Precision Laser Processing for Beam Shaping and Guiding Applications

Ultrafast Beams and Applications
UBA-19
02-05 July, 2019

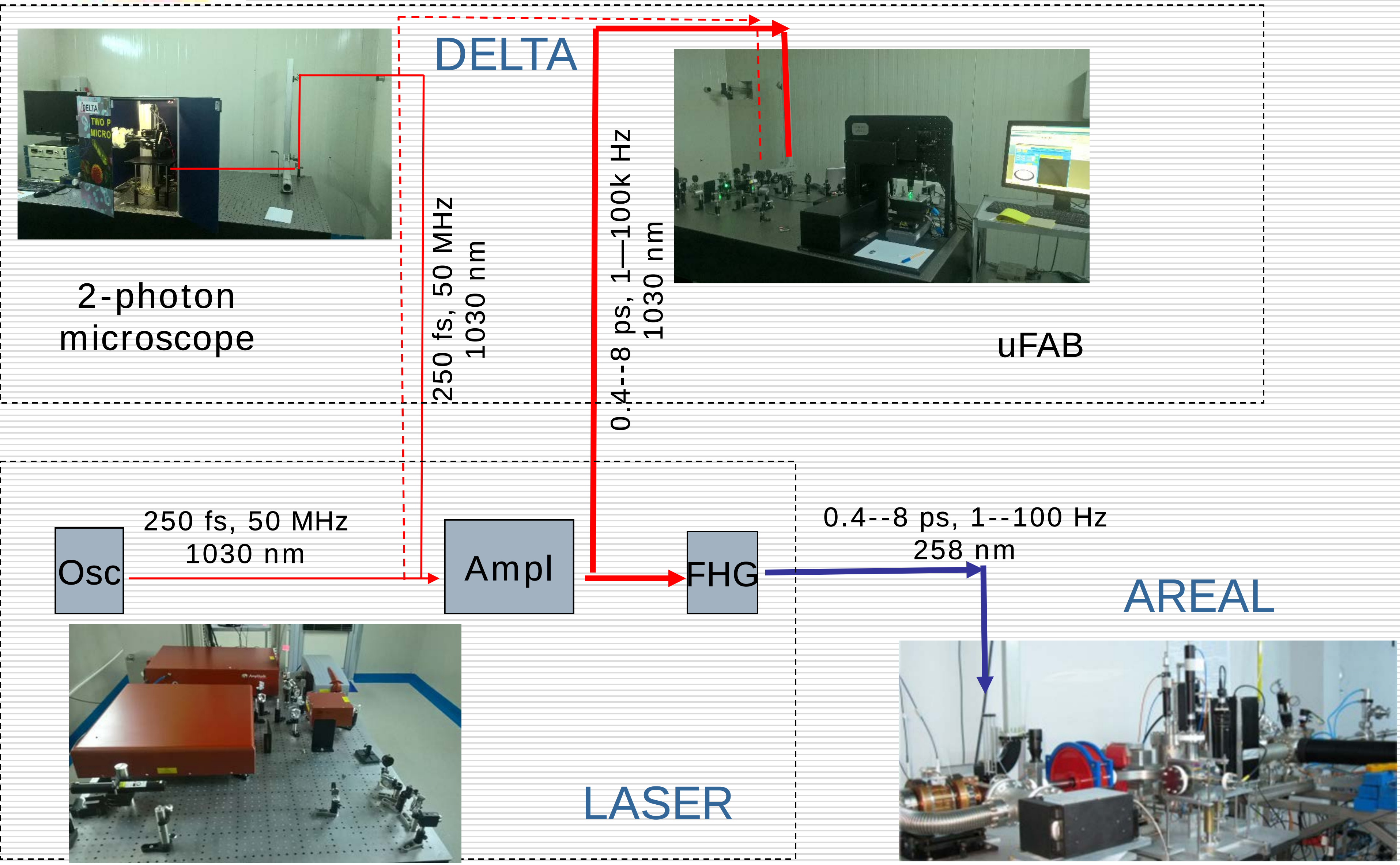
Presenter: Arsham Yeremyan

Photon Beams & Optics Group

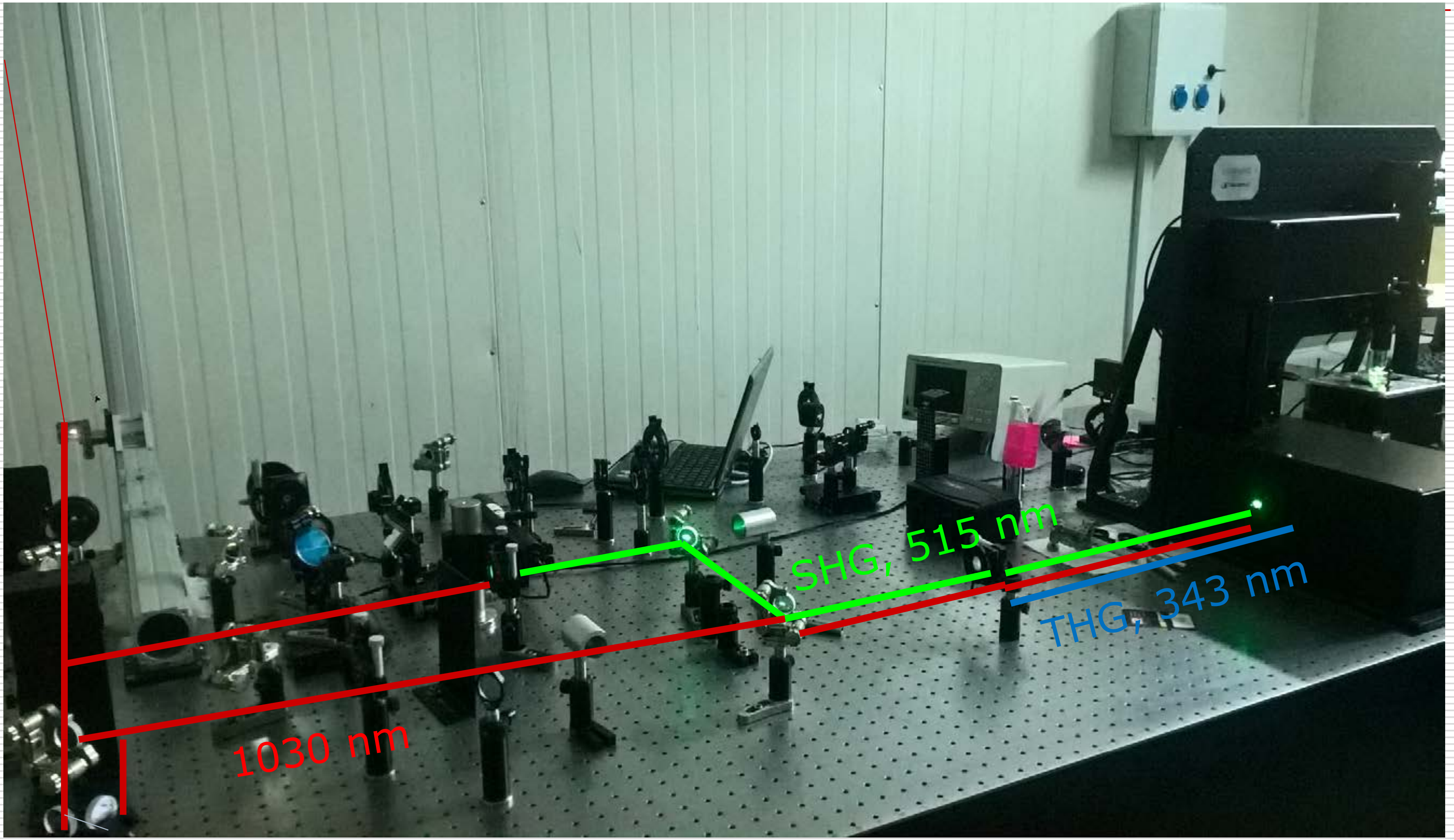
Outline

- Femtosecond laser processing and microfabrication
  - Laser system and uFab station: specs and capabilities
  - Advantages and potential applications
- Beam shaping and guiding applications
  - 2D and 3D direct laser writing on/in glass: waveguides, phase plates, diffraction gratings
  - Potential and relevance for spatial-temporal (3D) beam shaping applications
  - Other materials and techniques
- Summary

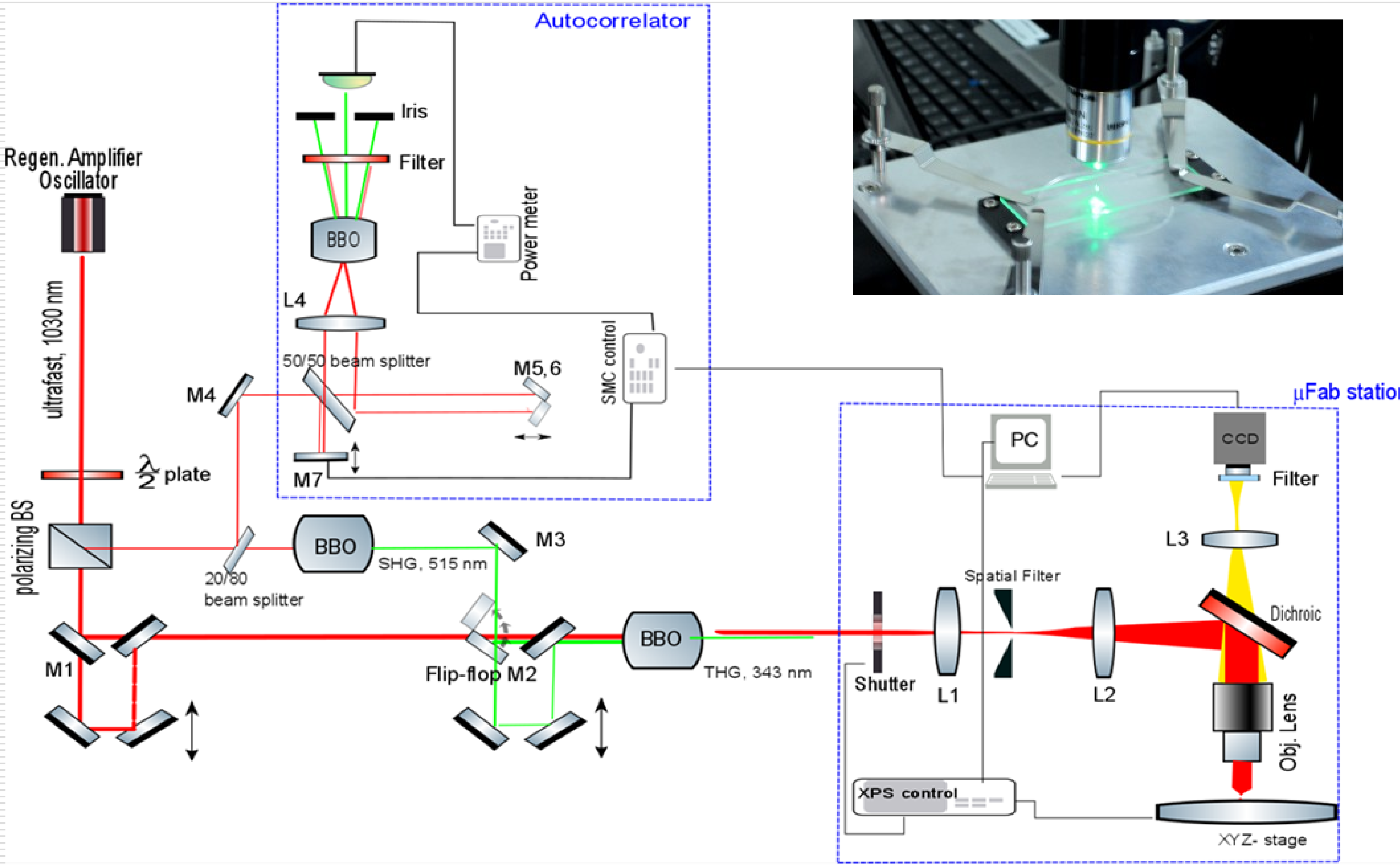
Laser Driven Experimental Stations



uFAB Microfabrication Station



uFAB Microfabrication Station



Laser System

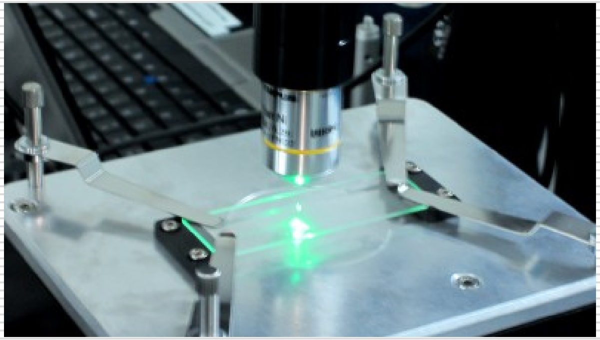
Specifications and features

	t-pulse	*S*-pulse	FHG	SHG*	THG*
Wavelength	1030 nm	1030 nm	258 nm	**515 nm**	**343 nm**
Pulse width	250 fs	400 fs—8 ps	400 fs—8 ps	**400 fs—8 ps**	**1—8 ps**
Rep. Rate	50 MHz	1Hz—100 kHz	1Hz—1 kHz	**1Hz—100 kHz**	**1Hz—100 kHz**
Energy/pulse	20 nJ	Up to 2 mJ	Up to 425 uJ	**Up to 1mJ**	

**** Conversion implemented in DELTA uFab***

IR and UV pulse-to-pulse energy stability ~0.5 %

uFAB Station



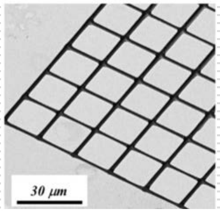
Operating Parameters

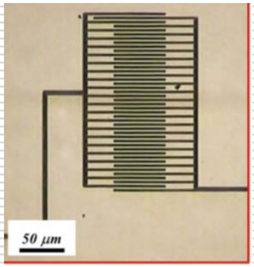
- Pulse duration: 400 fs –8 ps
- Repetition rate: 1 Hz –100 kHz
- Average power: up to 8 W
- Pulse energy: up to 2 mJ (1030 nm) and 1 mJ (515 nm)
- Wavelengths 1030 nm, 515 nm, 343 nm
- Sample positioning accuracy: ±50 nm
- Travel range: 100 x 100 mm (XY), 25 mm (Z)

Ultrashort-Pulse Laser Processing Applications

Processing technique | **Typical Applications**

Direct laser writing, micromachining, laser-assisted deposition, 2D patterning

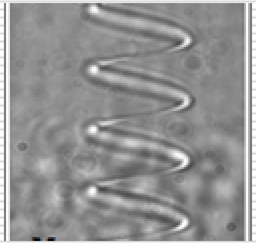


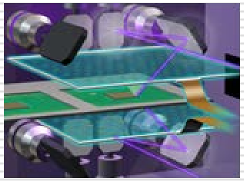


Micro- and nanoelectronics

Semiconductor technology, etc

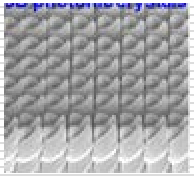
Bulk processing of transparent materials

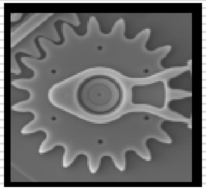


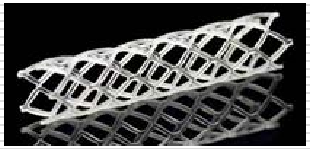


Microfluidics networks, waveguides, labs-on-a-chip

2-photon polymerization, ablation



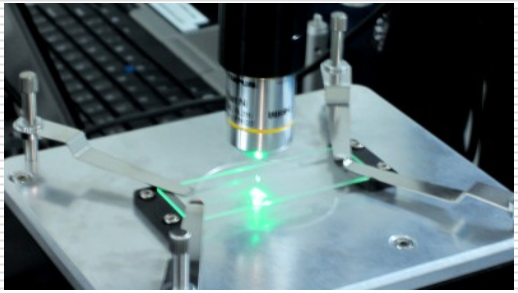


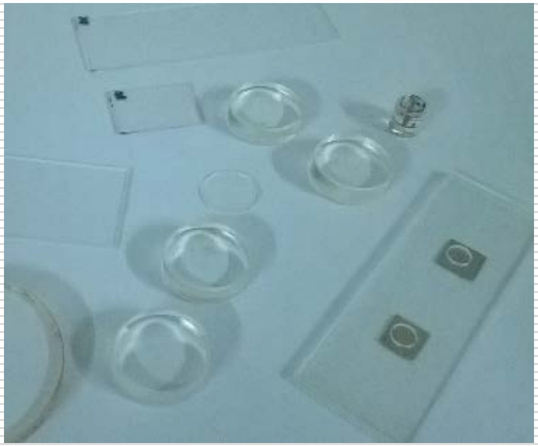


3D photonic crystals, MEMS biomedical

Ultrashort-pulse laser processing

Direct laser writing in/on glass



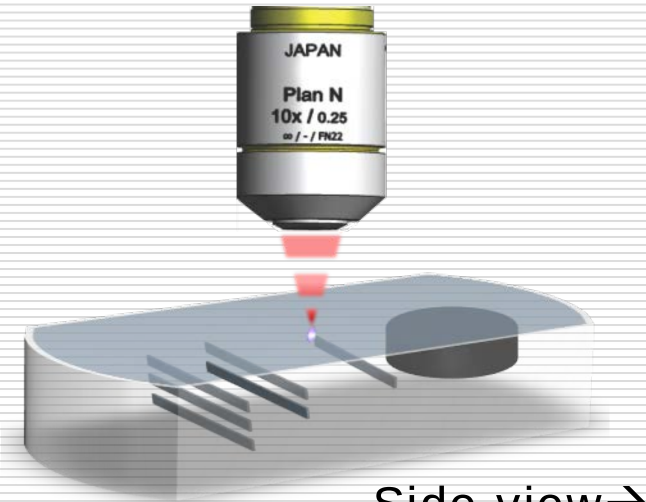


- Laser-induced modifications

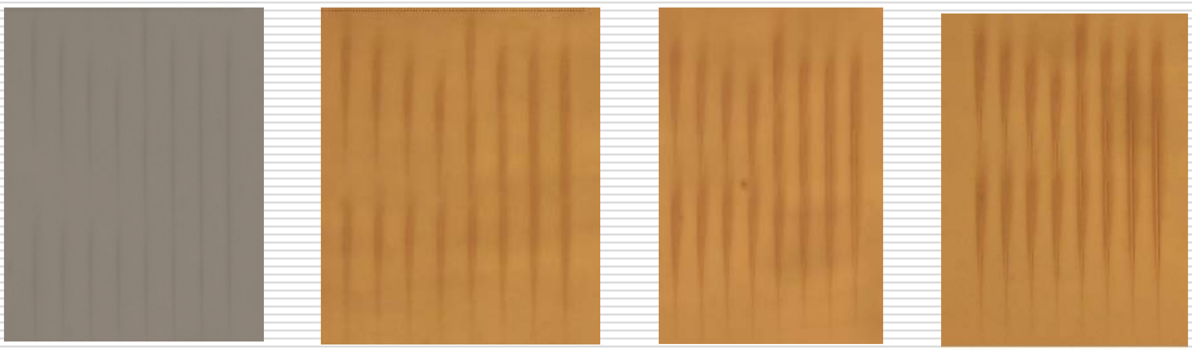
  such as refractive index change (RIC)
- Nonlinear (multiphoton) absorption confined to the focal point region→ high resolution in 3D
- Buried waveguides and other embedded components for integrated optics
- High-power applications due to the high damage threshold of glasses
- ...

Beam Shaping and Guiding Applications

Direct laser writing in BK7 glass



smooth RIC→nanostructuring →voids and damages

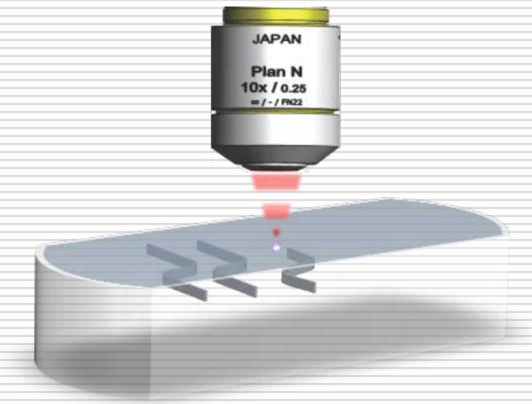


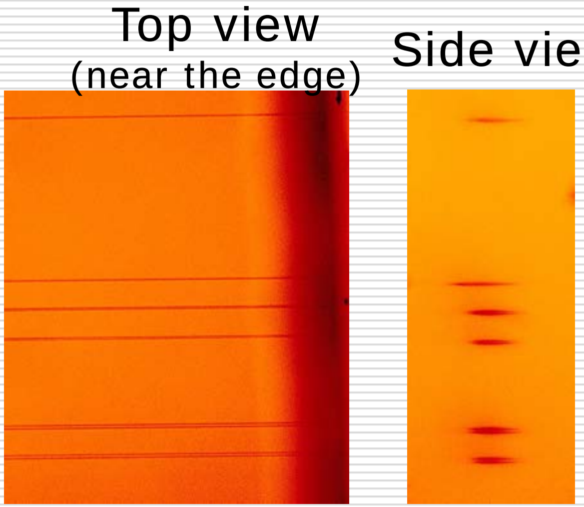
Energy dose defined as: $D=E_pR_p/Av$ ➔ D_{opt} ~2.4 [uJ/um^3]

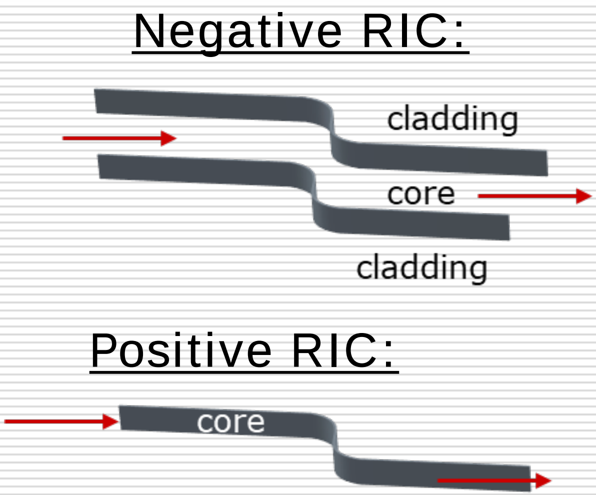
- ❖ Optimal regimes for fabrication of "smooth" structures with negative RIC
- ❖ Large volumes can be processed in "layer-by-layer" mode
- ❖ **RIC sign changes depending on the fabrication regime**:
  complex behavior at high pulse energies

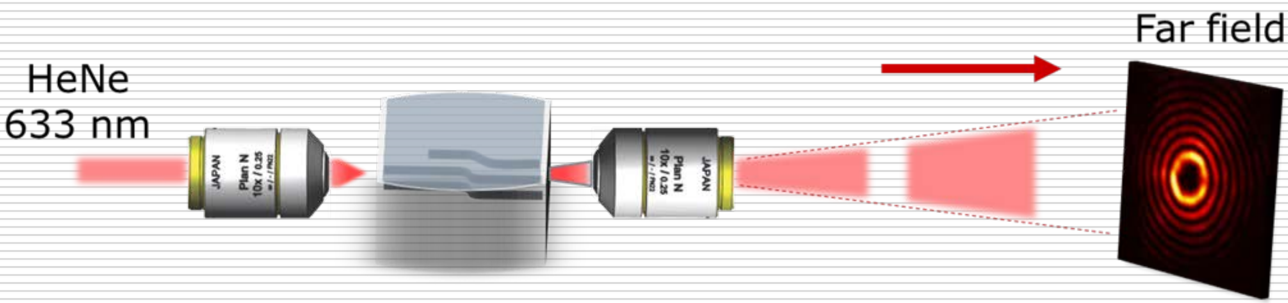
Beam Guiding Applications

Long waveguides inscribed in BK7 glass









Evaluation of RIC

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

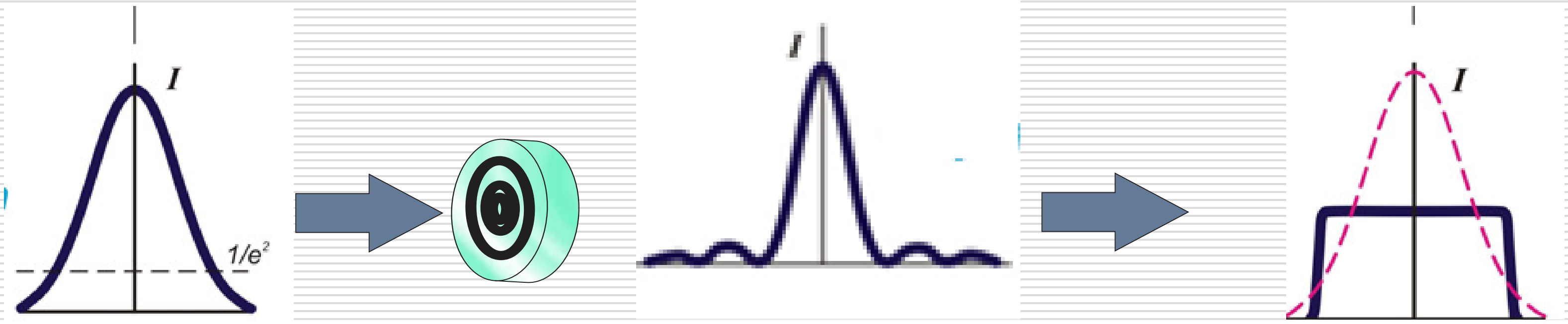
cf. presentation by M. Sargsyan

Beam Shaping Applications

Binary phase plate for laser beam shaping

Principle *Conversion of laser irradiance distribution*

Gaussian Bessinc*(r) or* "Airy disk" Homogeneous (Flattop)



Modulation of Gaussian with
a proper phase function

Far field (or f- plane of a lens)

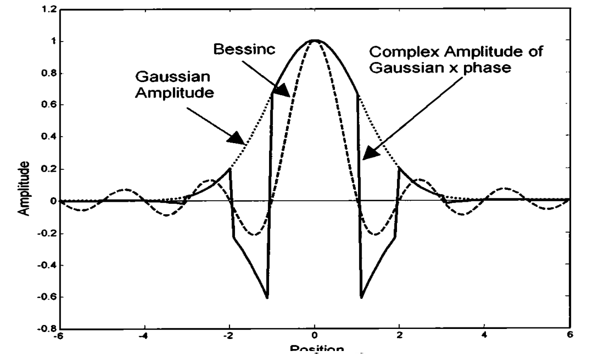
Fabrication in/on glass for high-power applications

Beam Shaping Applications

Binary phase plate for laser beam shaping

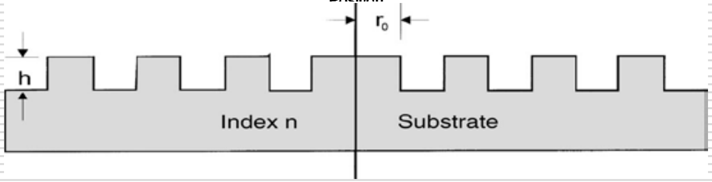
π-shaper Design and Fabrication

Design Parameters: Wavelength; Beam size; Traveling/focal distance; Phase depth



$$\varphi(r) = \frac{2\pi}{\lambda}\Delta n h(r)$$

Fabrication: (0,π) binary phase function (concentric rings) laser-written ON/IN glass

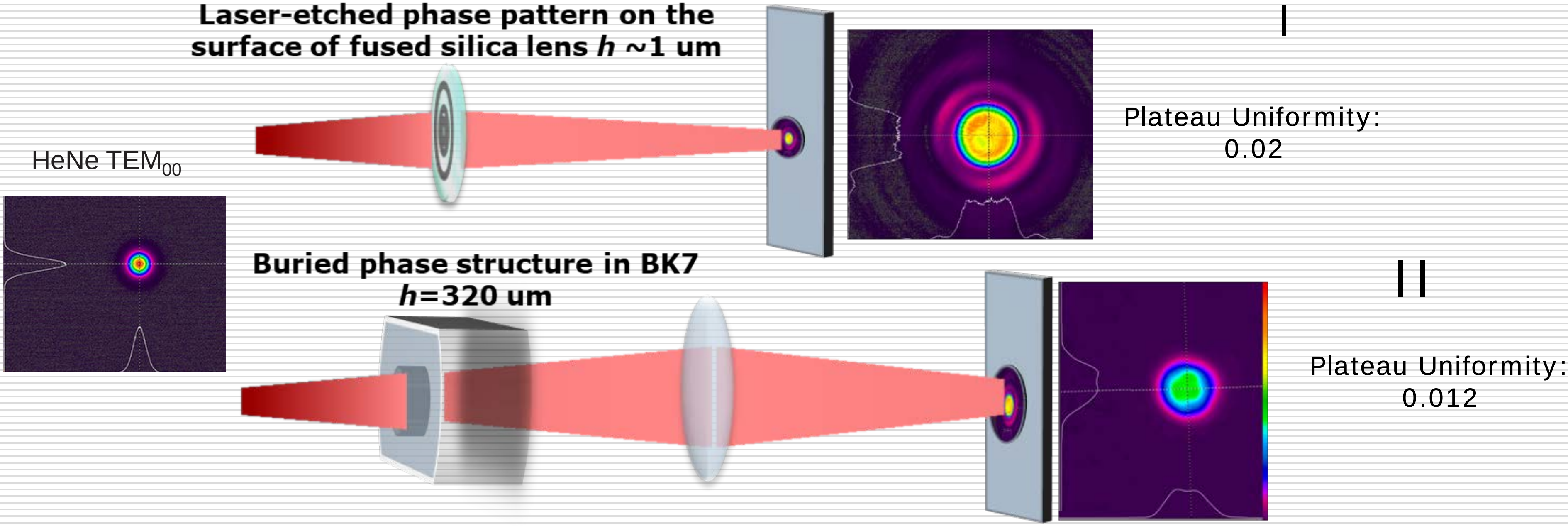


Surface etching VS Bulk RIC

Surface etching	Bulk RIC
$\Delta n = n - 1 = 0.53 \rightarrow h < 1$ um	$\Delta n \sim 10^{-2}$—$10^{-4} \rightarrow h >> 1$um
Higher scattering losses	Longer fabrication time
Higher contrast, easy to align	Easier phase-depth control

Beam Shaping Applications

Binary phase plate for laser beam shaping

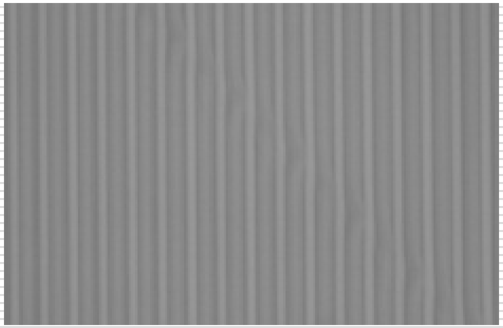


- ❖ Nearly the same uniformity in both cases
- ❖ Edge steepness lower in case II due to the lower refractive index contrast
- ❖ Scattering losses lower in case II: Efficiency >95 % at 633 nm
- ❖ Further studies of regimes are needed to improve quality and fabrication speed

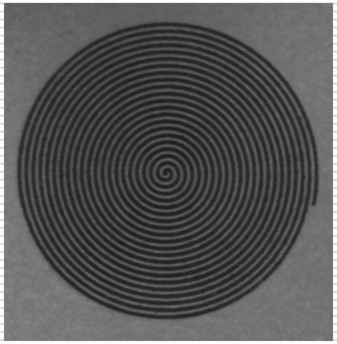
Beam Shaping and Guiding Applications

More glass-based optical elements

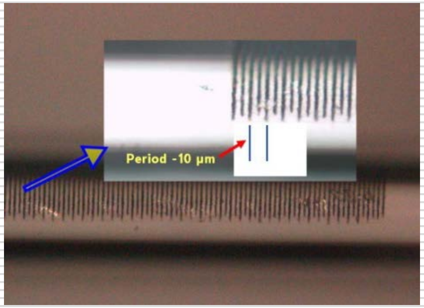
Relief diffraction gratings



spiral



Fiber diffraction grating



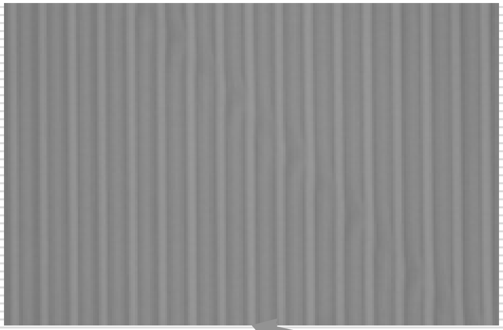
Features:

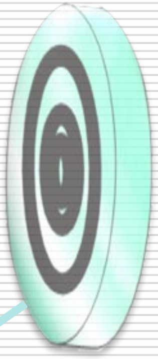
- Glass provides high damage threshold (suitable for high power applications)
- Both surface and bulk processing; 2D and/or 3D writing
- Diffraction efficiency can be increased by fabrication of volume structures

Beam Shaping Applications

Possible use for spatio-temporal (3D) shaping

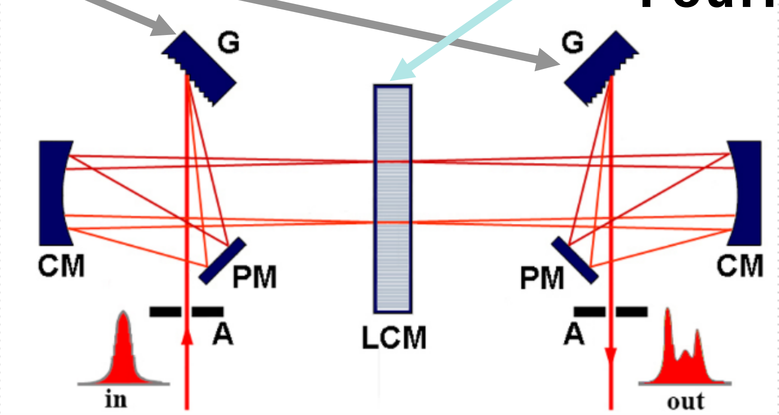
Relief diffraction gratings





linear mask

Temporal shaping
Fourier transform pulse shaper



Nanoscale resolution is required for diffraction gratings

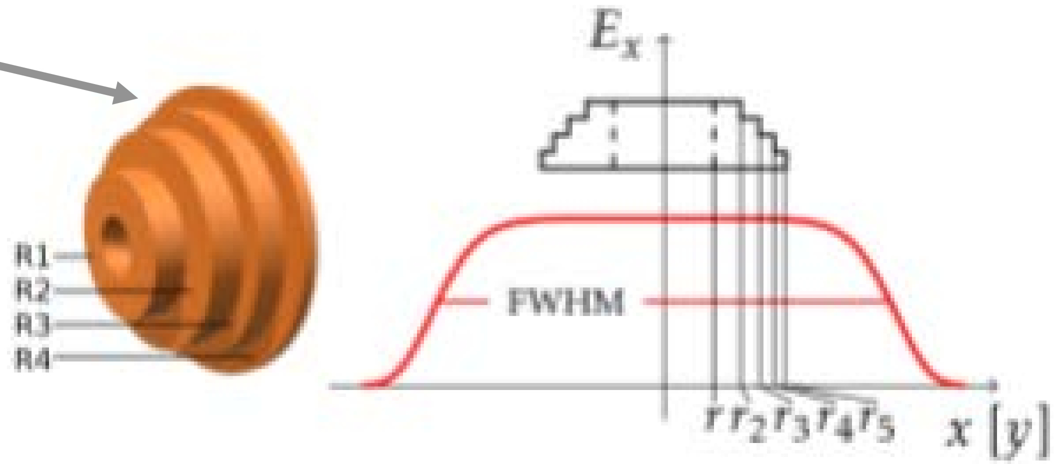
Subject for future research

Possible use for saptial-temporal (3D) shaping

Concentric-sectioned mask for time-delayed ring pulses

Pulse-delay given by the thickness of discs

? Possibility of laser-tailoring the refractive index profile to meet the goal

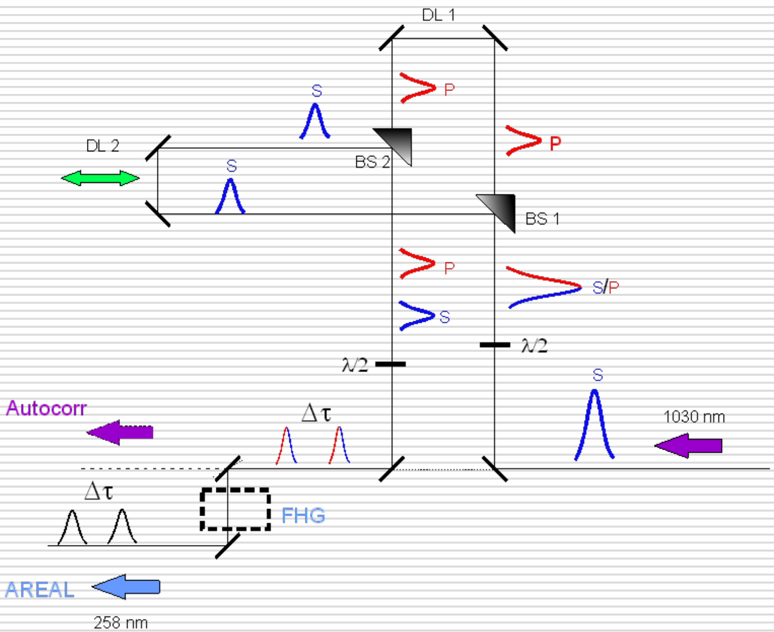


(a) 3D-model. (b) Transverse beam profile.

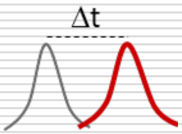
G. Vantaggiatto et al. Nucl.Instrum.Meth. A909 (2018) 114-117

Temporal Beam Shaping

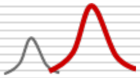
Delay-line for pulse doubling



- Tunable relative timing: **from 0 to >10 ps**



- Arbitrary contrast

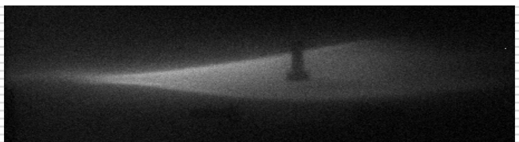


- Possibility to measure delay with the long-scan Autocorrelator

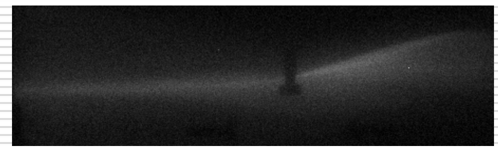
Temporal Beam Shaping

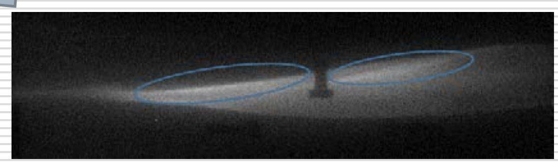
Two-bunch beam

Bunch 1. Q_1=-30.2±3.1 pC



Bunch 2. Q_2=-26.5±2.2 pC

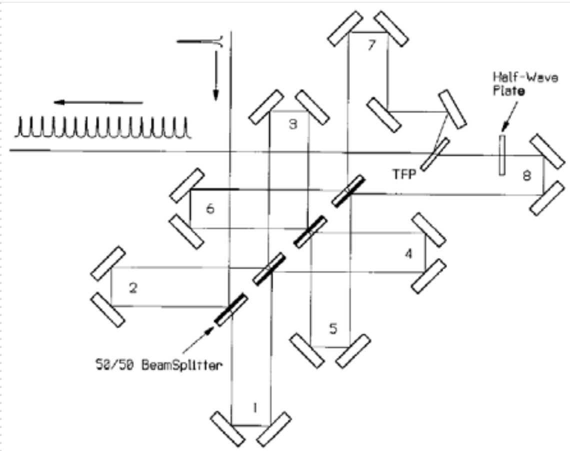




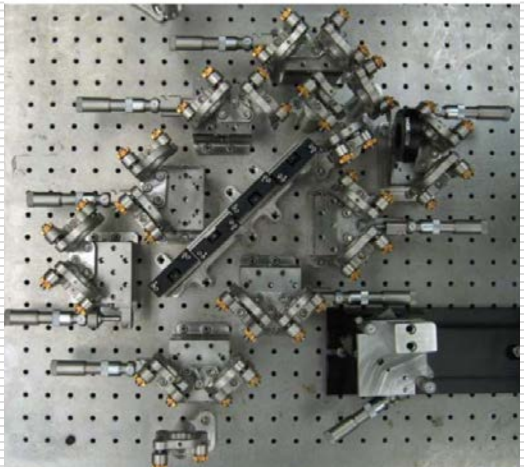
Delay: Δt=10 ps, Charge: Q_{tot}=-60±3.5 pC

Temporal Beam Shaping

Multi-pulse beam / pulse stacking

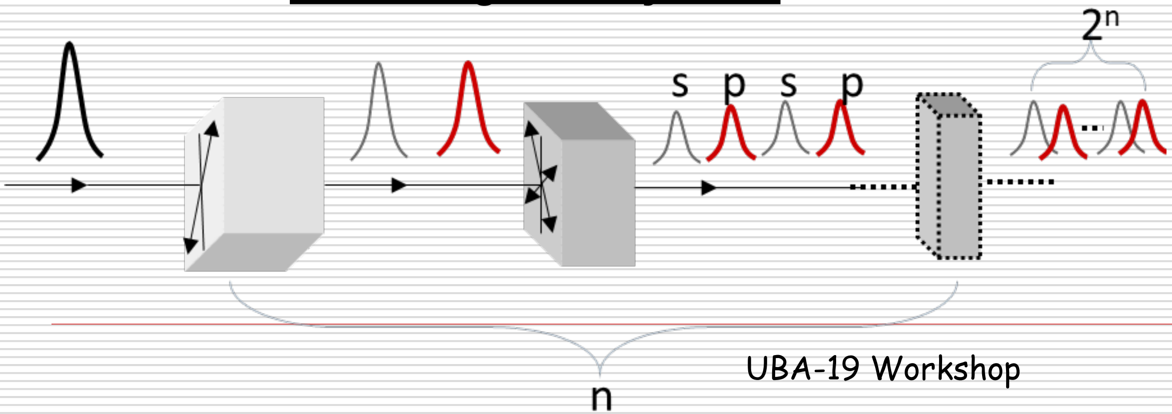


C. W. Siders et al., Appl. Opt. 37, 5302 (1998)



M. Y. Sheverdin, Proc. PAC07, p. 533 (2007). (LLNL PC gun drive laser)

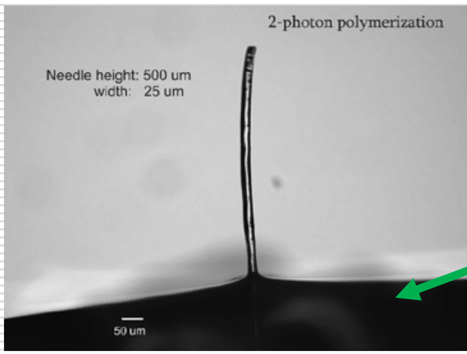
Birefringent crystals

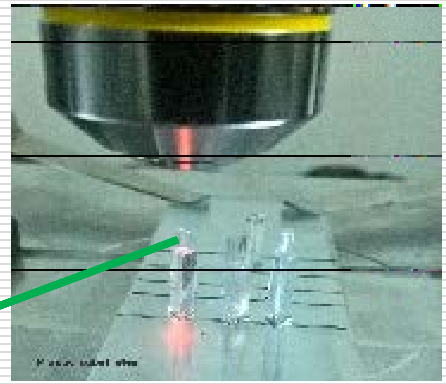


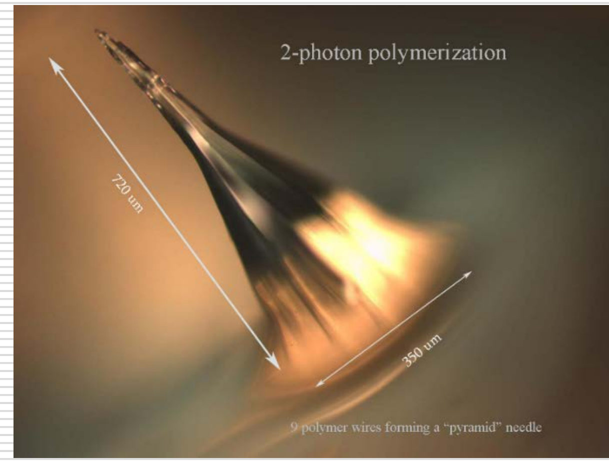
Pulse delay:

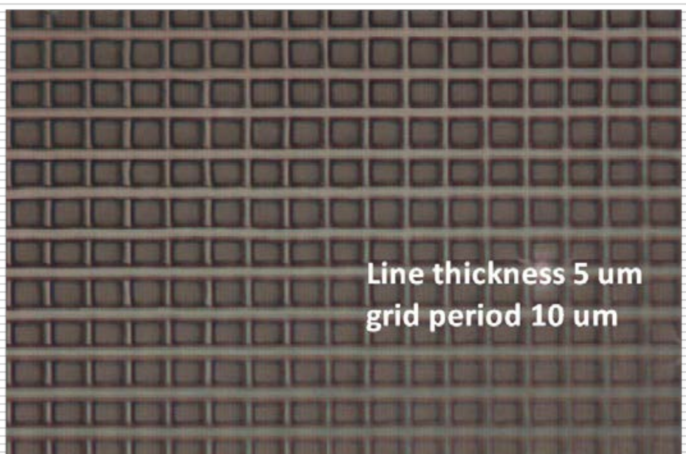
$$\Delta\tau = L\,(n_o - n_e)/c$$

Two-photon polymerization

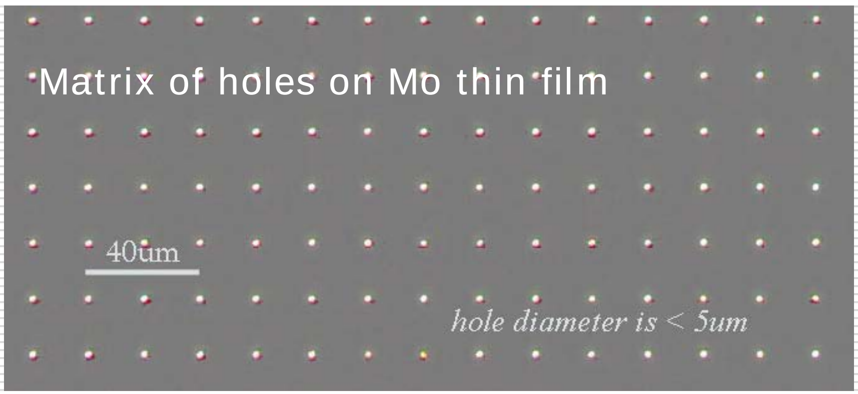


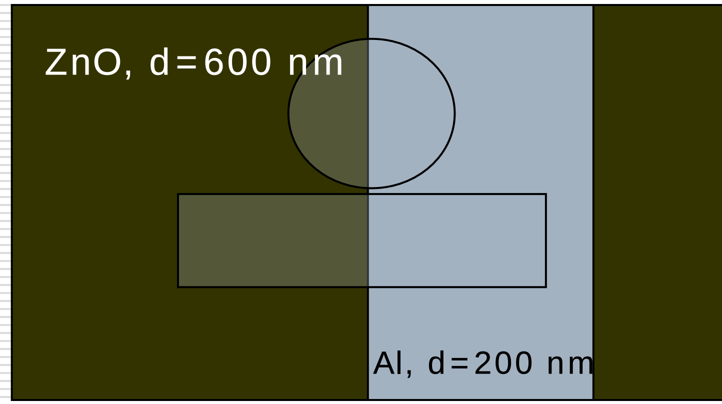


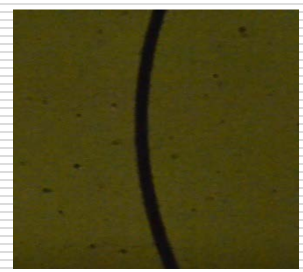


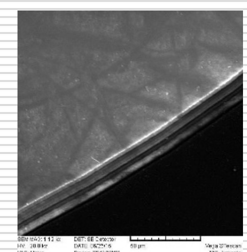


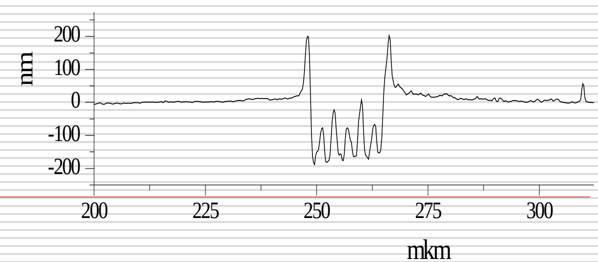
Surface patterning











Applications

micro-contacts
nano-film patterning
Photon/electron beam apertures

Summary

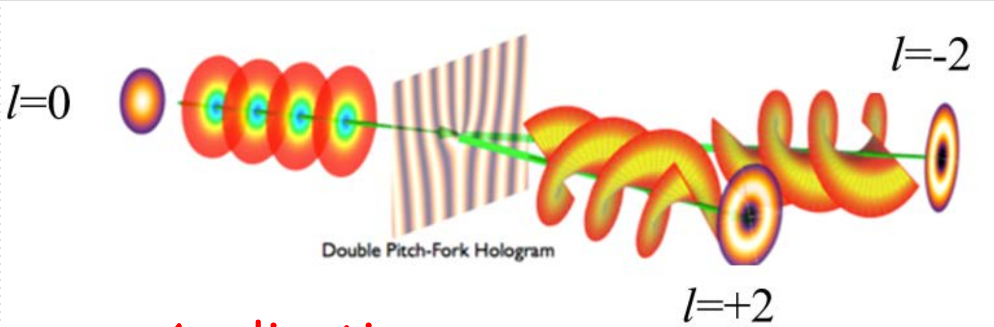
- Ultrashort-pulse laser processing applied for fabrication of glass-based beam shaping and guiding elements
- Optimal processing regimes found for fabrication of large, nearly homogeneous structures inside BK7 glass
- Flipping of sign of RIC is observed in BK7: further studies are needed
- Buried waveguides and phase plates were fabricated in BK7 and fused silica
- Spatial beam shaping by using surface patterned and volume phase structures
- Possible applications and approaches for 3D beam shaping are discussed

Thank you

Beam Shaping Applications

Optical Vortex Beams

Computer-generated "Fork" holograms
as a source of phase singularities



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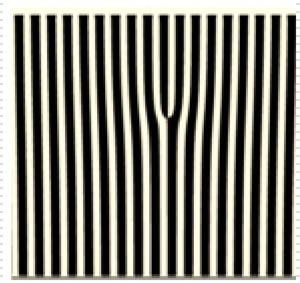

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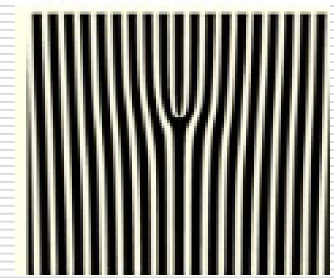

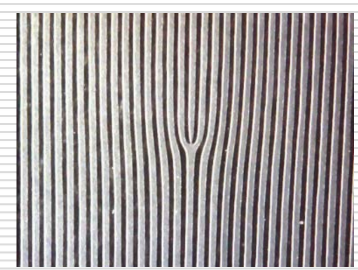

Laser-written
on glass

Applications

- Beam shaping
- STED (2P-)microscopy (**Nobel Prize, 2014**)
- Optical tweezers (**Nobel Prize, 2018**)
- Optical communications
- Etc.