Fabrication of Micro and Nano Structures in Glass using Ultrafast Lasers

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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

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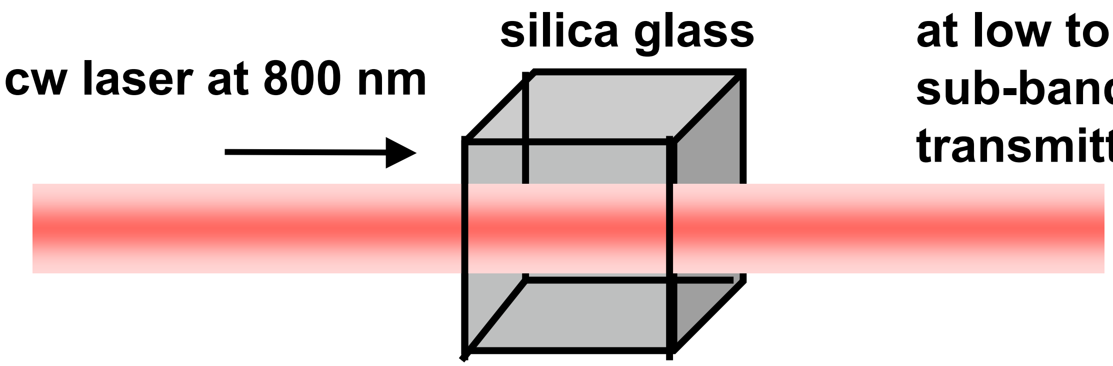
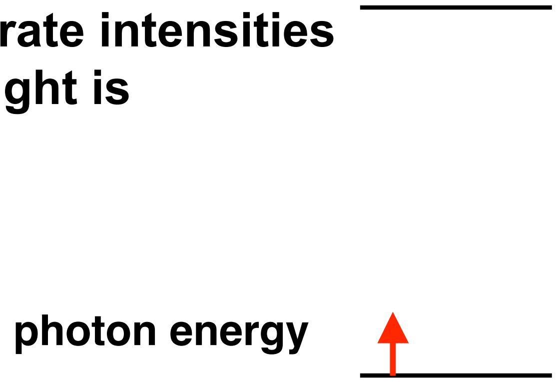
Interaction of glass with sub-bandgap, focused, fs laser pulses



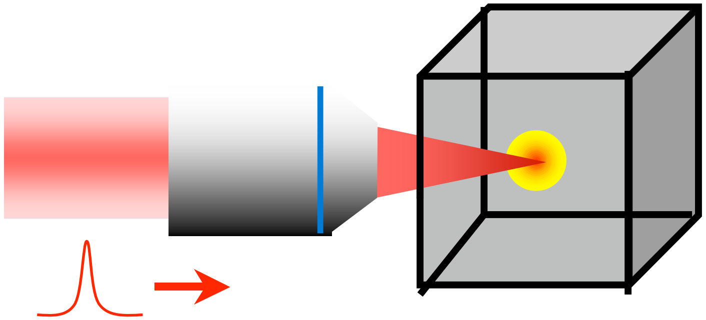
at low to moderate intensities sub-bandgap light is transmitted



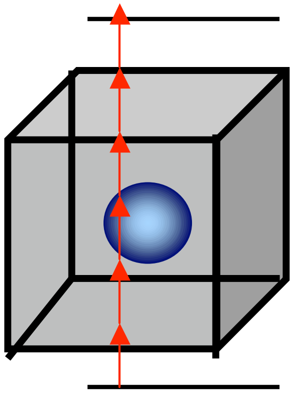
Light-matter Interaction is localized in time and space -> 3-D control of modification

ultrashort (100fs) pulses

and tight focusing (μm-size spot)

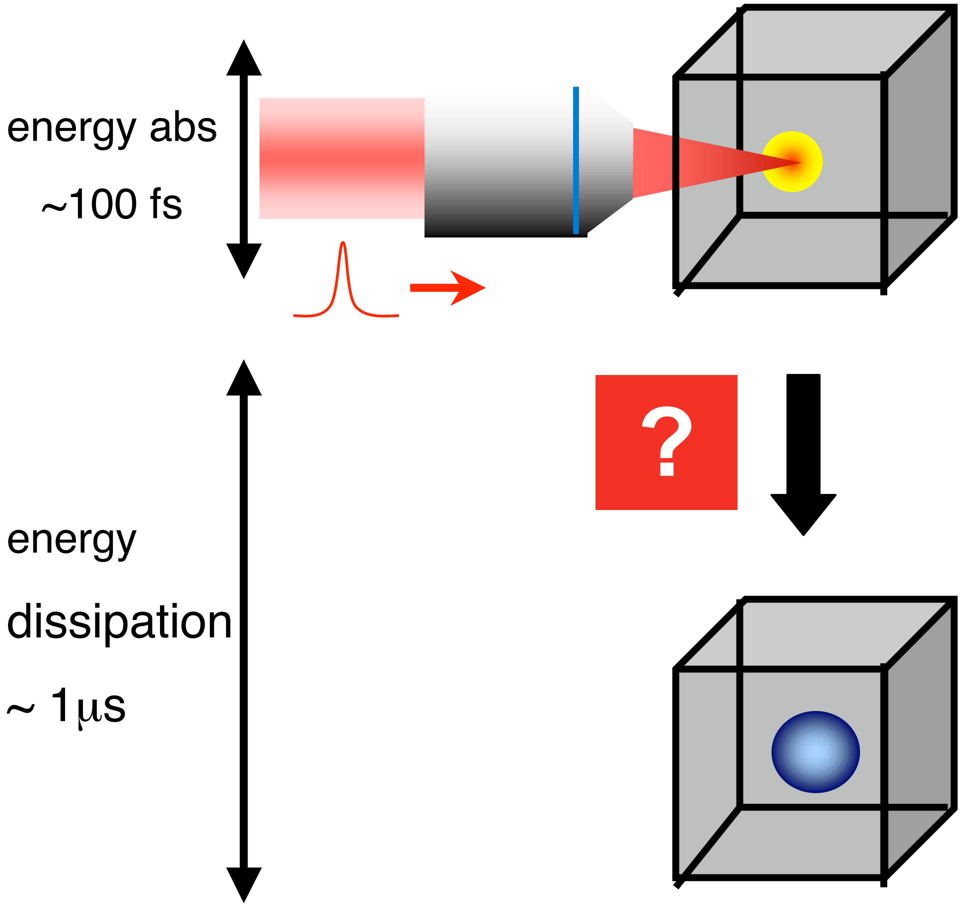


deposition of laser energy into glass



permanent modification

Femtosecond laser modification in glass



1) Multiphoton absorption
2) Avalanche photoionization
3) Plasma formation

4) Proposed mechanism:
- Shockwave propagation (microexplosion)
- Fast heating and cooling

5) Modified spot

How does the material change on an atomic scale?

Schaffer et al, MRS Bull 31, 620 (2006)

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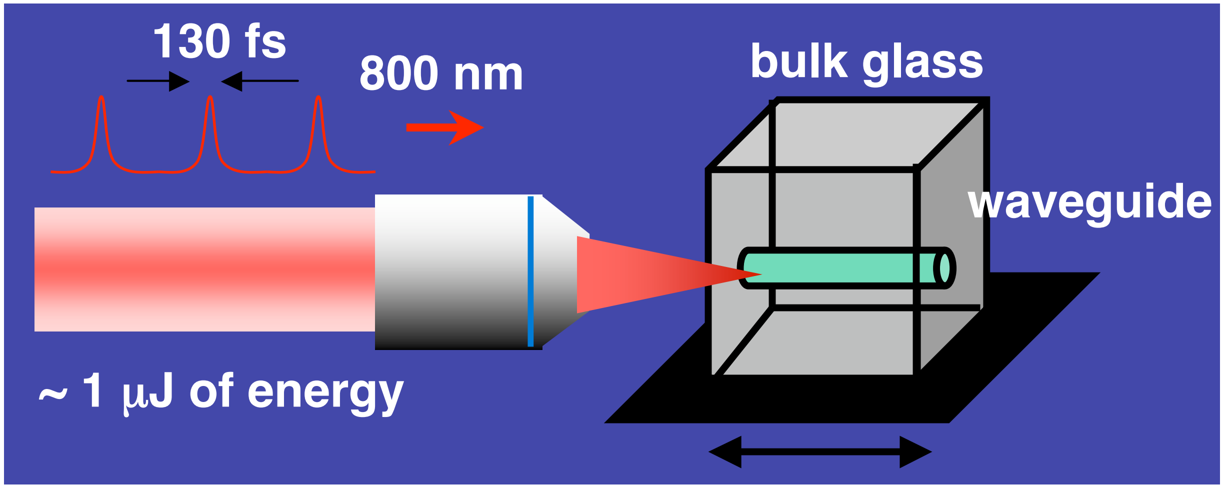
Femtosecond laser pulses can modify various glass properties

Properties:	**Applications:**
➢Refractive index	photonic devices
➢Absorption	
➢Composition (phase separation)	lab-on-chip
➢Valence state (Sm3+ -> Sm2+)	data storage
➢Crystal nucleation (Ag and Au colloids in glass)	optical switching



Davis *et. al*, Opt. Lett., 21, 1729 (1996)

Fs laser fabrication of lab-on-chip devices in Foturan glass

Foturan glass:

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

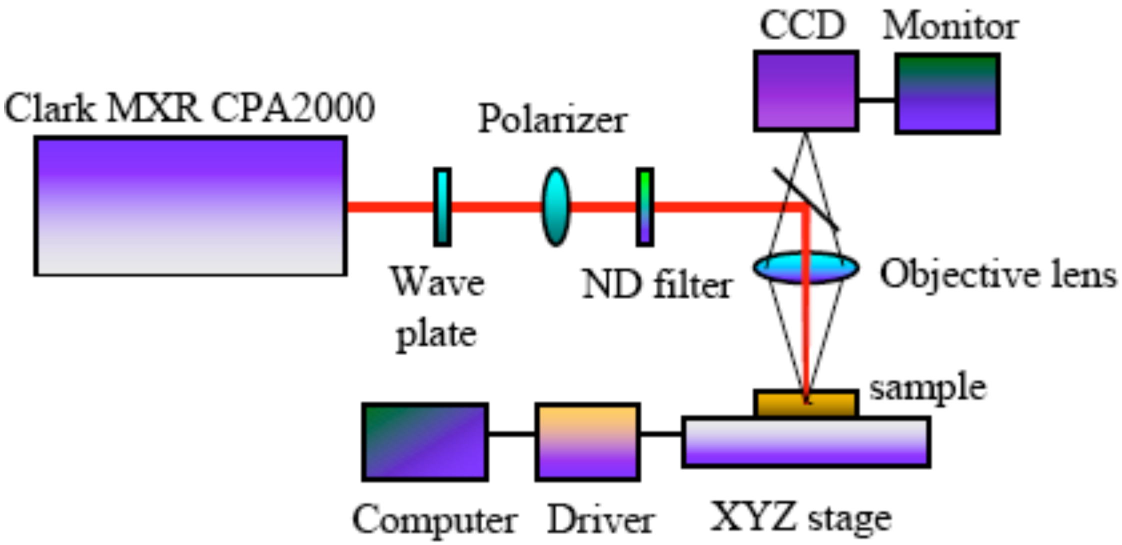
Fs laser fabrication involves 4-step process:

(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

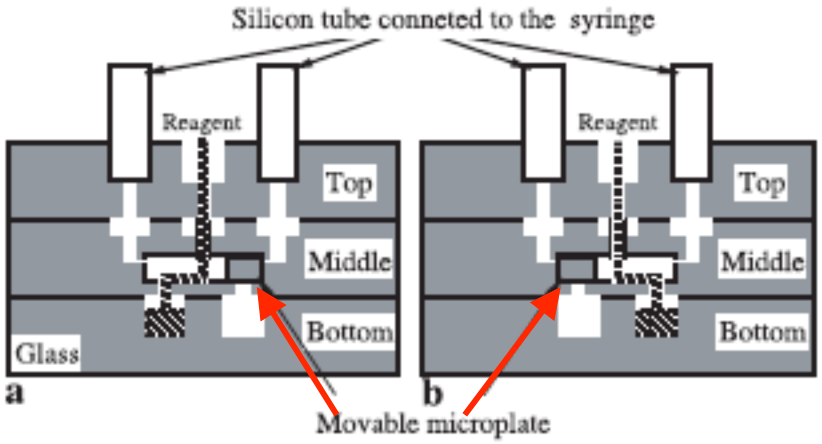
(3) etching of the sample in HF solution for selective removal of the modified regions,

(4) postbaking of the etched sample for further smoothing of the internal surfaces

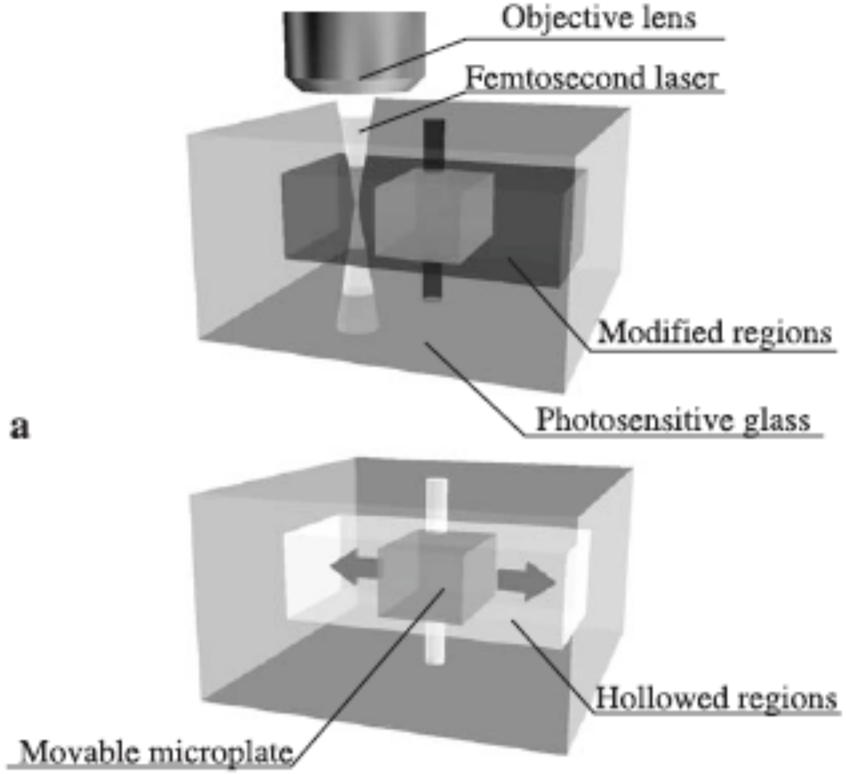


Cheng et al, Proc. of SPIE Vol. 6400, 640001 (2006)

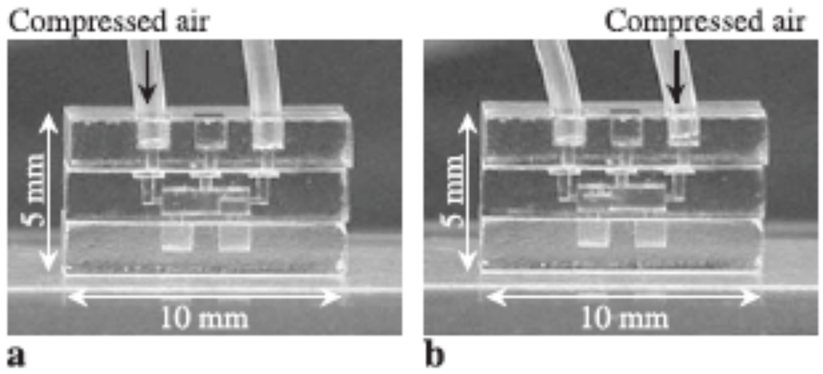
Fs laser fabrication of microfluidic reactor in Foturan glass



Schematic diagram of valve operation



Fs laser fabrication procedure

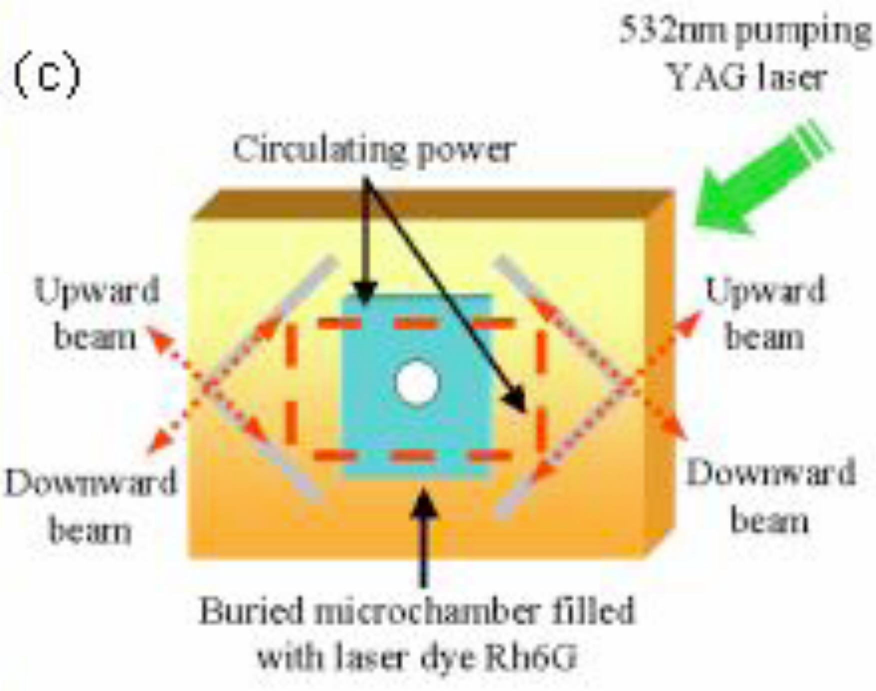


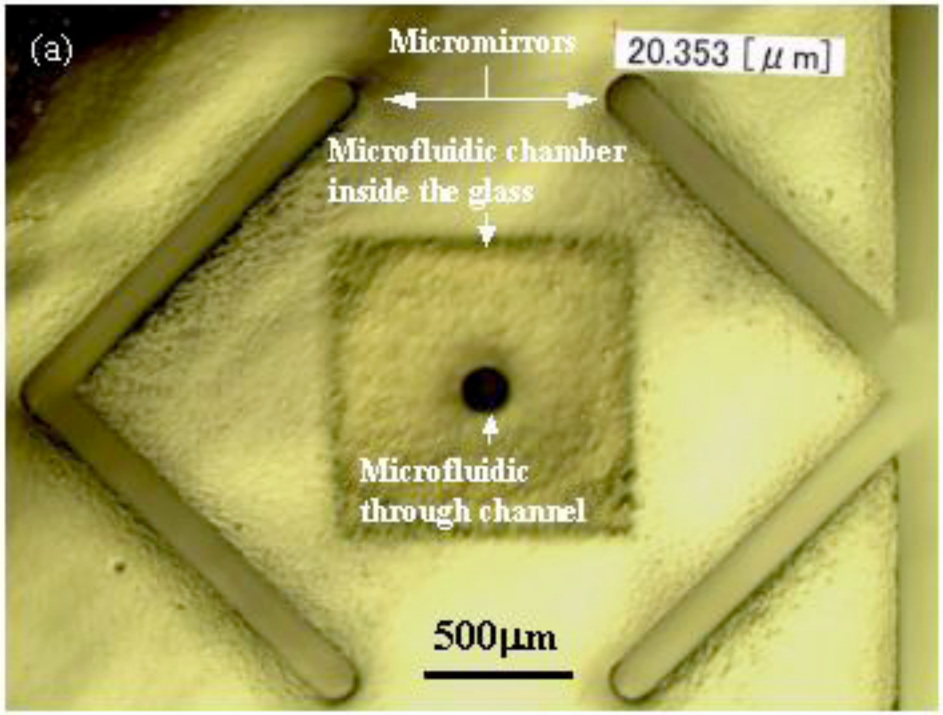
Actual device

Masuda et al, Appl. Phys. A 78, (2004)

Fs laser fabrication of microfluidic dye laser in Foturan glass

Integration of microfluidics and microoptics





Cheng et al, Proc. of SPIE Vol. 6400, 640001 (2006)

Fs laser fabrication of microchannels and nanogratings in BK7

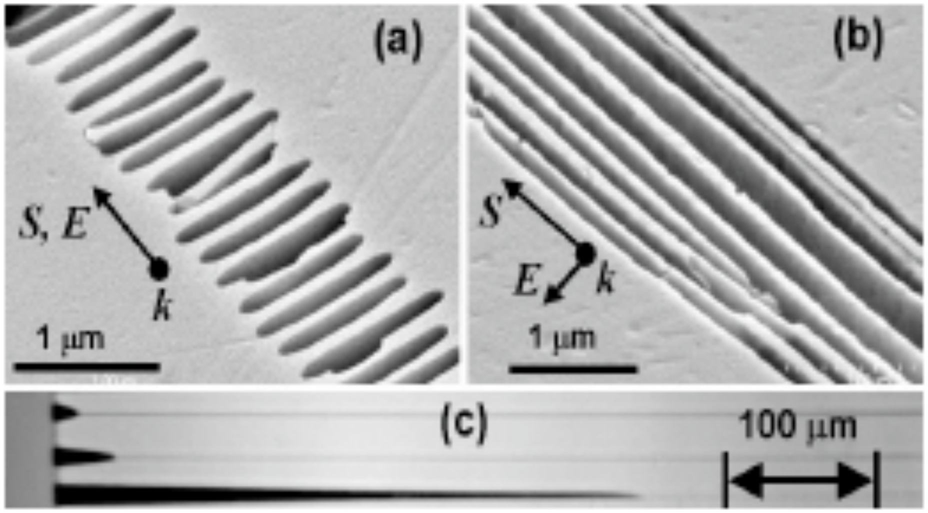


Fig. 6. SEM images of xy-sections of nanostructures with linear polarization (a) parallel; (b) perpendicular to S, 65 µm sub-surface with NA = 0.65, τ_p = 150 fs, E_p = 300 nJ, repetition rate f = 100 kHz, writing speed v = 30 µm/s; the samples were etched 20 min in 0.5% HF; (c) optical images of etched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

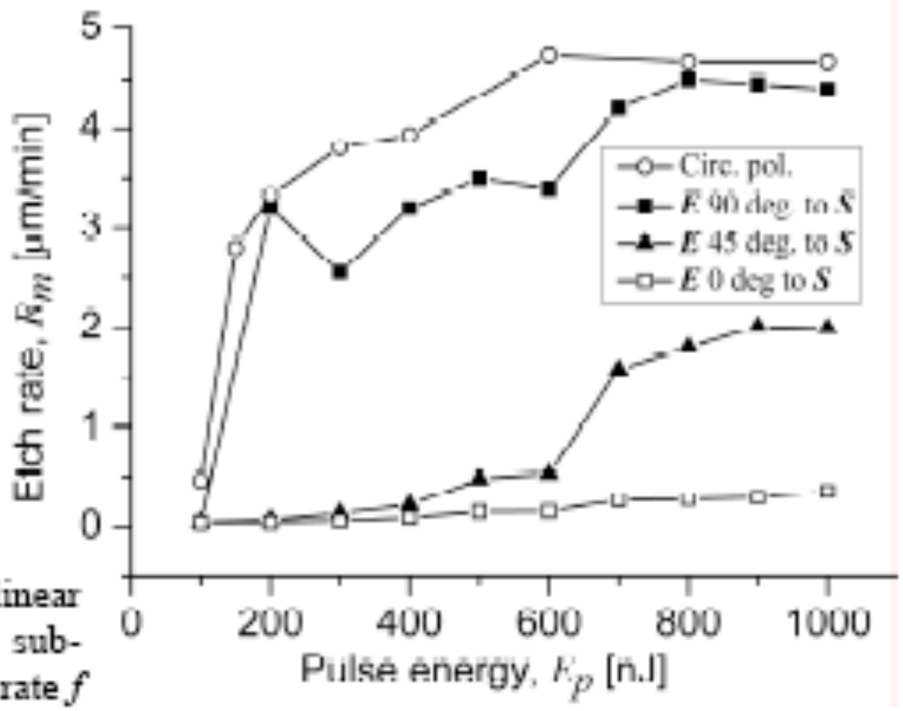
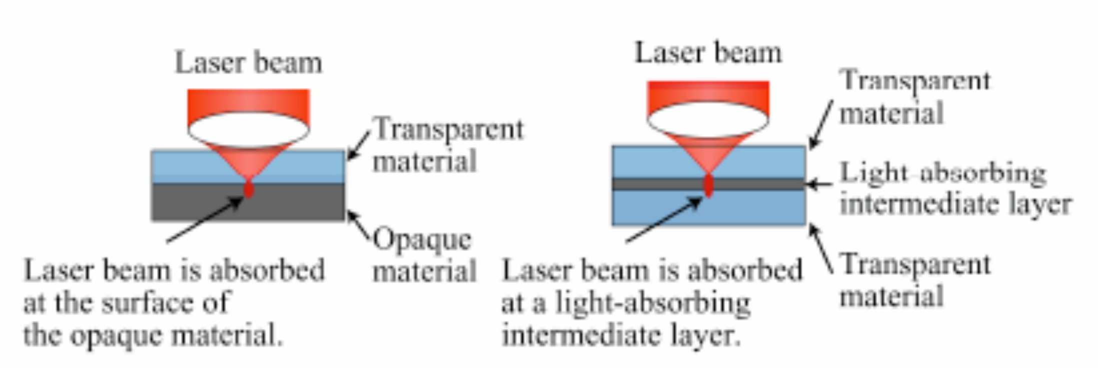


Fig. 7 Etch rates due to nanostructures [2]. Writing parameters as in Fig. 6.

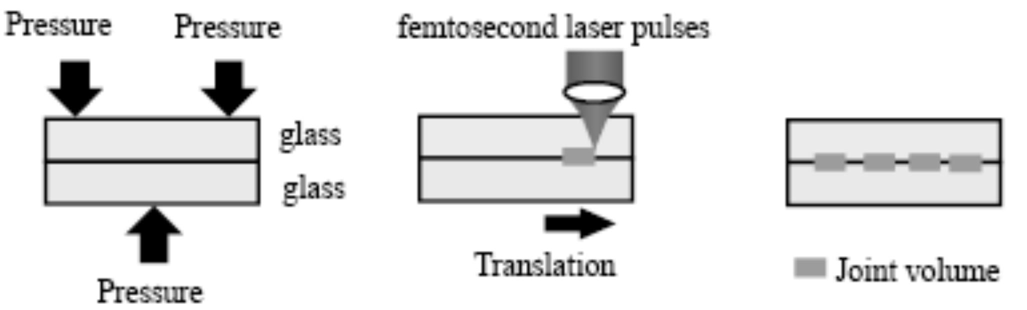
Simova et al, Proc. of SPIE Vol. 6458 64581B-1 (2007)

Fs laser micro-welding

conventional laser joining



fs laser joining



(a) Place one sample on another and press together

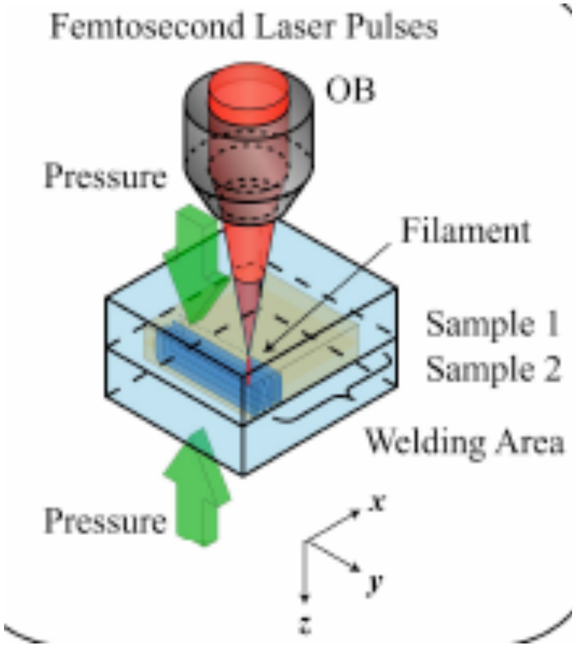
(b) Focus femtosecond laser pulses at the interface and translate the samples

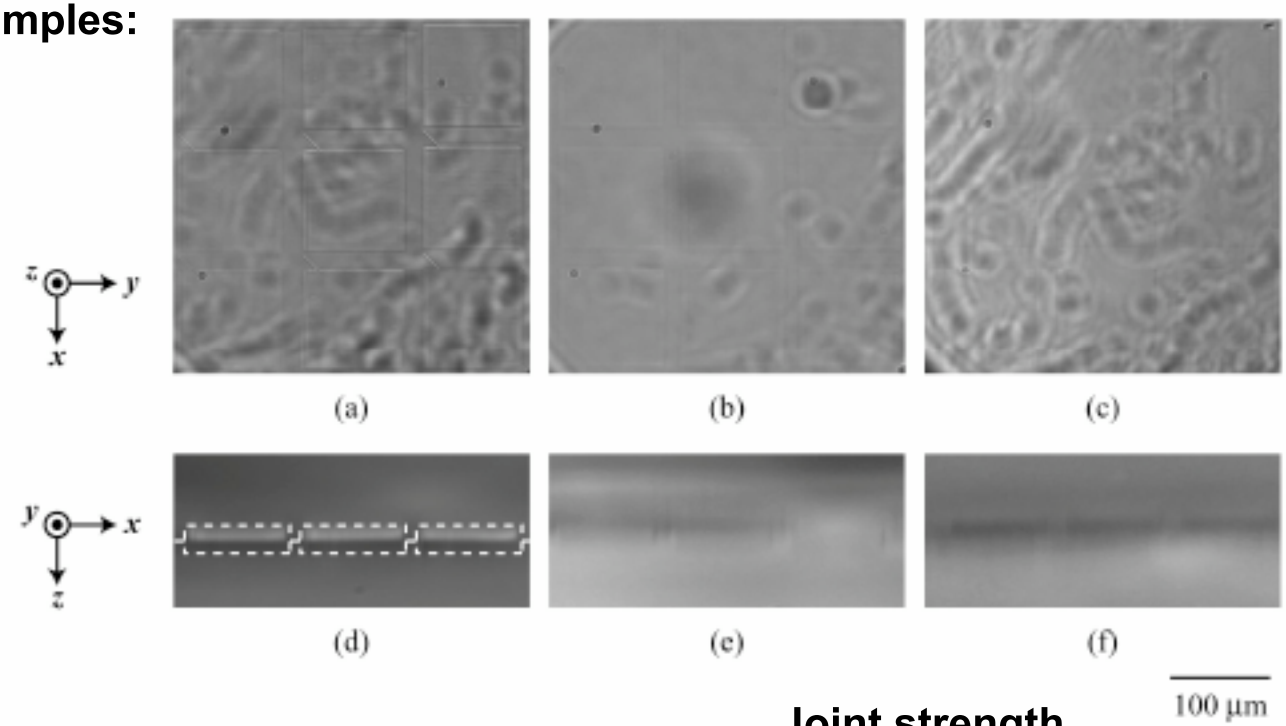
(c) Resolidification after localized melting

Watanabe et al, Proc. of SPIE Vol. 6460, 646017-1 (2007)
Tamaki et al, Proc. of SPIE Vol. 6460, 646018-1 (2007)

Fs laser micro-welding

Welding of 2 borosilicate samples:





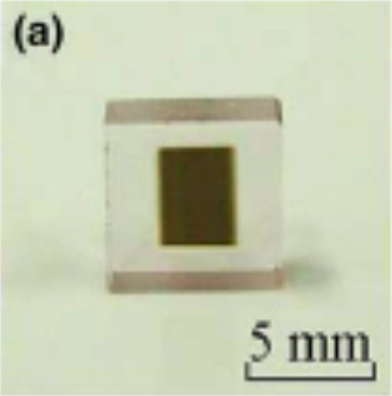
Joint strength

9.87 MPa **6.81 MPa**

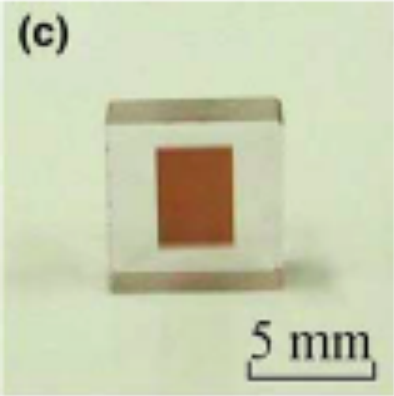
Laser parameters:
λ = 1558 nm
E = 0.8 μJ
Rep rate = 500 kHz
τ = 950 fs

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

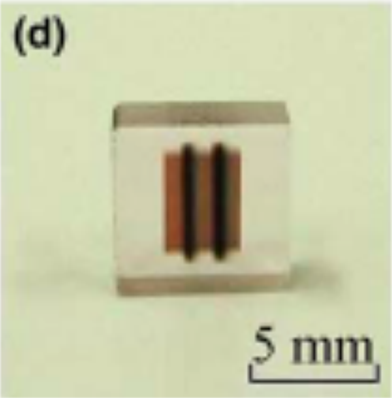
Fs pulses have been used for spatially selective crystallization of metal nanoparticles in glass



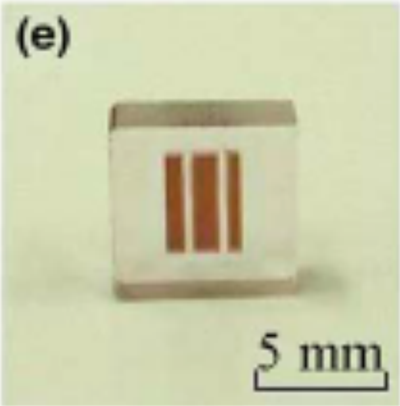
irradiation with fs laser



subsequent heat treatment at 520 C



re-irradiation with fs laser



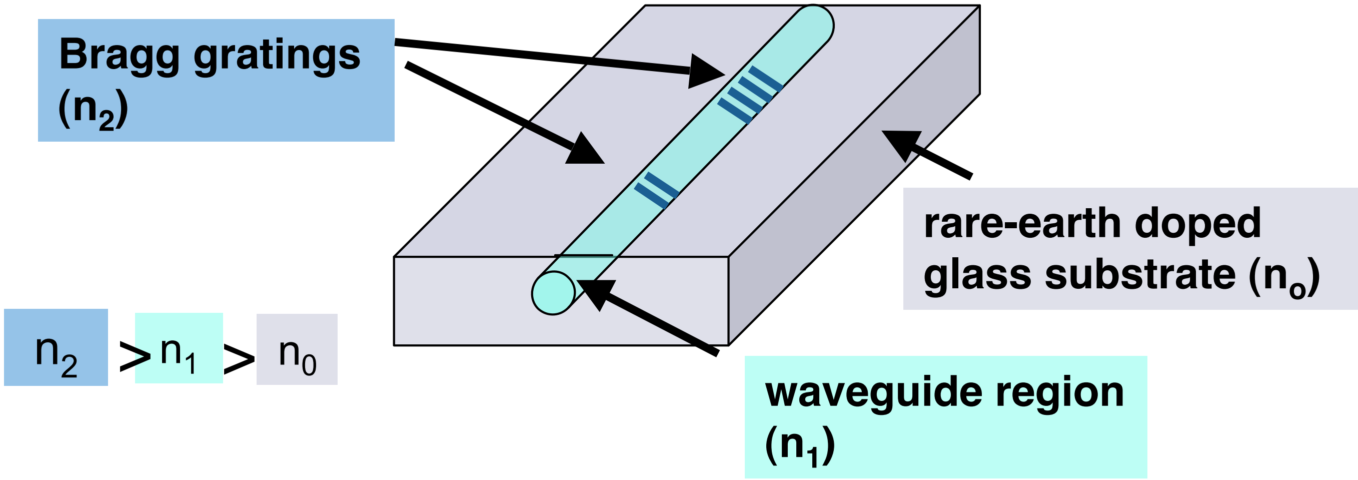
further heating at 300 C

Jiang et al, Chem Phys Lett 391 (2004) 91–94

Fs laser fabrication of components for integrated optics

- **Integration of functionalities**

example: waveguide laser



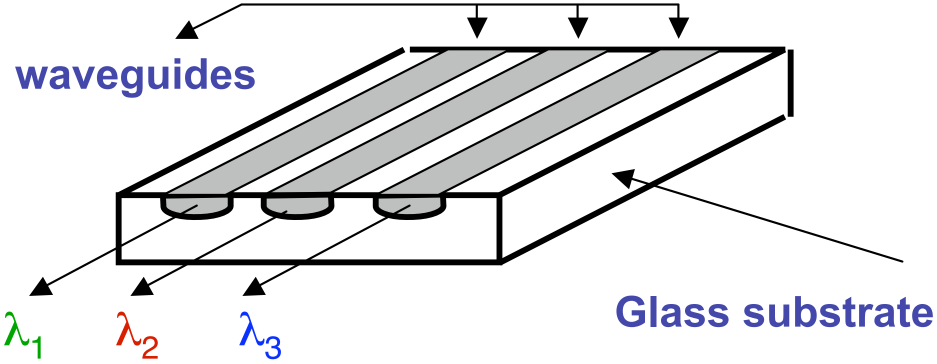
Bragg gratings (n_2)

rare-earth doped glass substrate (n_o)

waveguide region (n_1)

$n_2 > n_1 > n_0$

- **Component arrays**



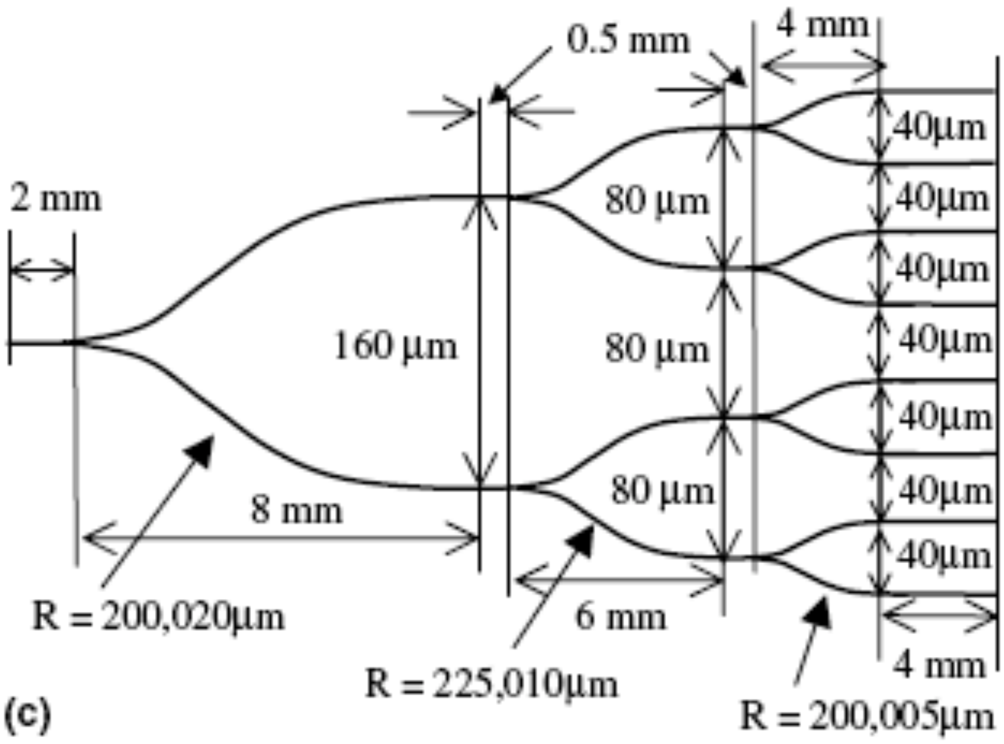
waveguides

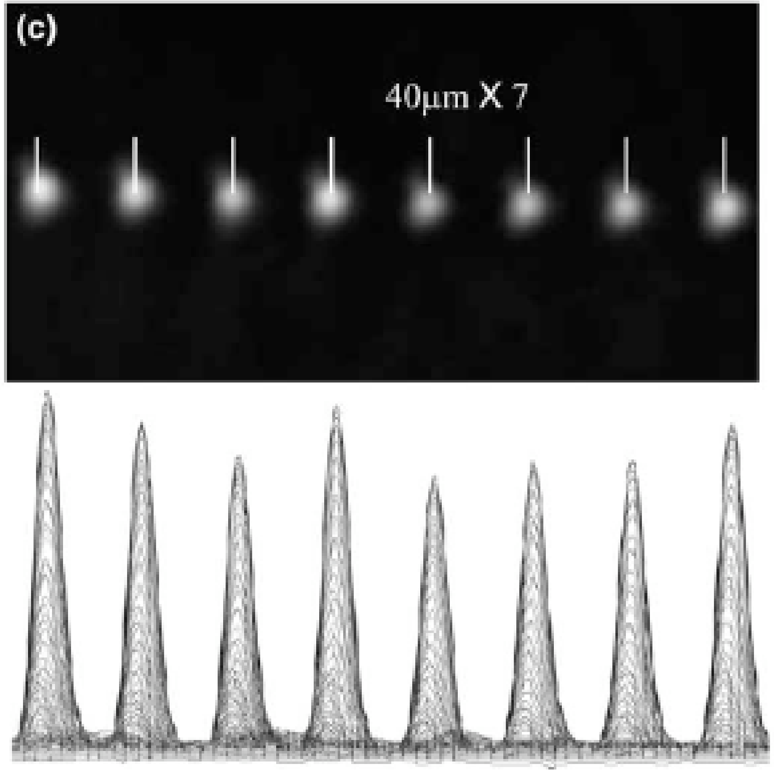
λ_1 λ_2 λ_3

Glass substrate

- **Ability to fabricate 3D structures**

Fs laser pulses have been used to fabricate optical splitters





Liu et al. Opt. Comm. 253 (2005) 315–319

Fs laser pulses have been used to write fiber Bragg gratings

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

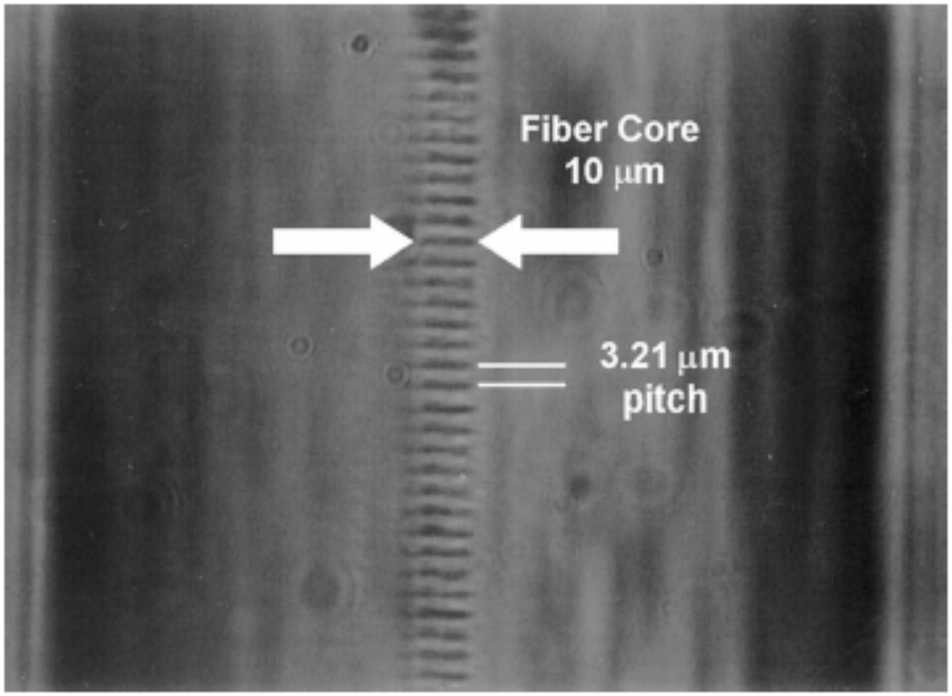
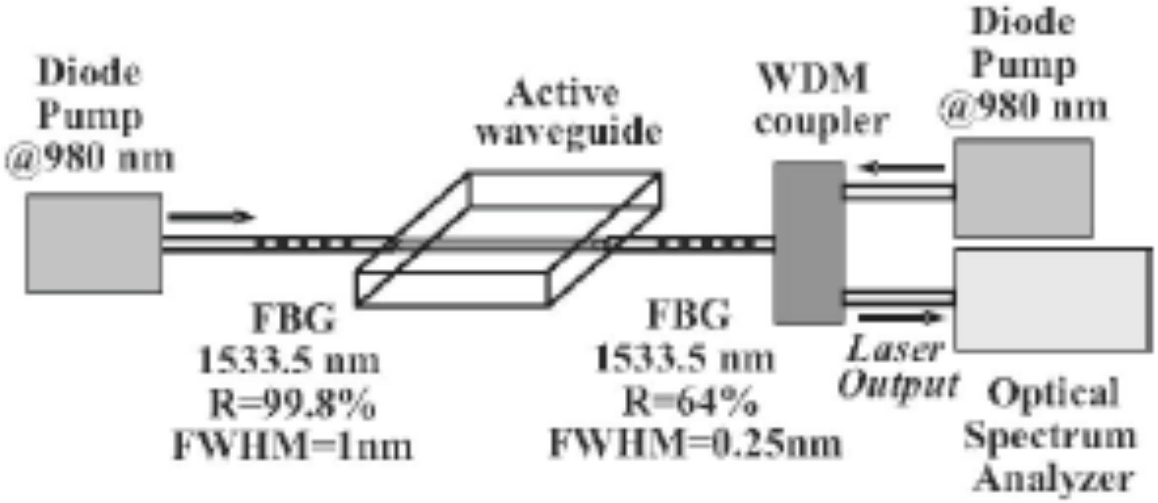


Fig. 4. Photographic image of photoinduced index modulation as seen through an optical microscope. The spacing between lines in the image corresponds to the 3.213-μm period of the phase mask.

Fs laser pulses have been used to fabricate waveguide lasers



Laser parameters:
Cavity dumped ML Yb: glass
λ=1 μm
270 nJ
685 KHz
100 μm/s

Er:Yb-doped phosphate glass waveguide

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

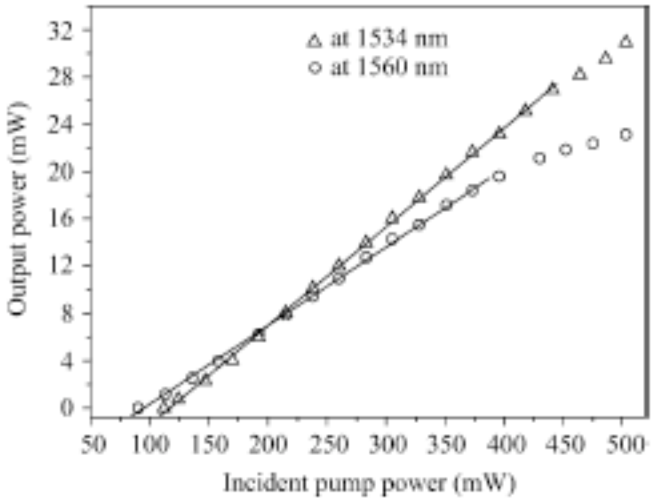


Fig. 11. Output power of waveguide laser as function of incident pump power at two different wavelengths: 1534 nm (triangles), 1560 nm (circles). Interpolating lines for slope efficiency evaluation.

Osellame et al, IEEE J. Sel Tops QE 12, 277 (2006)

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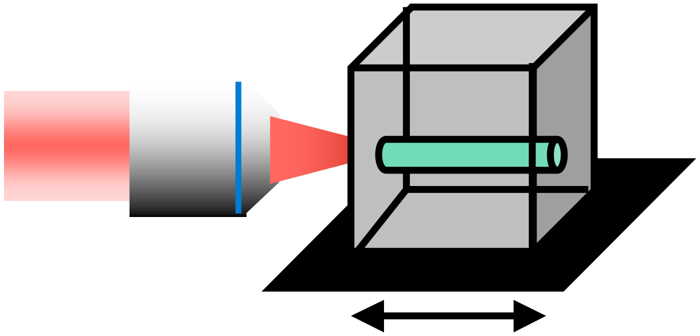
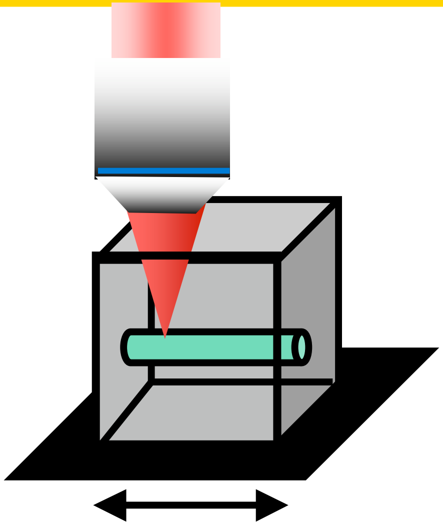
Experimental parameters in fs-laser writing

- **writing geometry:**



longitudinal writing



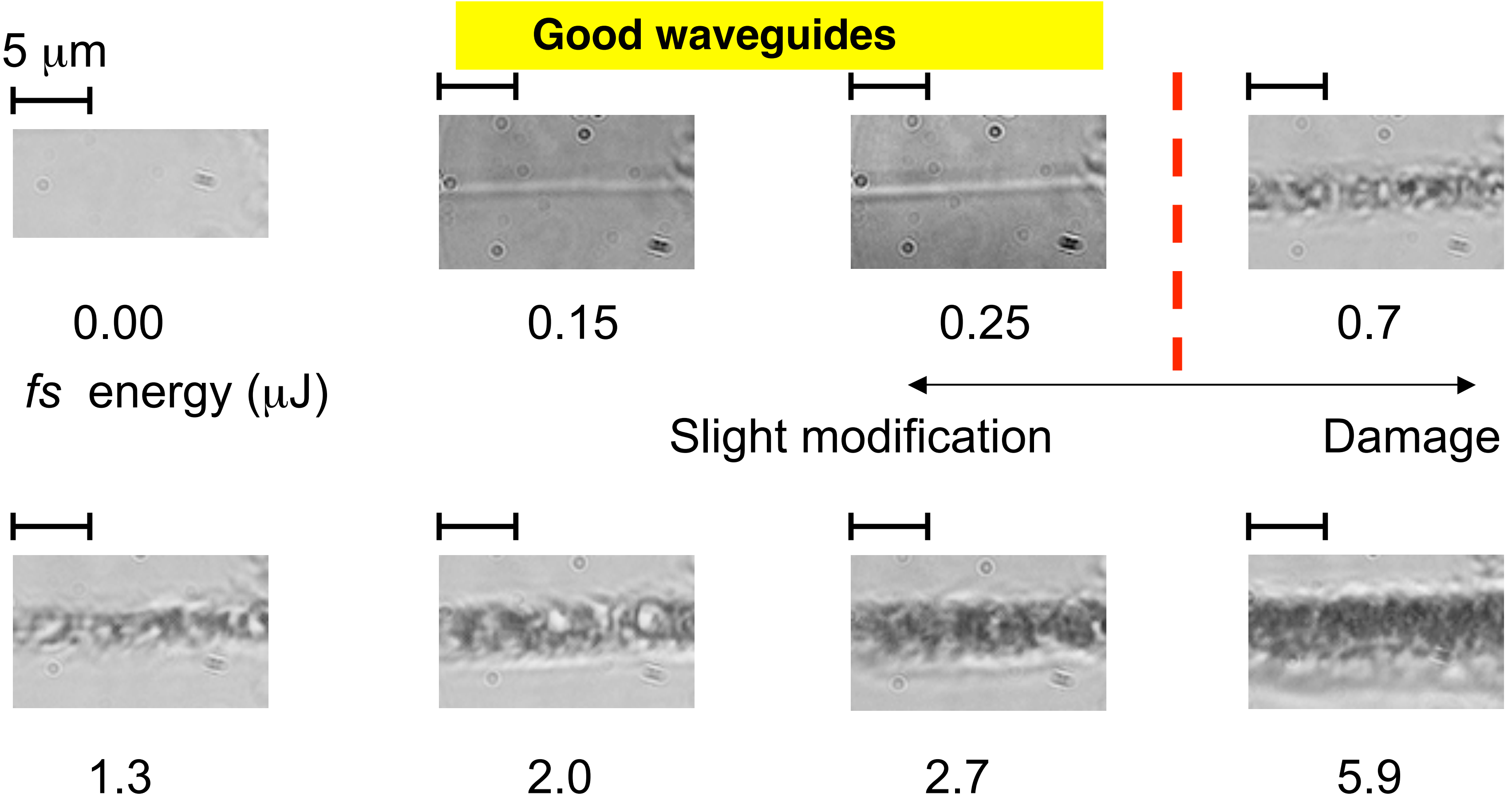
transverse writing

- **pulse energy: 0.1-10 μJ:**

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



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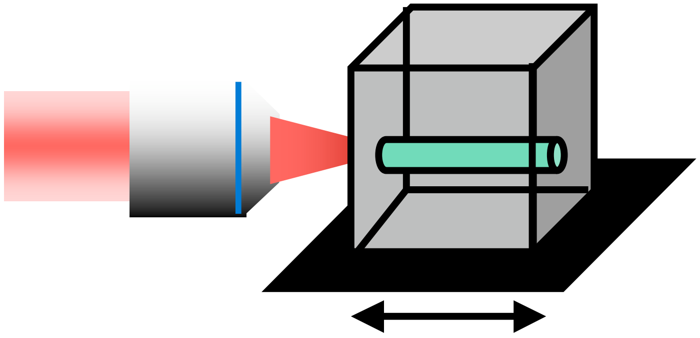
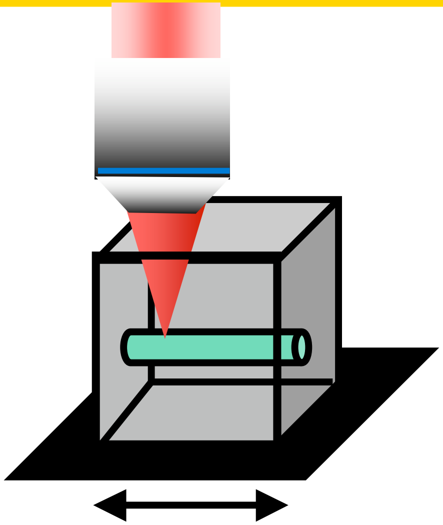
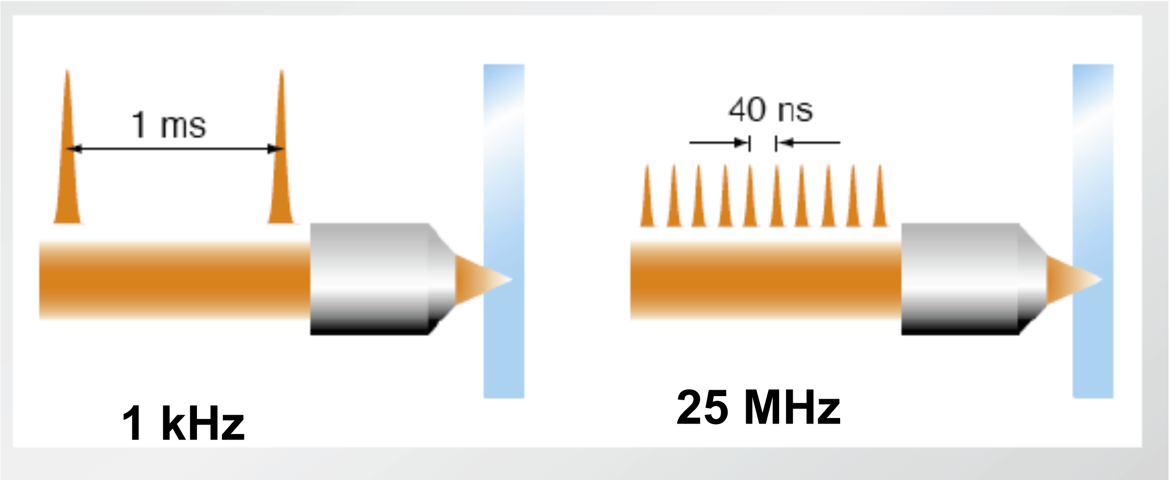


longitudinal writing

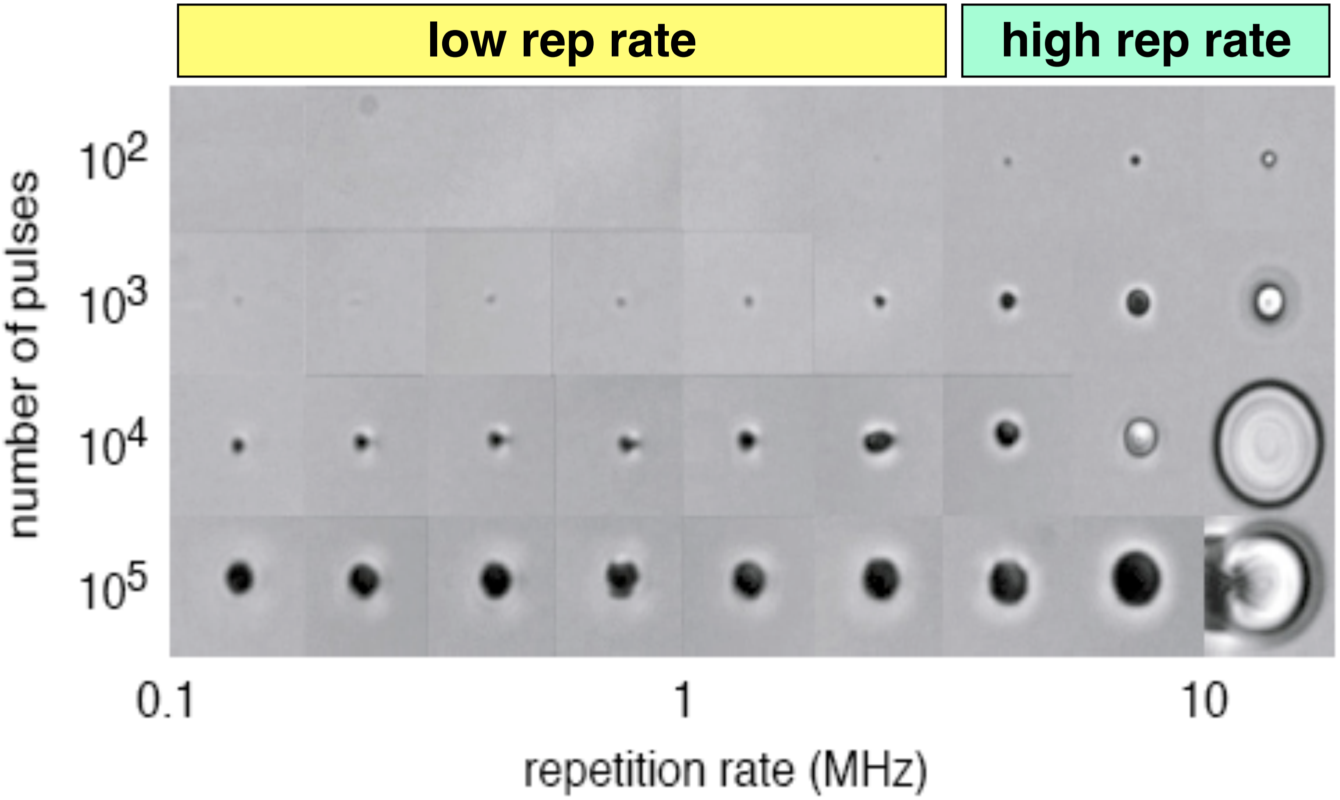


transverse writing

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

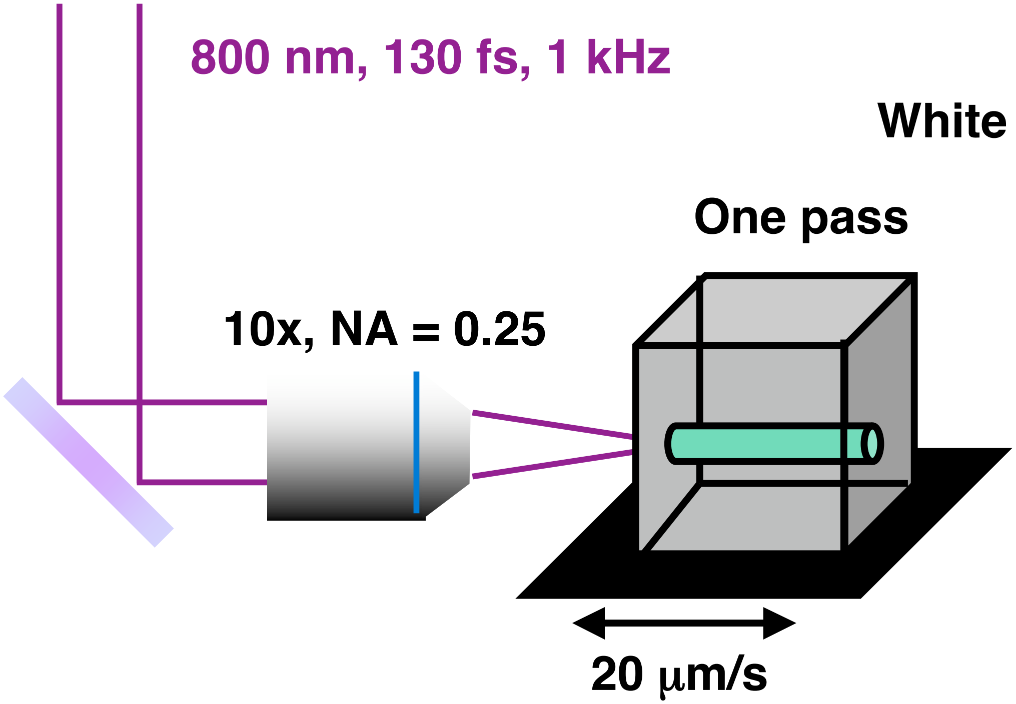


Difference between high and low pulse repetition rate



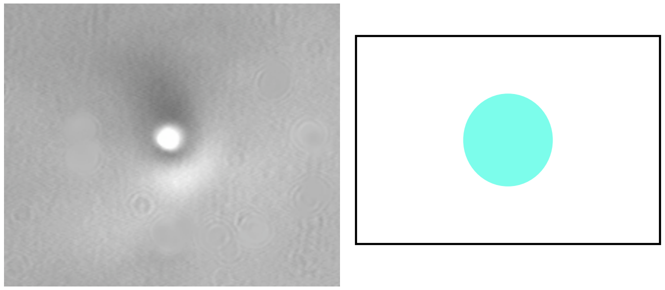
E. Mazur et al., Harvard Univ.

Modification in IOG-1 is different from fused silica

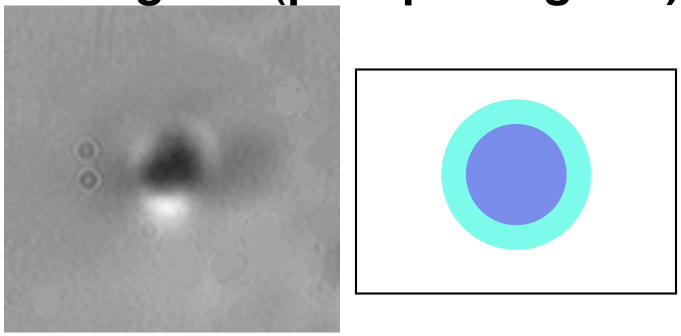


White light transmission images of :

fused silica



IOG-1 glass (phosphate glass)



high index region

low index region

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Characterization of fs-laser modified glass

modified features are (sub)micron size

⇩

We can probe the fs-modified glass with high spatial resolution using confocal fluorescence and Raman microscopy

➡Fluorescence spectroscopy reveals

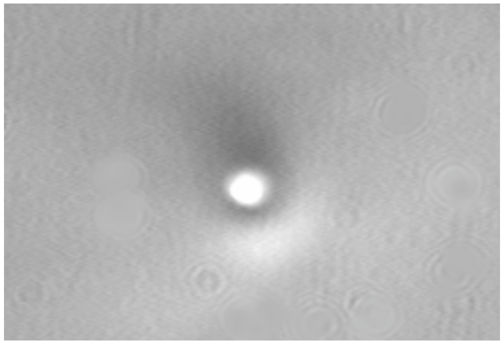
- **color center defect formation**
- **photobleaching of color centers upon exposure to laser light**

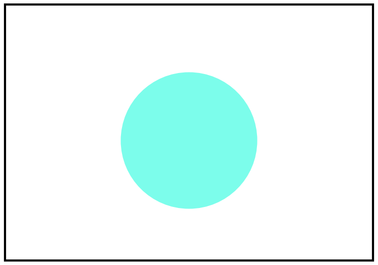
➡Raman spectroscopy shows

- **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}**

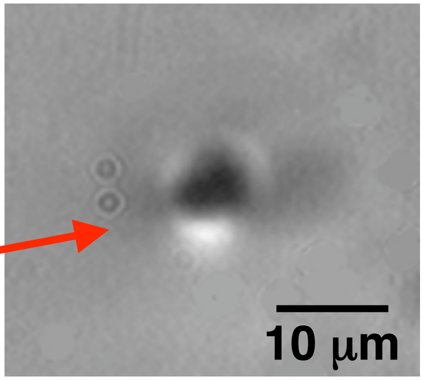
Comparison between fused silica and phosphate glass IOG-1

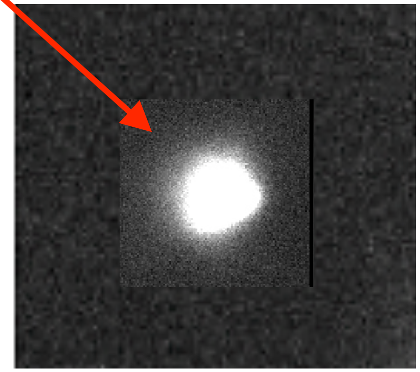
fused silica

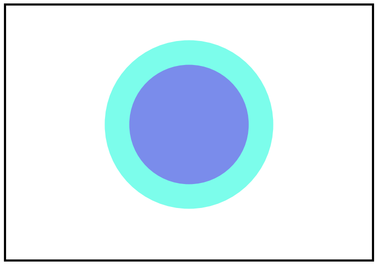




phosphate glass







white light images

NO color centers in w.g. regions

w.g. regions not directly exposed to fs pulses

fluorescence images

high index region

low index region

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

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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 may 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

If you want to know more…..

Special issue, MRS Bulletin August 2006

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.

acoustics, for experiments that probe heat transfer or carrier dynamics, and for many forms of optical spectroscopy; it is not generally sufficient for materials modification, except with pulses that are tightly focused by high-numerical-aperture microscope objectives. Higher-energy pulses are available from so-called "extended-cavity oscillators" that operate with a lower repetition rate, on the order of 10 MHz, but this technology is currently limited to <100 nJ in commercial Ti:sapphire lasers and <1 μJ in Yb:tungstate lasers.

Optical pulses from laser oscillators must therefore be amplified to reach energies of >1 μJ. The ability to amplify ultrafast lasers was an elusive goal for 20 years following the development of the ultrafast oscillator in the mid-1960s. In 1985, high-intensity ultrafast lasers emerged with the development of the chirped-pulse amplifier.[2] In a chirped-pulse amplifier, pairs of diffraction gratings are used to temporally stretch the optical pulse prior to amplification and then temporally compress the pulse after it leaves the amplifier. Twenty