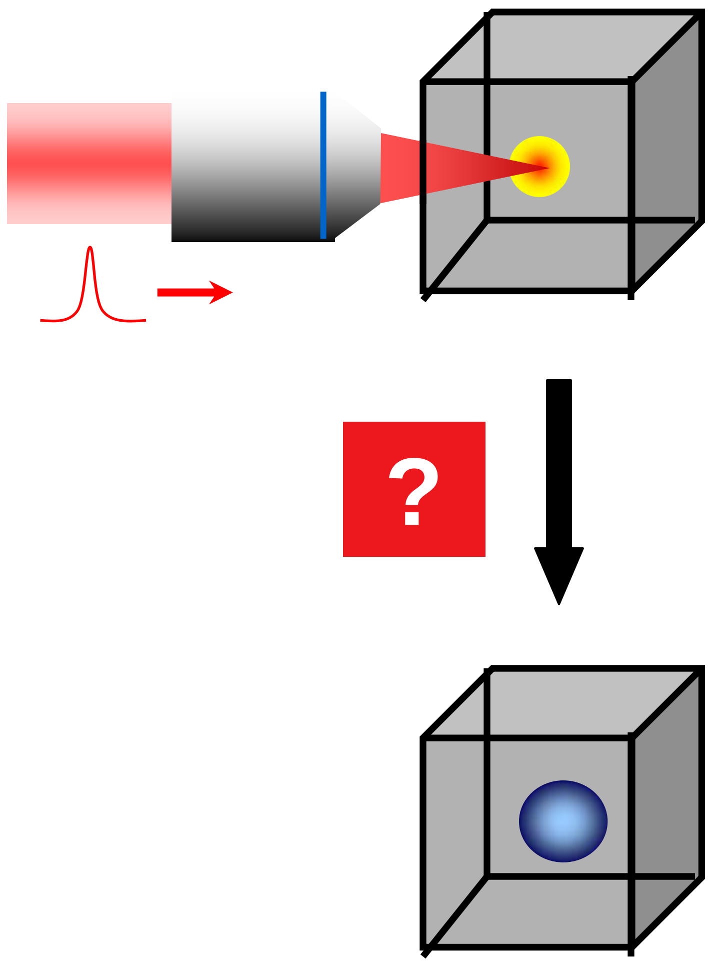
Fig. 4. Laser output power versus incident pump power for two different output couplers. The inset shows the RIN laser spectrum corresponding to 32% output coupling.

Objectives

- **Investigate the use of fs laser pulses to fabricate optical devices in glass**
  - write waveguides: pulse energies, scan speed
  - characterize waveguides: mode profile, loss

what is the effect of glass composition?

Femtosecond laser modification in glass



1) Multiphoton absorption
2) Avalanche photoionization
3) Plasma formation
   Stuart *et. al*, Phys. Rev. Lett., 74, 2248 (1995)
   Lenzner *et. al*, Phys. Rev. Lett., 80, 4076 (1998)

4) Proposed mechanism:
   Shockwave propagation - microexplosion
   Glezer *et. al*, Appl. Phys. Lett., 71, 882 (1997)

5) Modified spot
   <u>Localized Δn</u>

How does the material change on an atomic scale? - relation to Δn?

Objectives

- **Investigate the use of fs laser pulses to fabricate optical devices in glass**
  - write waveguides: pulse energies, scan speed
  - characterize waveguides: mode profile, loss

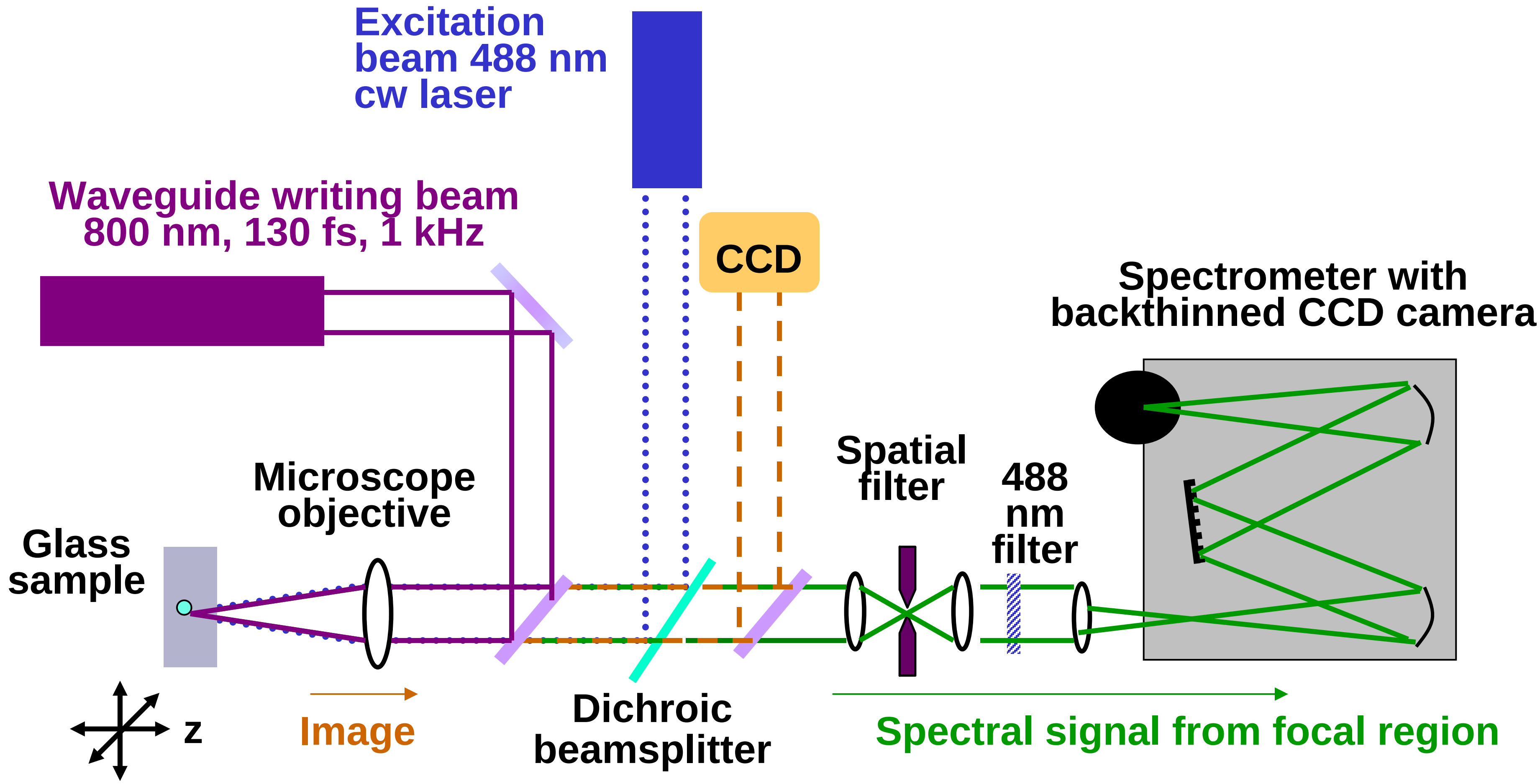
- **Study <u>atomic scale structural changes</u> in the glass network due to exposure to fs laser pulses**

We want to selectively probe the fs-modified glass using confocal fluorescence microscopy

- Raman spectroscopy - information on glass network
- Fluorescence spectroscopy - information on defects

what is the effect of glass composition?

Scanning confocal spectroscopy setup



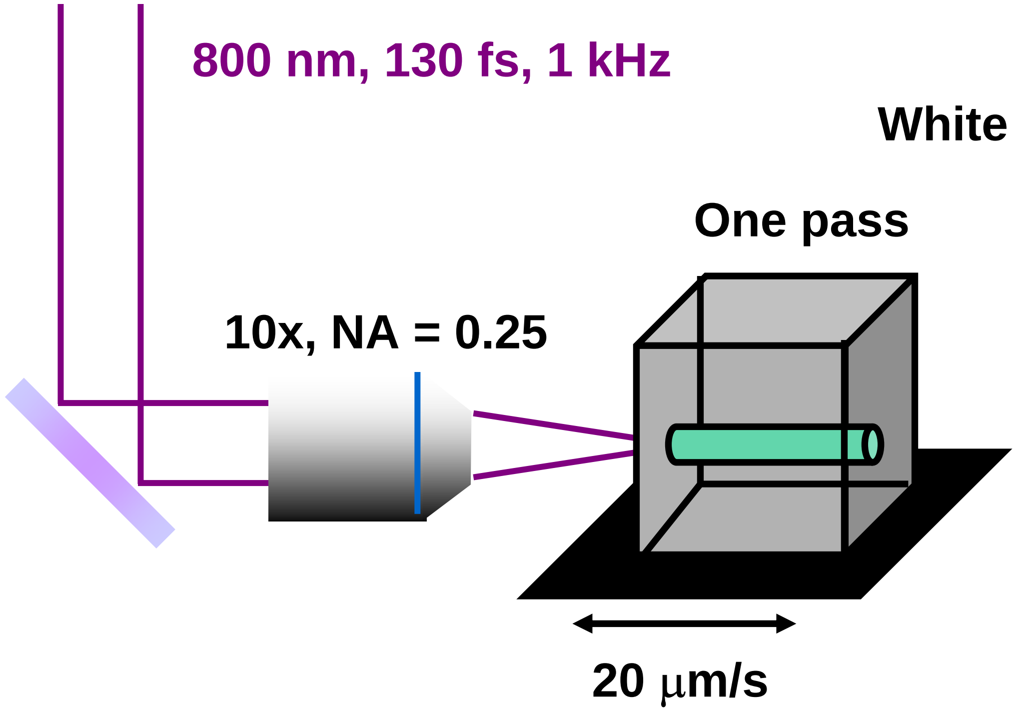
Comparison between

Fused silica (Corning 7940)

and

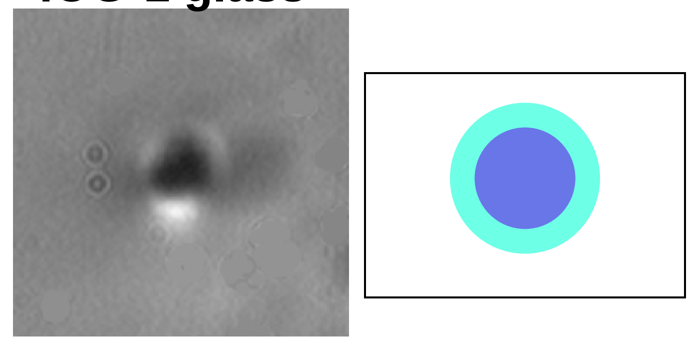
Phosphate glass (Schott Glass IOG-1)

Modification in IOG-1 is different from fused silica

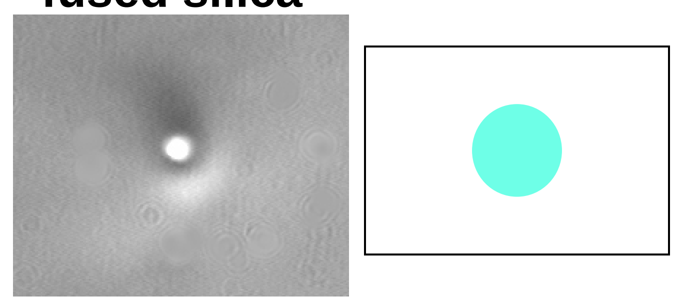


White light transmission images of :

IOG-1 glass



fused silica



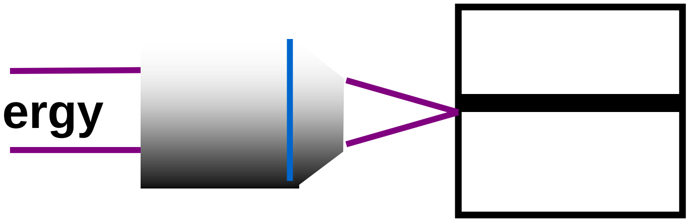
high index region

low index region

The induced modification is sensitive to laser propagation direction

top view

3.5 μJ fs pulse energy



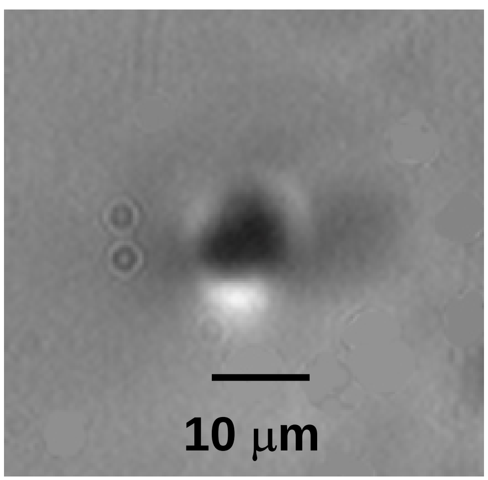
waveguide

z - axis (scan axis)

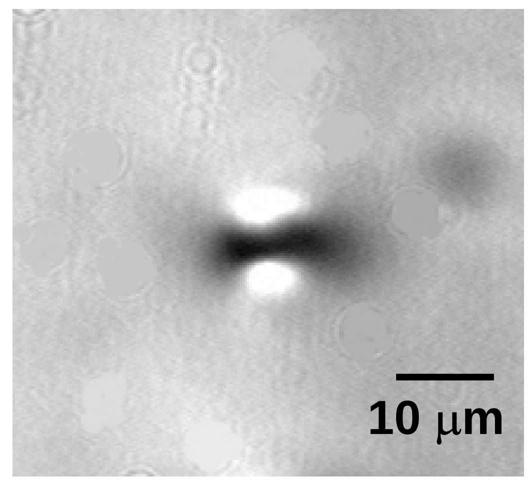
laser beam axis

z - axis (scan axis)

laser beam axis

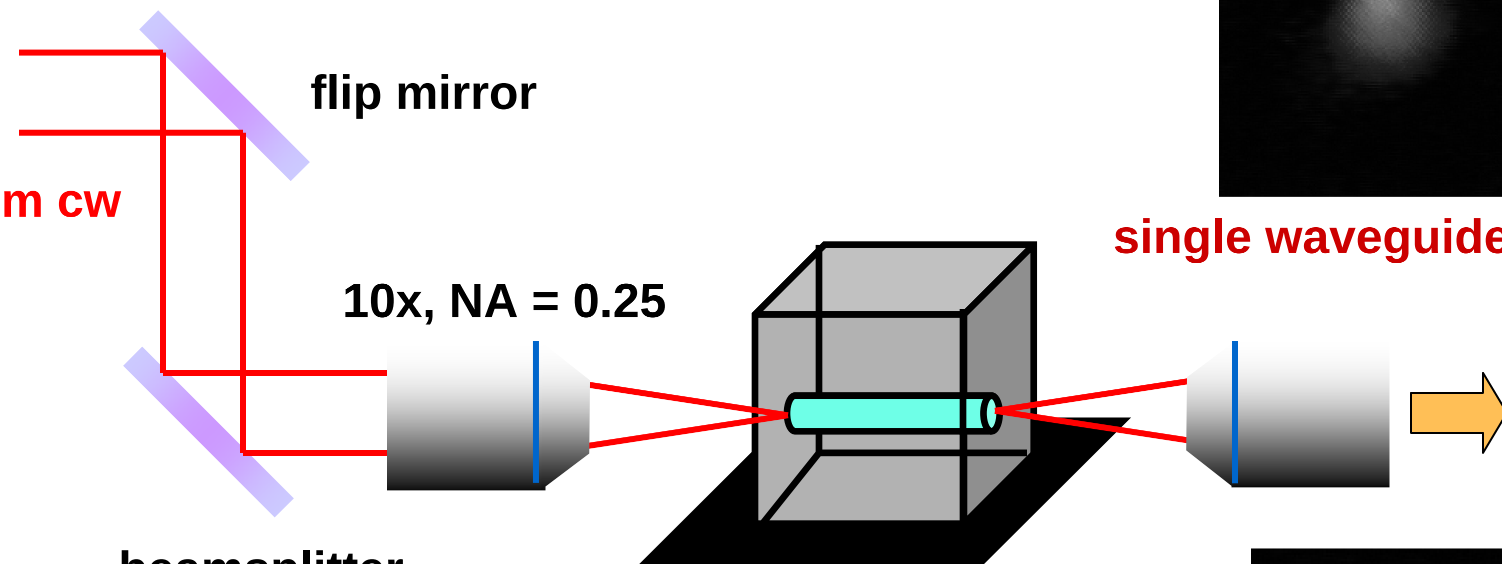


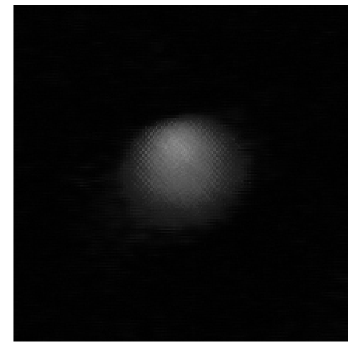
circular damage



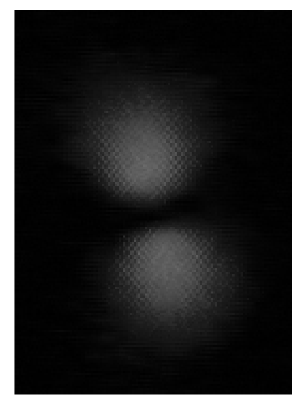
elliptical damage

Near field profiles confirm that two waveguides are created in case of elliptical damage





single waveguide coupling



simultaneous coupling

Objectives

- **Investigate the use of fs laser pulses to fabricate optical devices in glass**
  - write waveguides: pulse energies, scan speed
  - characterize waveguides: mode profile, loss
  - what is the effect of glass composition?

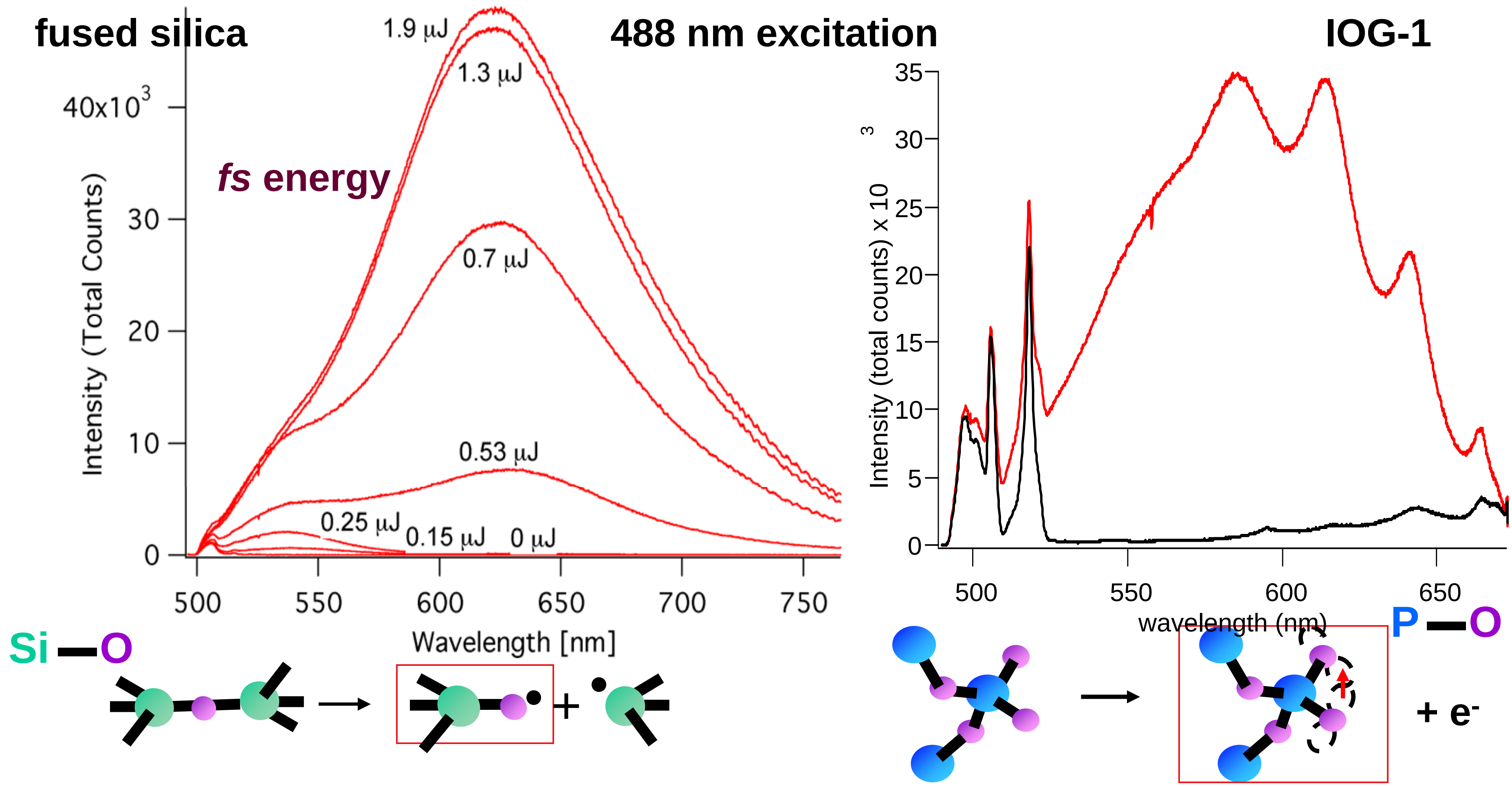
waveguides in
fused silica (Corning 7940) & phosphate glass (Schott Glass IOG-1)
are different

- **Study <u>atomic scale structural changes</u> in the glass network due to exposure to fs laser pulses**

We want to selectively probe the fs-modified glass using confocal fluorescence microscopy

- Raman spectroscopy - information on glass network
- Fluorescence spectroscopy - information on defects

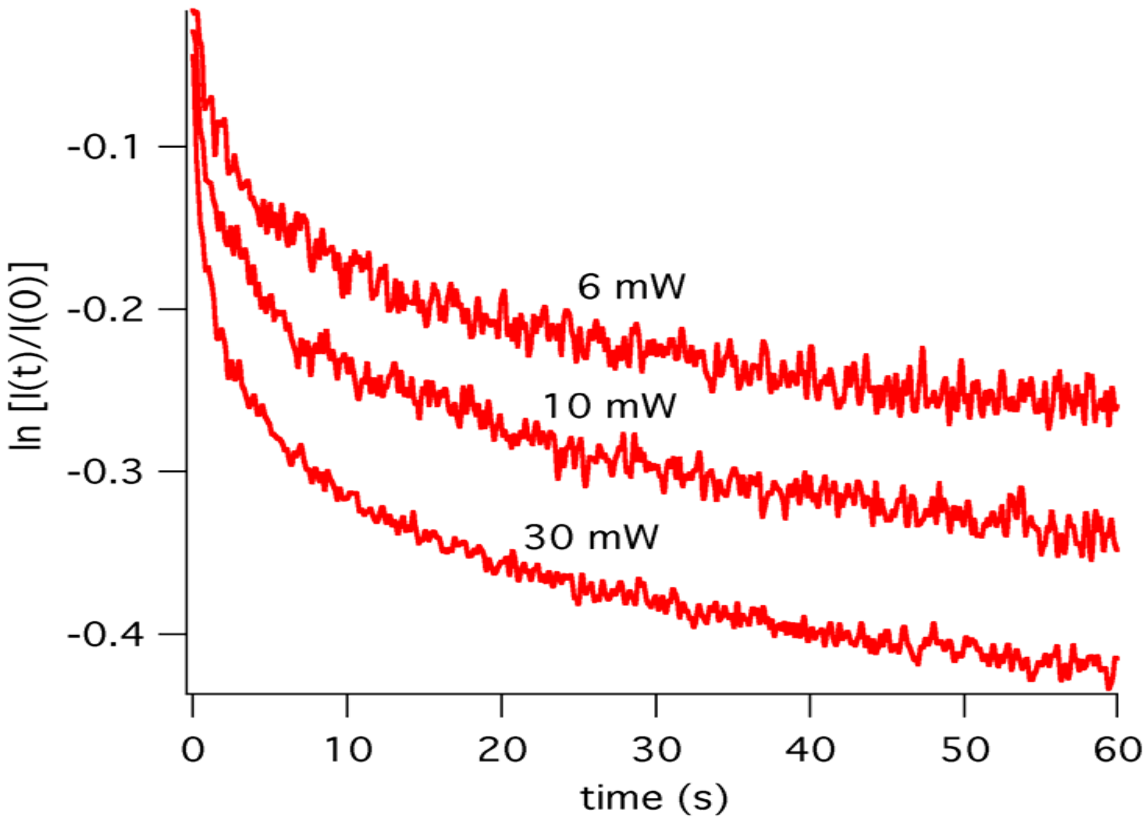
Fluorescence spectra of fs-modified glass



fs-laser modification produces non-bridging oxygen hole centers (NBOHC)

Chan *et. al*, Appl. Phys. A, 76, 367 (2003), Sun *et. al*, J. Phys. Chem. B, 104, 3450 (2000), Chan *et. al*, J.Am. Ceram. Soc. 85, 1037 (2002).

NBOHC fluorescence bleaches with cw 488 nm exposure

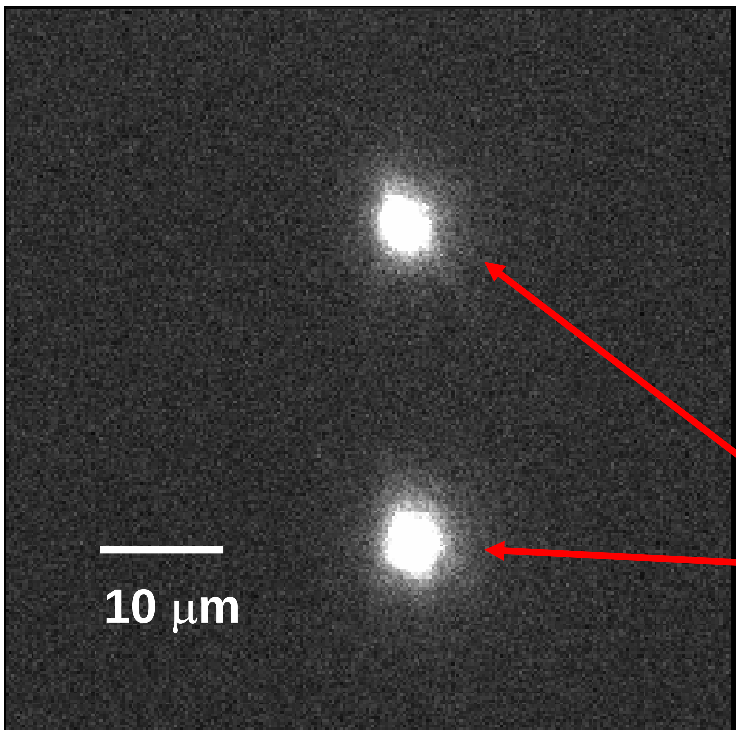


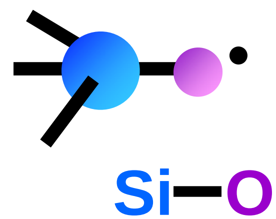
Decay of 630 nm fluorescence from modified fused silica continuously exposed to 488 nm light.

broken bonds are healed by 488 nm light

Fluorescence images of waveguides show spatial profile of color centers

scan sample with focused 488 nm beam (100x objective) yields x-y spatial profile of color centers

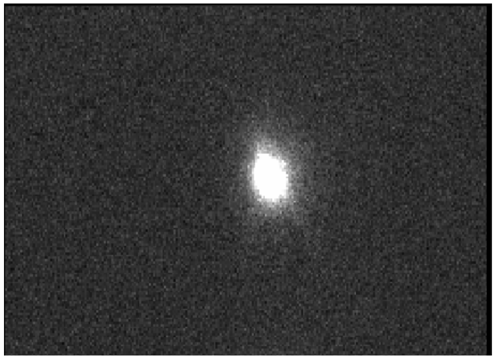


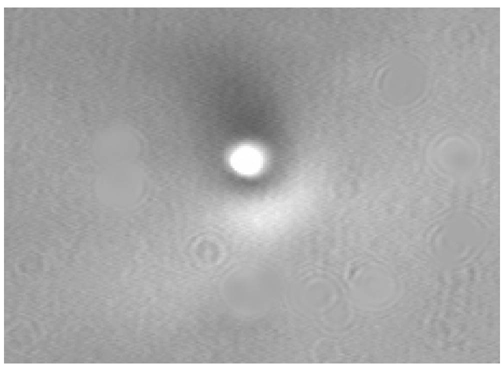


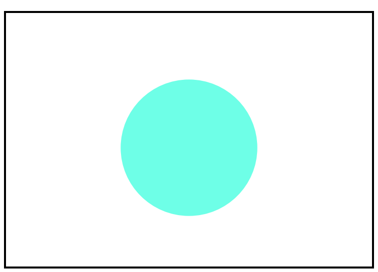
non-bridging oxygen hole centers (NBOHC) located within waveguide regions

Color centers are located in the central damaged region of the modified glass

fused silica







fluorescence images

NO color centers in w.g. regions

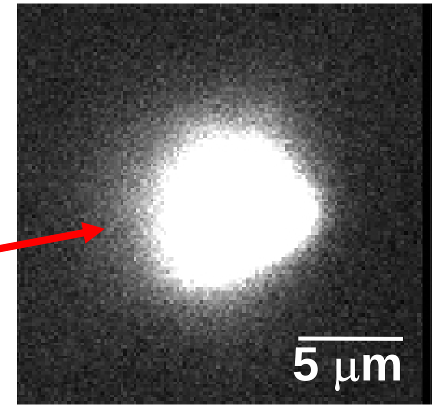
w.g. regions not directly exposed to fs pulses

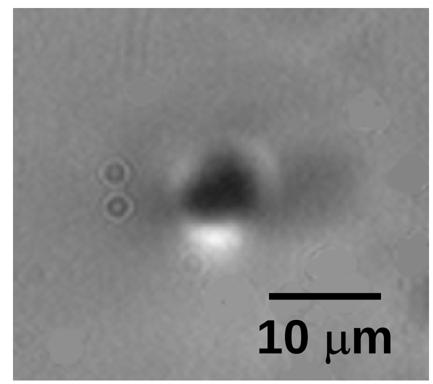
white light images

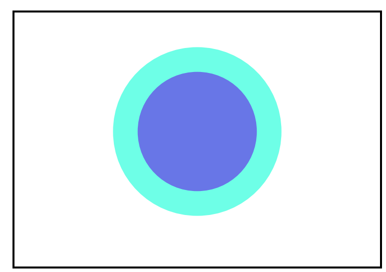
high index region

low index region

phosphate glass

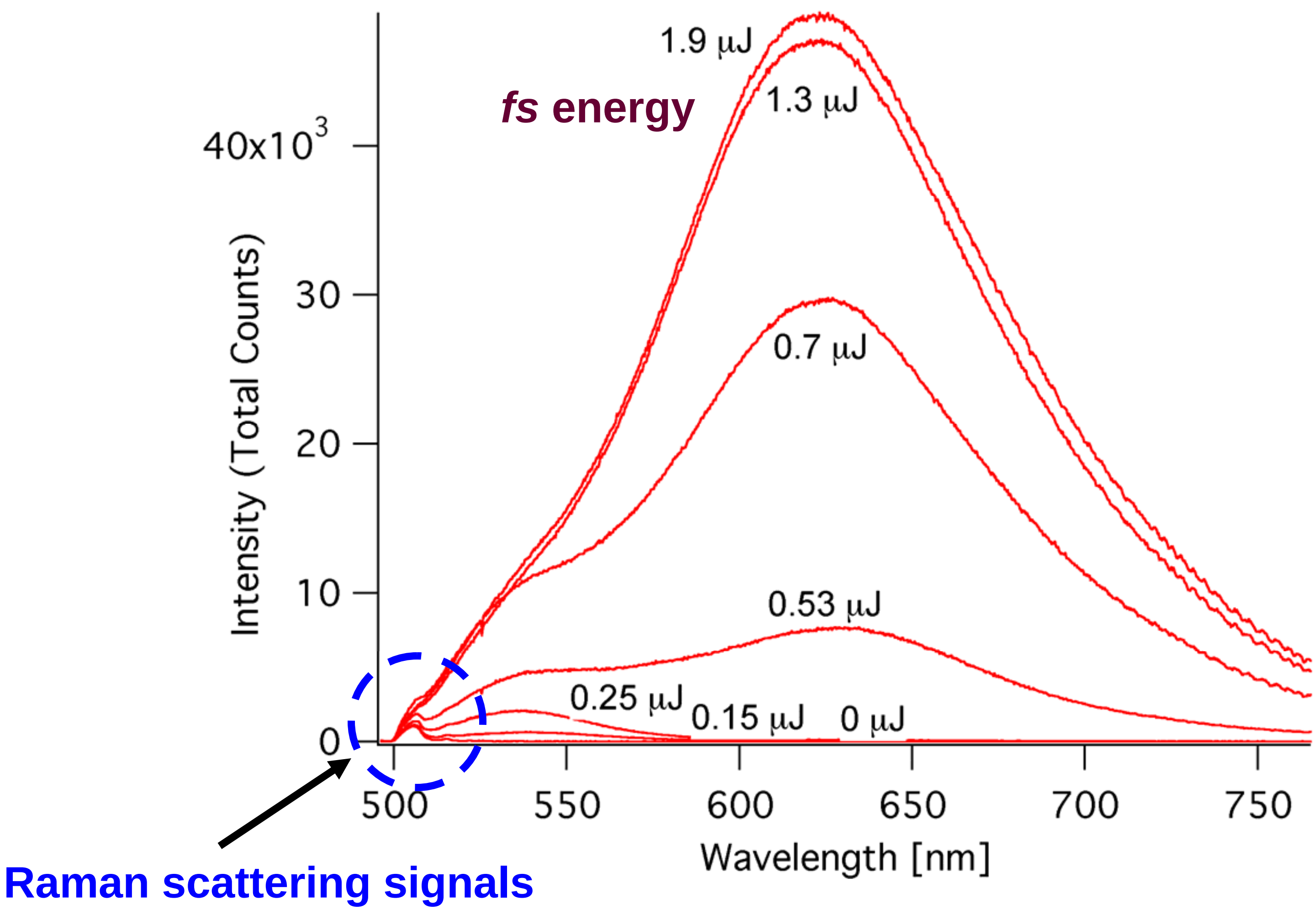




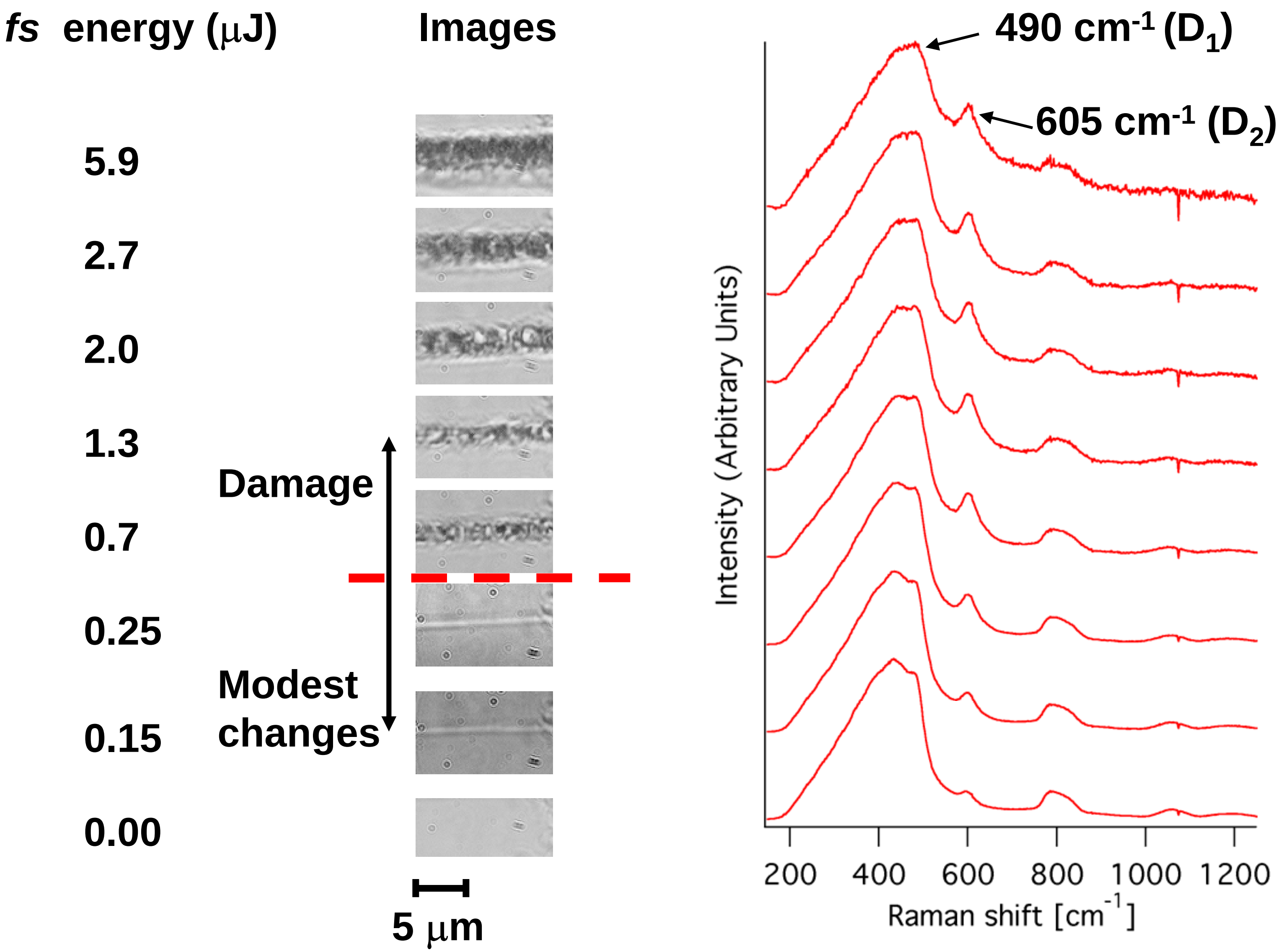


Raman scattering signals lie on the edge of broad fluorescence

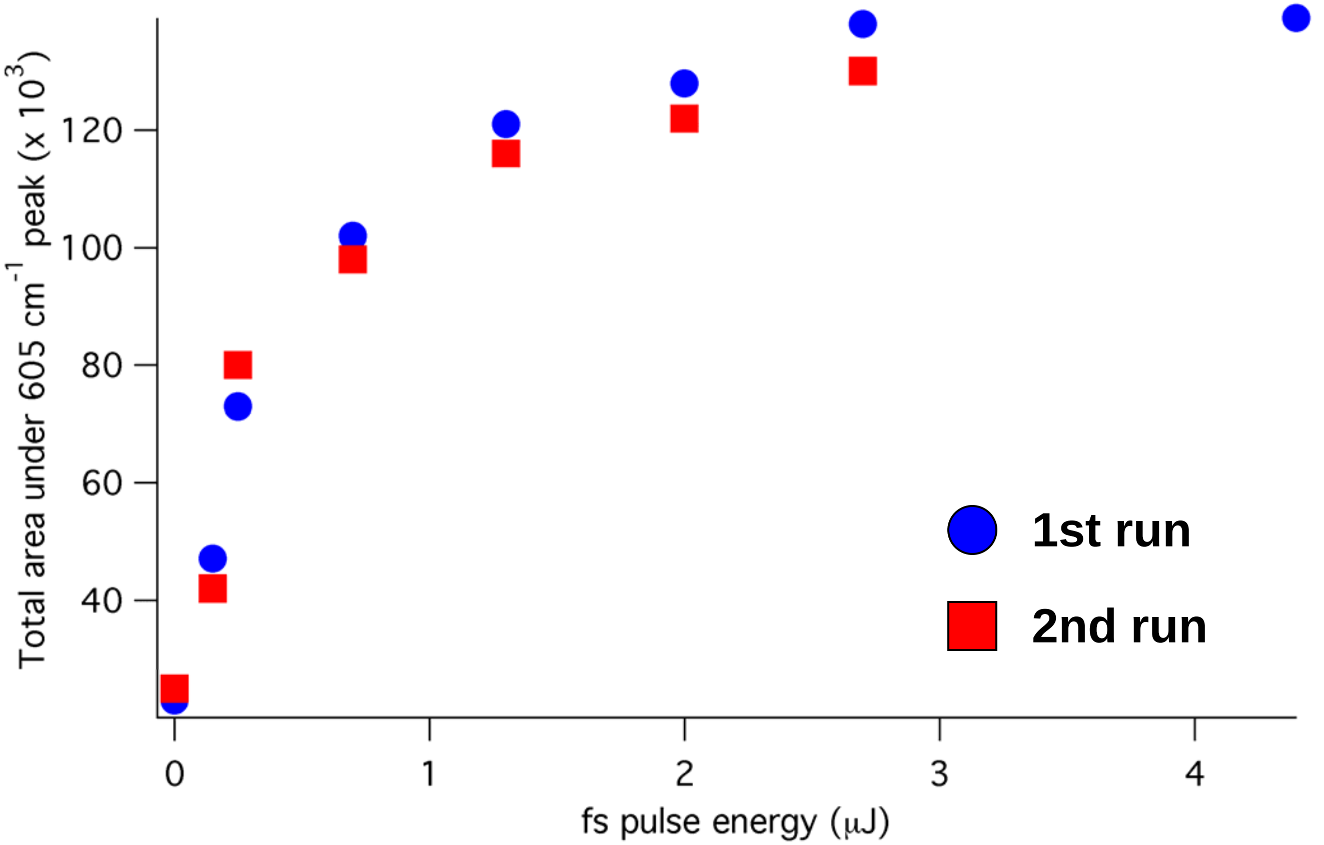
15 mW 488 nm light



The 490 cm^{-1} and 605 cm^{-1} peaks in the Raman spectra increase with fs pulse energy



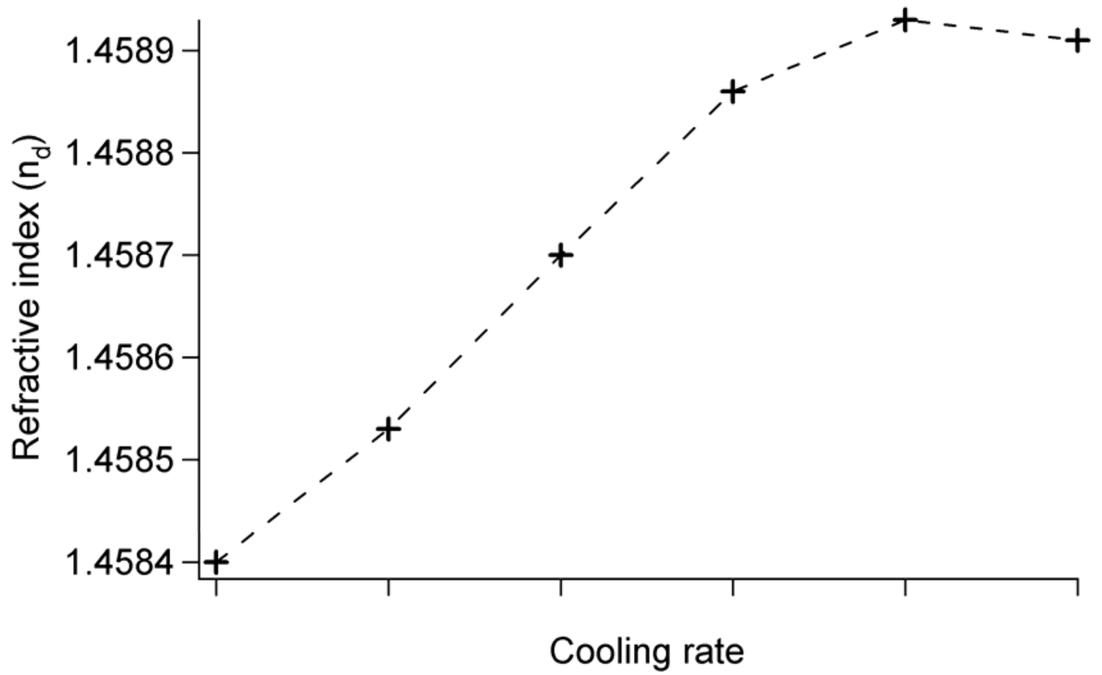
Increase of the D_2 peak area with fs pulse energy



***fs* pulses induce an increase in the number of 3- and 4- membered rings**

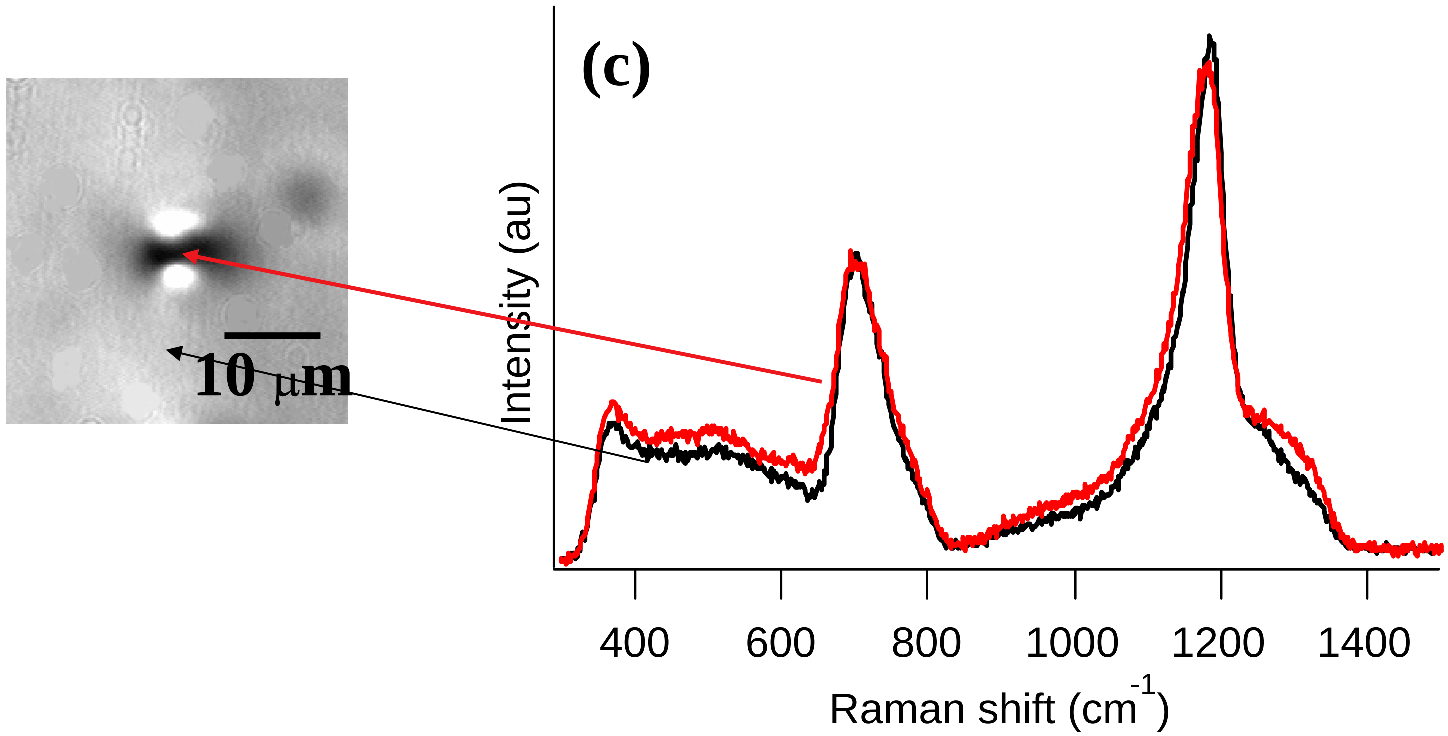
increase in density and index

Refractive index of fused silica vs quenching rate



Data from R. Bruckner, J. Non-Cryst. Solids 5, 123 (1970)

Raman spectrum of modified IOG-1



Raman changes consistent with break-up of phosphate network

Refractive index of IOG-1 vs quenching rate

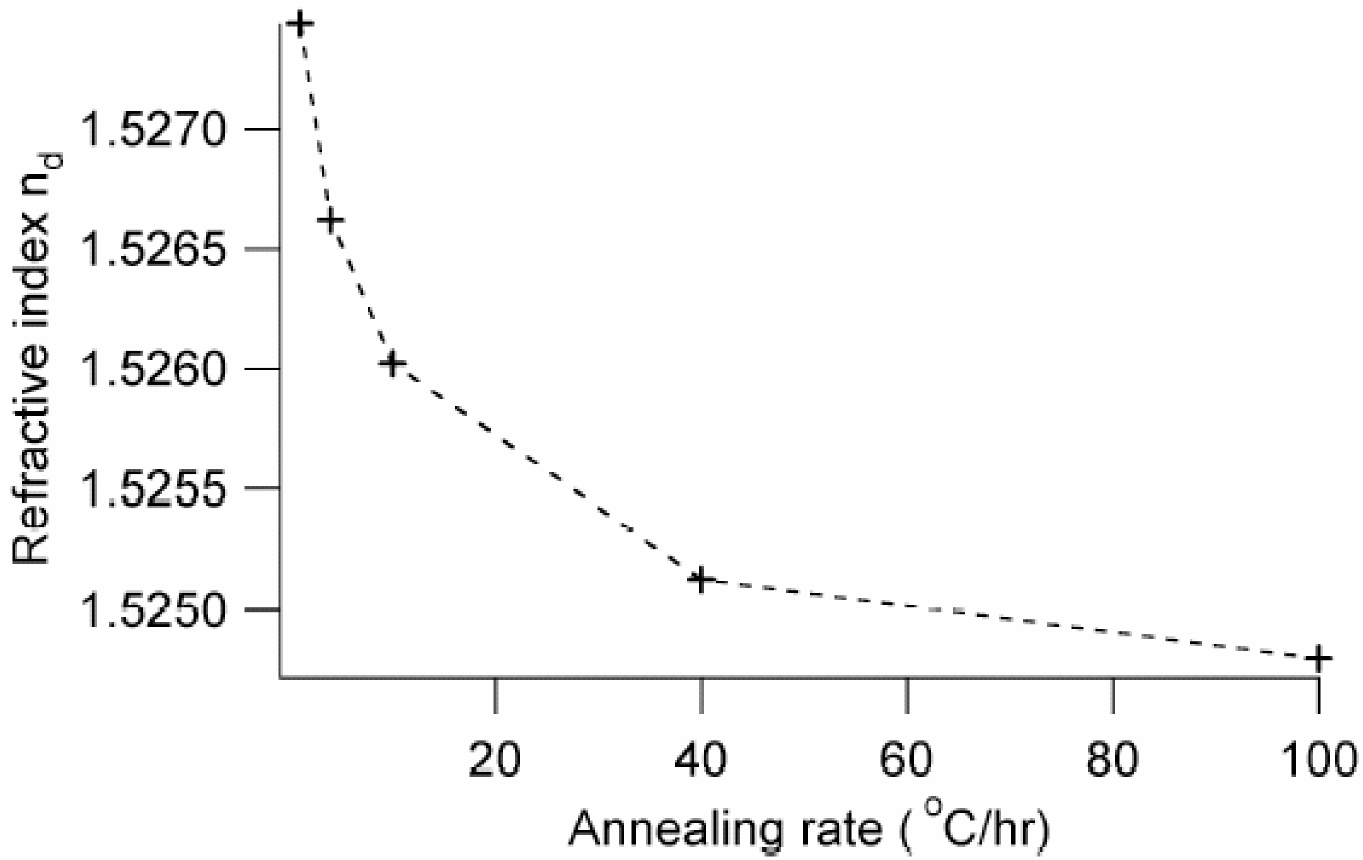


Fig. 3. Dependence of refractive index of IOG-1 glass on the quenching rate from above the glass transition temperature. (Data from Schott Glass Tech., Inc.)

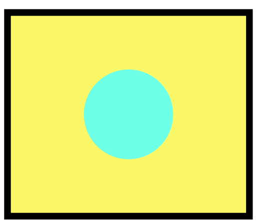
Comparison between fused silica and IOG-1

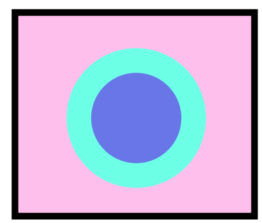
Fused silica	Phosphate glass

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



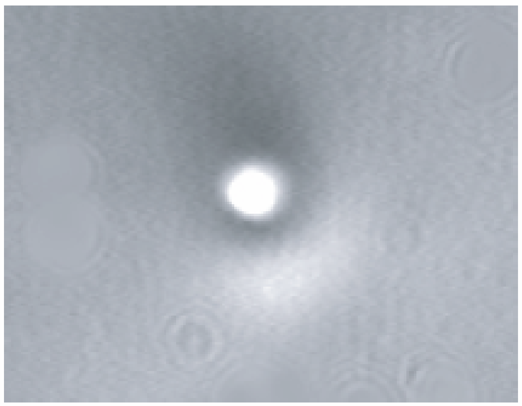


high index (guiding) regions

low index regions

What about other glass compositions??

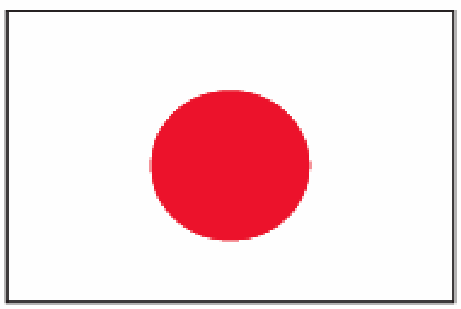
Type 1	Type 2
Fused Silica	Soda Lime Silicate Glasses



	SCG 4-2	SCG 6
SiO_2	60	70
CaO	20	15
Na_2O	20	15

n increases with quenching rate

n decreases with quenching rate



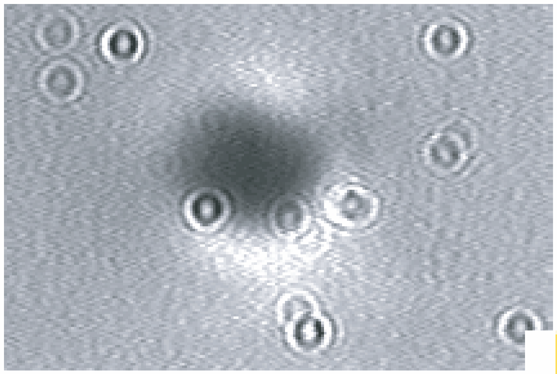
high index region

low index region

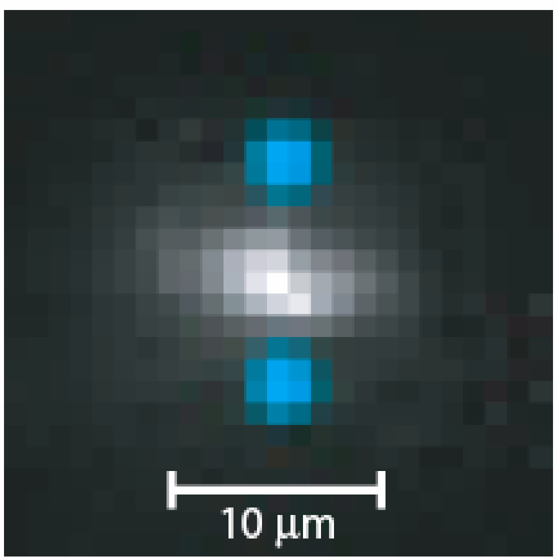
?

Results for 15 Na_2O 10 CaO $70SiO_2$

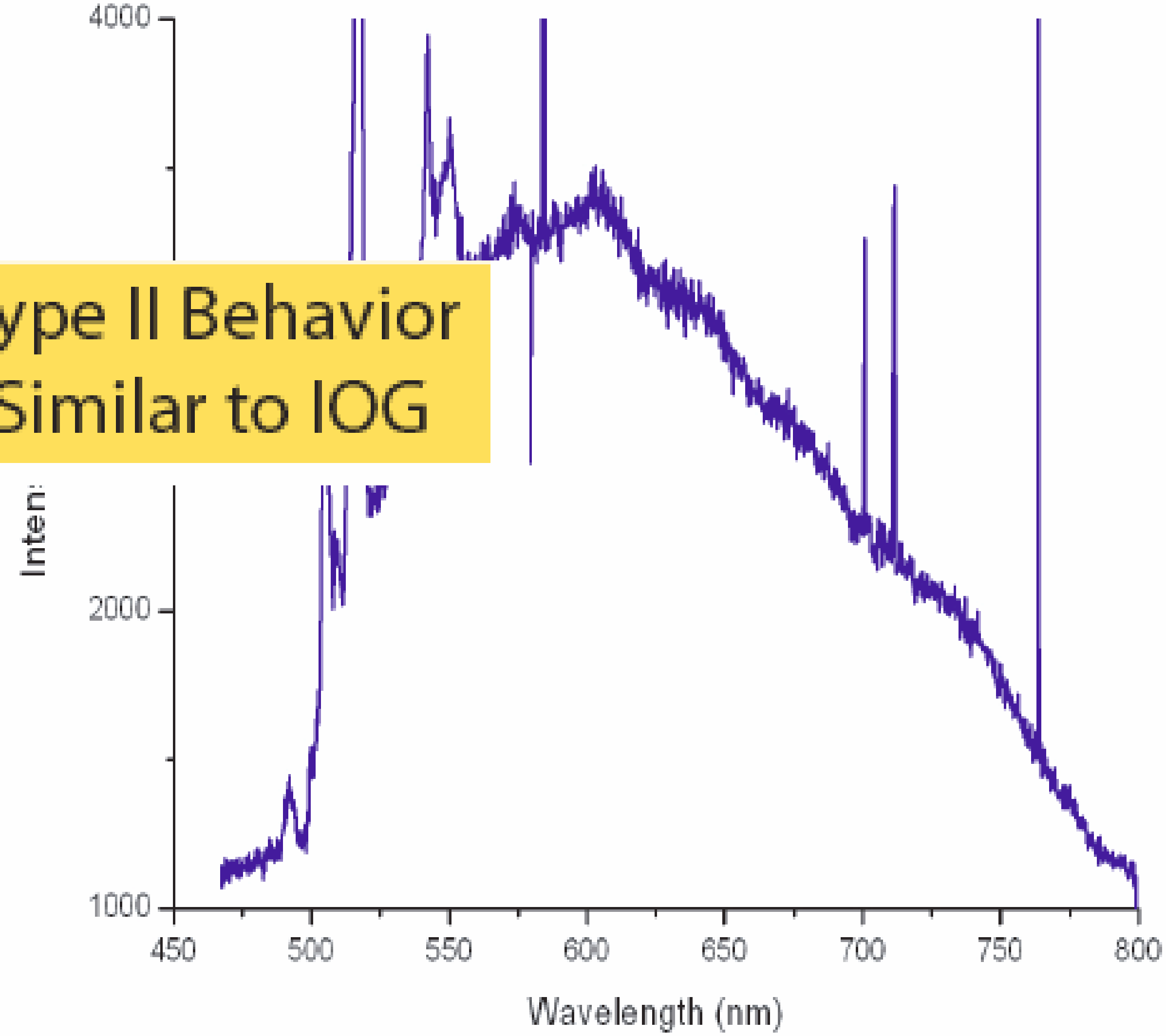
White Light Transmission



Fluorescence Intensity, with Waveguides Superimpos

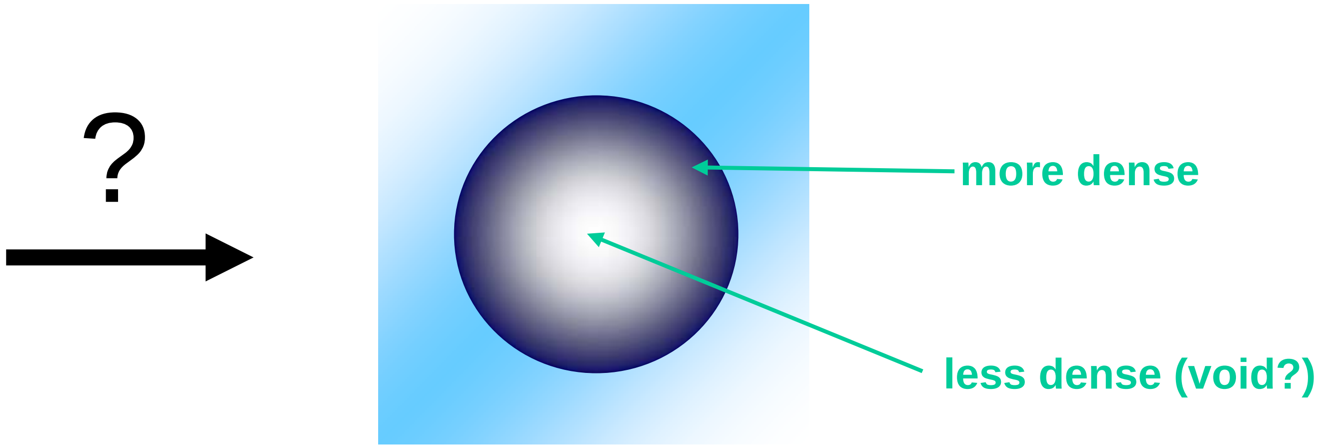


Fluorescence Spectra indicate the presence of Non-Bridging Oxygen Hole Center (NBOHC) Defects



Type II Behavior Similar to IOG

Mechanism revisited

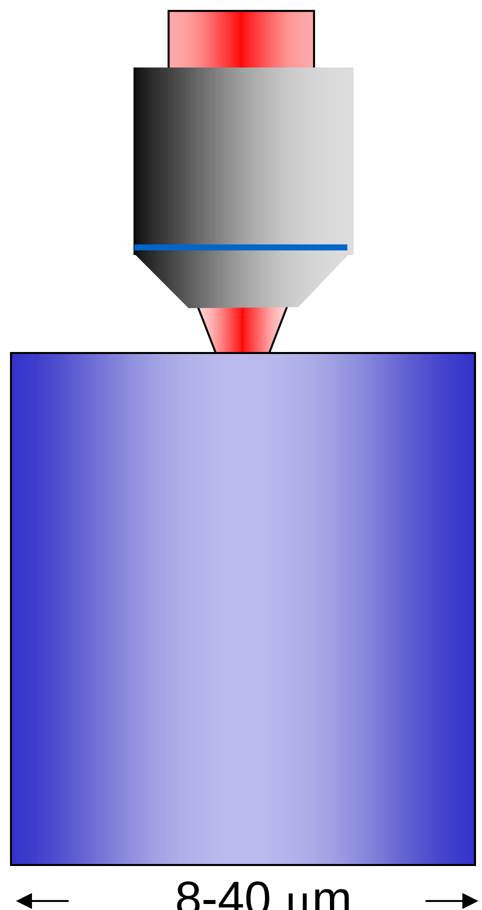


- **Results show that densification occurs in some region of modified spot -> conservation of matter means that other regions must be less dense**
- **Modified spot with central void?**

- **The spatial profile of the resulting spot's atomic structure as measured by Raman and fluorescence spectroscopy may indicate if this idea is correct.**

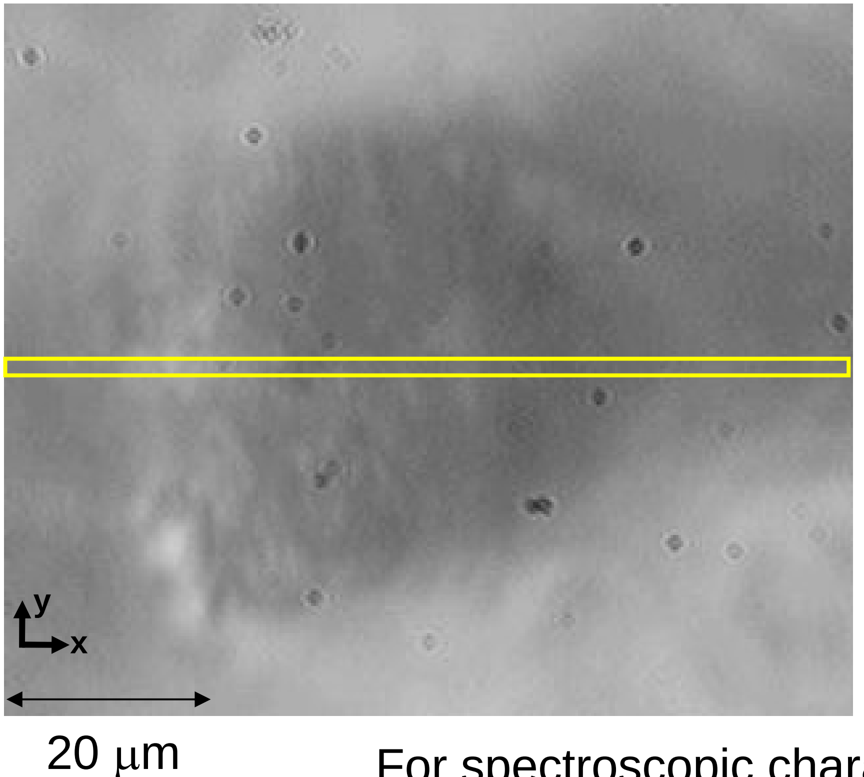
Objective

To determine the spatial profile of the modified lines using fluorescence and Raman spectroscopy.

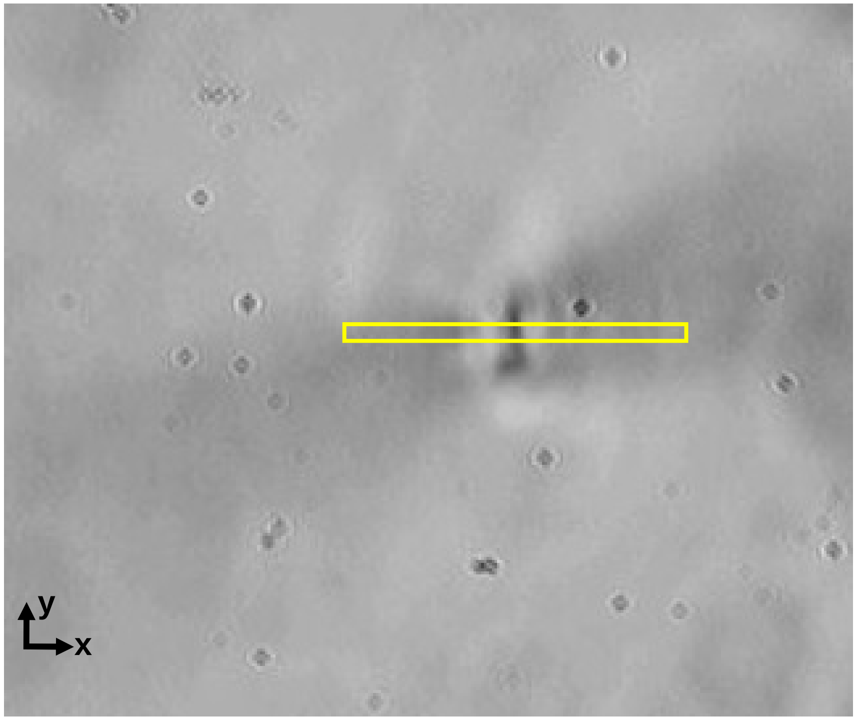


White Light Images

25 μJ Line



9 μJ Line

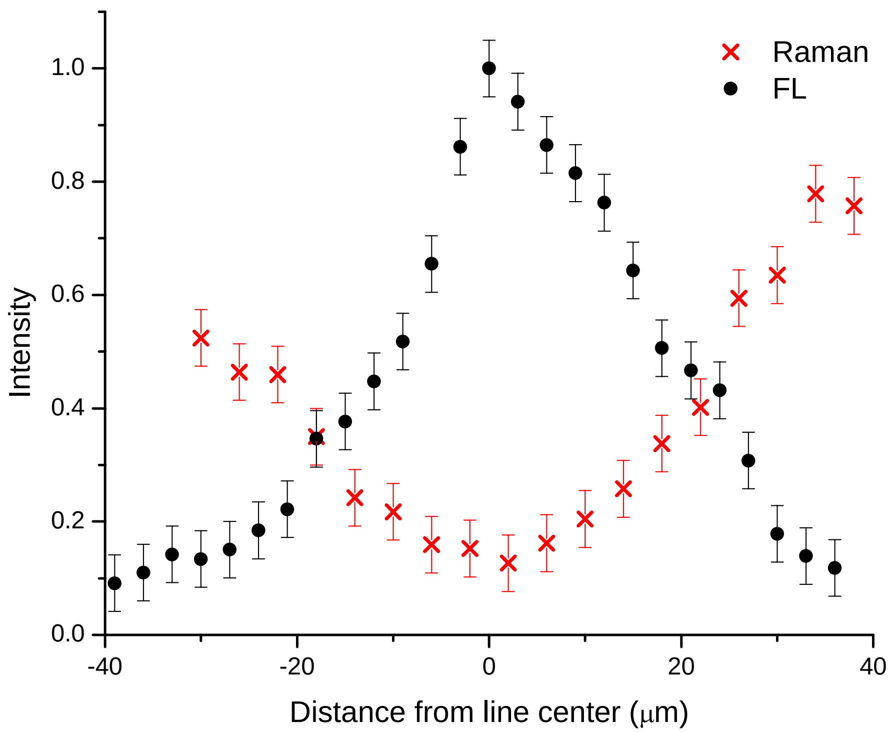


For spectroscopic characterization, the 25 μJ line was scanned with a 3 μm spot spacing, and the 9 μJ line was scanned with a 2 μm spot spacing along the paths shown.

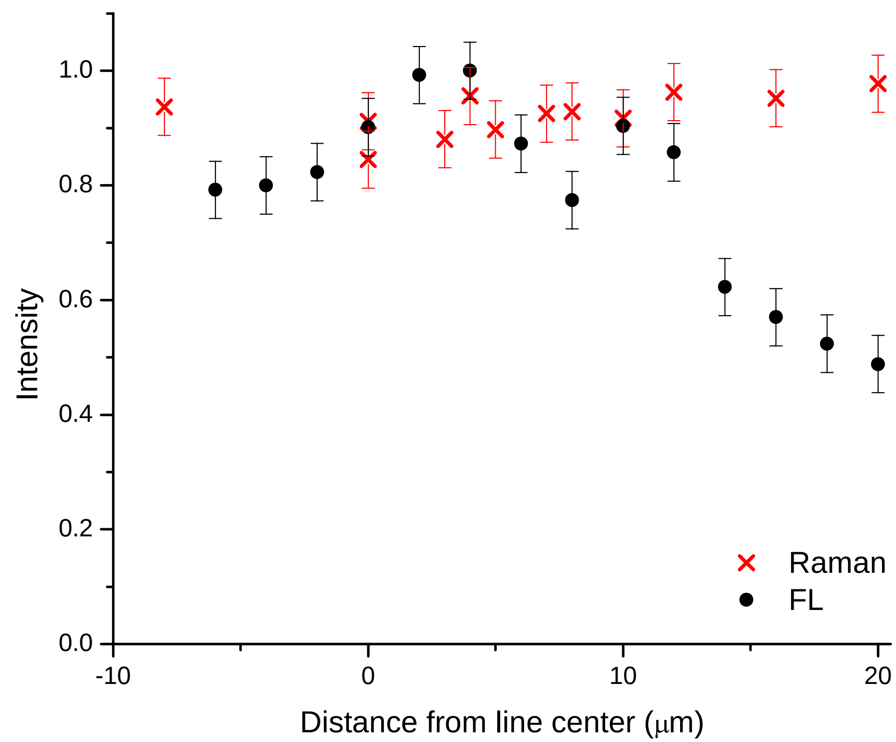
Fluorescence and Raman cross-sections

The Raman intensity reaches a minimum and the fluorescence intensity reaches a maximum at the center of each line.

25 μJ Line



9 μJ Line



Fluorescence and Raman results for large spots

Fluorescence Results

- **The concentration of laser-induced defects increases towards the center of the modified spot.**

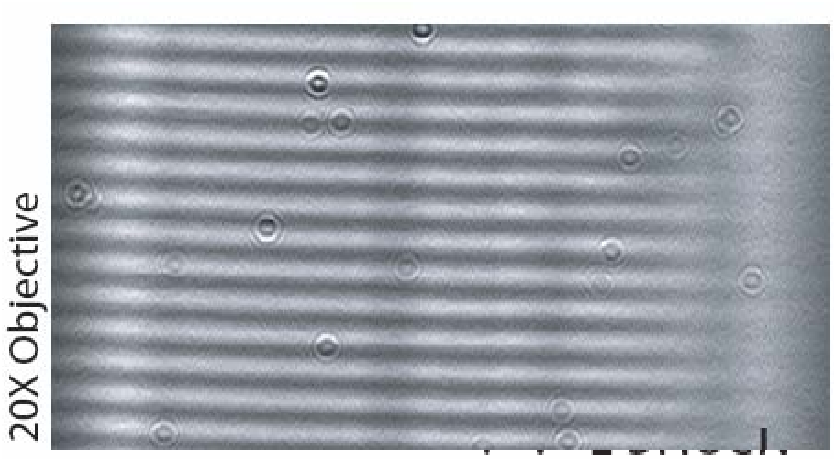
Raman Results

- **There is no apparent variation in the concentration of three- and four-membered rings across the modified spot.**
- **The total Raman intensity decreases towards the center of the modified spot.**

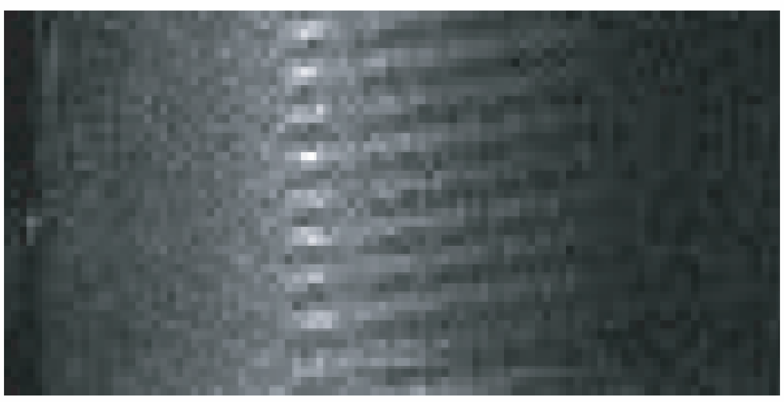
Possible explanations:

- **Rarefaction of the silica – not a void.**
- **Scattering / absorption.**

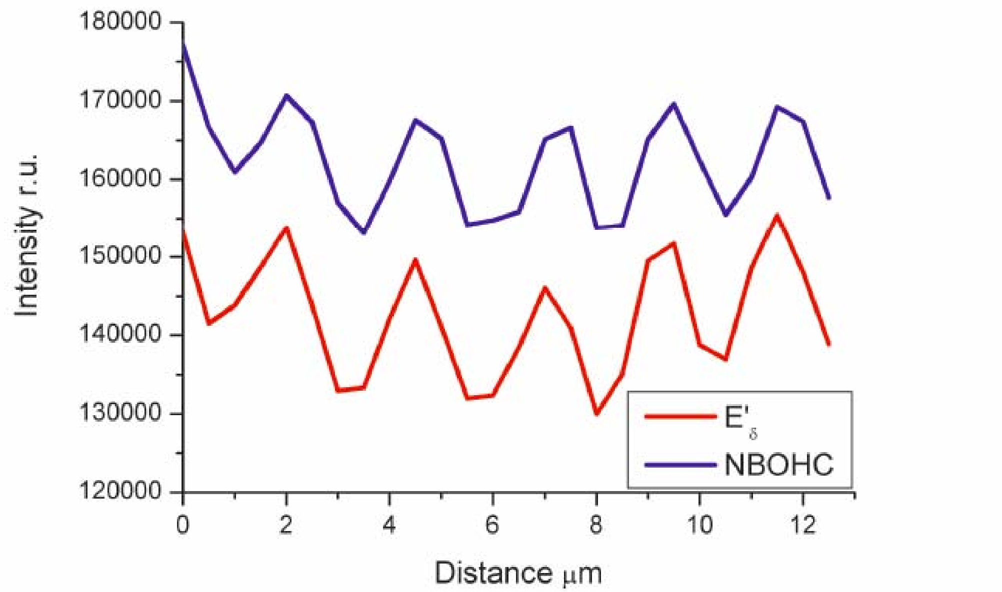
Bragg gratings fabricated with ultrafast lasers



White light microscope image



fluorescence image



Summary

➔**Ultrafast lasers can be used to directly write photonic structures in glass**

➔**A confocal microscope setup was used to probe the fs-modified regions of the glass for Raman changes and fluorescence signals**

➔**Results indicate that the material response to fs pulses is not the same for all glass systems**

Dependence of refractive index on cooling rate explains observed behavior for glasses investigated so far

Still many aspects not well understood:
-Dynamics
-**Laser rep rate**
-**….**

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