Institute of Applied Physics

Friedrich-Schiller-Universität Jena

Ultrashort pulse laser processing – current industrial applications and beyond

Stefan Nolte

Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany

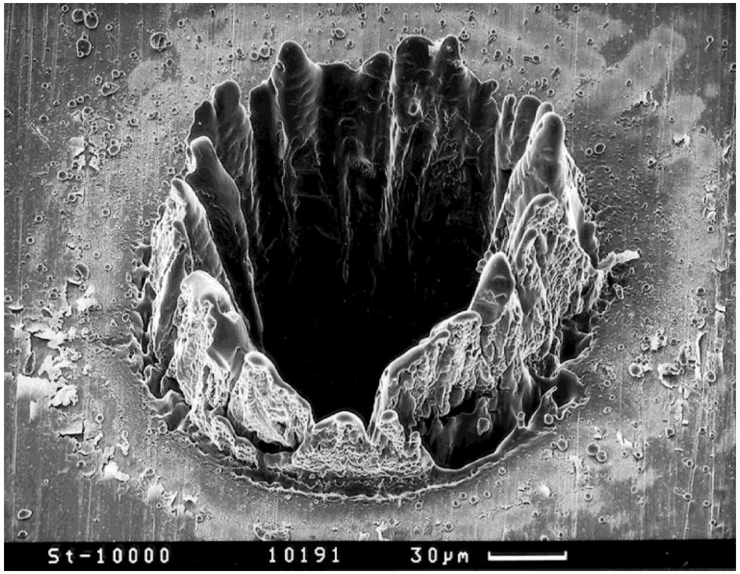
Center for Innovation Competence Ultra Optics

Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany

Fraunhofer IOF

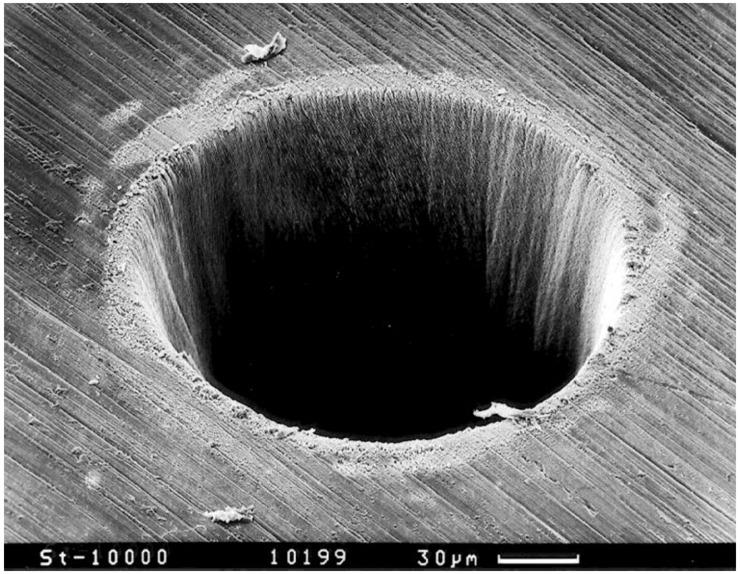
ultra optics

Micromachining of metals



“long” pulses (3.3 ns)

- melting and creation of burr
- heat diffusion
- non reproducible process



ultrashort pulses (200 fs)

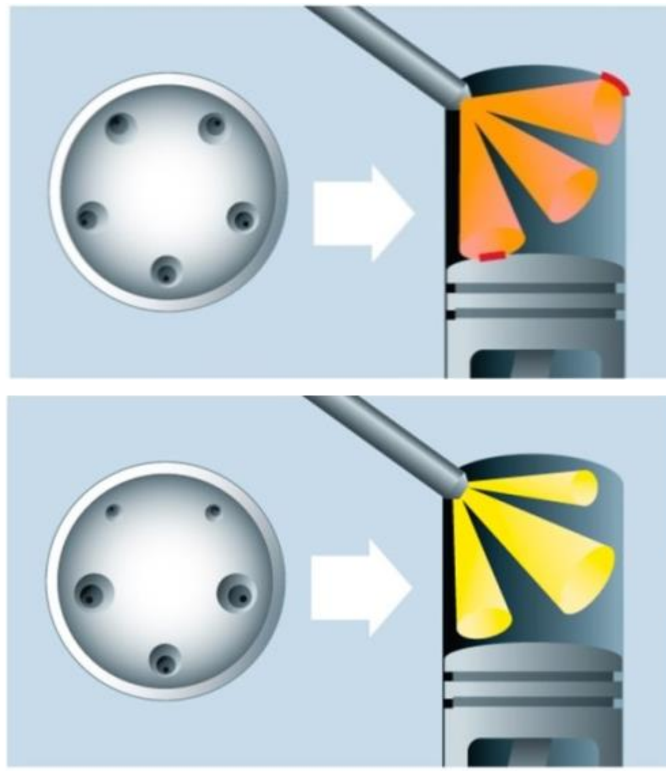
- practically burr- and melting-free ablation
- low ablation threshold
- negligible heat diffusion
  → minimized heat affected zones
- high process efficiency
- stable ablation process
  → high reproducibility

B.N. Chichkov, C. Momma, S. Nolte, F. v. Alvensleben, A. Tünnermann, “Femtosecond, picosecond and nanosecond laser ablation of solids“, Appl. Phys. A **63**, 109 – 115 (1996)

Microstructuring with ultrashort laser pulses in industrial mass production

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Drilling of injection nozzles in series production



Images:
BOSCH

up to 20% less
fuel consumption

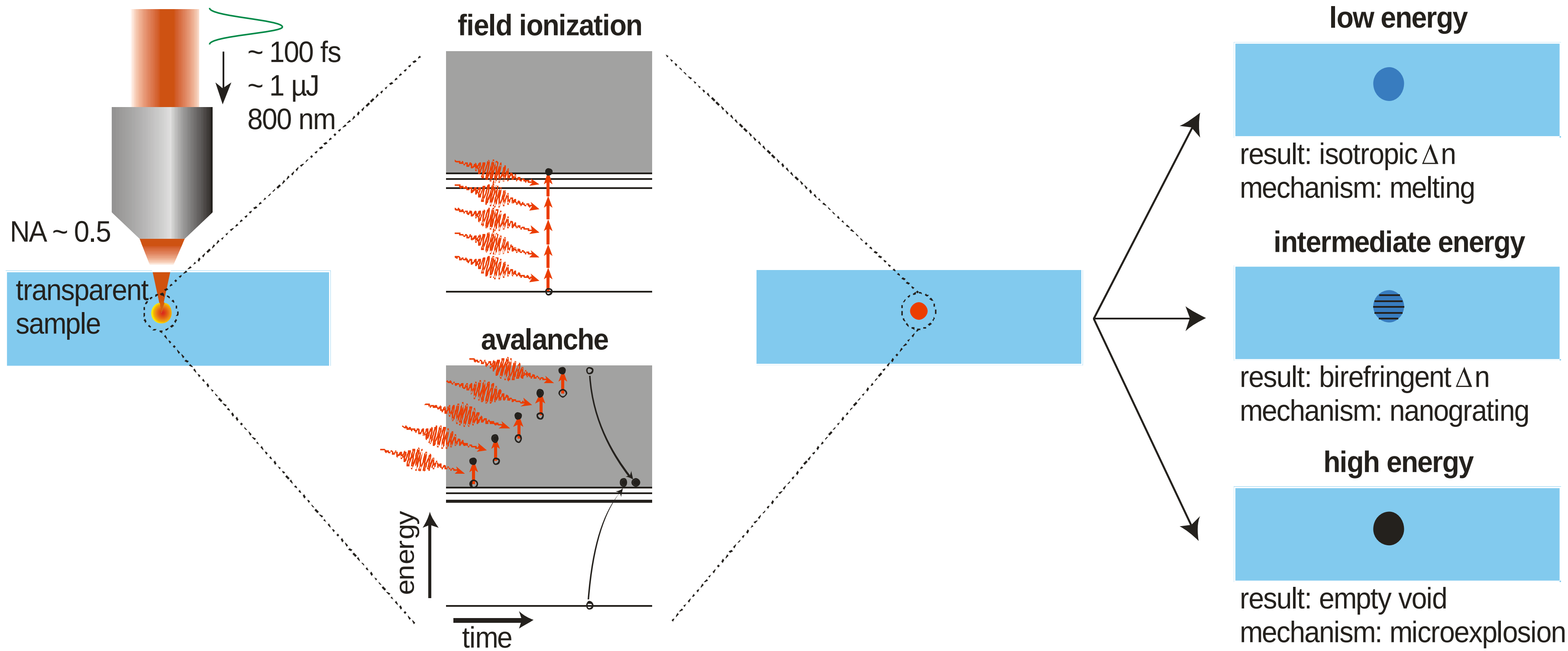
TRUMPF

BOSCH

DEUTSCHER ZUKUNFTSPREIS
Preis des Bundespräsidenten
für Technik und Innovation

Fraunhofer
IOF

fs laser induced structural changes in glasses



high laser intensity in focal volume

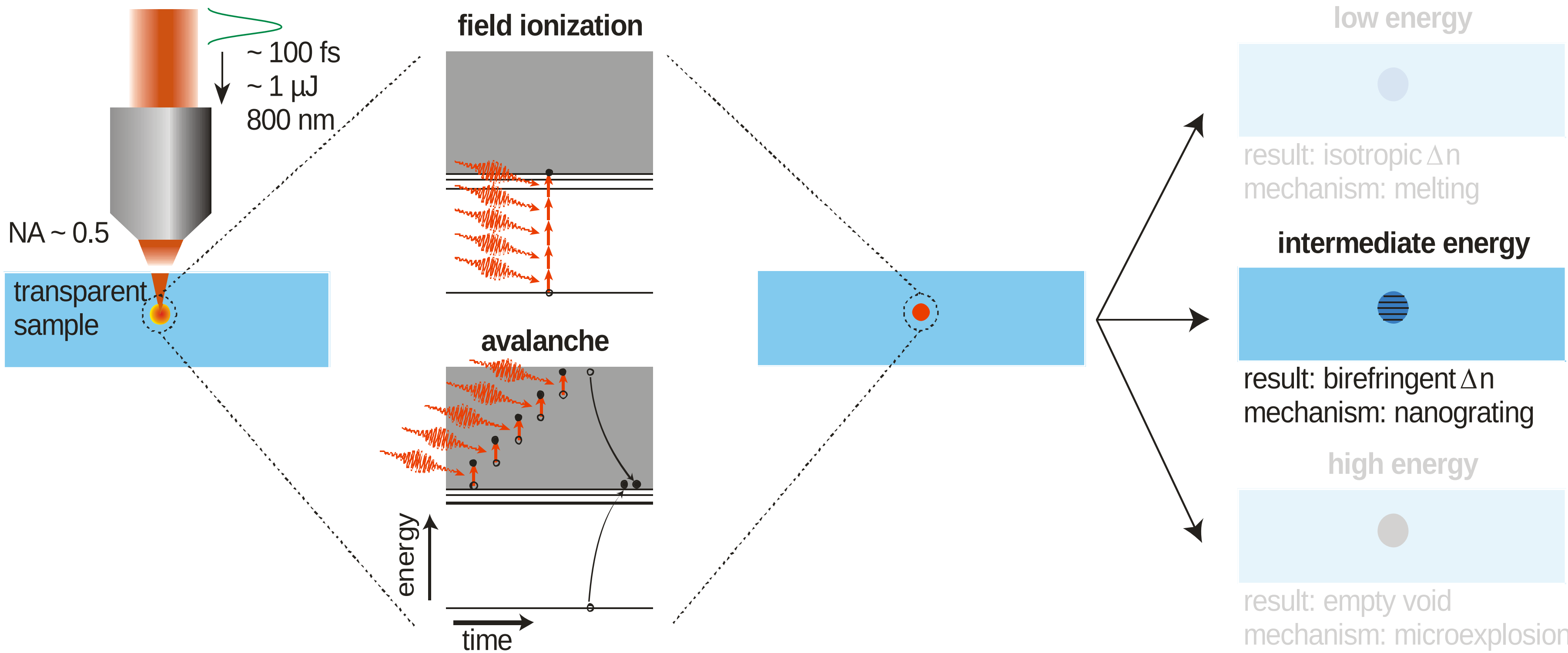
nonlinear absorption of laser energy

hot electron plasma transfers energy to lattice

permanent material change

K. Itoh, W. Watanabe, S. Nolte, C.B. Schaffer, MRS Bulletin **31**, 620, (2006)

fs laser induced structural changes in glasses



high laser intensity in focal volume

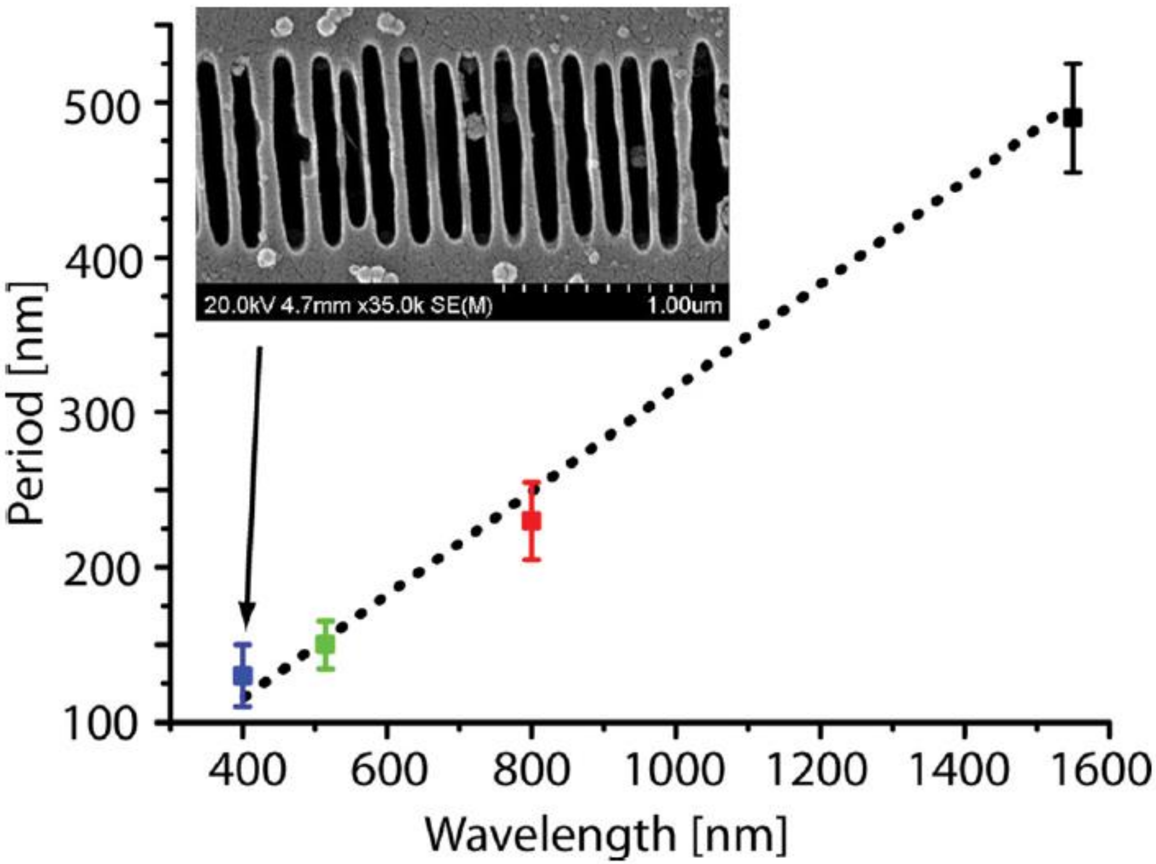
nonlinear absorption of laser energy

hot electron plasma transfers energy to lattice

permanent material change

K. Itoh, W. Watanabe, S. Nolte, C.B. Schaffer, MRS Bulletin **31**, 620 (2006)

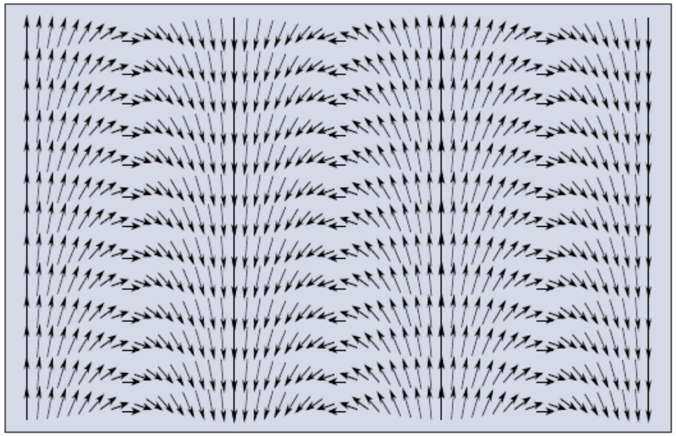
Nanograting period – local artifical birefringence

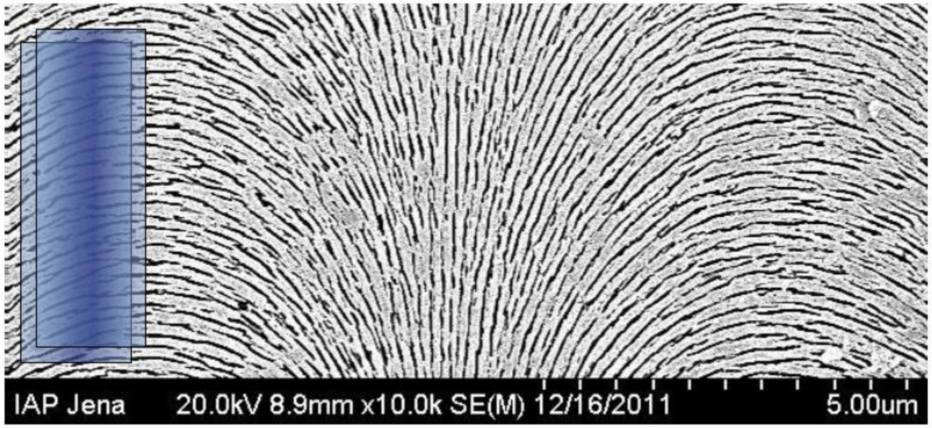


- Nanogratings oriented perpendicular to laser polarization
- Period scales with laser wavelength
- Period determined roughly by $\lambda/2n$

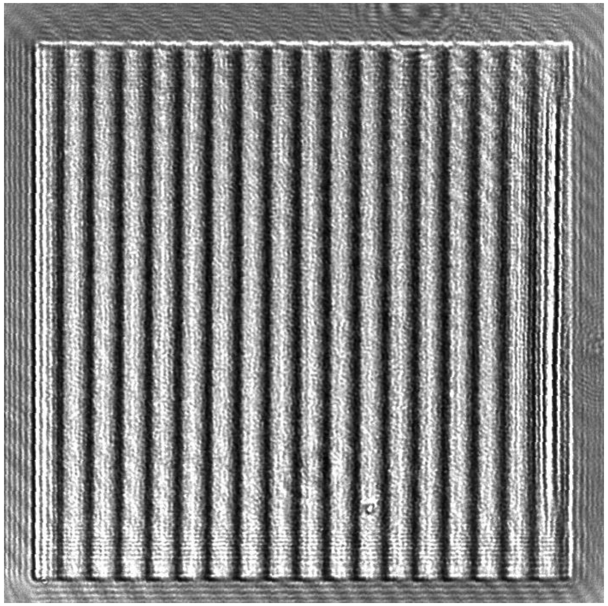
S. Richter et al., J. Laser Appl. 24(4), 4020081 (2012)

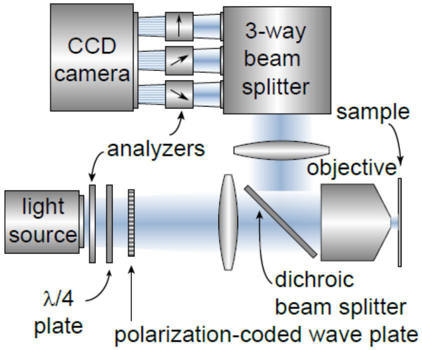
Grid pattern wave plate





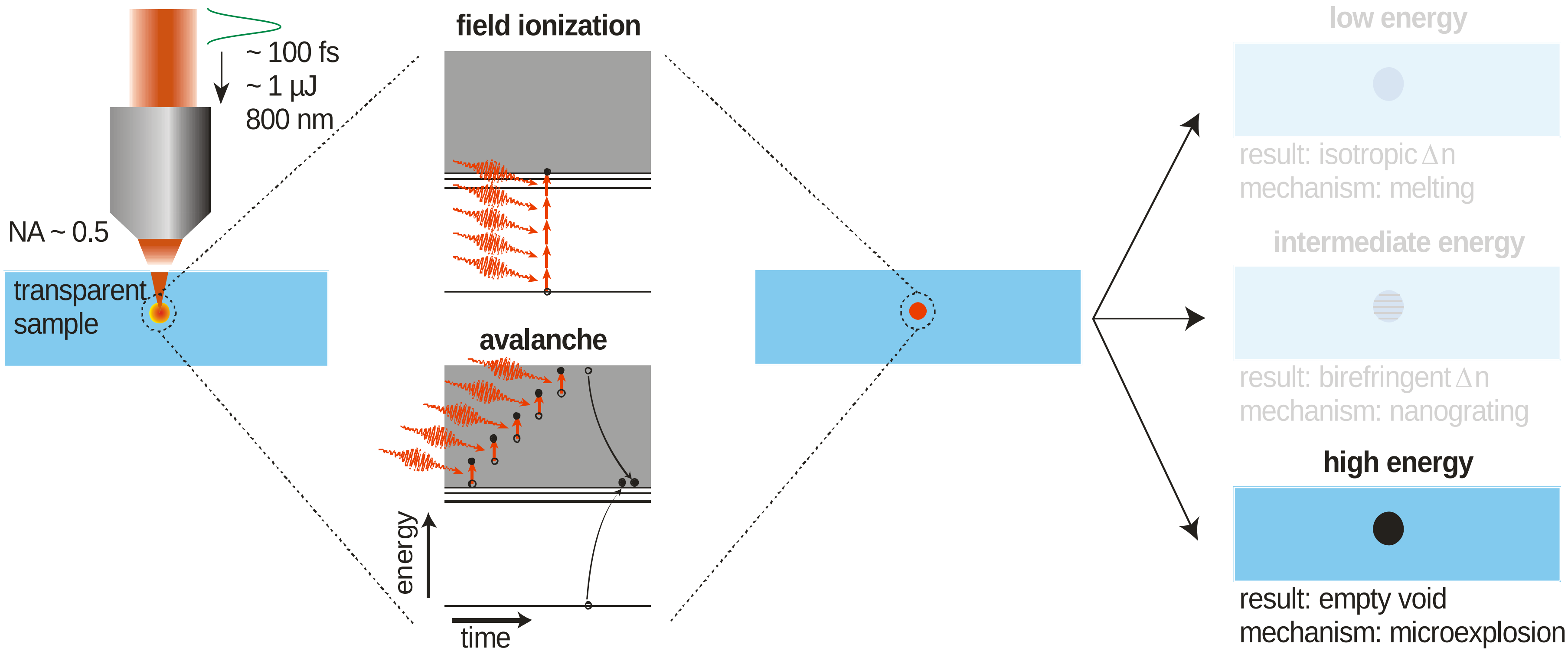
Transmission measurement with rotating polarizer





Application example: structured illumination microscopy

fs laser induced structural changes in glasses



high laser intensity in focal volume

nonlinear absorption of laser energy

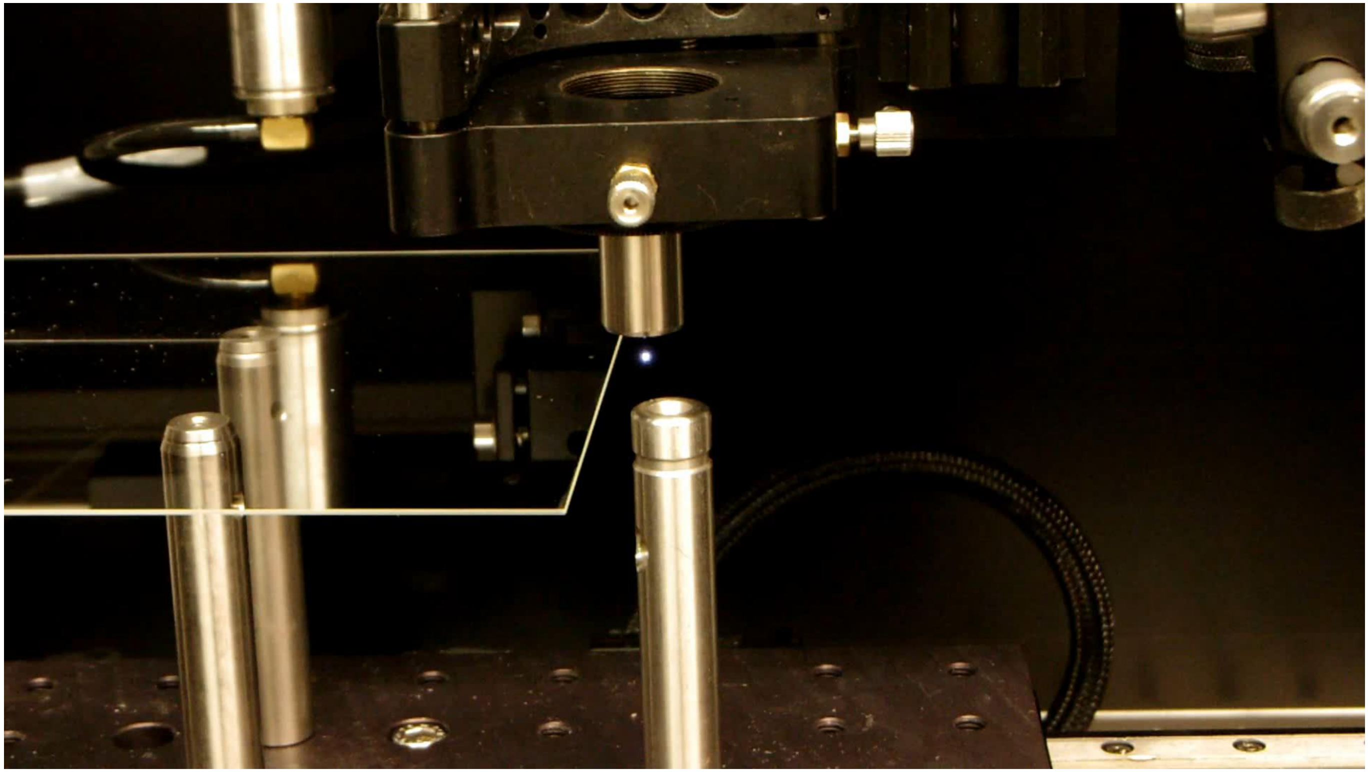
hot electron plasma transfers energy to lattice

permanent material change

K. Itoh, W. Watanabe, S. Nolte, C.B. Schaffer, MRS Bulletin **31**, 620 (2006)

Laser cutting of hardened glass

Institute of Applied Physics
Friedrich-Schiller-Universität Jena



Volume modification as breaking layer

- Process speed
- Wide range of transparent material
- Debris free

Challenging tasks

- Controlled breaking
- Quality (break strength & edge)
- Color centers
- Stress fields and complex contours

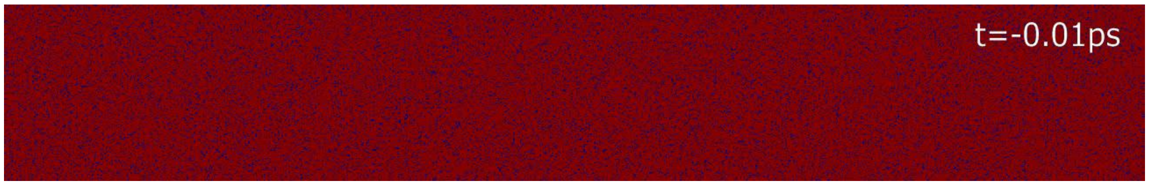
Fraunhofer IOF

Initiation process and development in Corning® Gorilla® Glass, NA 0.35, 200µJ

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Plasma development for pulse duration < 1ps

Beam propagation



1000µm

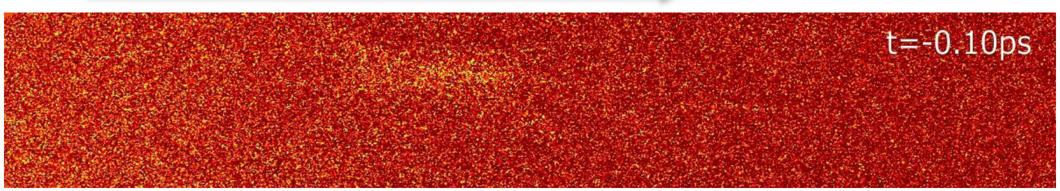
$\tau = 200\text{fs}$

- $P \approx 300 \times P_{cr}$
  'Multi-filament regime'[1]
- Beam breaks up into single filaments[1-3]
- In focus: $n_e \approx 2.0 \times 10^{19}\text{cm}^{-3}$
- Off focus: $n_e < 2.0 \times 10^{18}\text{cm}^{-3}$
- Interaction area ≈ 1mm

[1] A. Couairon, A. Mysyrowicz, Phys. Reports 441, 47– 189 (2007)
[2] S. Mao, et al., Appli Phys. A 79(7), 1695–1709 (2004)
[3] G. Méchain, et al., Phys. Rev. Lett. 93, 035003 (2004)

Plasma development for pulse duration > 5ps

Beam propagation



240µm

$\tau = 12\text{ps}$

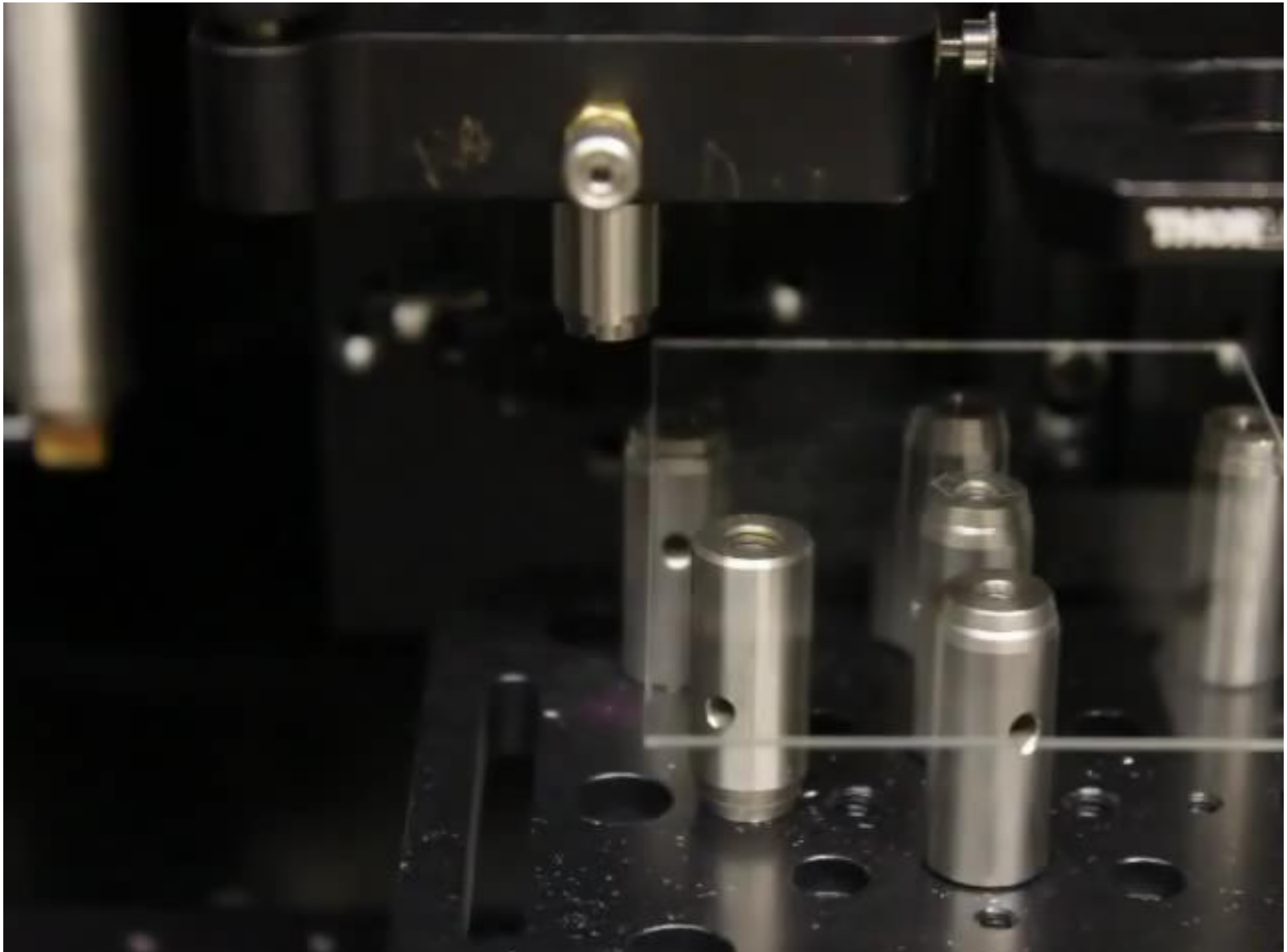
- Plasma ignition in focal area
- 'Moving breakdown'[4-6] towards incoming beam
- In focus: $n_e \approx 1.0 \times 10^{20}\text{cm}^{-3}$
- Off focus: $n_e \approx 5.0 \times 10^{19}\text{cm}^{-3}$
- Interaction area ≈ 250µm

[4] Y. P. Raizer, Soviet Phys. Uspekhi 8(5), 650 (1966)
[5] F. Docchio, et al, Appl. Opt. 27(17), 3661–3668 (1988)
[6] D. X. Hammer, et al., Appl. Opt. 36(22), 5630–5640 (1997)

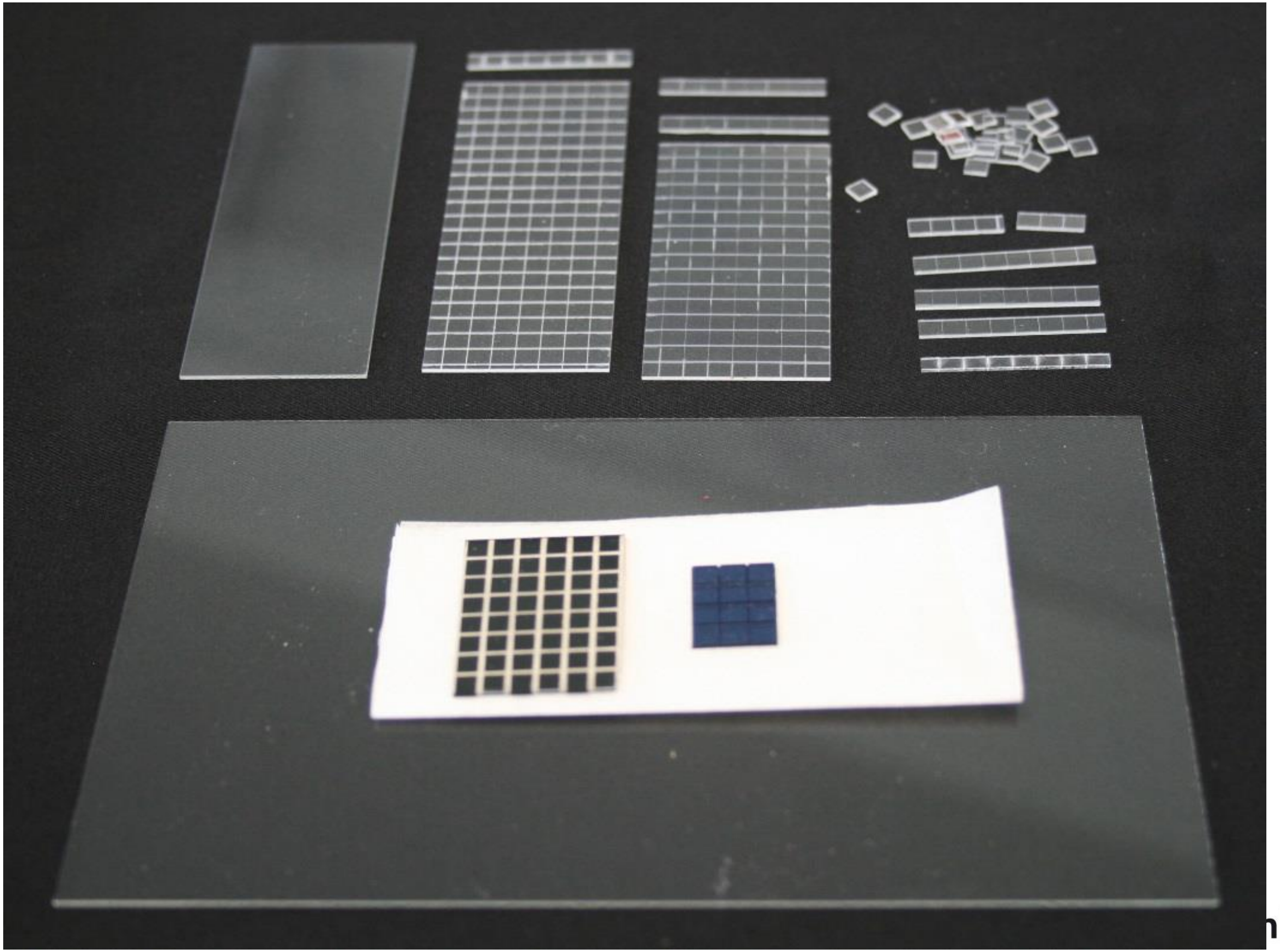
Fraunhofer IOF

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Improved Laser cutting of hardened glass



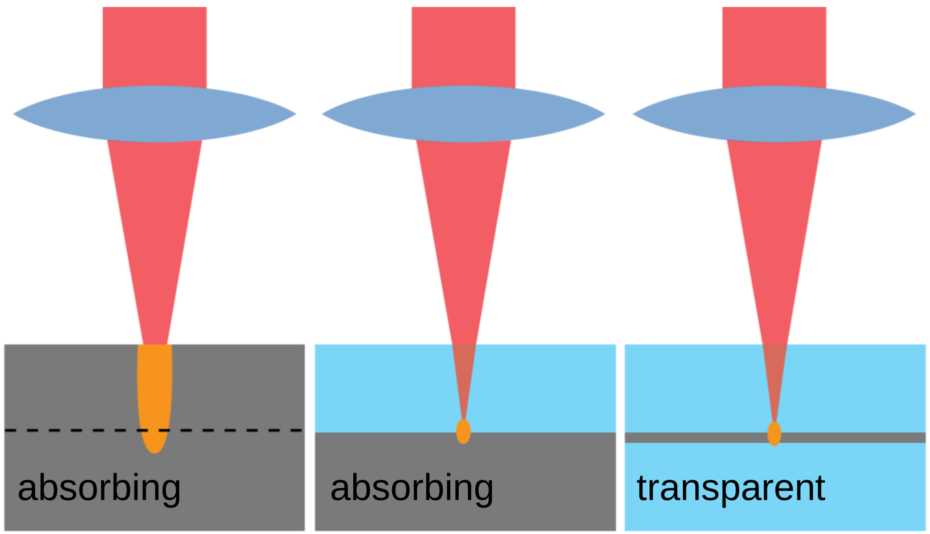
Improved laser cutting of unhardened and functionalized glass



Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Conventional laser bonding

completely or partially absorbing material

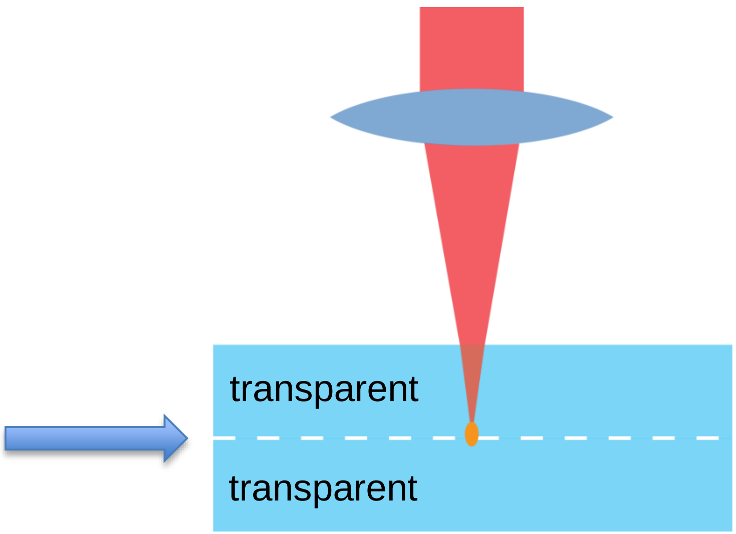


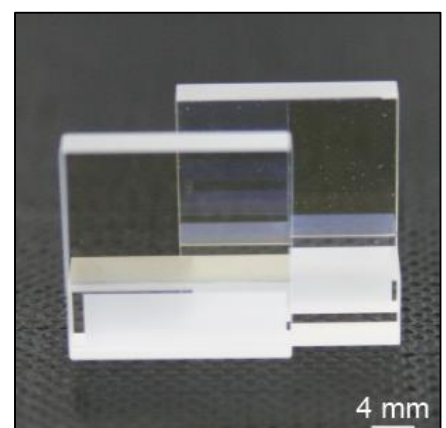
TRUMPF GmbH + Co. KG

LPFK Laser & Electronics AG

Ultrashort pulse laser bonding

without intrinsic absorption

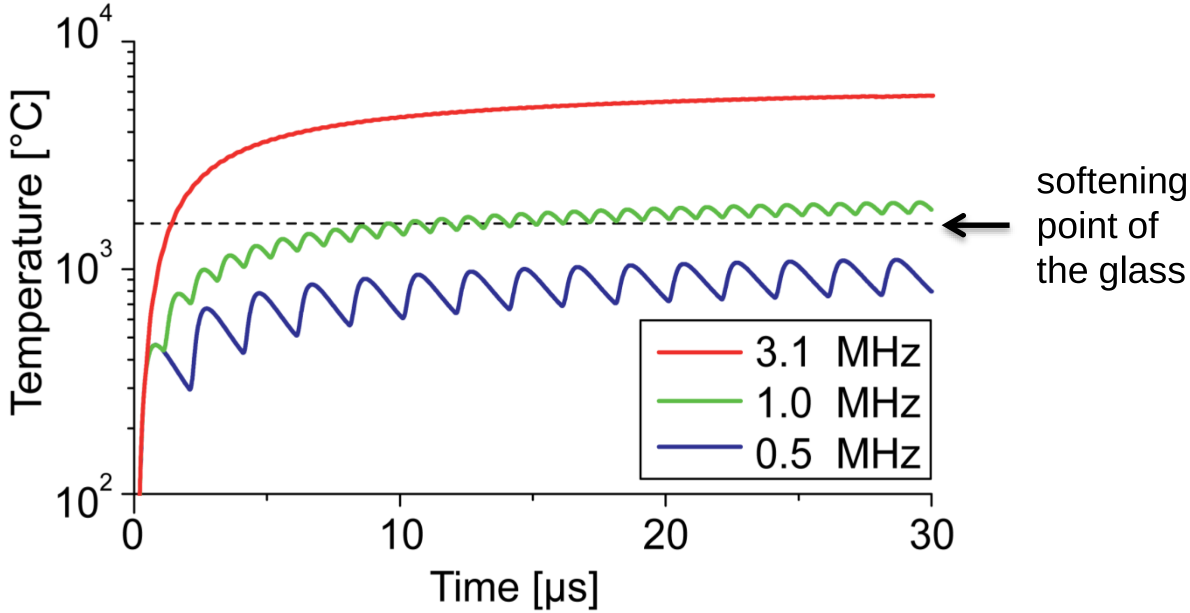




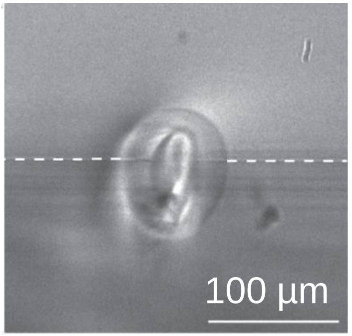
Local melting by heat accumulation

Time interval between pulses < Time for thermal relaxation
ca. 1 µs at MHz pulse repetition rate ≈ 1 µs

Temperature evolution
(simulation at 2 µm distance from laser focus)



Point heat source



local melting
without cracks

C.B. Schaffer et al., OPN **12(4)**, 20 (2001)
S. Eaton et al., Optics Express, 13, 4708 (2005)
S. Richter, S. Döring et al., Proc. of SPIE 8244, 824402 (2011)

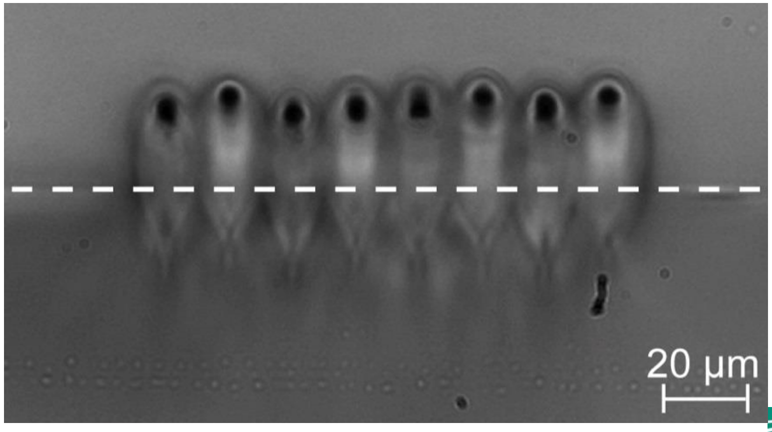
Laser Bonding Procedure

(1) Optical Contacting

(2) Adjustment of laser focus

(3) Laser bonding process

- typical weld seam:



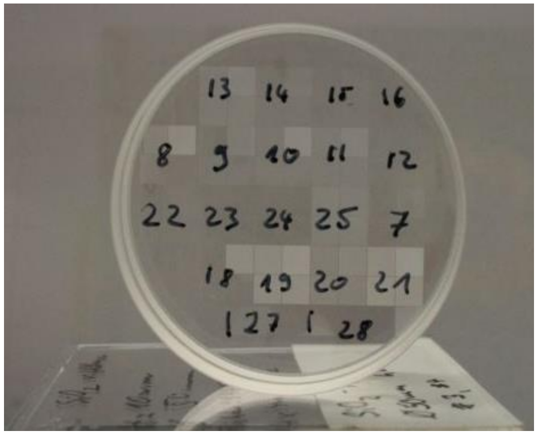
sample interface

S. Richter, S. Döring et al., Appl. Phys. A 103, 257–261 (2011)

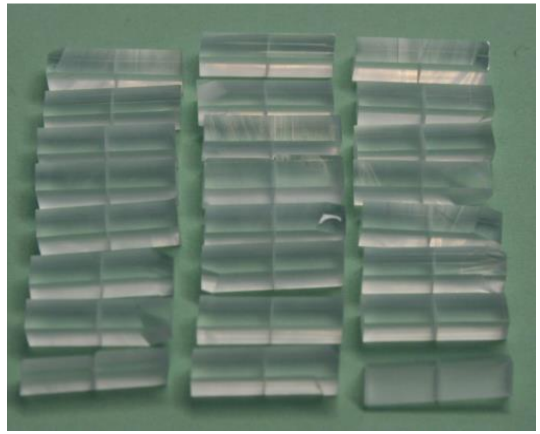
Characterization of the Bond Quality

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

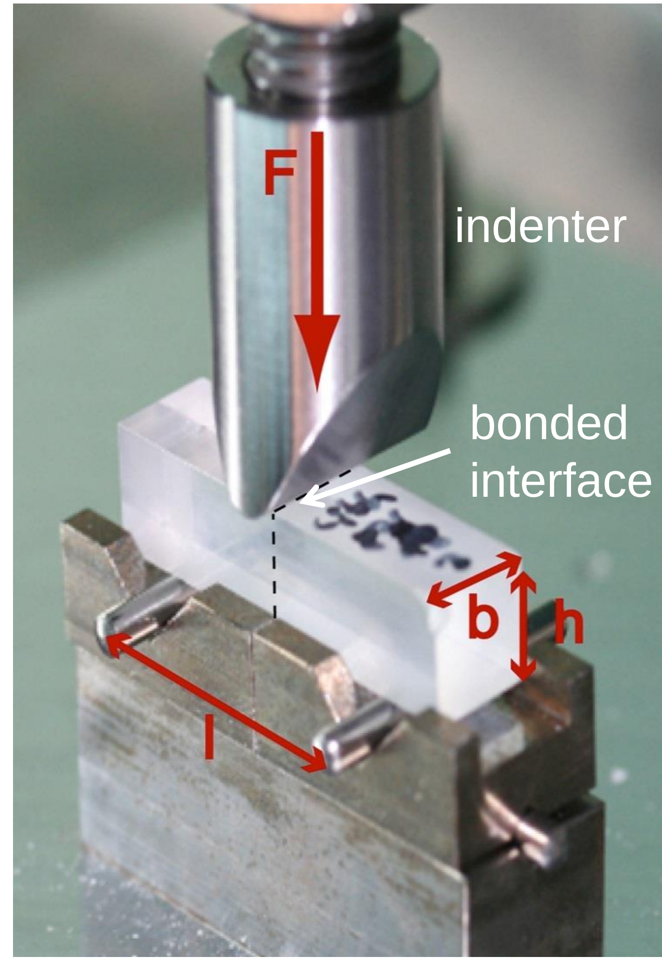
Laser Bonding (parameter study)



Preparation of rectangular rods



3-Point-Bending-Test



➔ Measurement of the breaking strength σ

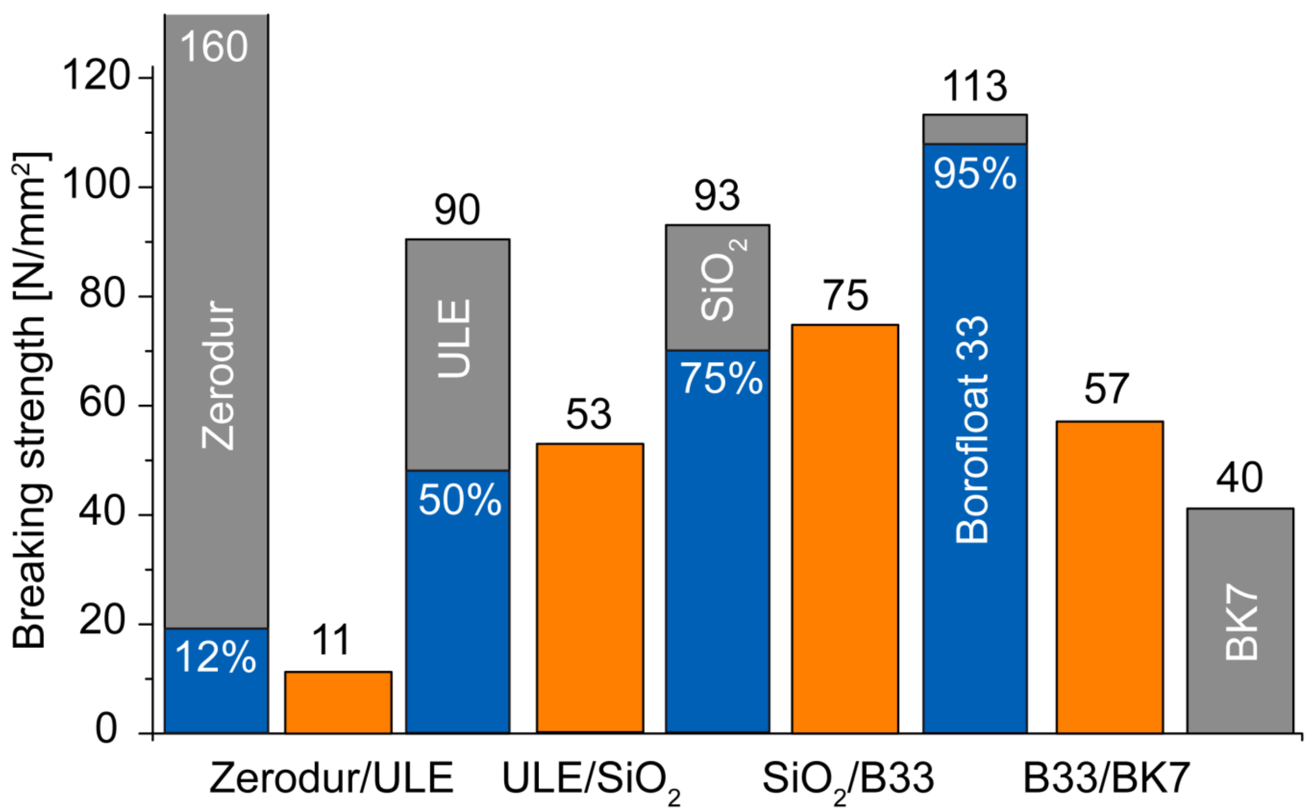
$$s = \frac{3F_{max} l}{2bh^2}$$

S. Richter, S. Döring et al., Appl. Phys. A 103, 257–261, 2011

Bonding of Different Glass Types

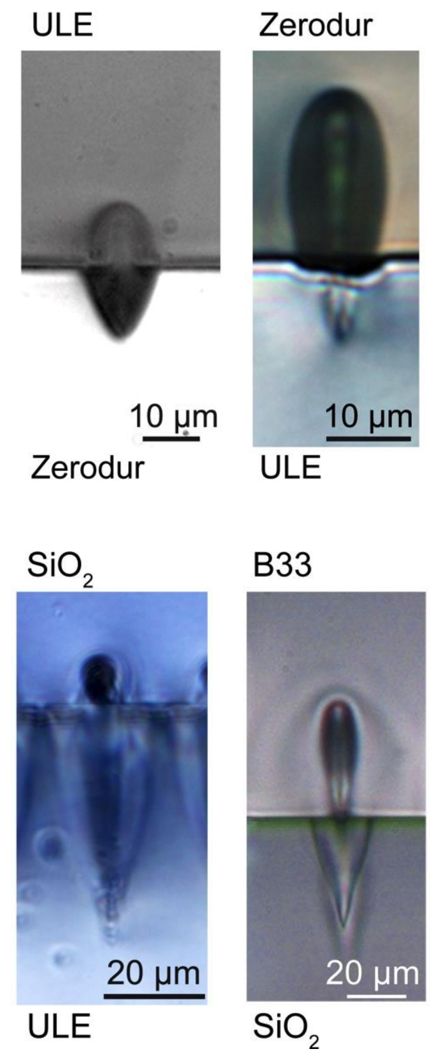
Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Breaking strength with continuous pulse train



	Zerodur	ULE	SiO_2	B33	BK7
α [10^{-6} K^{-1}]	< 0.1	< 0.001	0.5	3.25	7.1

- bonding with different coefficient of thermal expansion



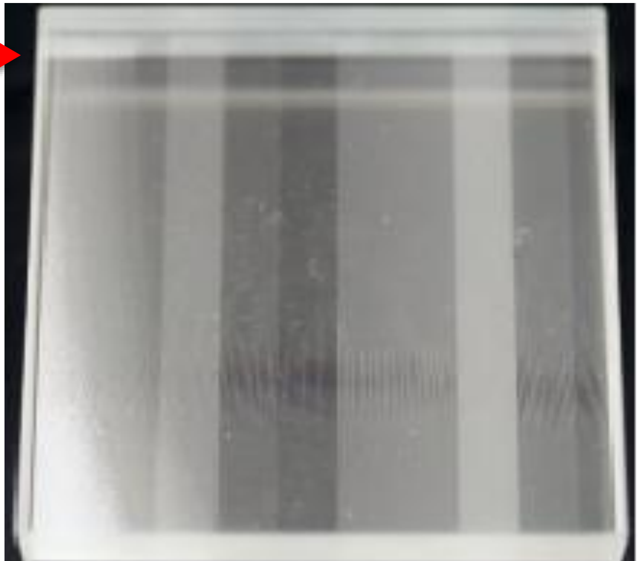
S. Richter, S. Döring et al., Appl. Phys. A 110, 9–15 (2013)

Fraunhofer IOF

Welding without optical contacting

thick samples
„just put together“
→ no pressure
→ no contact

Laser welding
8 W average power

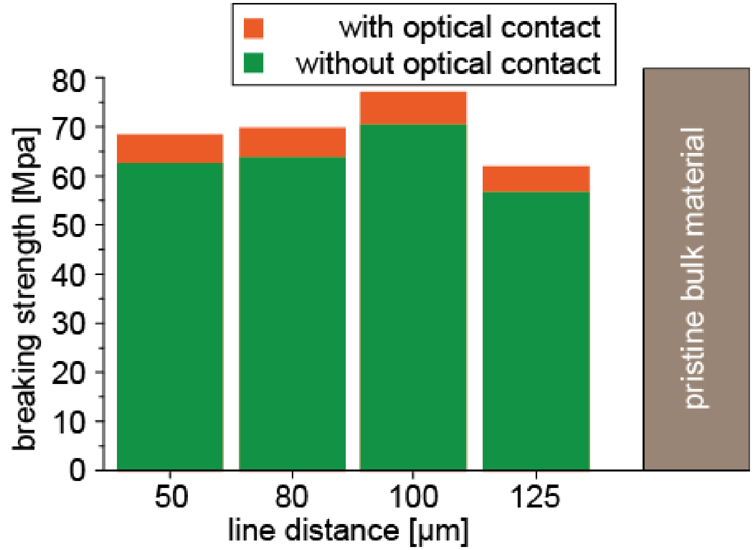


translation velocity: 10 mm/s

Welding results:

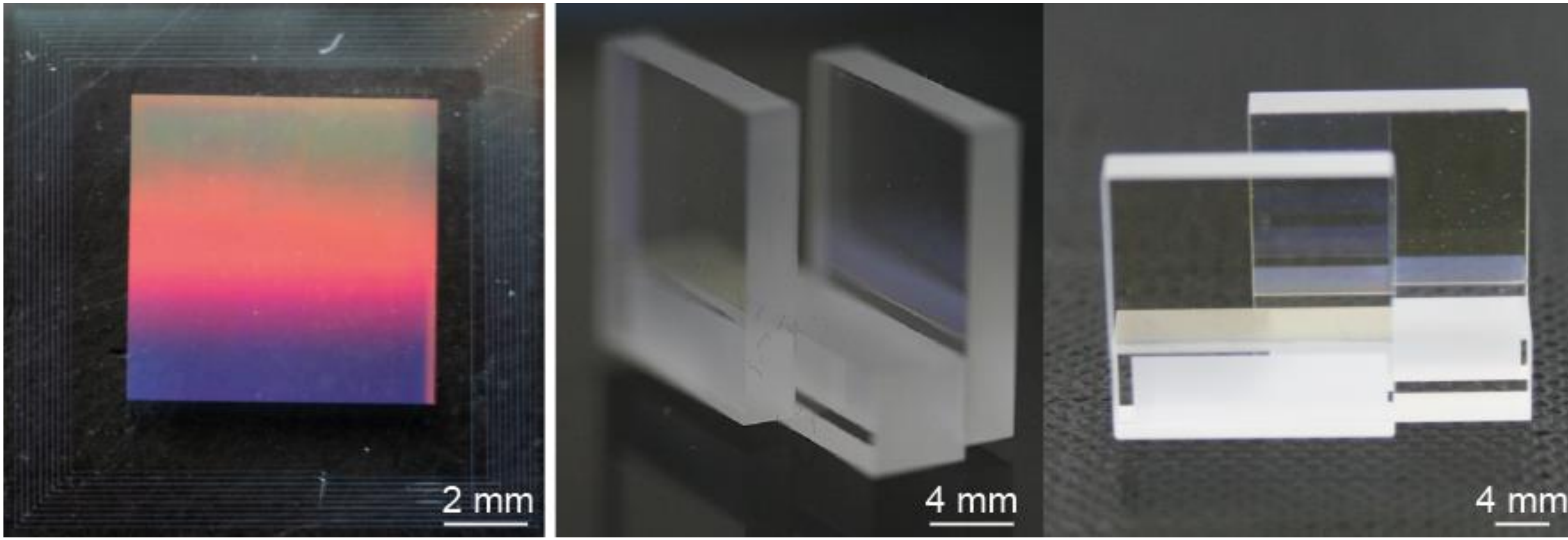
Three point bending test

→ **85% of pristine bulk material** without optical contacting



S. Richter et al., Appl. Phys A 121(1), 1-9 (2015)

Application Potential



- encapsulation of optical components
- special bond-geometries without influence on functional areas
- stable joining of optical components without interface layer
- realization of gas-proof bonding

Many thanks to all colleagues, partners and for financial support

Bundesministerium für Bildung und Forschung

ZENTREN FÜR INNOVATIONSKOMPETENZ
UNTERNEHMEN REGION
Die BMBF-Innovationsinitiative Neue Länder

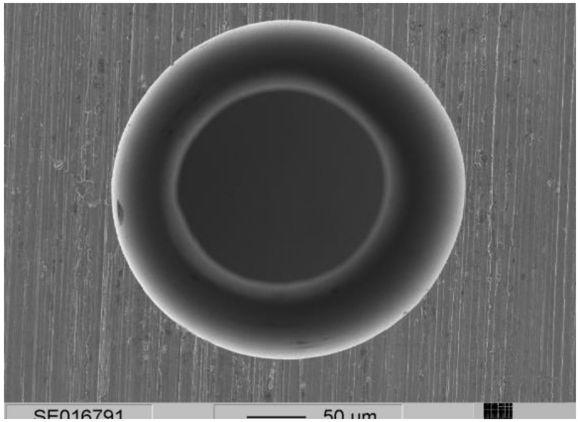
Thüringer Ministerium für Bildung, Wissenschaft und Kultur

EFRE
EUROPA FÜR THÜRINGEN
EUROPÄISCHER FONDS FÜR REGIONALE ENTWICKLUNG

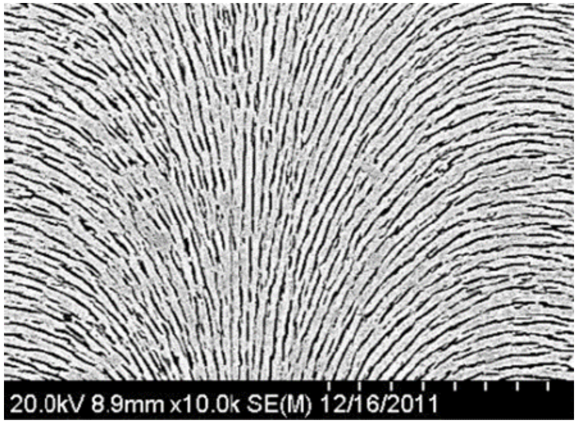
DFG

Ultrashort pulse laser processing

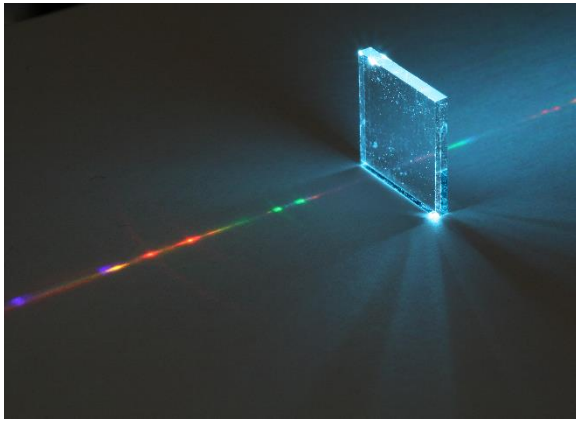
micromachining



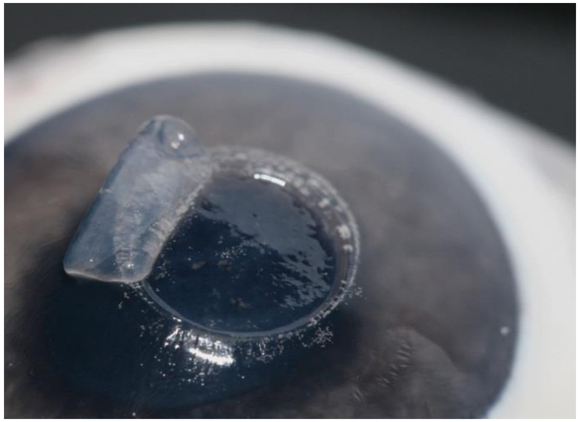
nanogratings - artificial birefringence



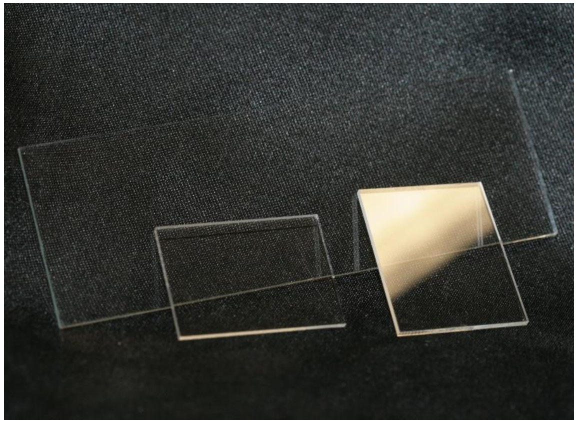
fiber / volume Bragg gratings



medicine



cutting



ultrashort pulse laser welding