Optical waveguide fabrication for integrated photonic devices

Optical and Electronic Device Technology for Access Network:
Nanophotonics and functional device technology
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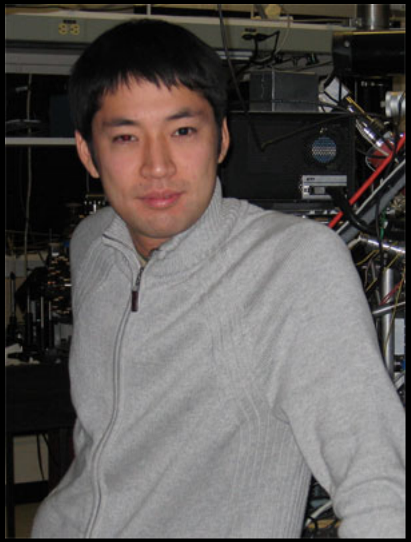
Rafael Gattass


Loren Cerami


Masanao Kamata


Eric Mazur

and also....

Iva Maxwell
Eli Glezer
Chris Schaffer
Nozomi Nishimura
Jonathan Ashcom
Jeremy Hwang
Dr. André Brodeur
Dr. Limin Tong
Dr. Prissana Thamboon

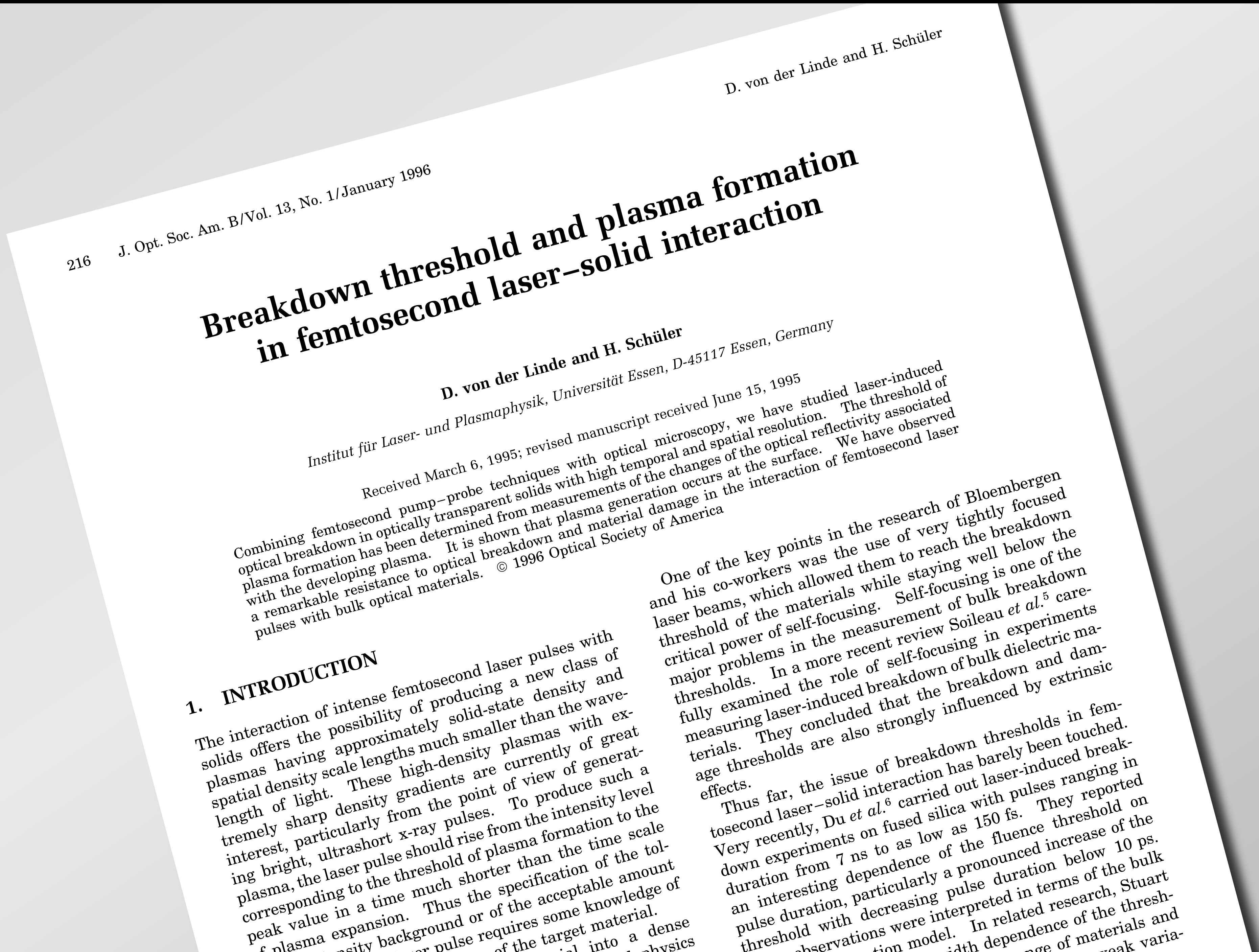
Prof. Denise Krol (UC Davis)
Dr. Yossi Chay (Sagitta, Inc.)
Dr. S.K. Sundaram (PNNL)

My message

fs micromachining: great technique for “wiring light”

Introduction

Introduction



Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schüler

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Combining femtosecond pump–probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond laser pulses with bulk optical materials.

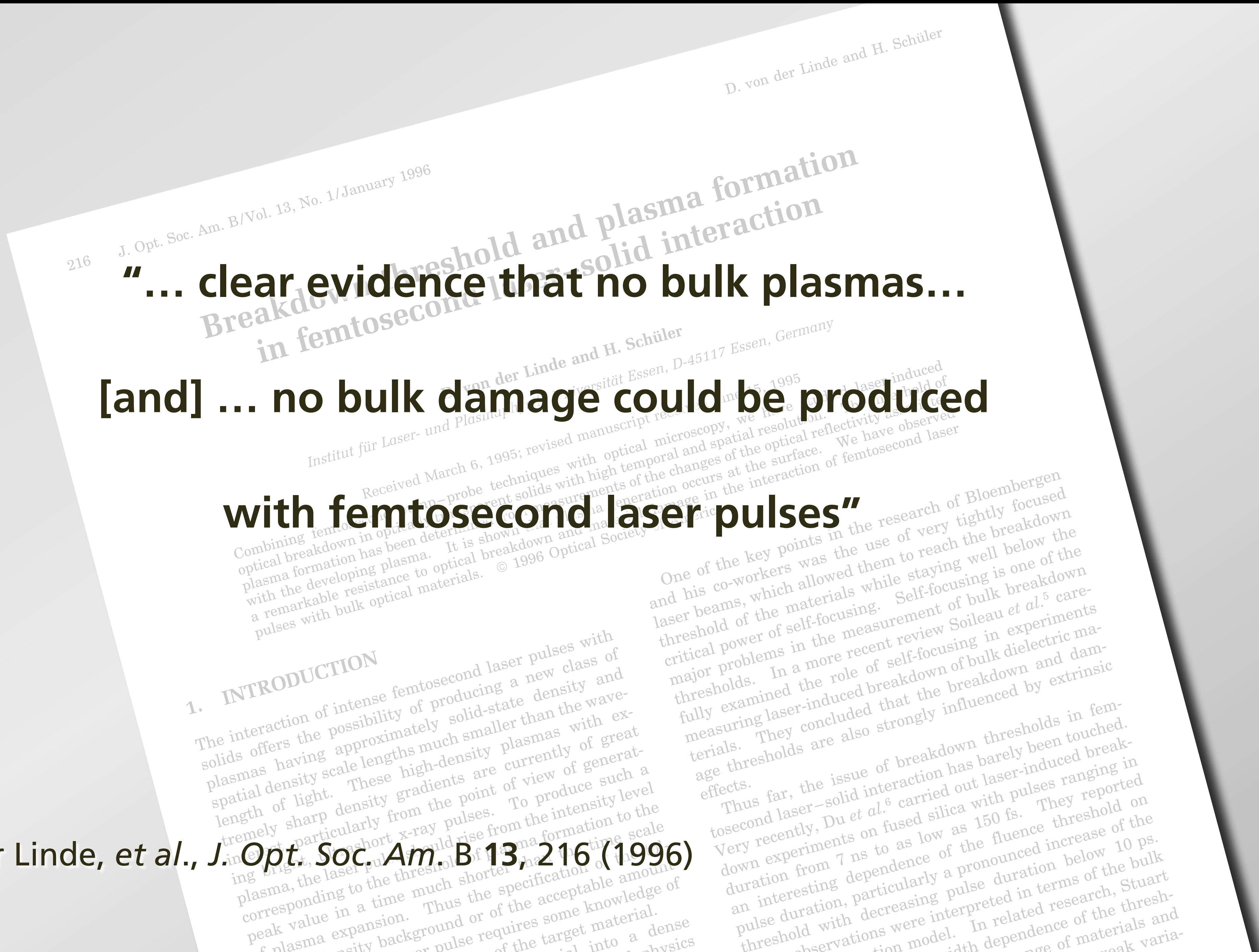
1. INTRODUCTION

The interaction of intense femtosecond laser pulses with solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great interest, particularly from the point of view of generating bright, ultrashort x-ray pulses. To produce such a plasma, the laser pulse should rise from the intensity level corresponding to the threshold of plasma formation to the peak value in a time much shorter than the time scale of plasma expansion. Thus the specification of the tolerable intensity background or of the acceptable amount of prepulse energy requires some knowledge of the threshold of the target material.

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau *et al.*[5] carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic effects.

Thus far, the issue of breakdown thresholds in femtosecond laser–solid interaction has barely been touched. Very recently, Du *et al.*[6] carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration from 7 ns to as low as 150 fs. They reported an interesting dependence of the fluence threshold on pulse duration, particularly a pronounced increase of the threshold with decreasing pulse duration below 10 ps. ... observations were interpreted in terms of the bulk ... model. In related research, Stuart ... width dependence of the thresh... of materials and ...

Introduction



"… clear evidence that no bulk plasmas…

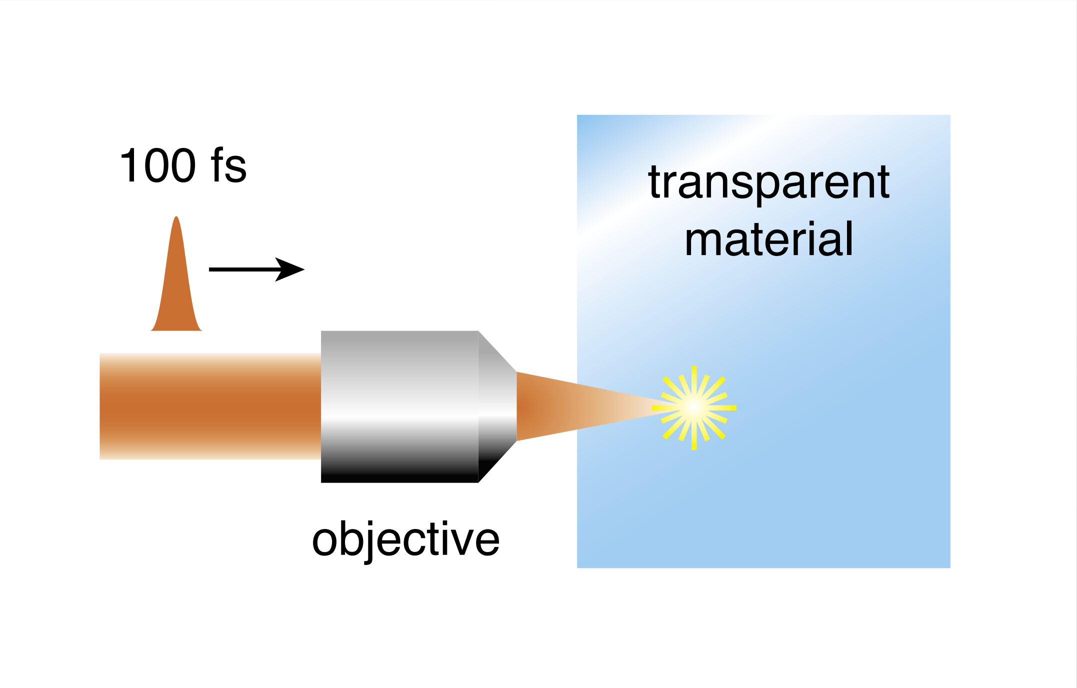
[and] … no bulk damage could be produced

with femtosecond laser pulses"

von der Linde, *et al*., *J. Opt. Soc. Am*. B **13**, 216 (1996)

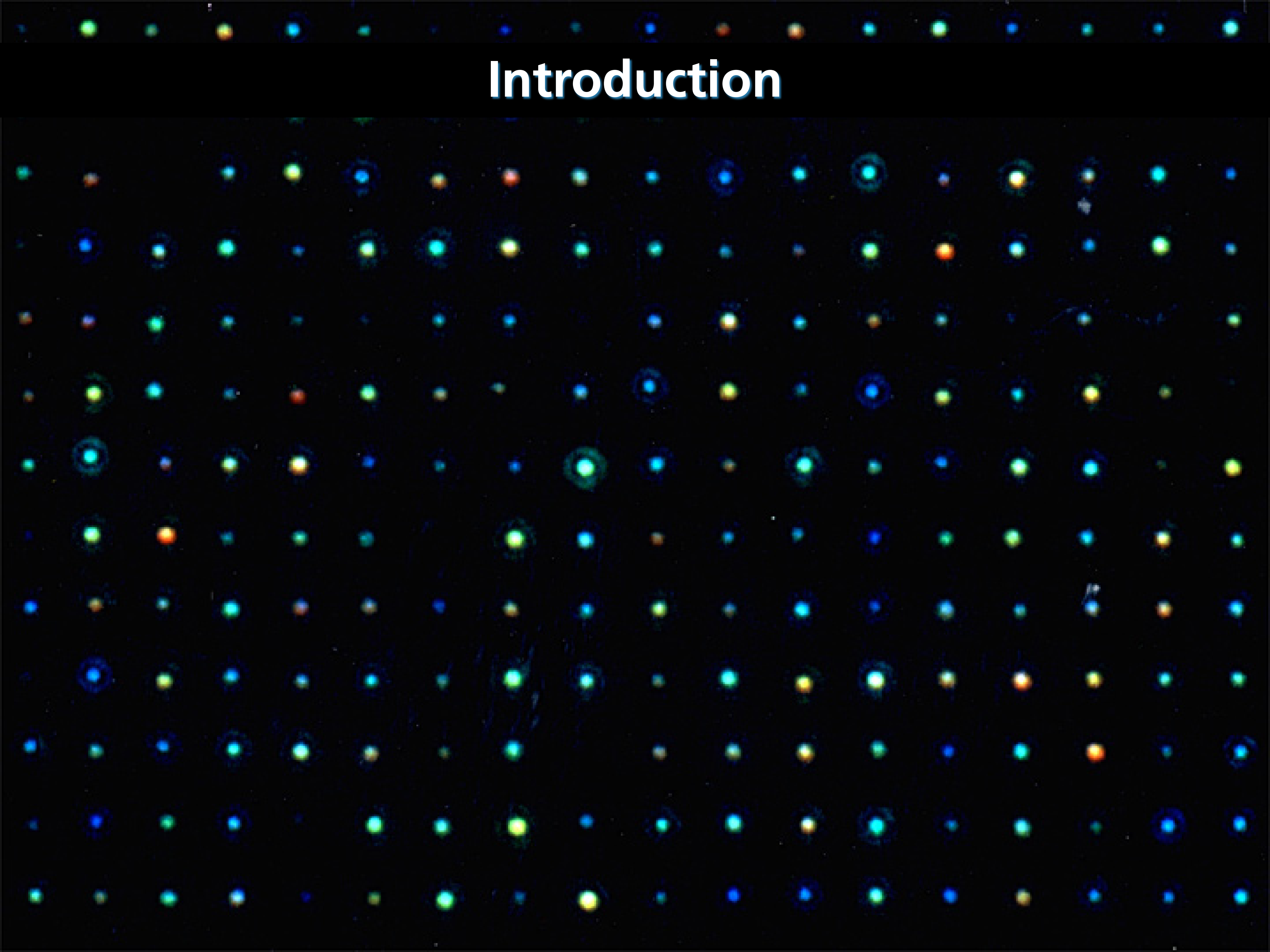
Introduction

focus laser beam inside material



Opt. Lett. **21**, 2023 (1996)

Introduction

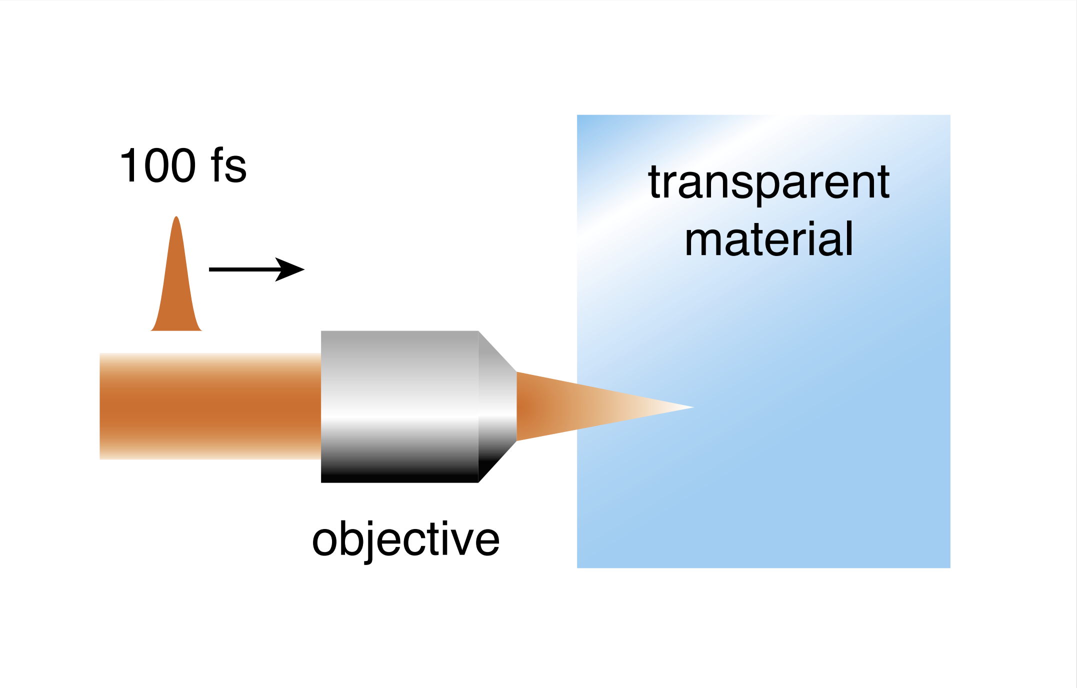


Outline

- femtosecond micromachining
- low-energy machining
- photonic applications

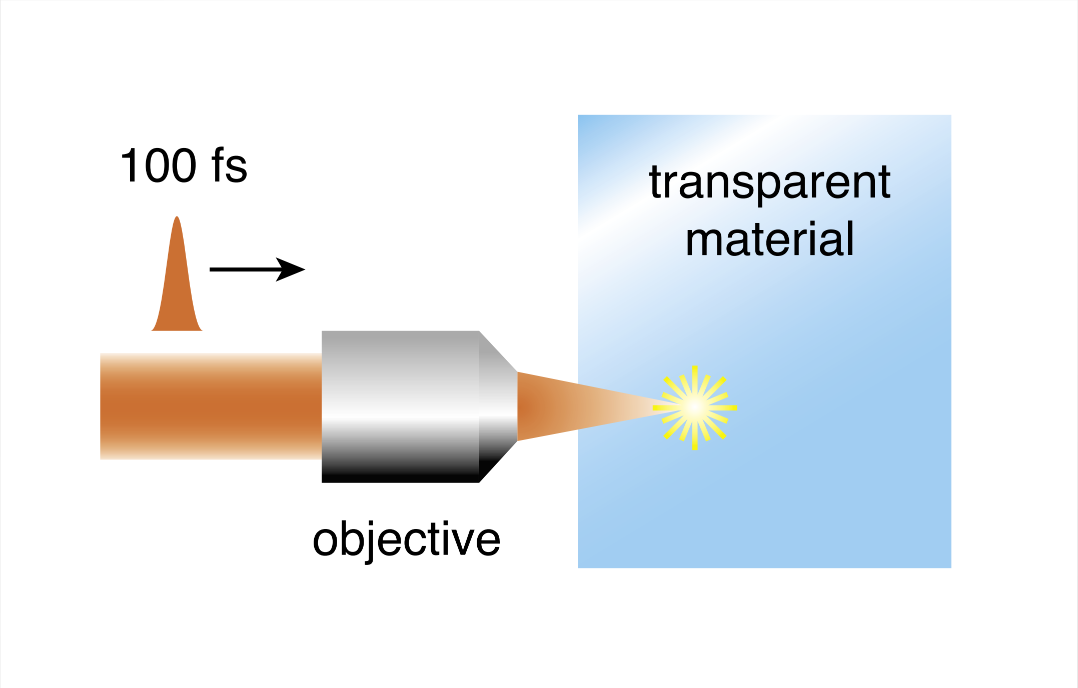
Femtosecond micromachining

high intensity at focus…



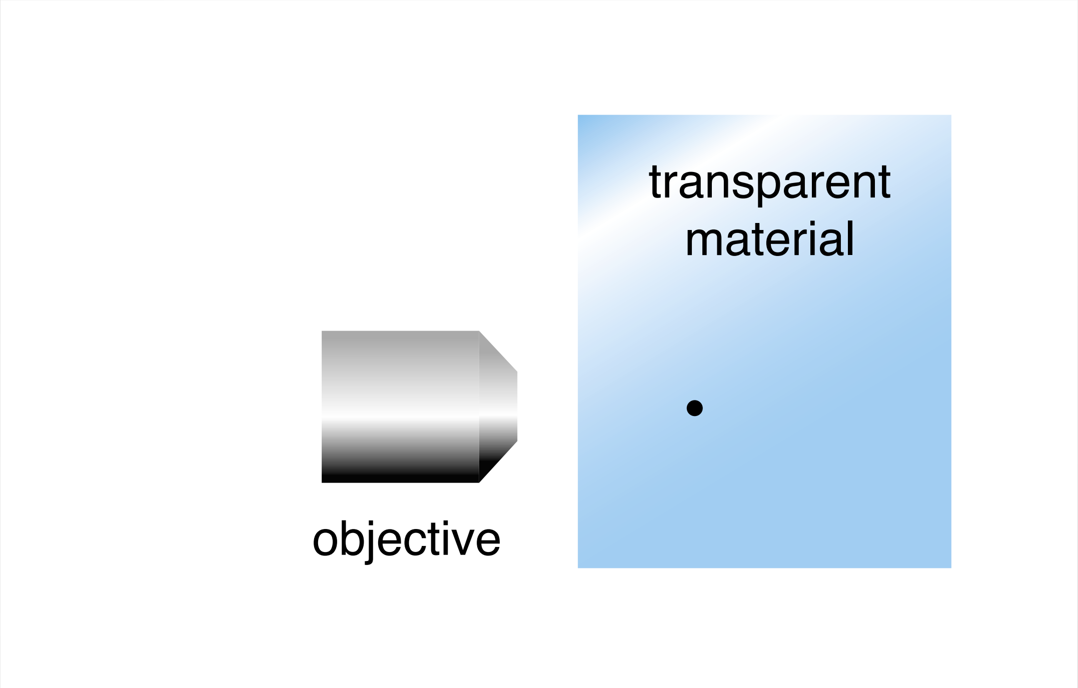
Femtosecond micromachining

…causes nonlinear ionization…



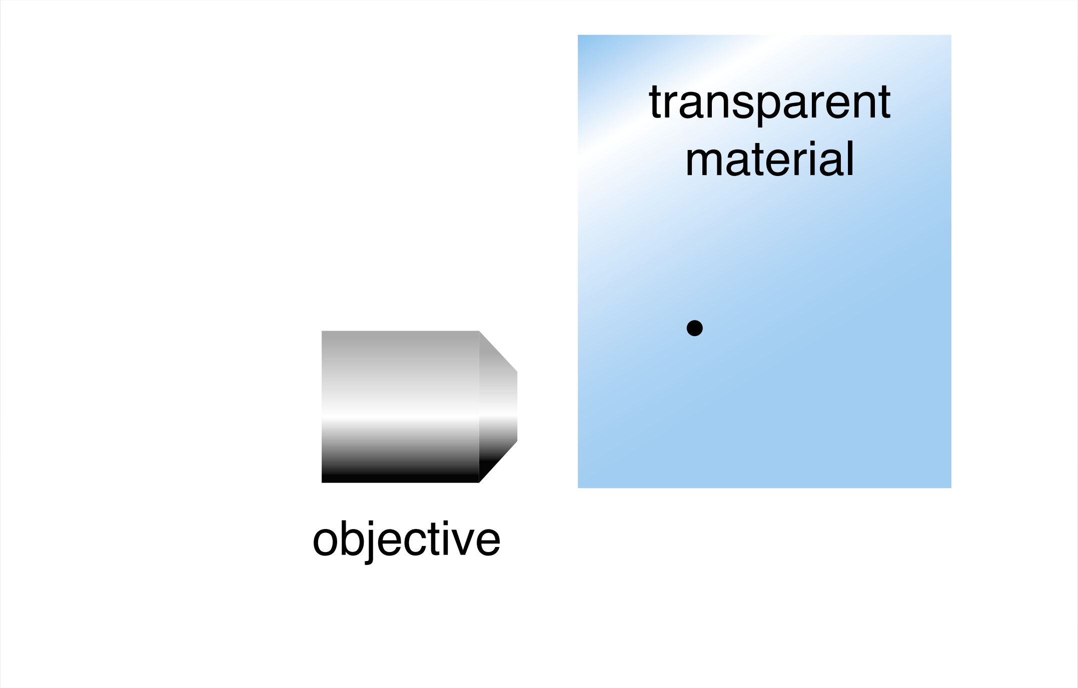
Femtosecond micromachining

and ‘microexplosion’ causes microscopic damage…



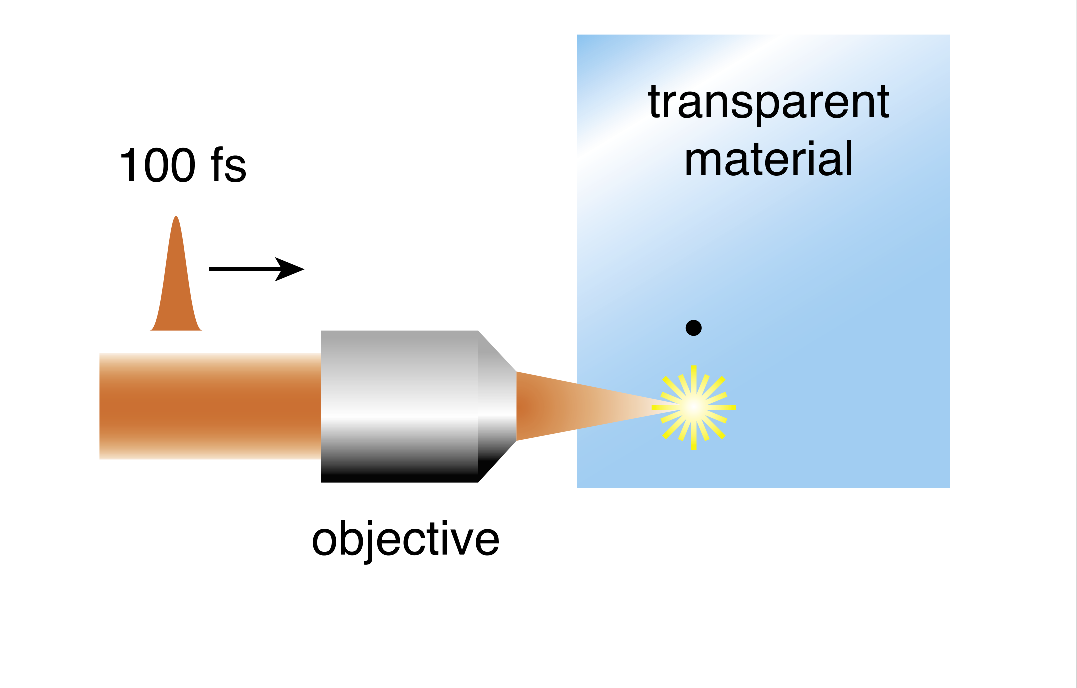
Femtosecond micromachining

translate sample



Femtosecond micromachining

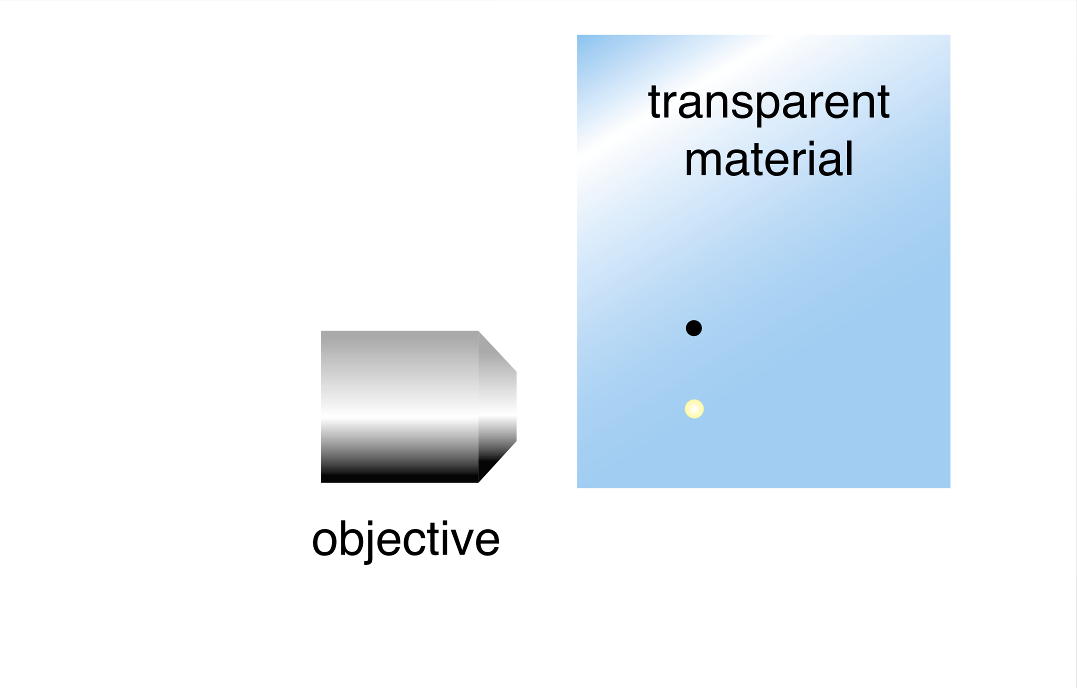
time scales



100 fs: laser energy transferred to electrons

Femtosecond micromachining

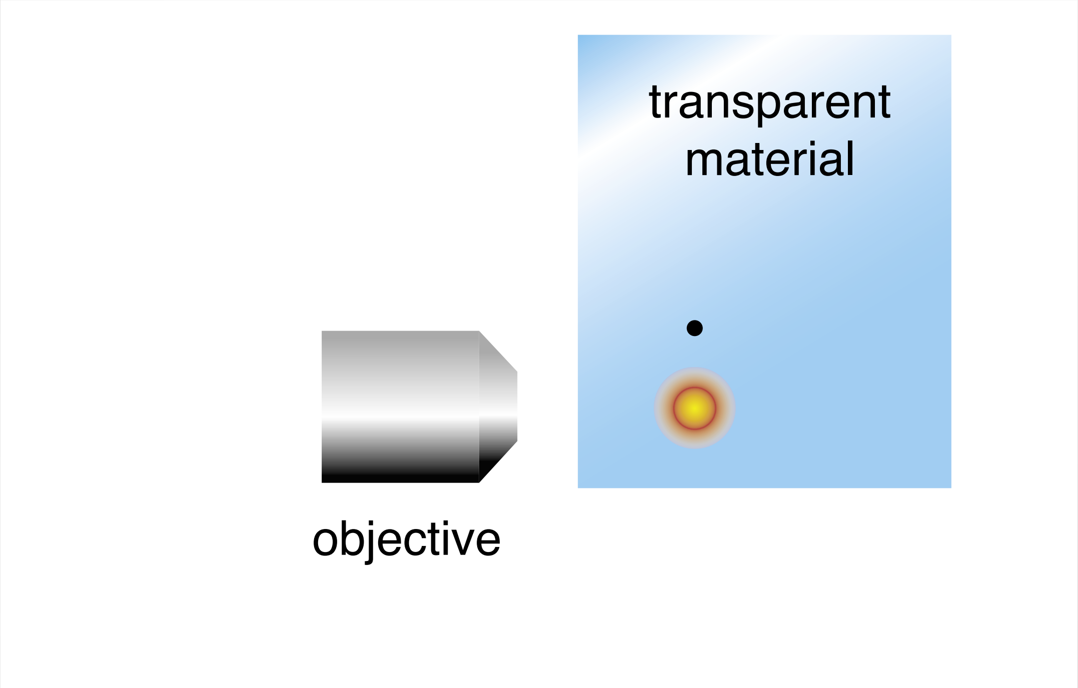
time scales



10 ps: energy transfer to ions

Femtosecond micromachining

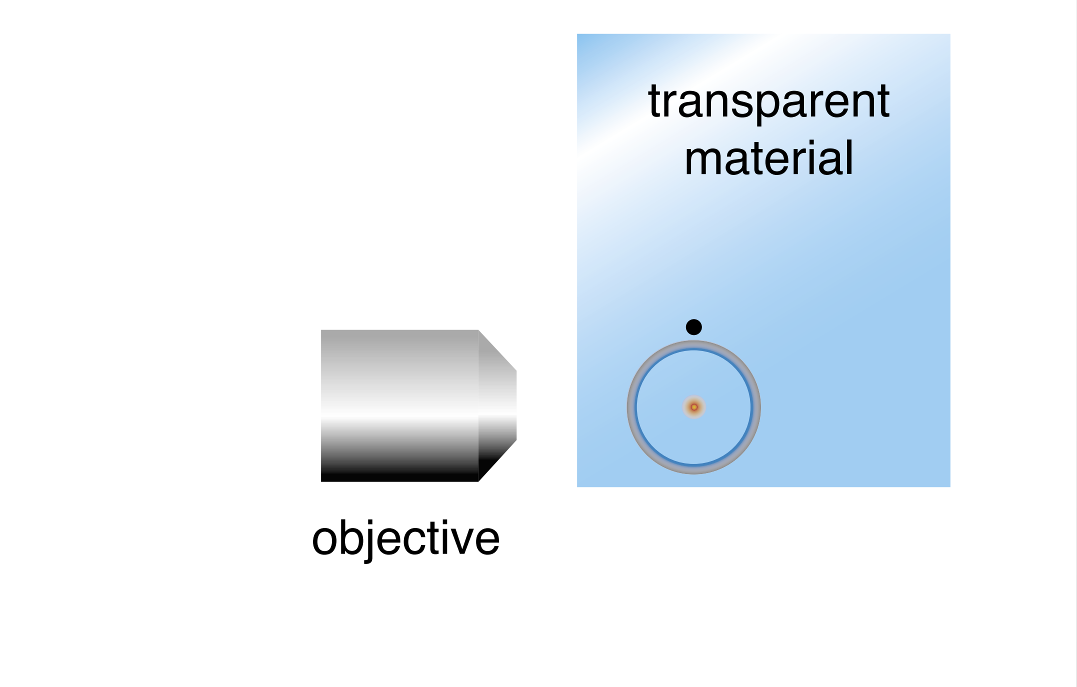
time scales



100 ps: plasma expansion

Femtosecond micromachining

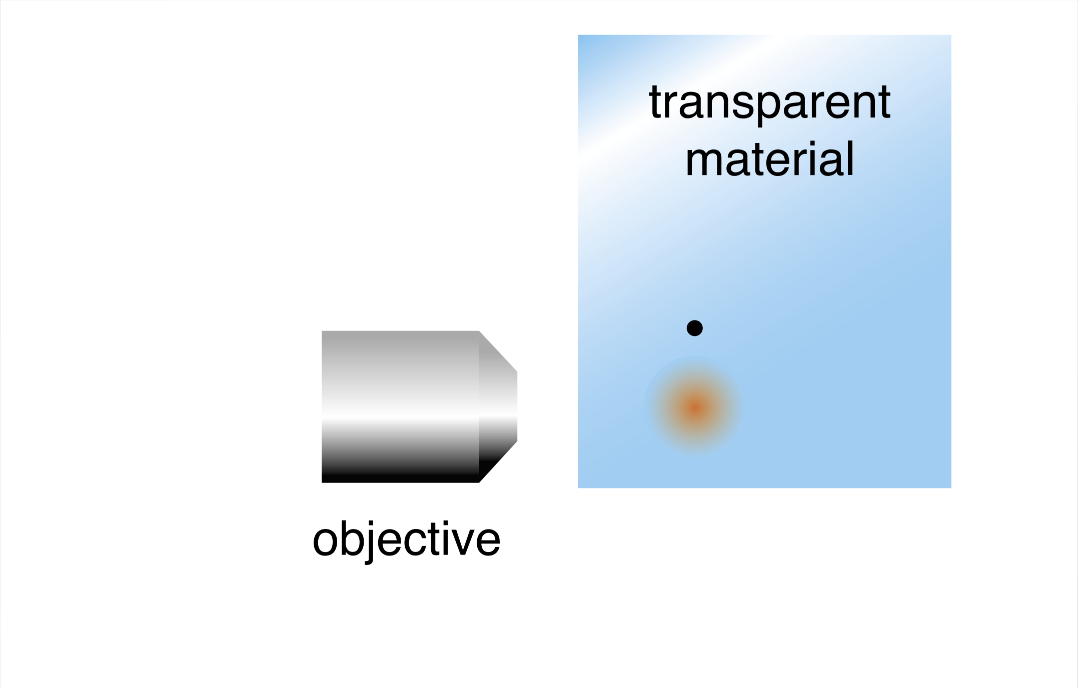
time scales



10–100 ns: shock propagation

Femtosecond micromachining

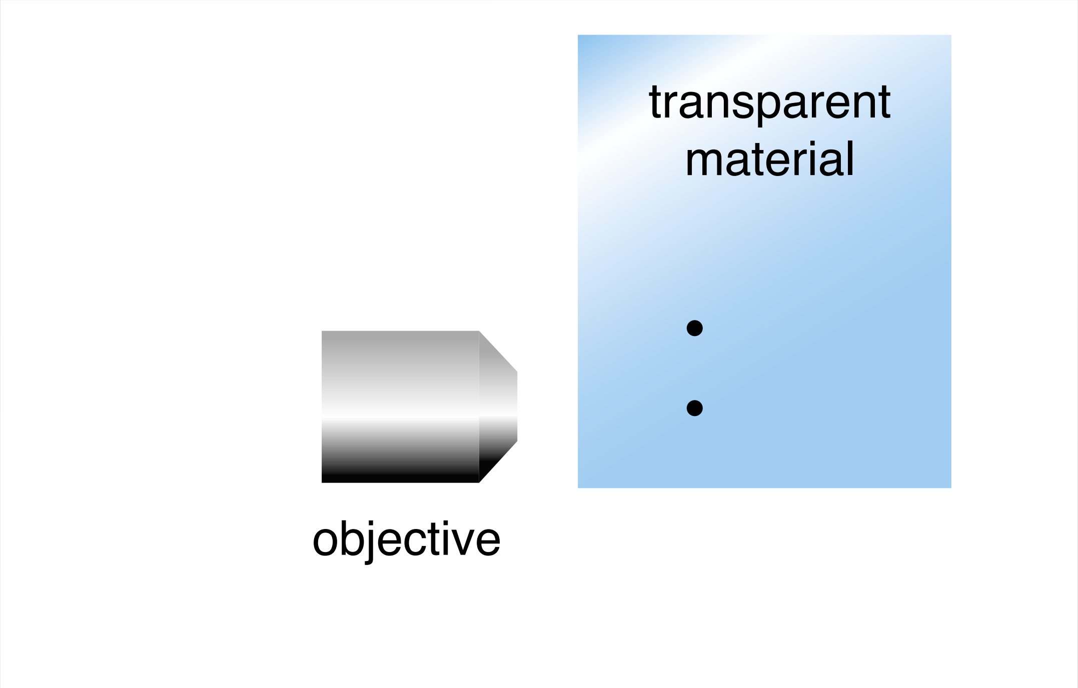
time scales



1 μs: thermal expansion

Femtosecond micromachining

time scales

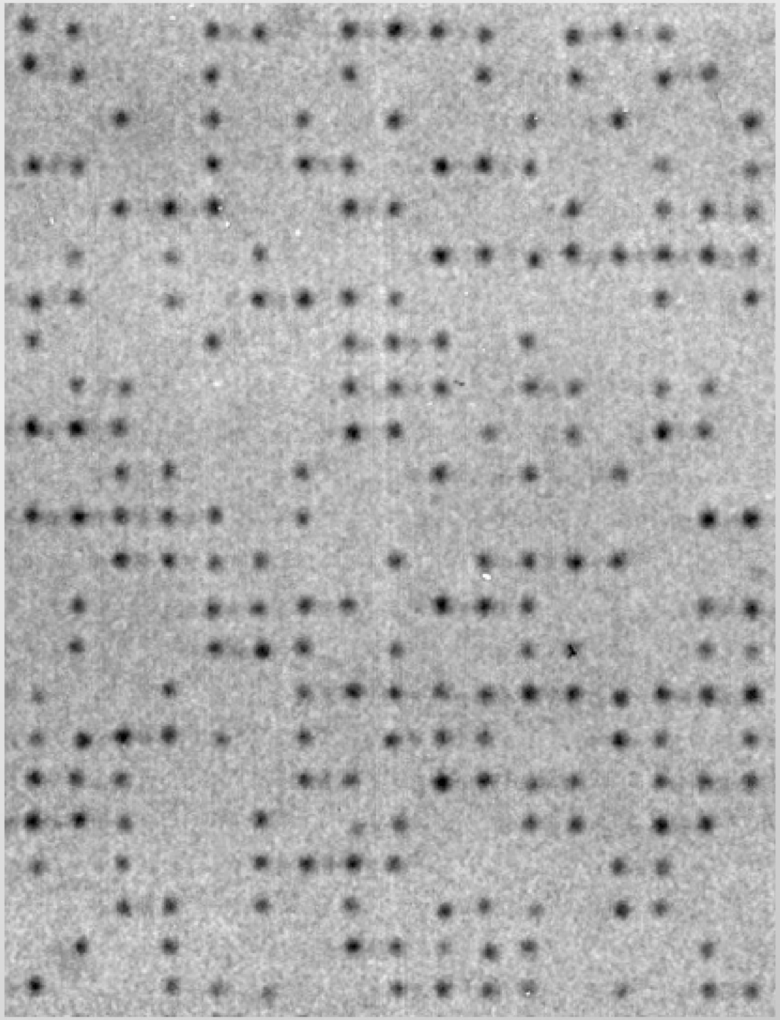


1 ms: permanent structural damage

Femtosecond micromachining

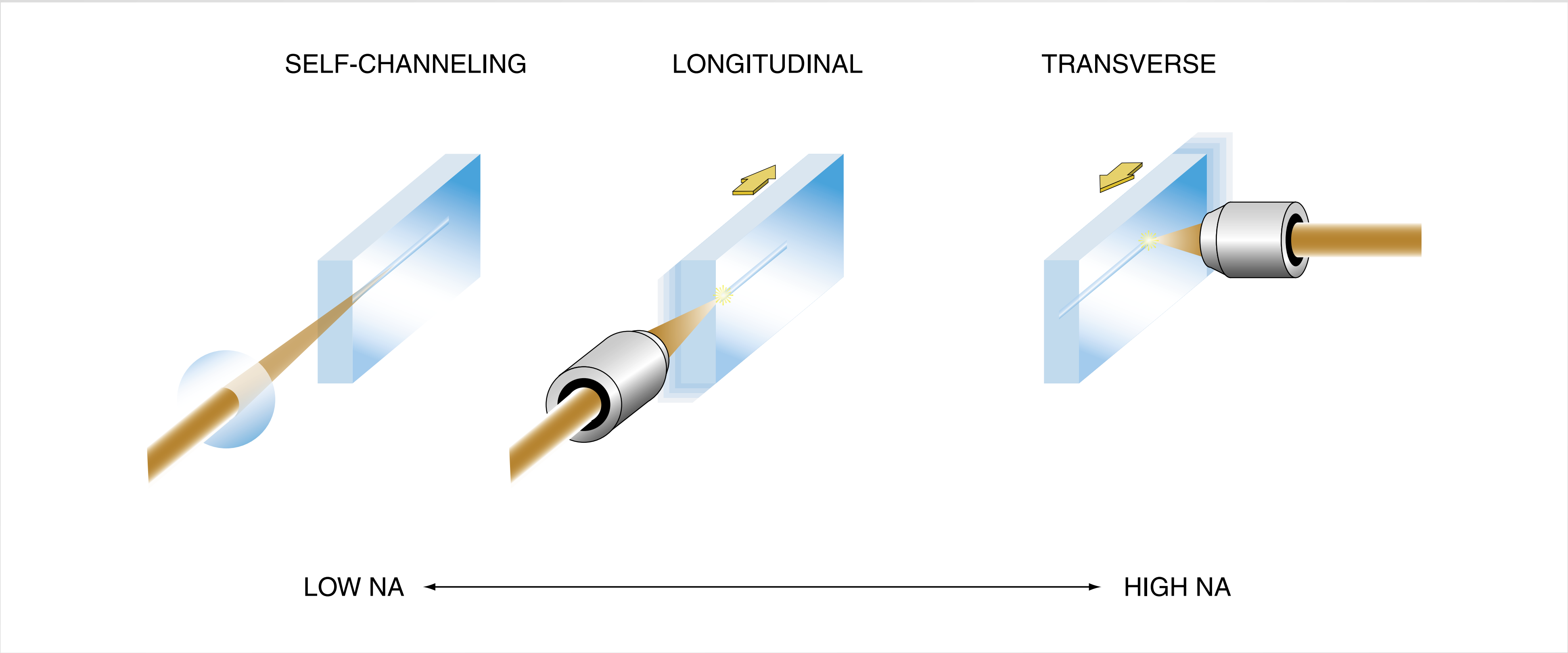
Some applications:

- data storage
- waveguides
- microfluidics



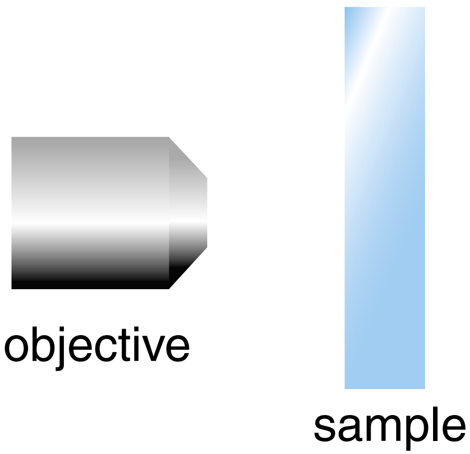
Femtosecond micromachining

waveguide micromachining geometries



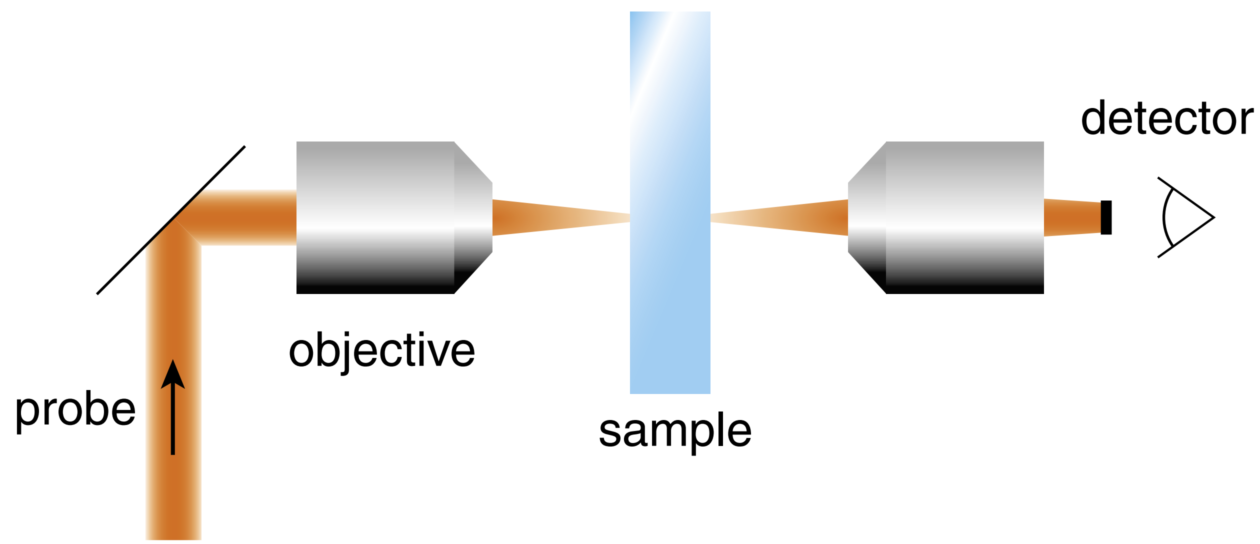
Femtosecond micromachining

Dark-field scattering



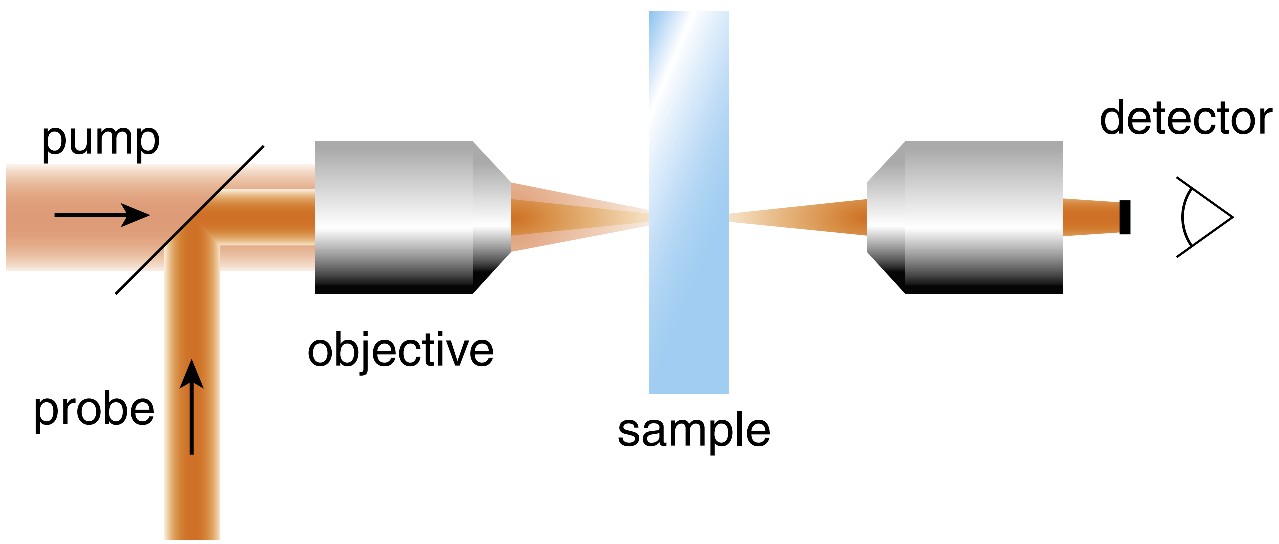
Femtosecond micromachining

block probe beam…



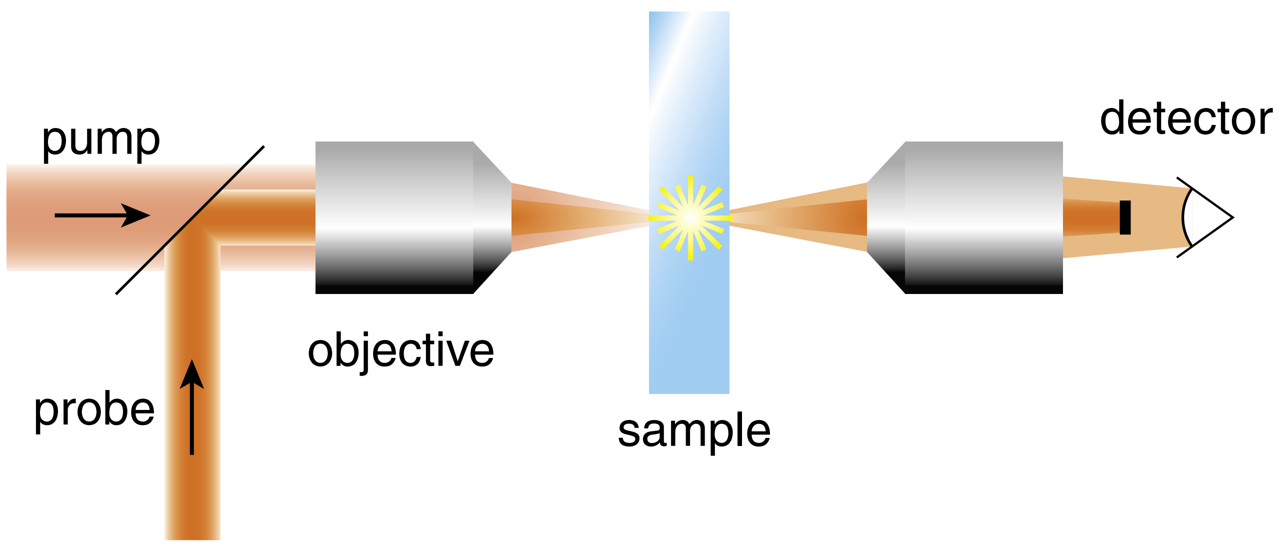
Femtosecond micromachining

… bring in pump beam…



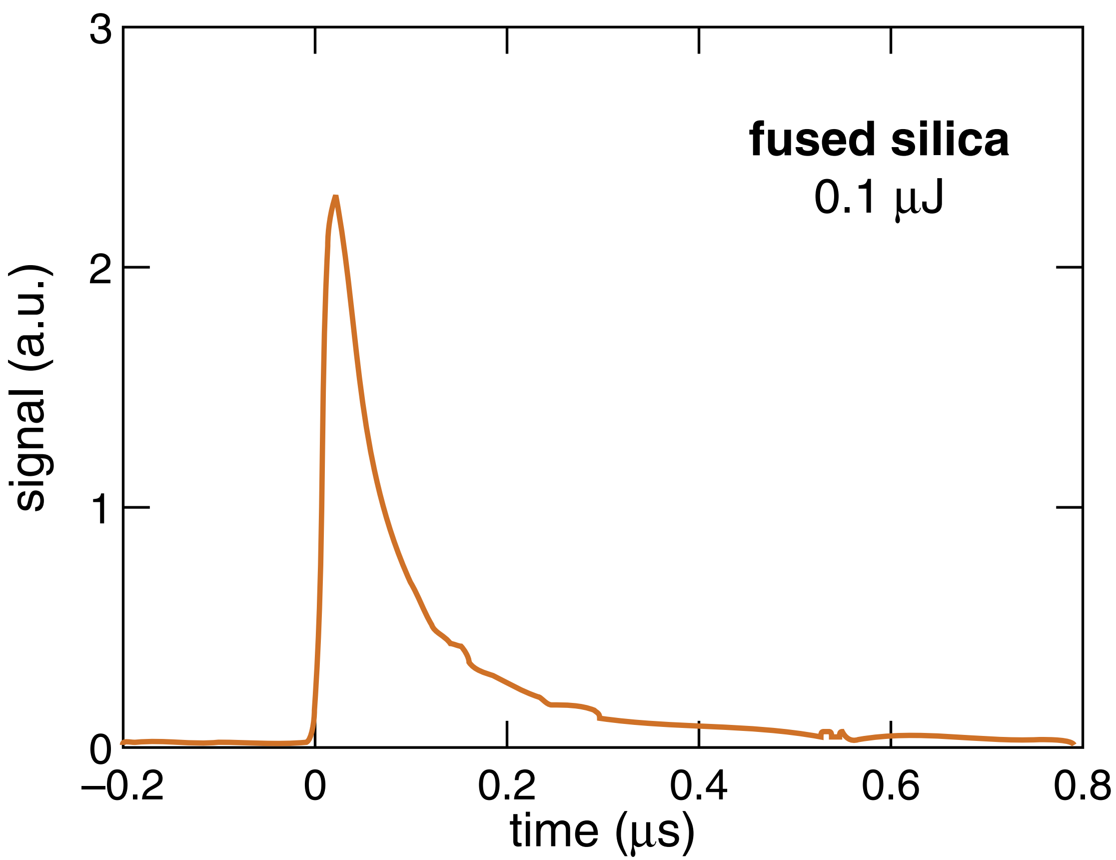
Femtosecond micromachining

… damage scatters probe beam



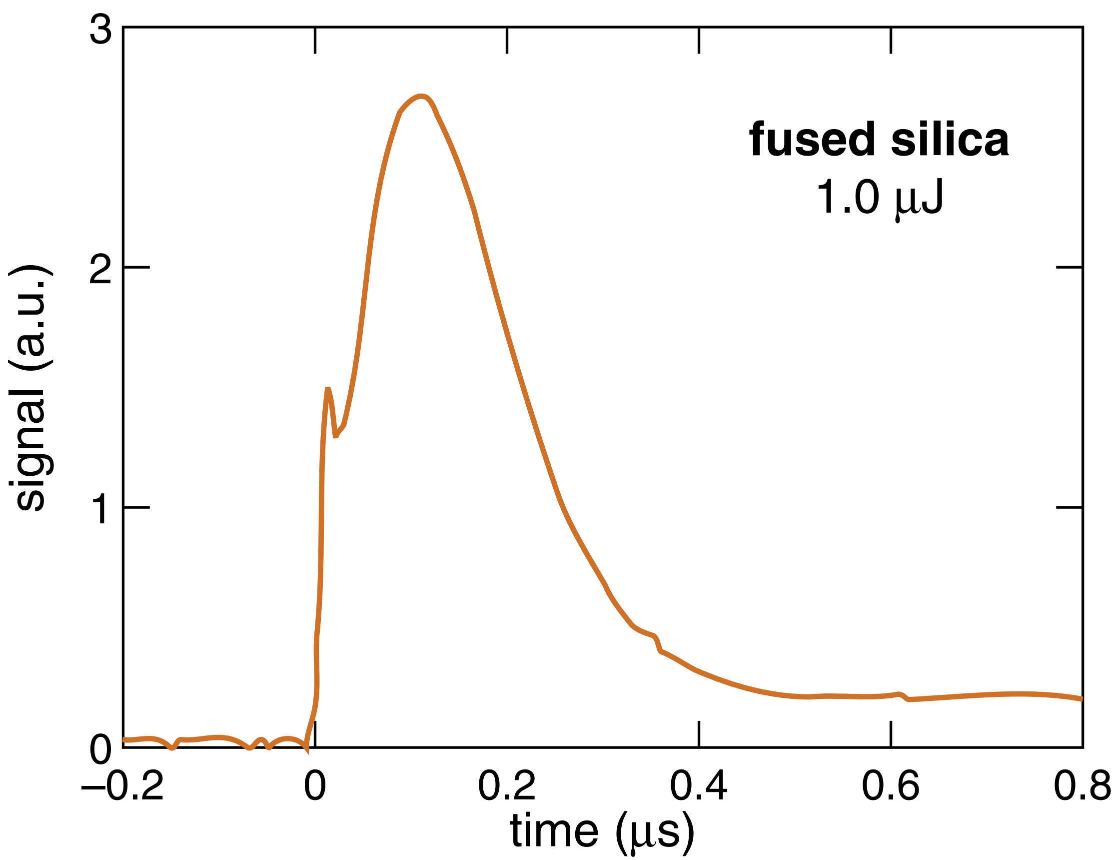
Femtosecond micromachining

scattered signal



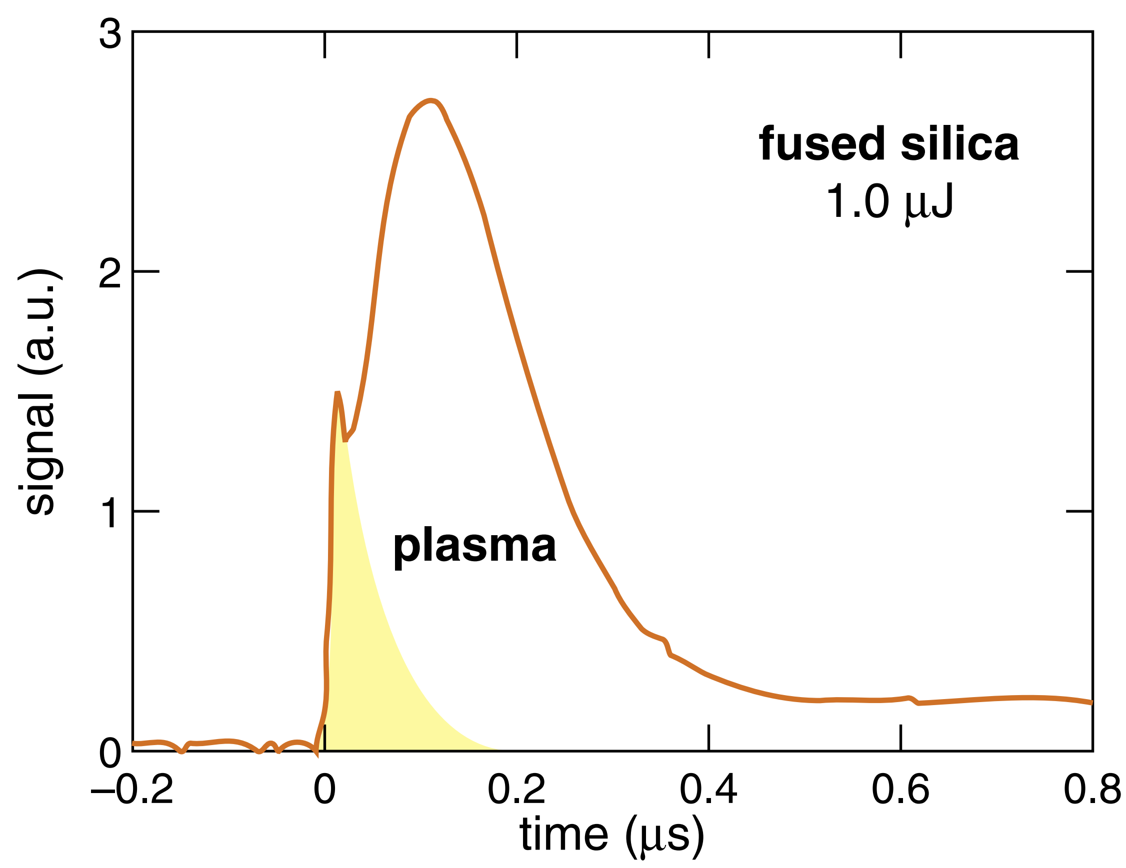
Femtosecond micromachining

scattered signal



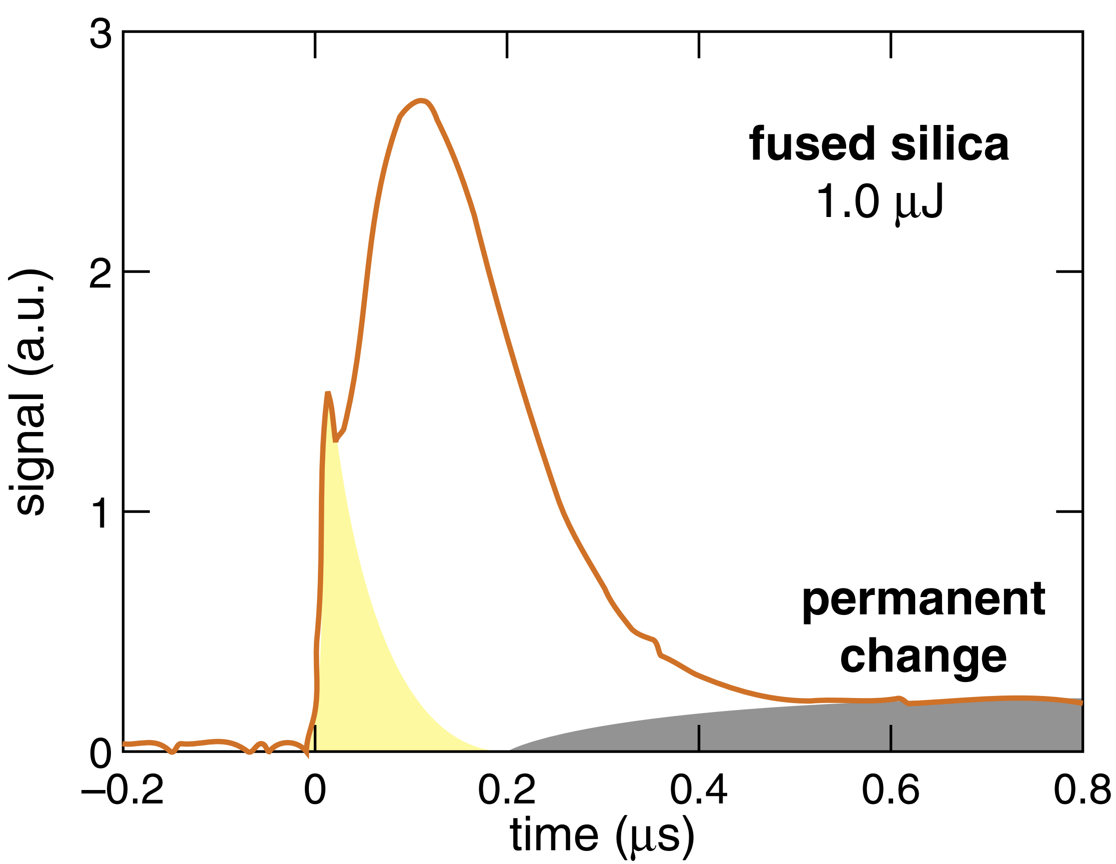
Femtosecond micromachining

scattered signal



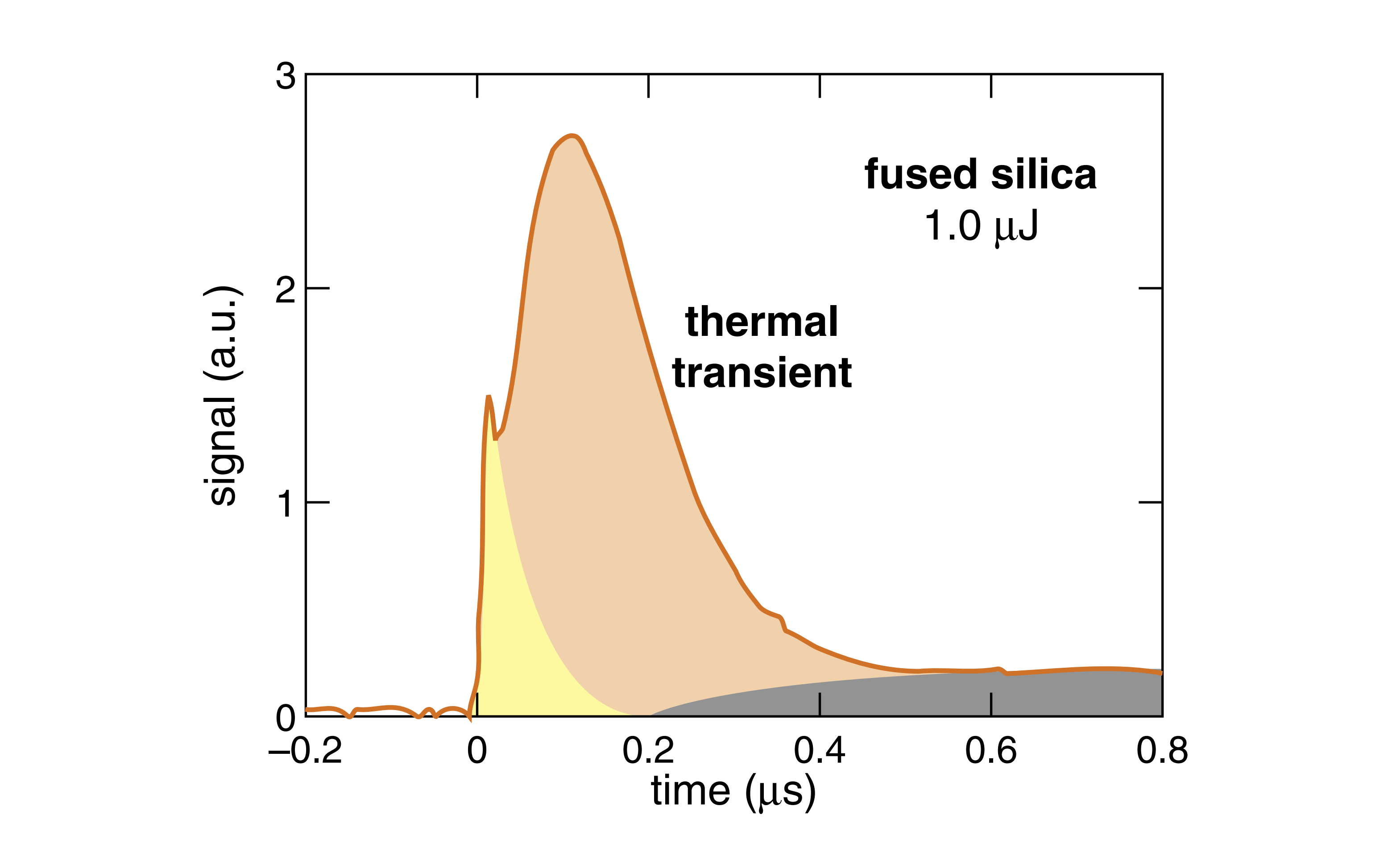
Femtosecond micromachining

scattered signal



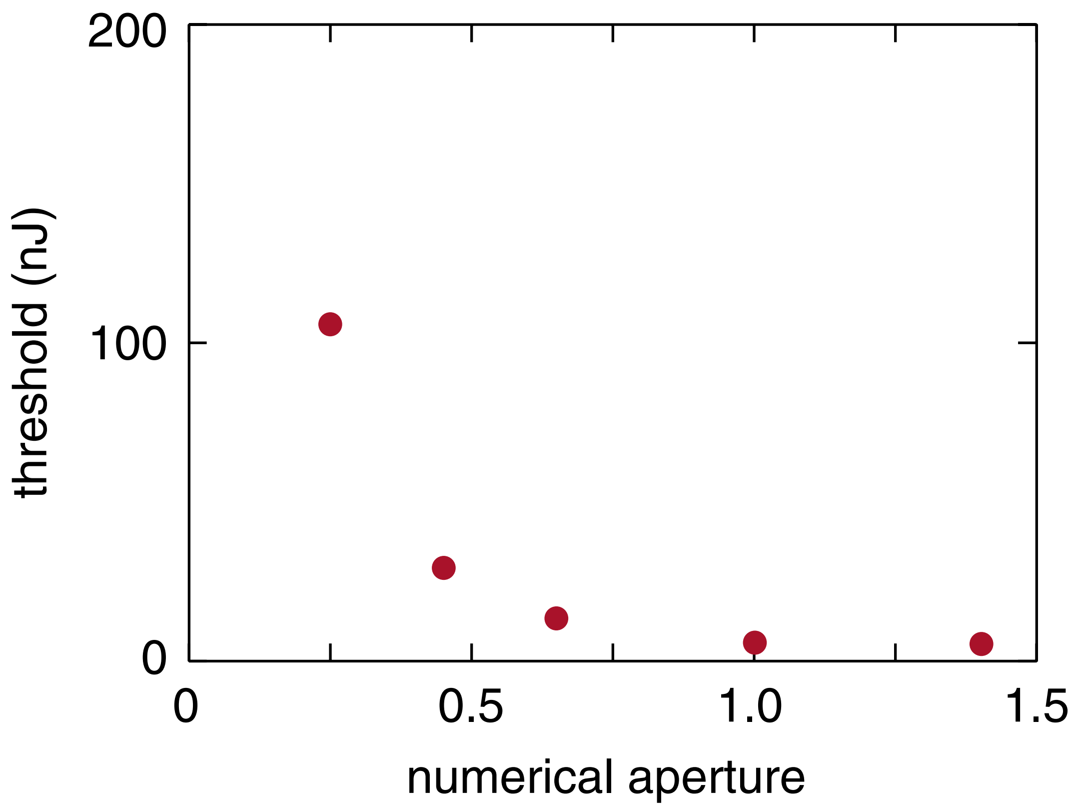
Femtosecond micromachining

scattered signal



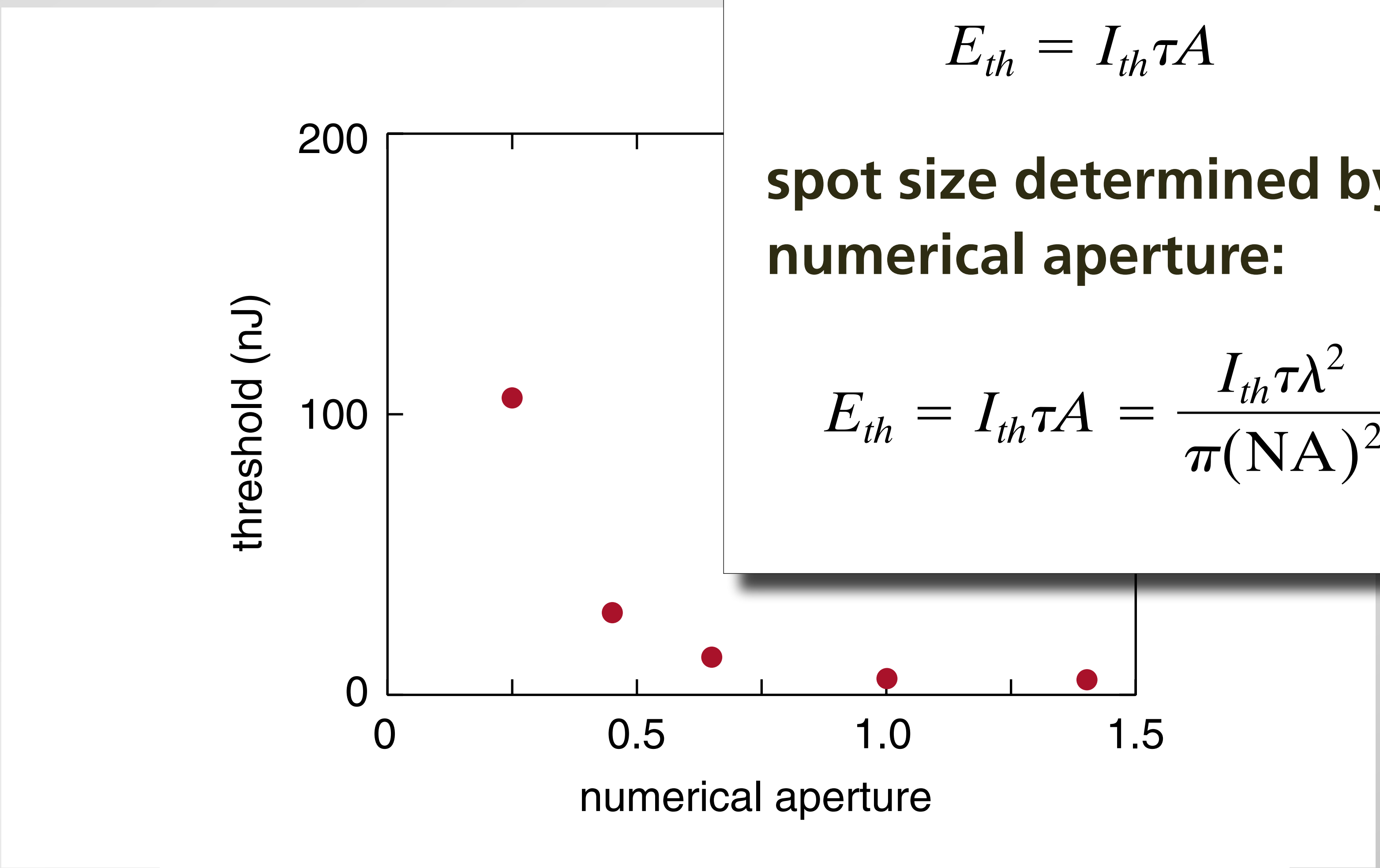
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

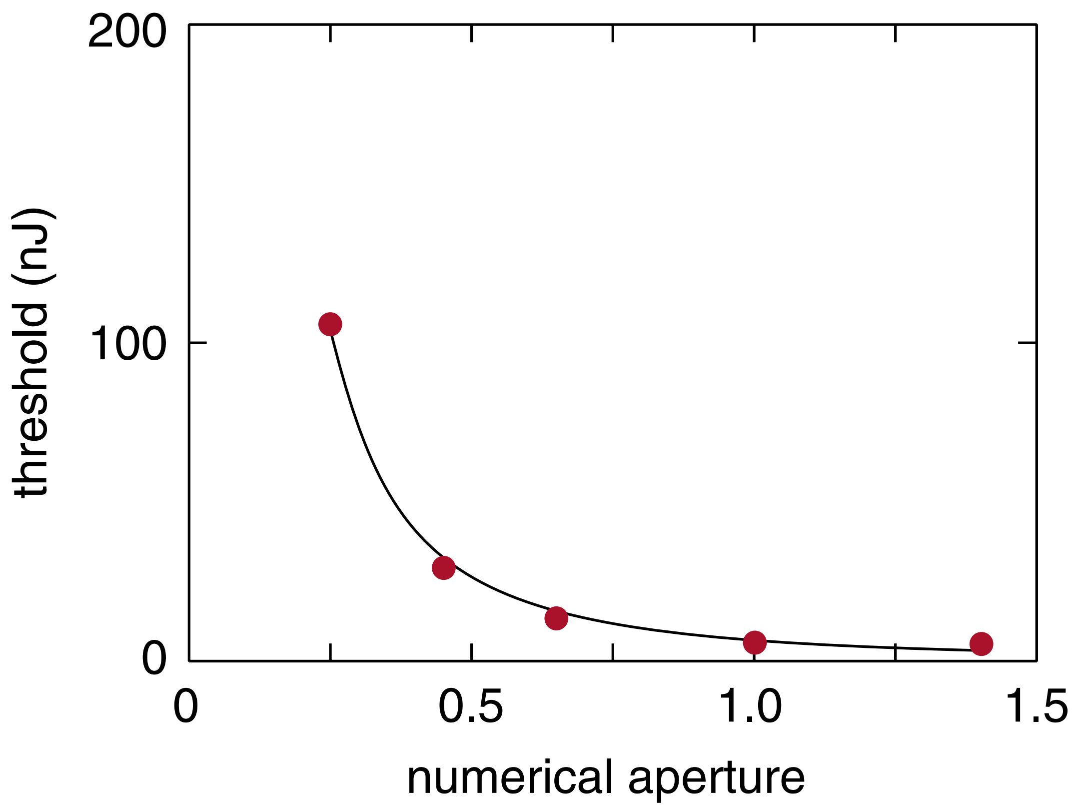
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

$$E_{th} = I_{th}\tau A = \frac{I_{th}\tau\lambda^2}{\pi(\mathrm{NA})^2}$$

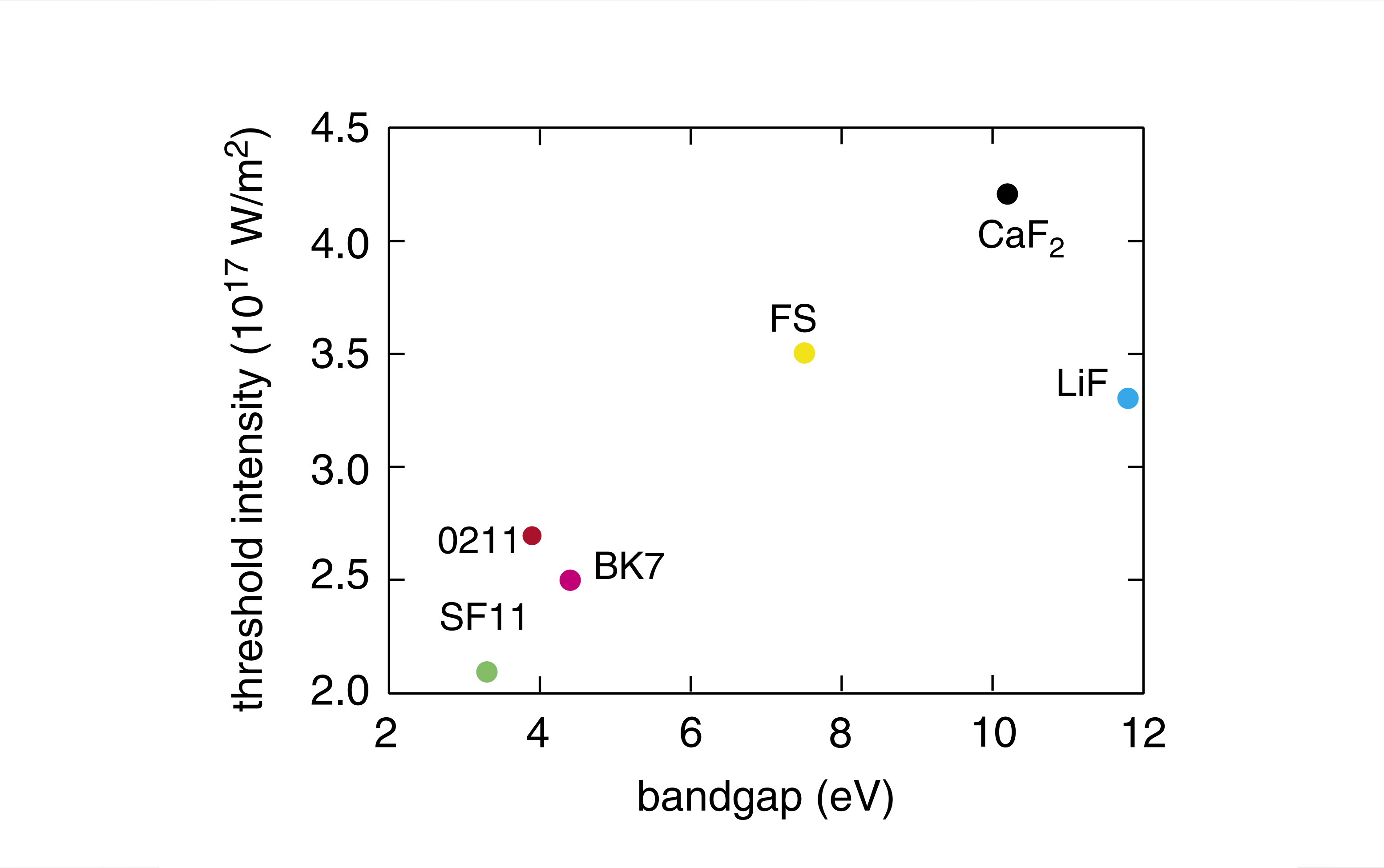
Femtosecond micromachining

fit gives threshold intensity: I_{th} = 2.5 x 10^{17} W/m^2



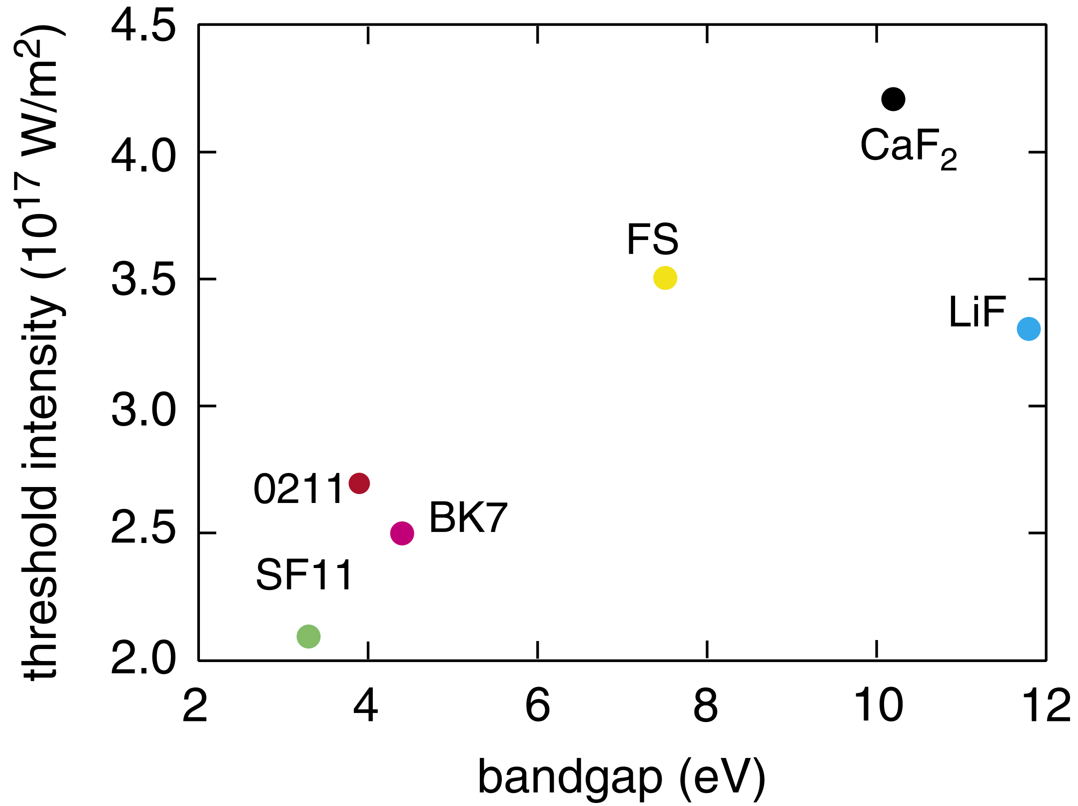
Femtosecond micromachining

vary material…



Femtosecond micromachining

…threshold varies with band gap (but not much!)

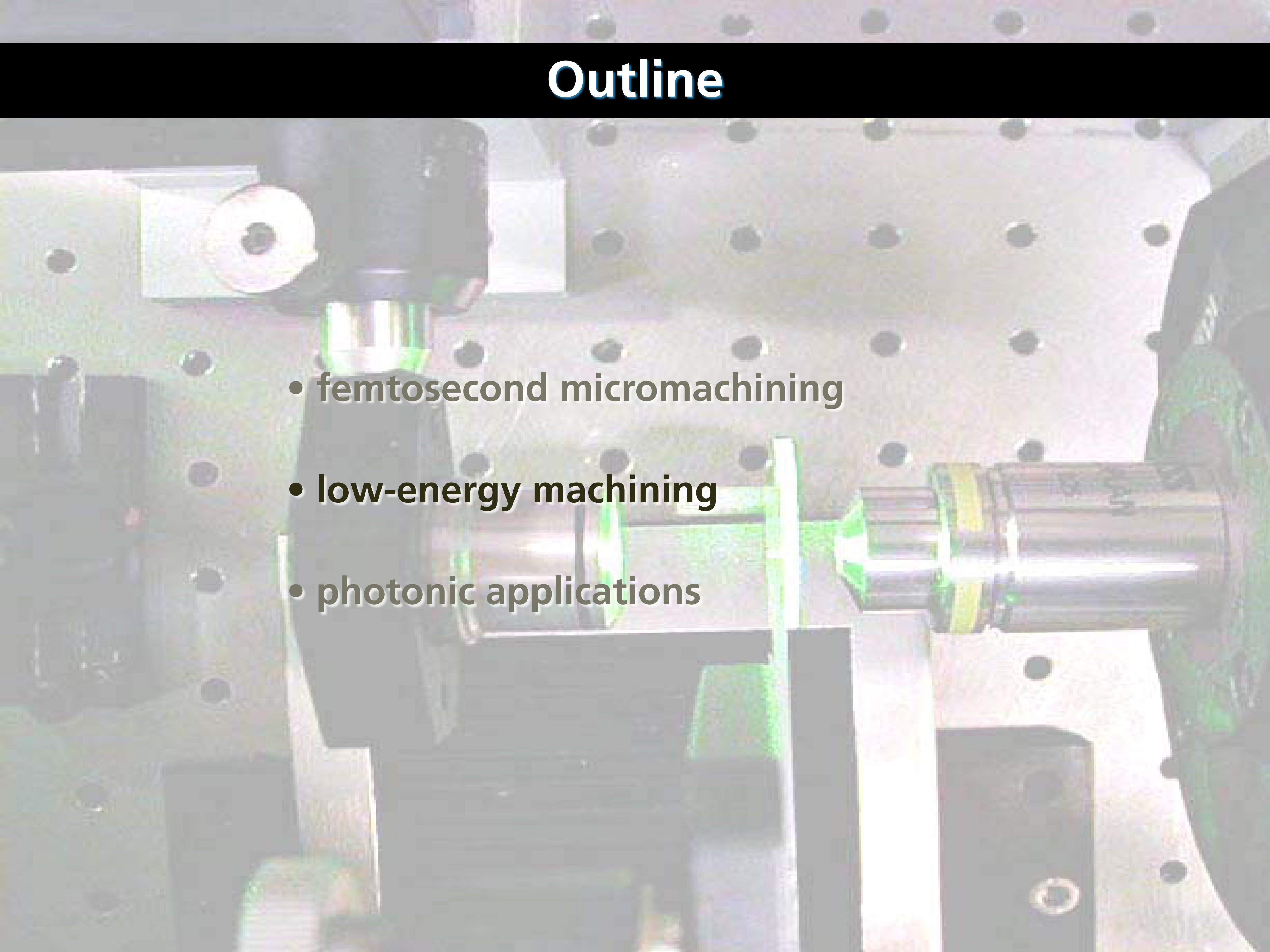


Femtosecond micromachining

Points to keep in mind:

- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

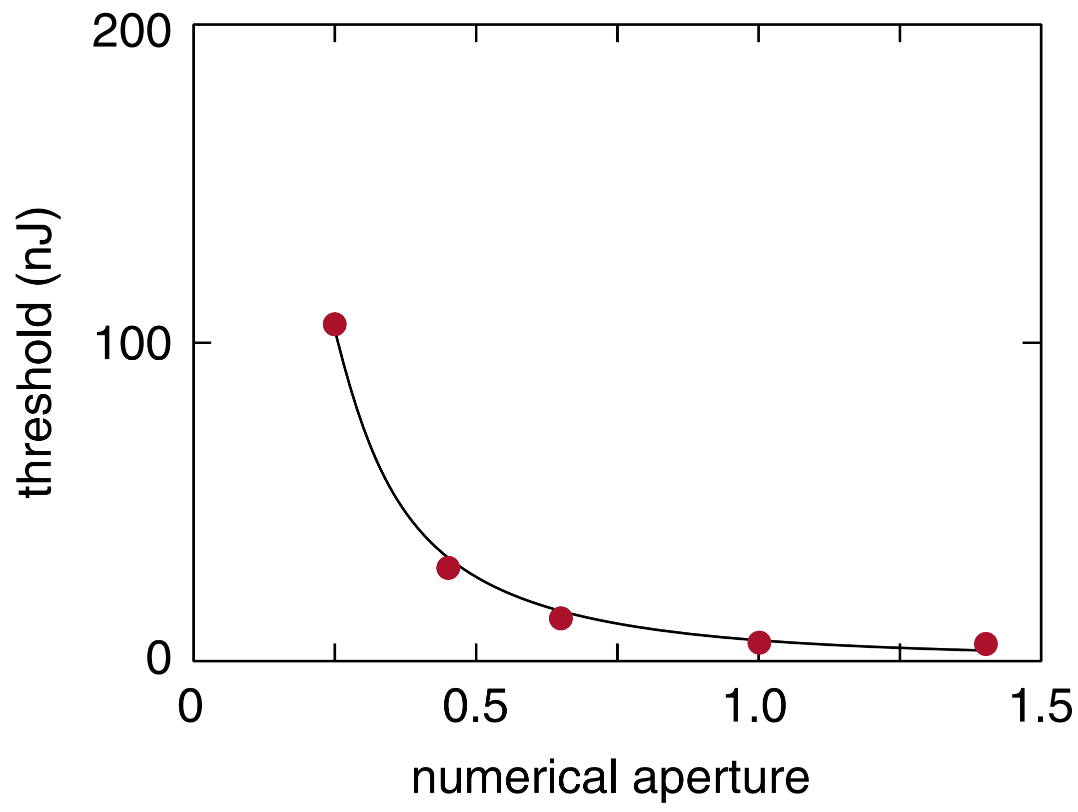
Outline



- femtosecond micromachining
- **low-energy machining**
- photonic applications

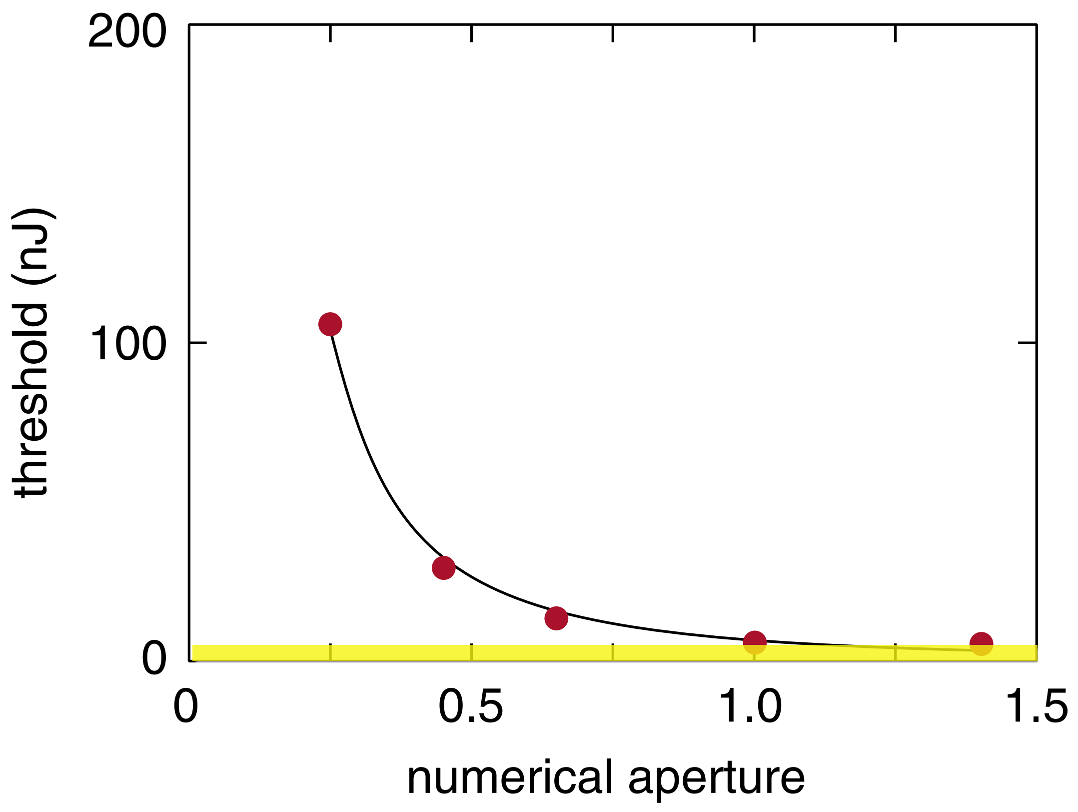
Low-energy machining

threshold decreases with increasing numerical aperture



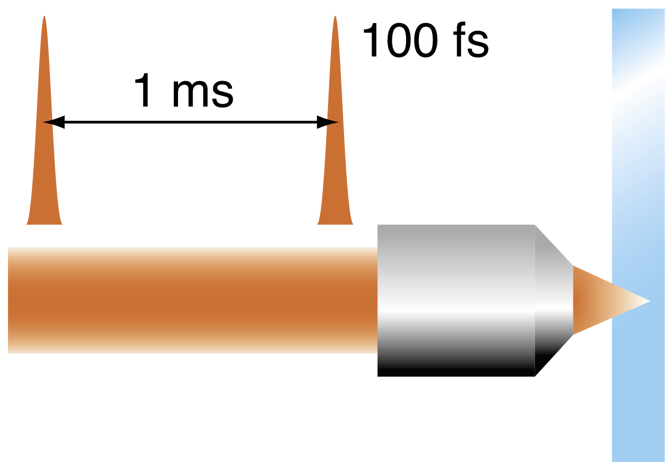
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

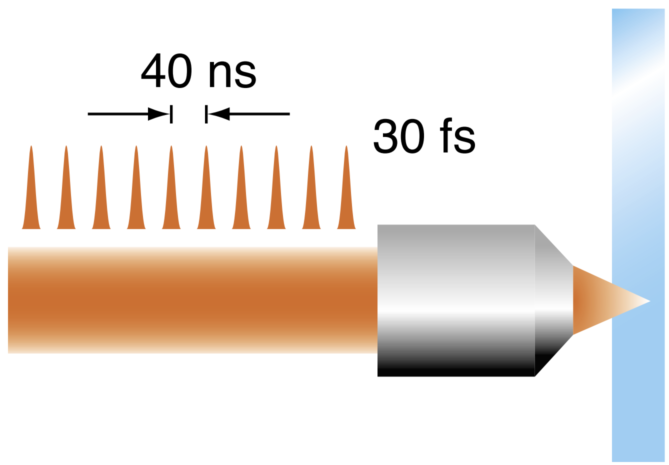
amplified laser: 1 kHz, 1 mJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

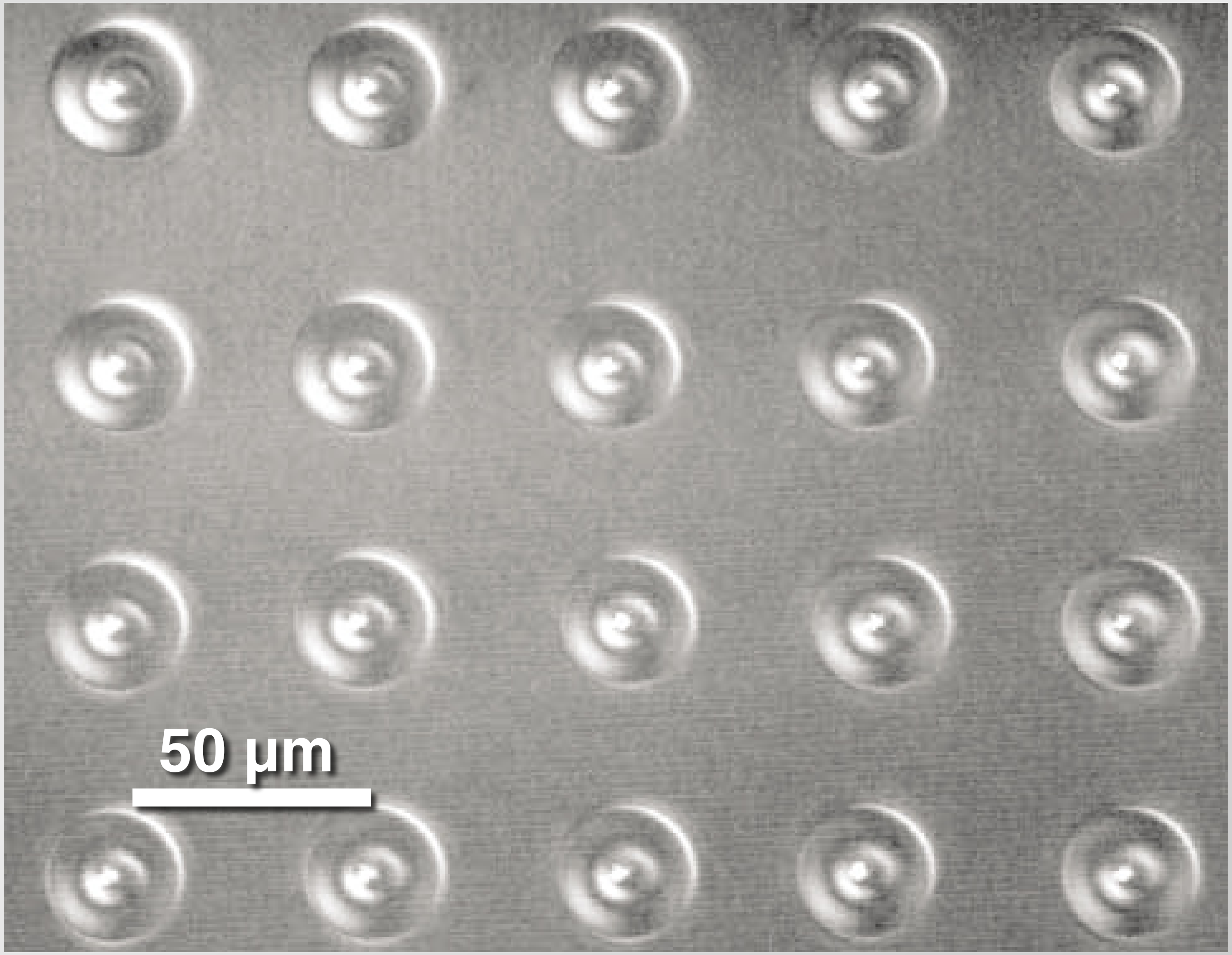
Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

Low-energy machining



Low-energy machining

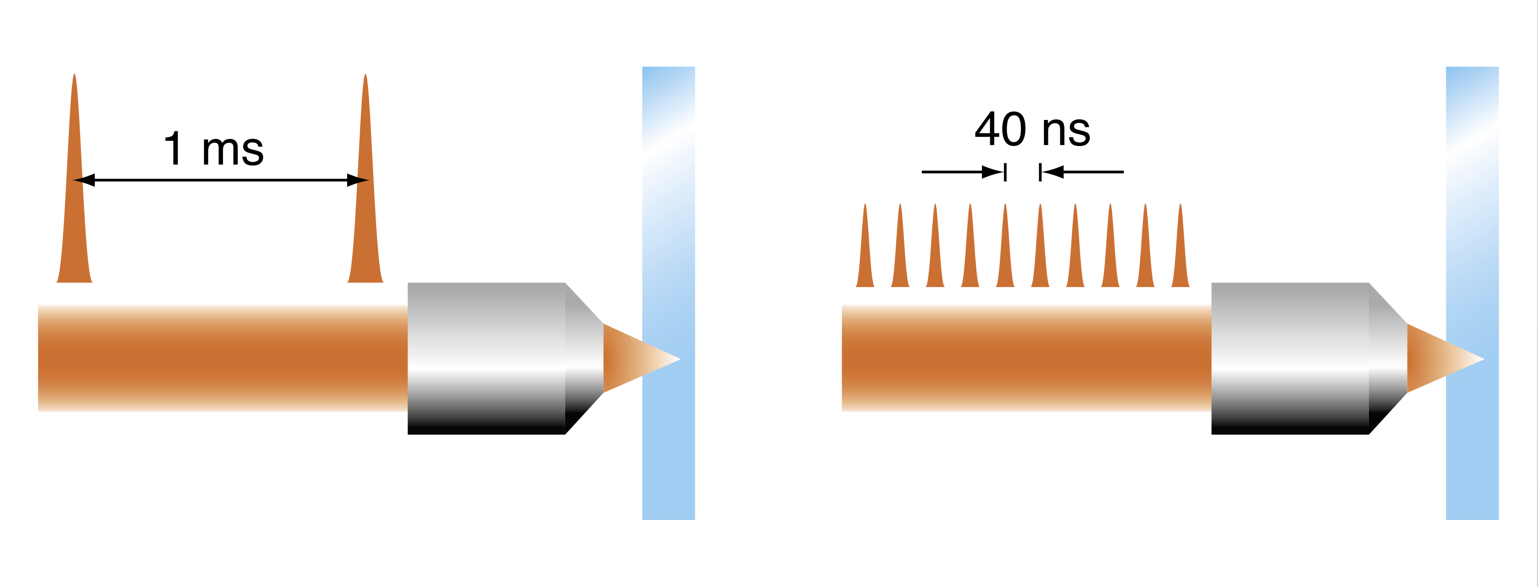
High repetition-rate micromachining:

- structural changes exceed focal volume
- spherical structures
- density change caused by melting

Low-energy machining

amplified laser

oscillator

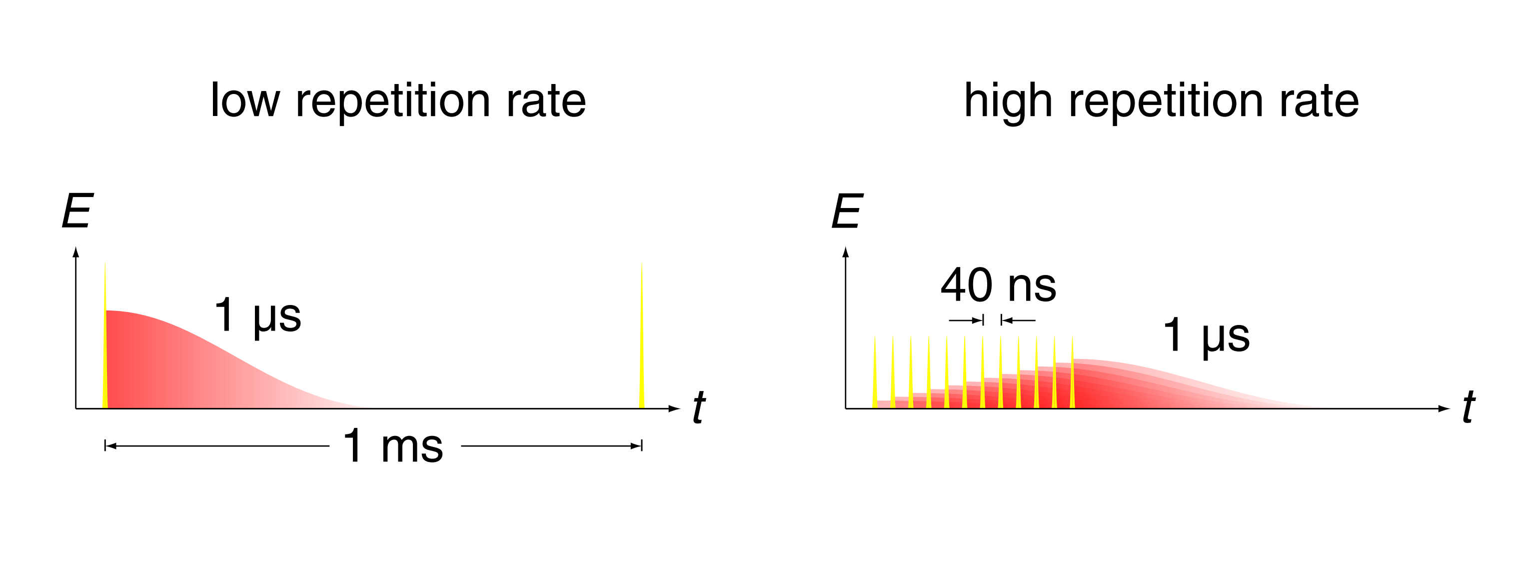


repetitive

cumulative

Low-energy machining

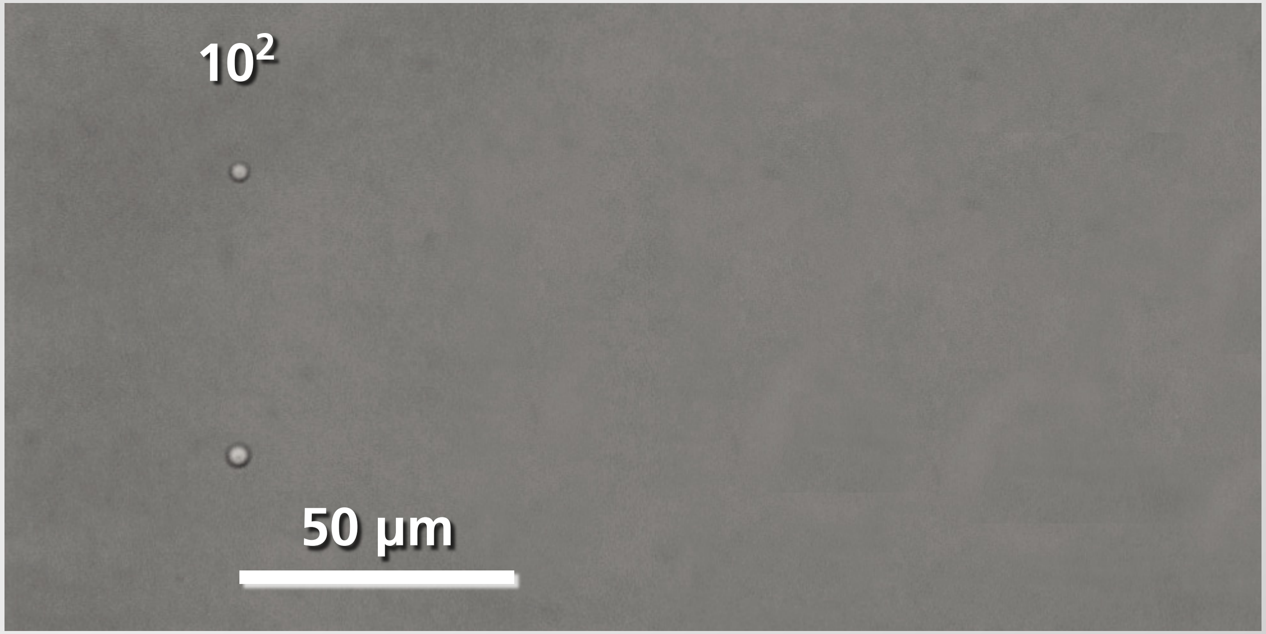
amplified laser **oscillator**



repetitive **cumulative**

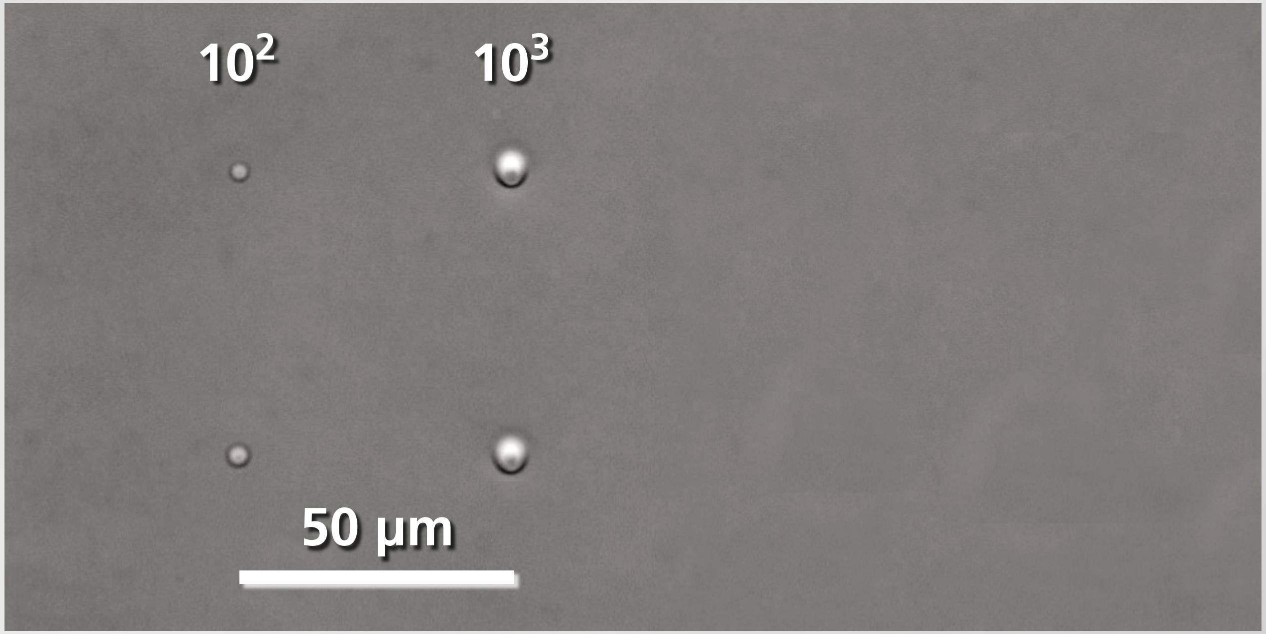
Low-energy machining

the longer the irradiation…



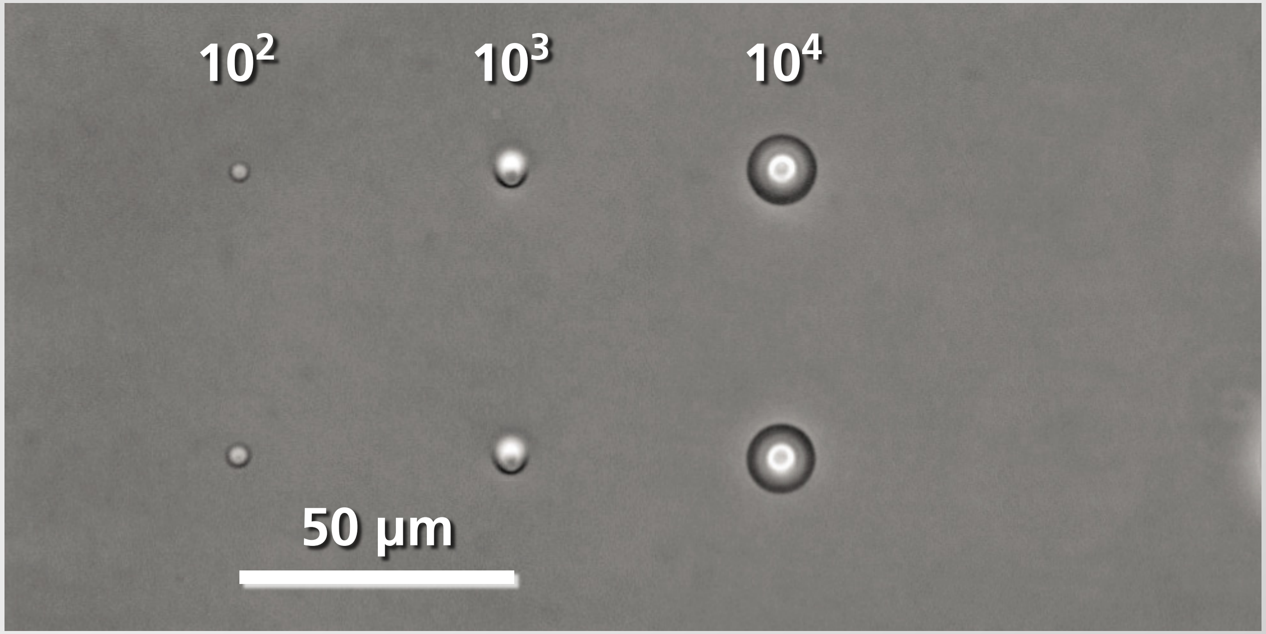
Low-energy machining

the longer the irradiation…



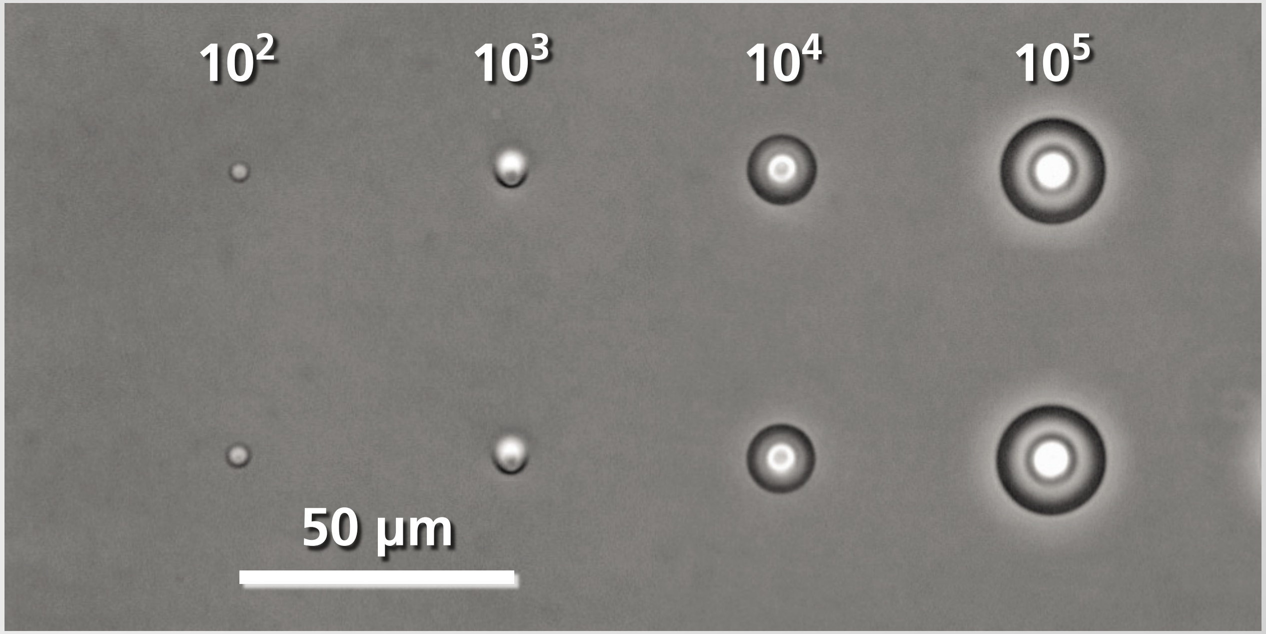
Low-energy machining

the longer the irradiation…



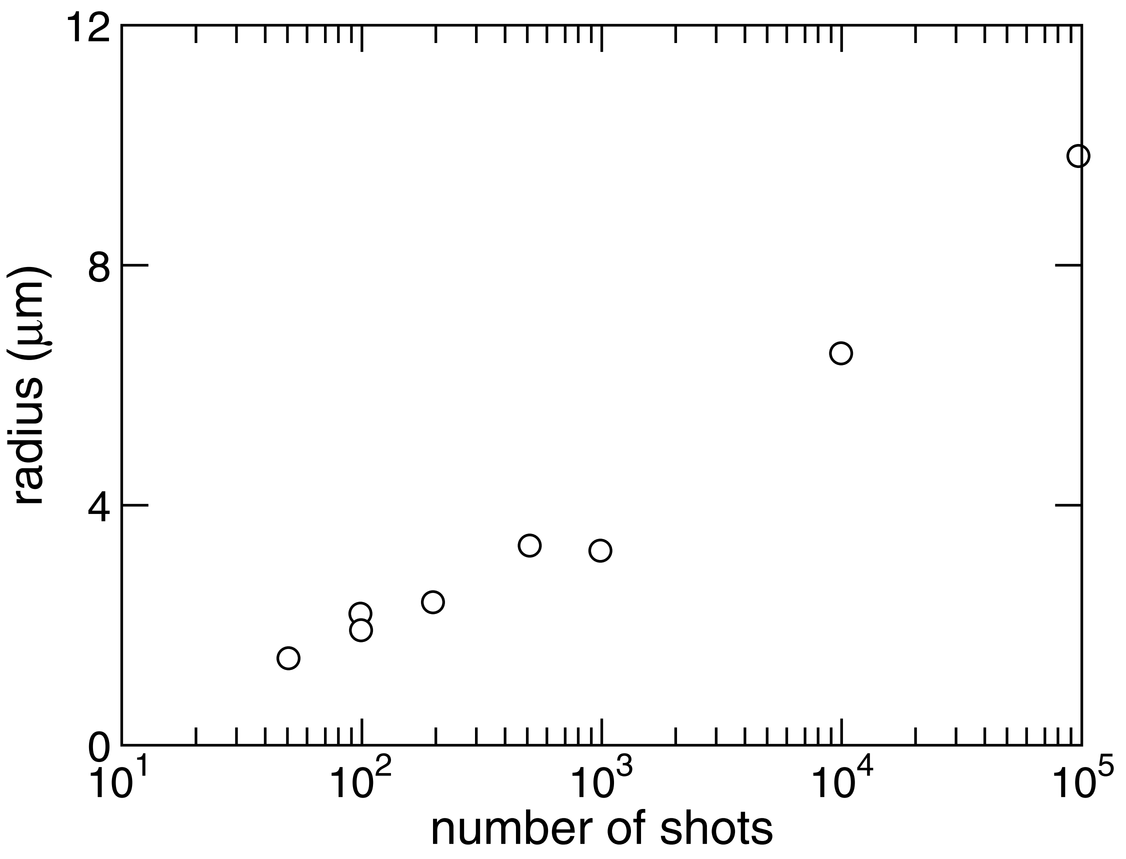
Low-energy machining

the longer the irradiation…



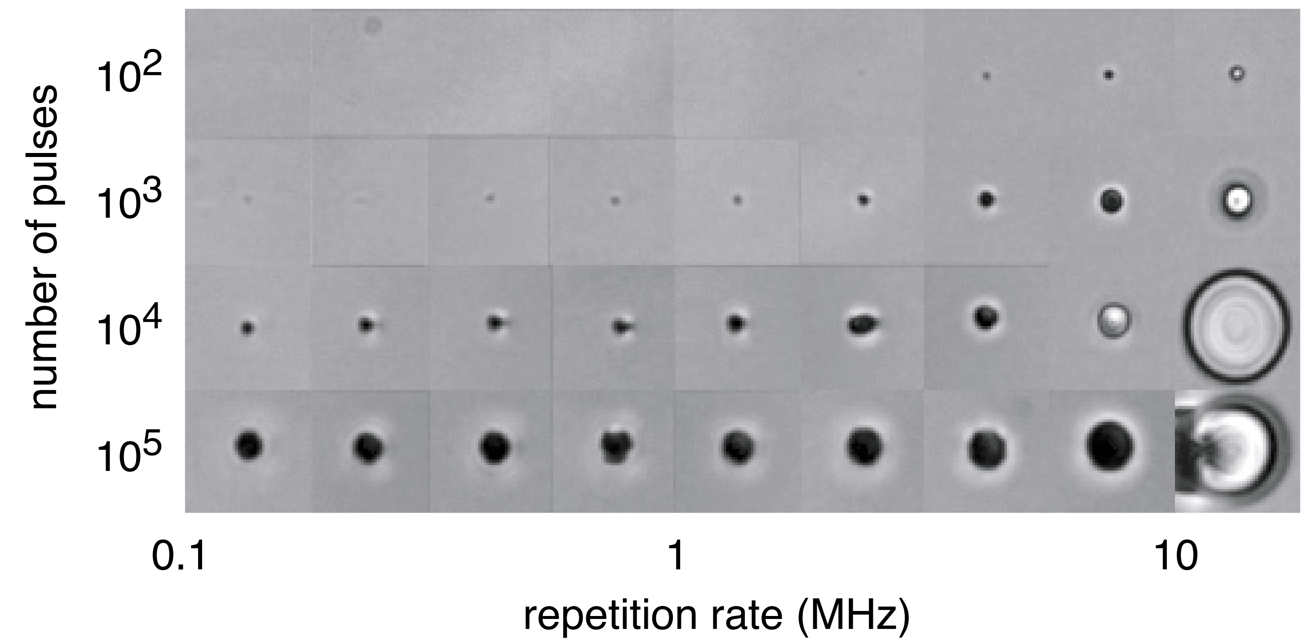
… the larger the radius

Low-energy machining



Low-energy machining

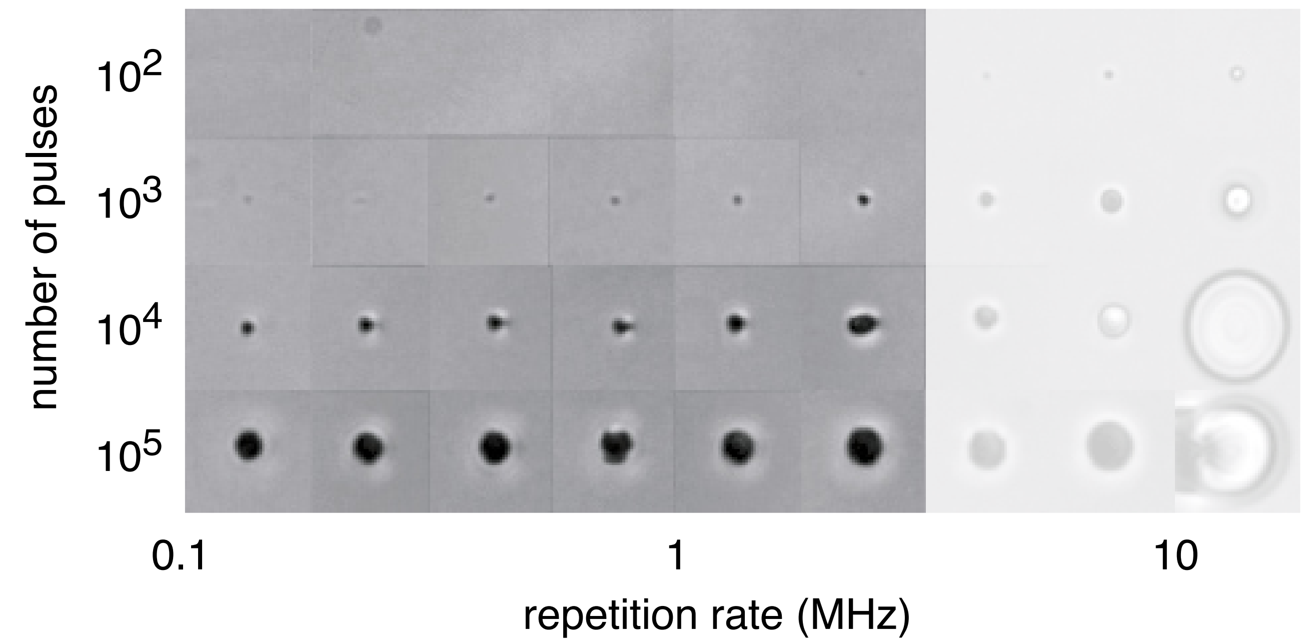
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

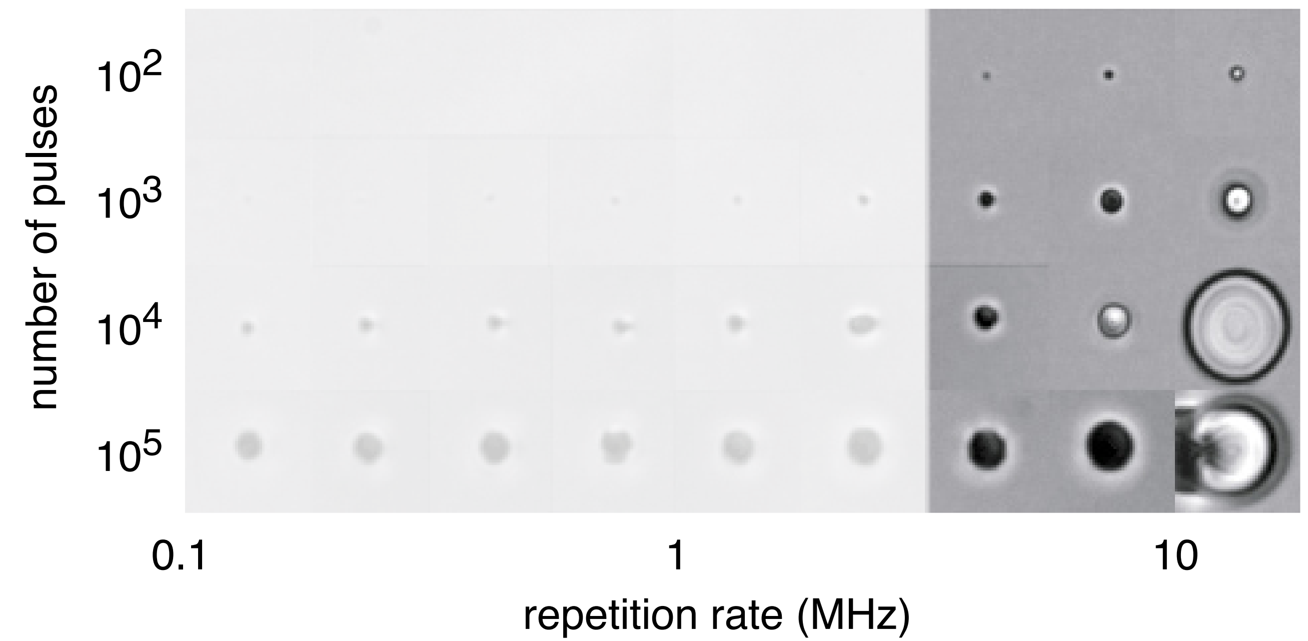
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

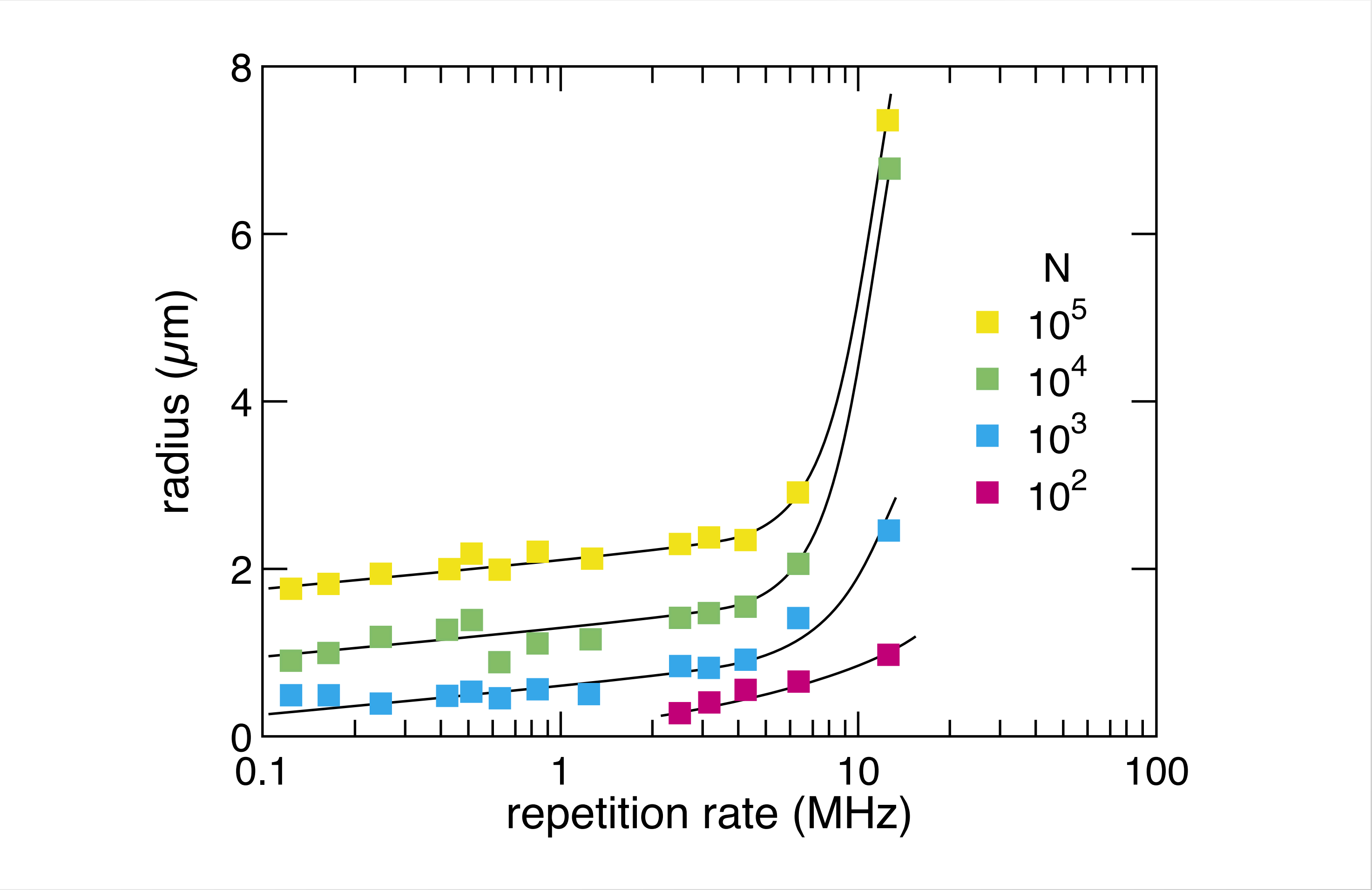
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

repetition-rate dependence



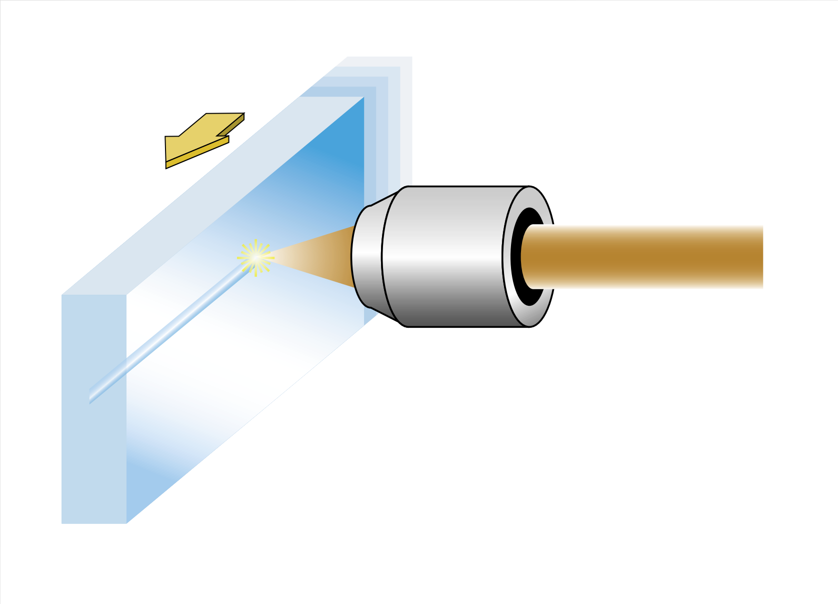
As_2S_3, 100 fs, 7 nJ

Low-energy machining

above 5 MHz: internal “point-source of heat”

Low-energy machining

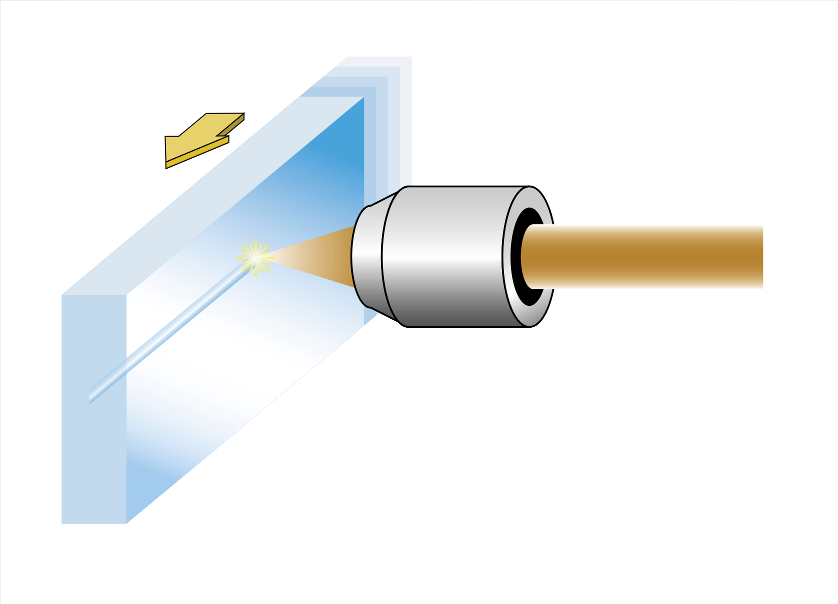
waveguide micromachining

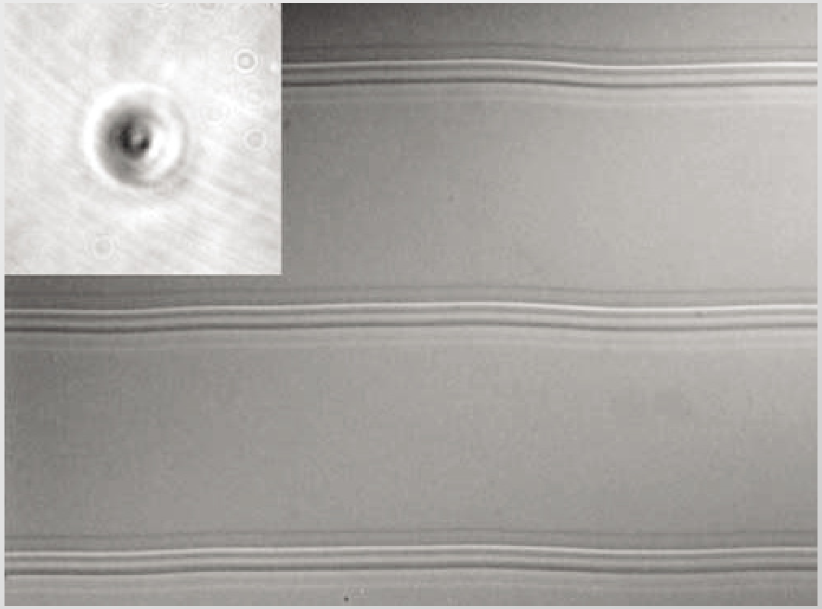


Opt. Lett. **26**, 93 (2001)

Low-energy machining

waveguide micromachining

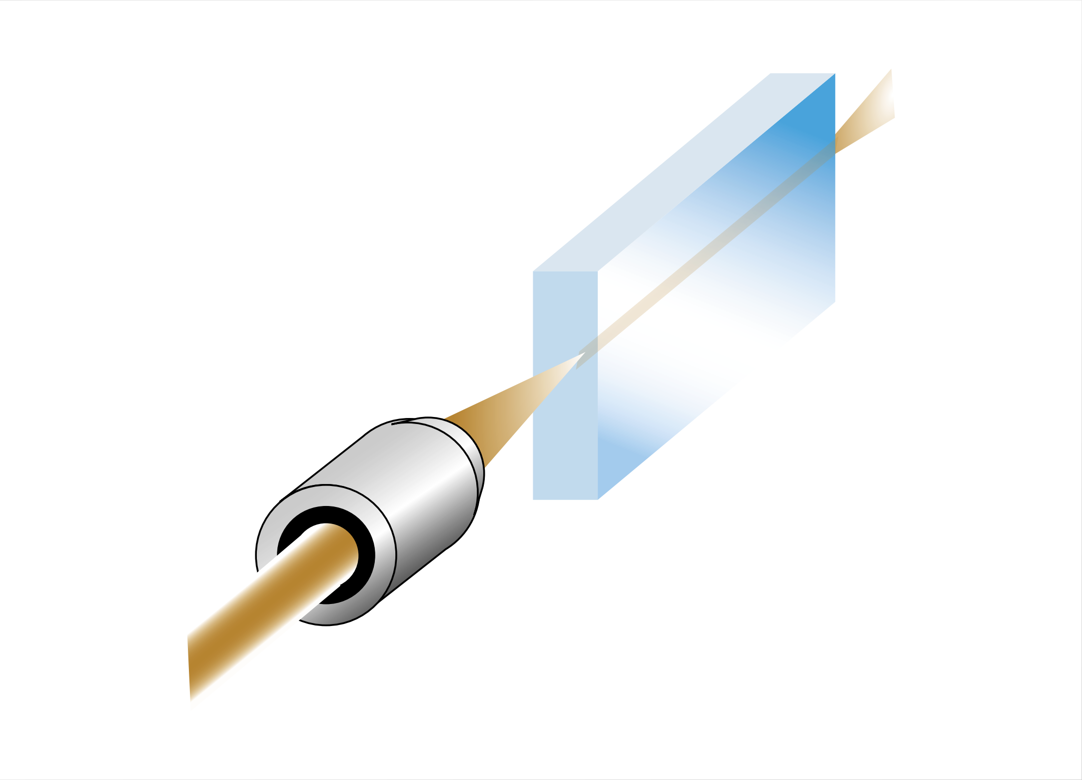




Opt. Lett. **26**, 93 (2001)

Low-energy machining

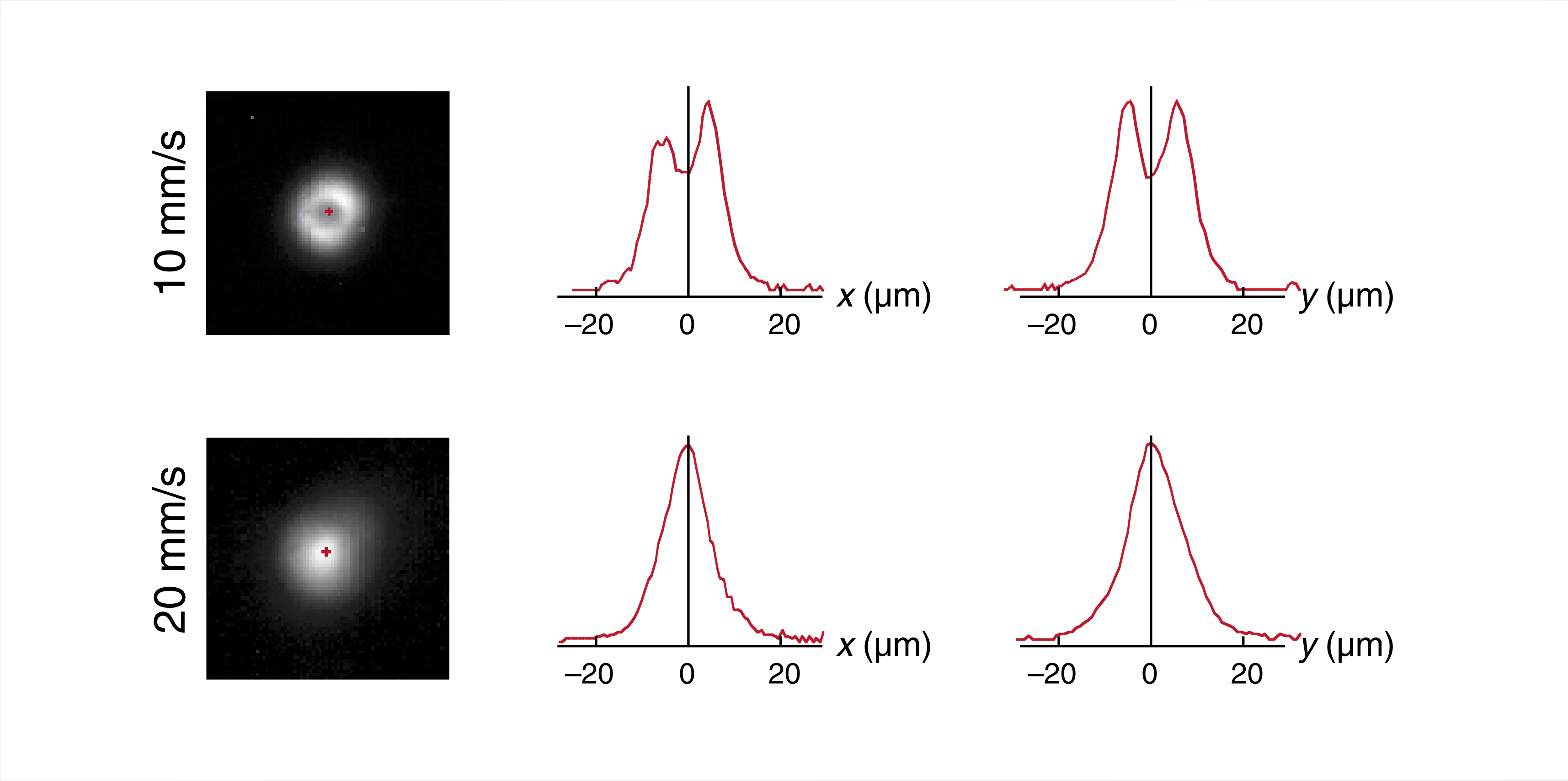
structures guide light



Opt. Lett. **26**, 93 (2001)

Low-energy machining

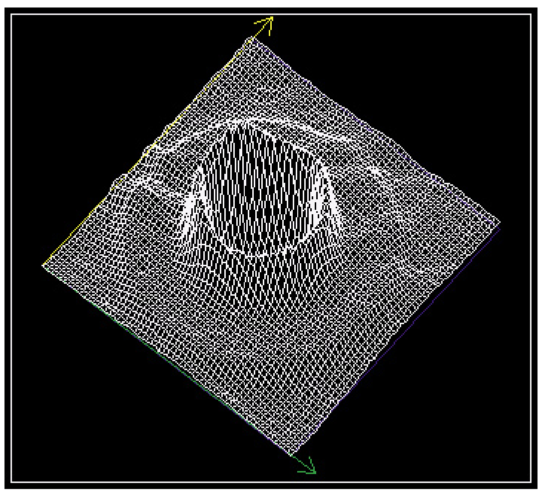
near-field profiles

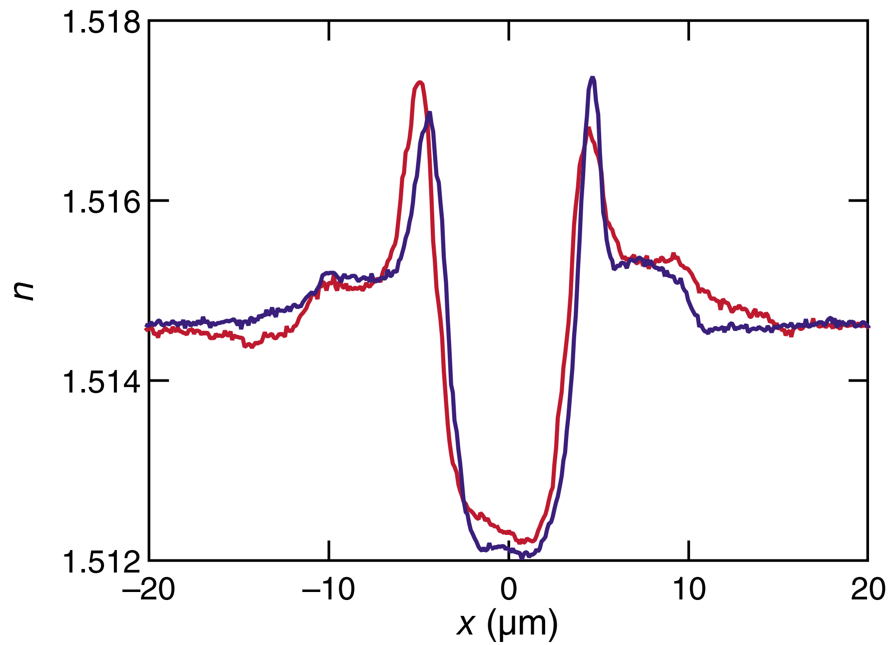


Sagitta, Inc.

Low-energy machining

index profile at 2.5 mm/s





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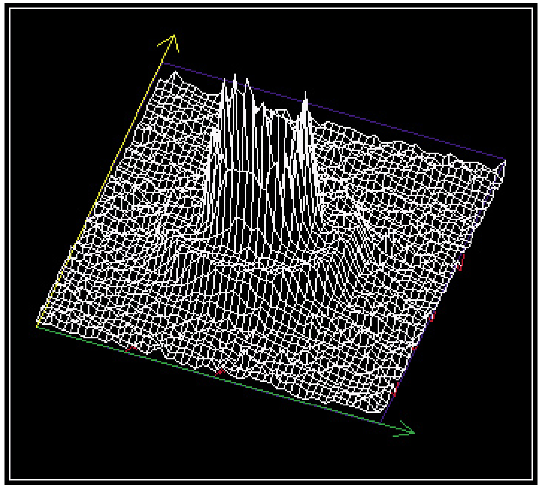
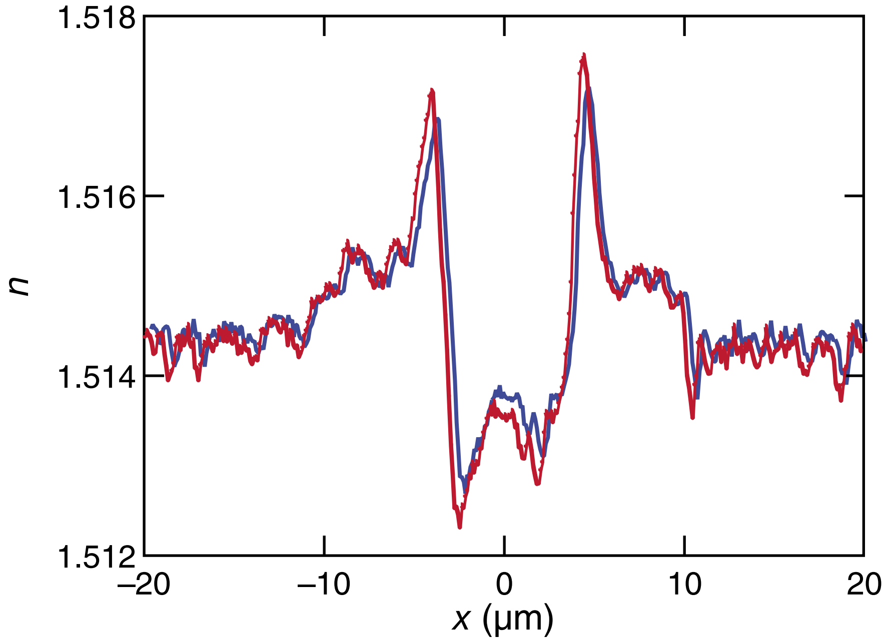
Low-energy machining

index profile at 10 mm/s





Sagitta, Inc.

Outline

- femtosecond micromachining
- low-energy machining
- **photonic applications**

Photonic applications

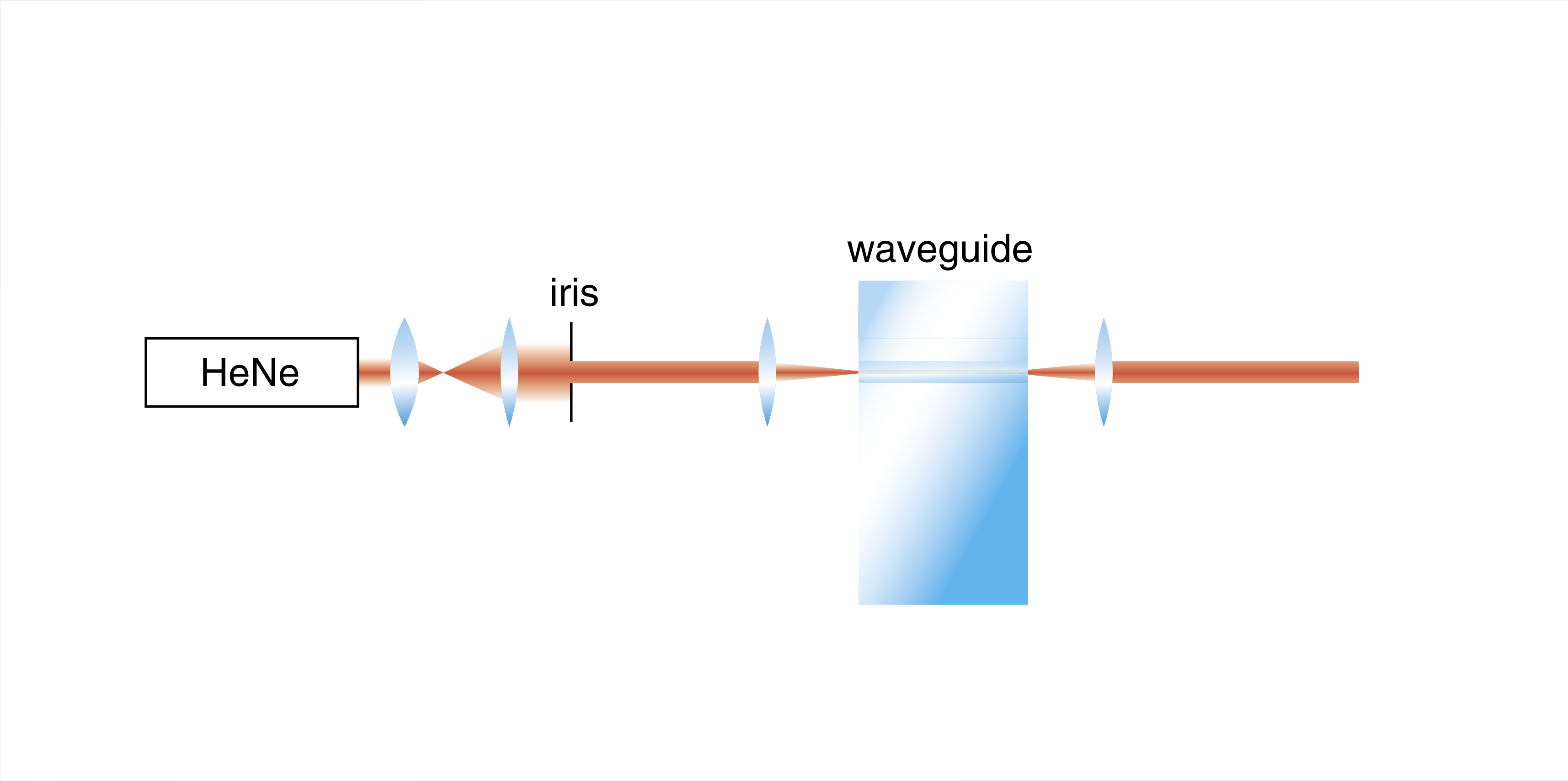
loss measurement

Photonic applications

loss measurement

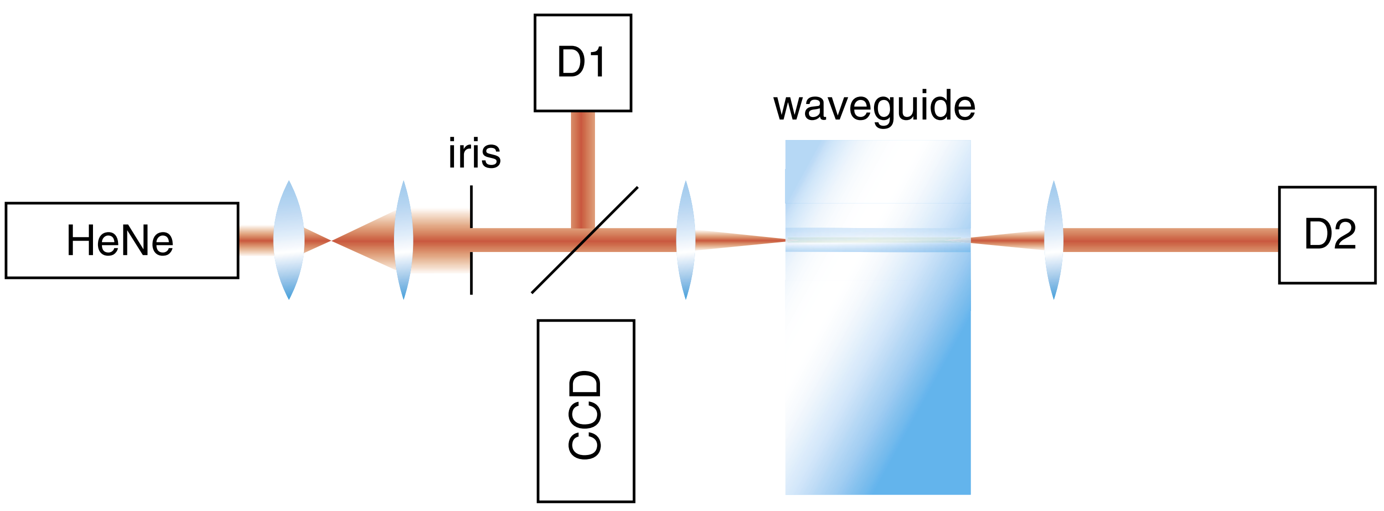
Photonic applications

loss measurement



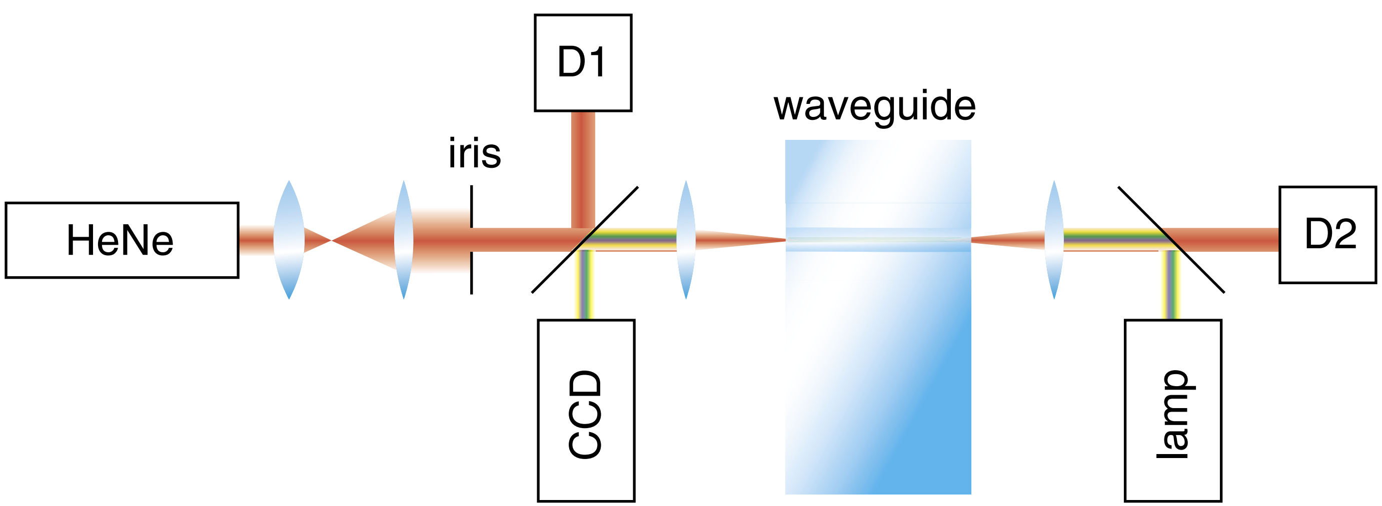
Photonic applications

loss measurement



Photonic applications

loss measurement

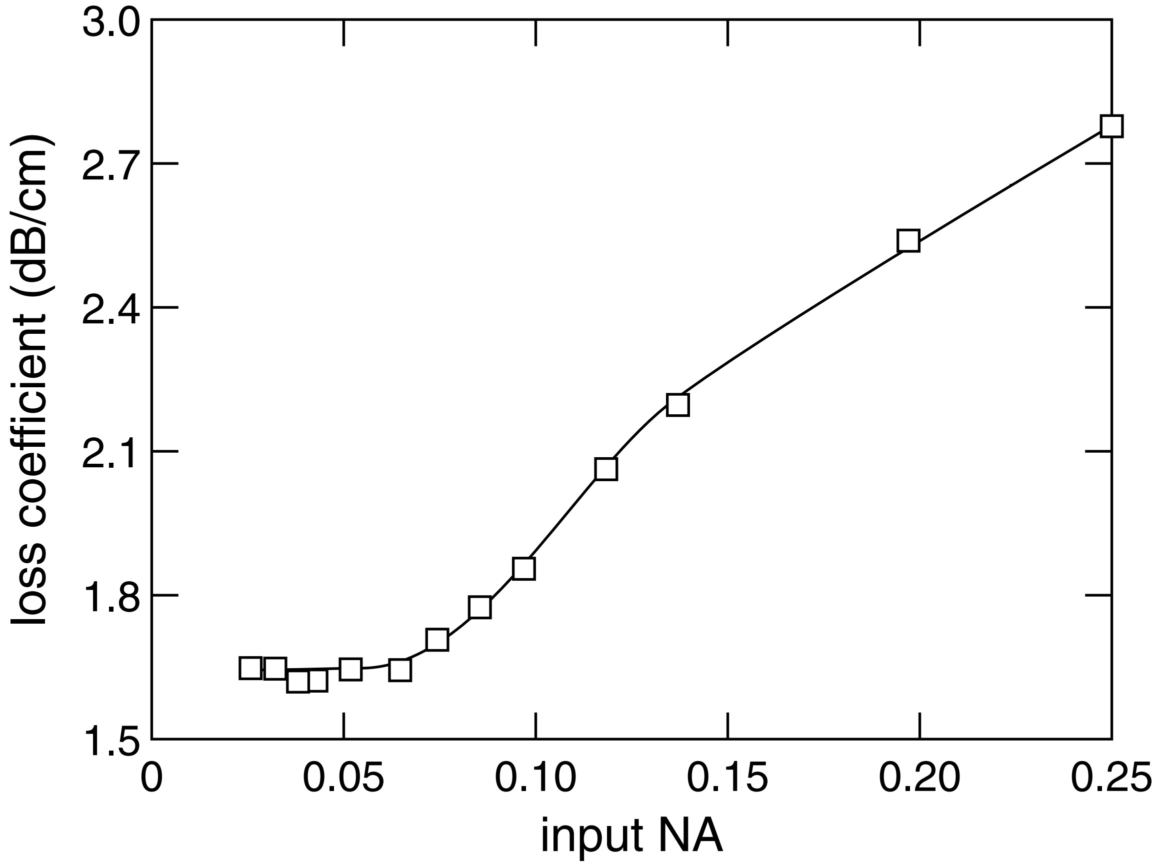


Photonic applications

- at low NA: loss $\approx$ 2 dB/cm
- at 1550 nm: loss $<$ 0.5 dB/cm
- no polarization dependence
- losses mostly due to scattering

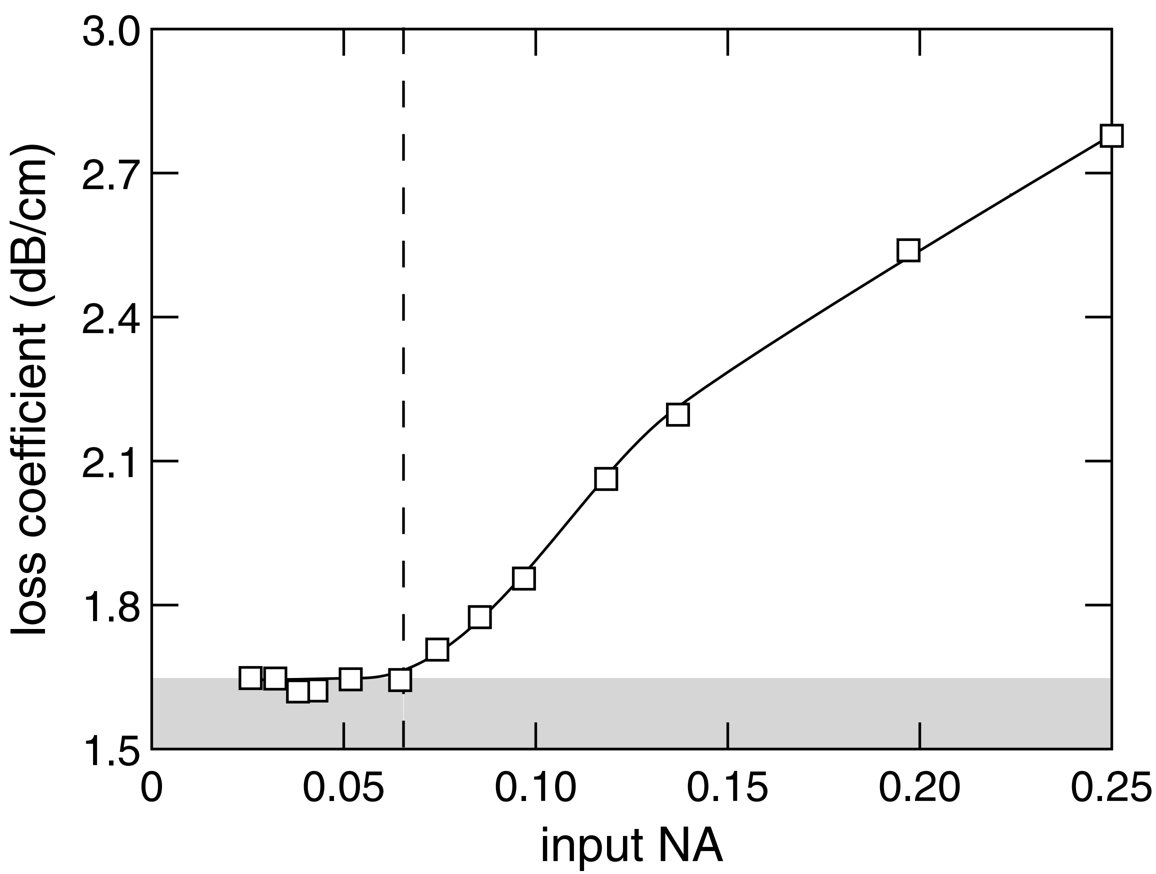
Photonic applications

numerical aperture of waveguide



Photonic applications

numerical aperture of waveguide



Photonic applications

numerical aperture of waveguide

$$NA = \sqrt{{n_1}^2 - {n_2}^2} = 0.065$$

Photonic applications

numerical aperture of waveguide

$$NA = \sqrt{n_1^{\,2} - n_2^{\,2}} = 0.065$$

$$n_2 = 1.52$$

Photonic applications

numerical aperture of waveguide

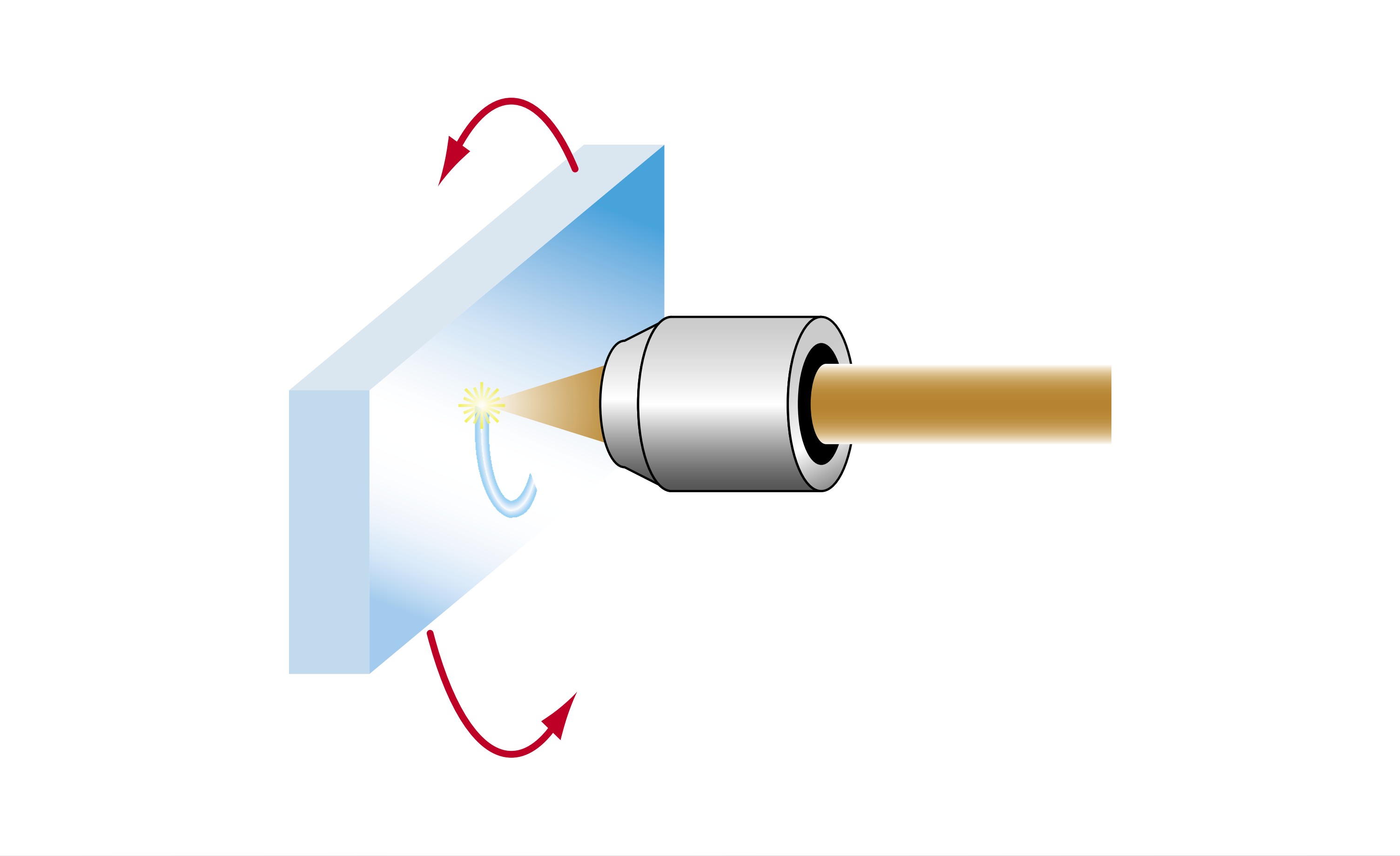
$$NA = \sqrt{n_1{}^2 - n_2{}^2} = 0.065$$

$$n_2 = 1.52$$

$$\Delta n = 1.4 \times 10^{-3}$$

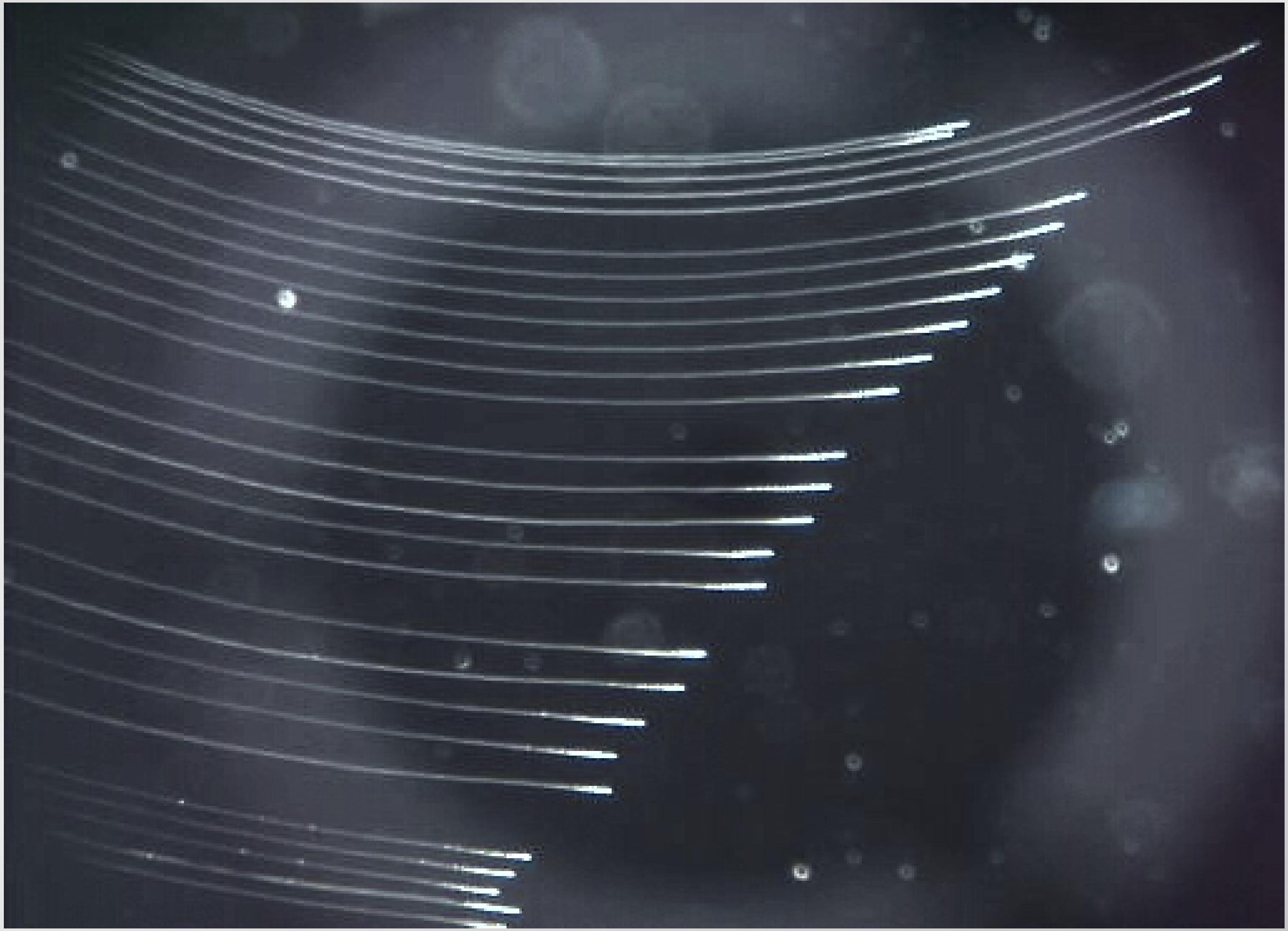
Photonic applications

curved waveguides



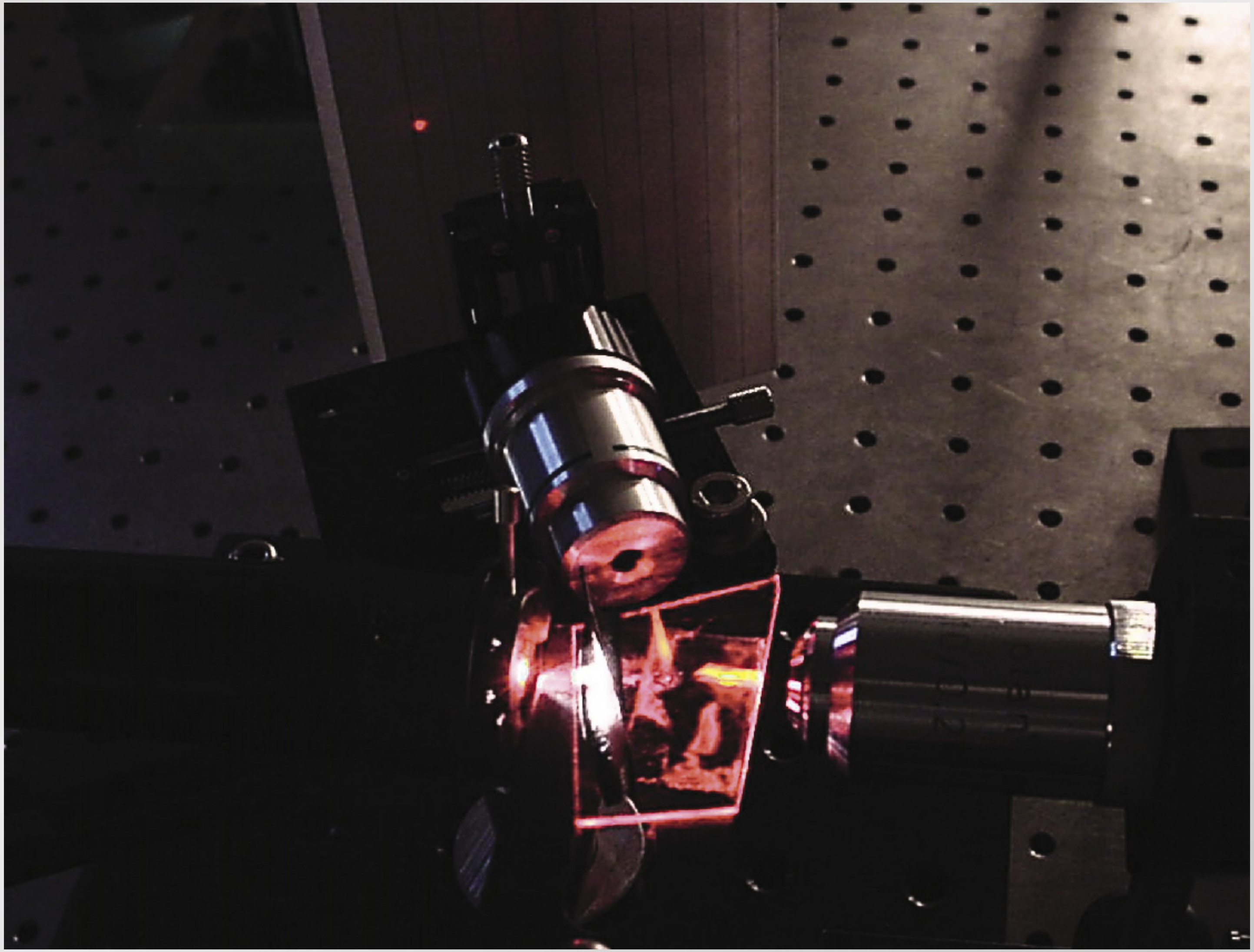
Photonic applications

curved waveguides



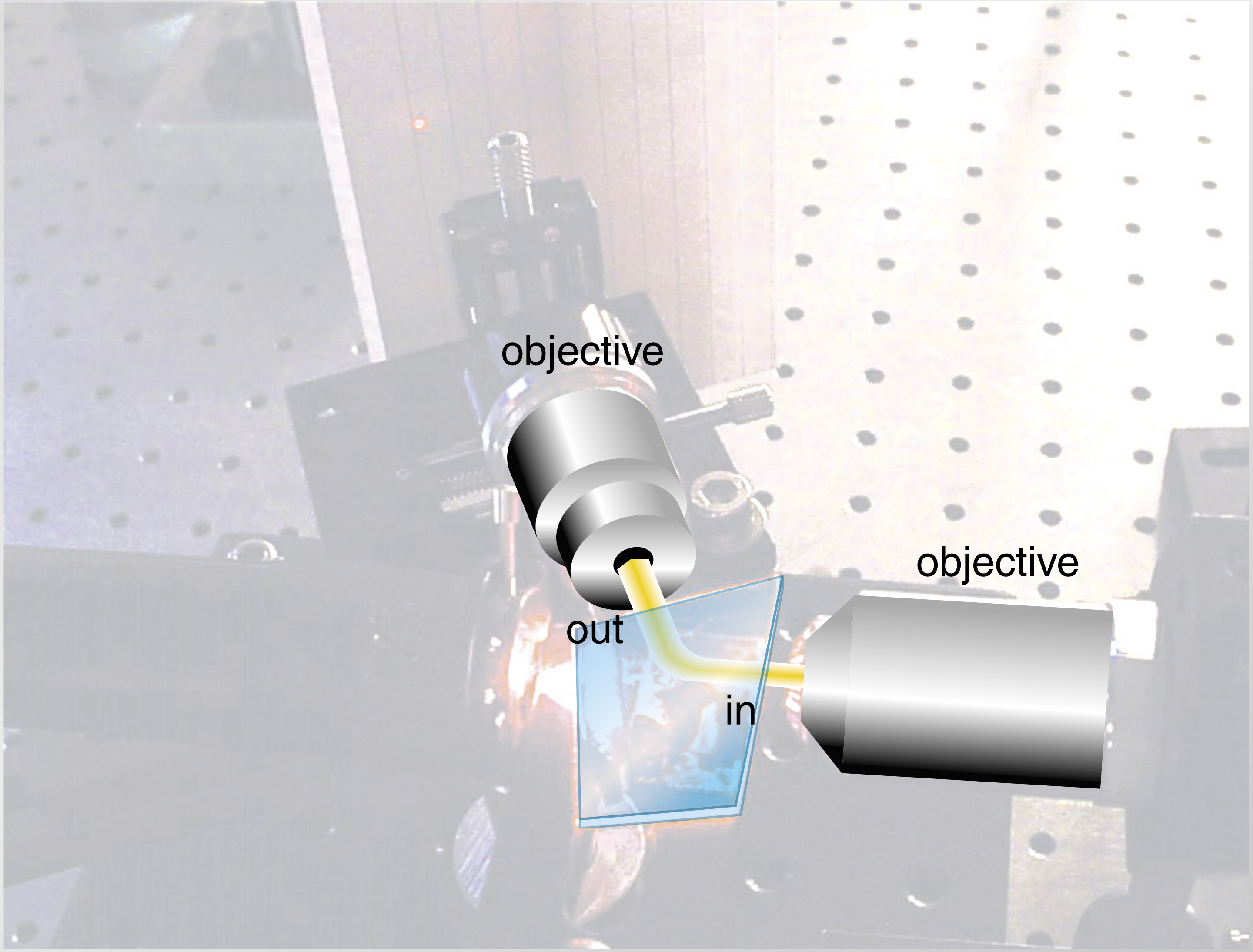
Photonic applications

curved waveguides



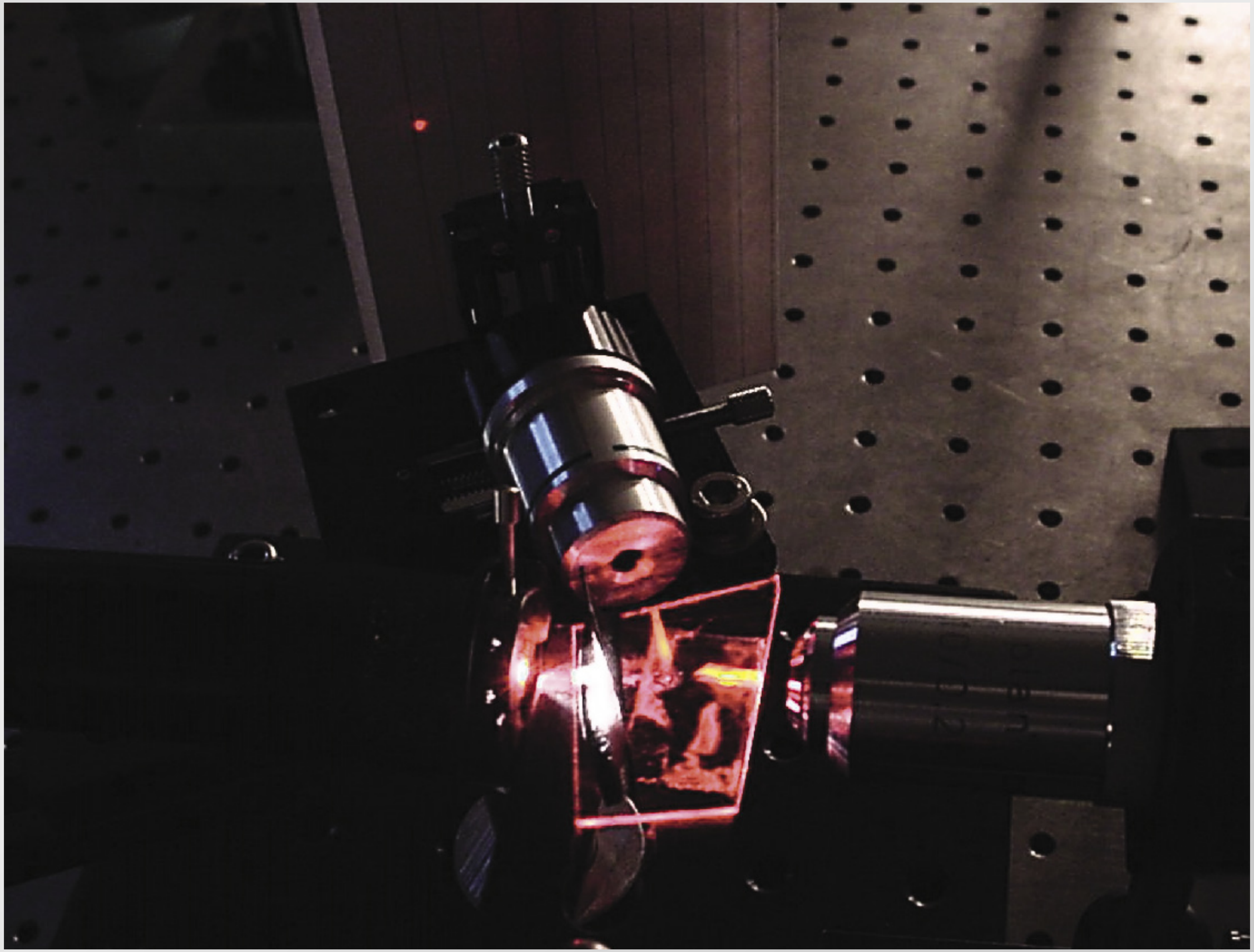
Photonic applications

curved waveguides



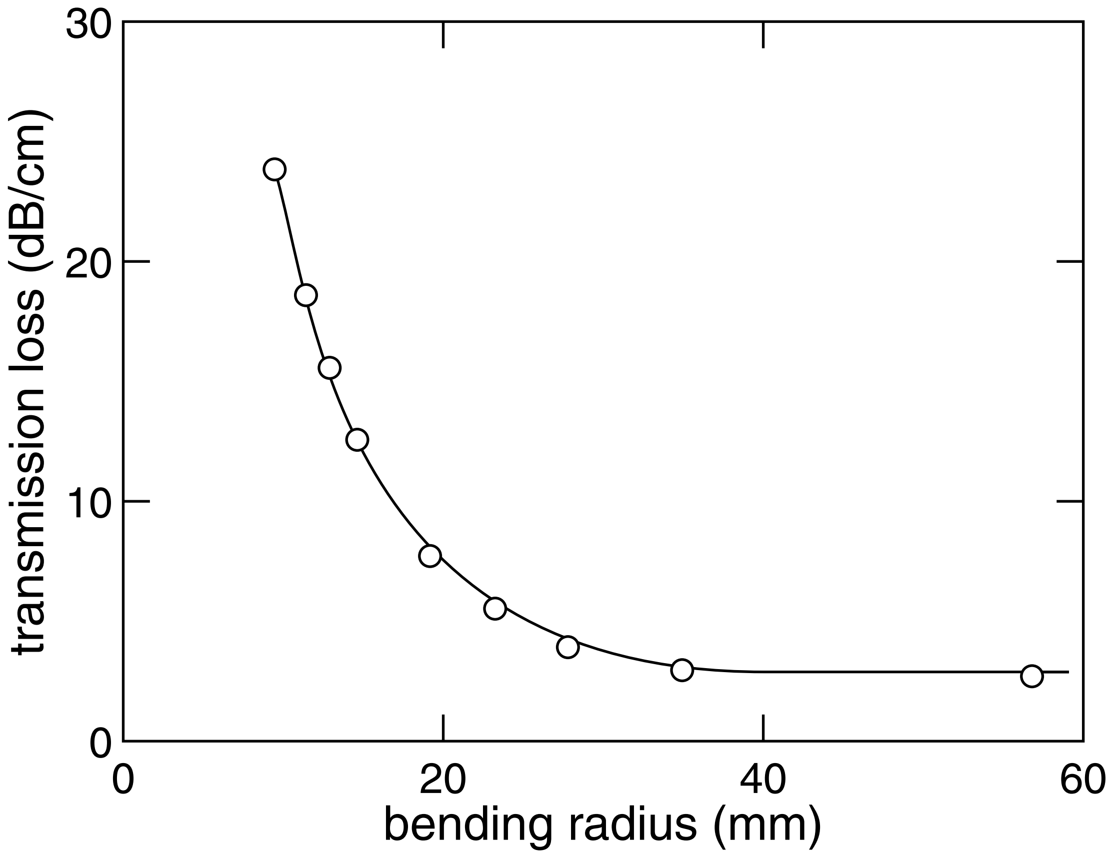
Photonic applications

curved waveguides



Photonic applications

curved waveguides



Photonic applications

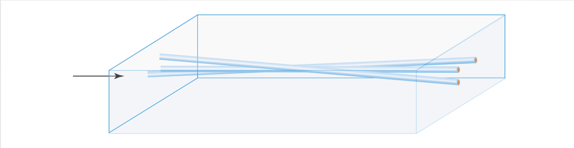
photonic fabrication techniques

	fs micromachining	other
loss (dB/cm)	< 3	0.1–3
bending radius	36 mm	30–40 mm
Δn	2×10^{-3}	10^{-4} – 0.5
3D integration	Y	N

Photonic applications

photonic devices

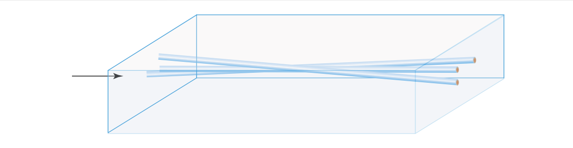
3D splitter



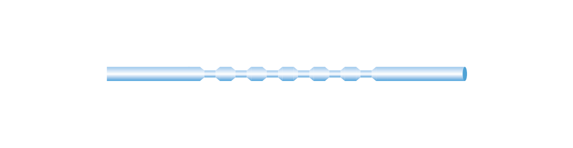
Photonic applications

photonic devices

3D splitter

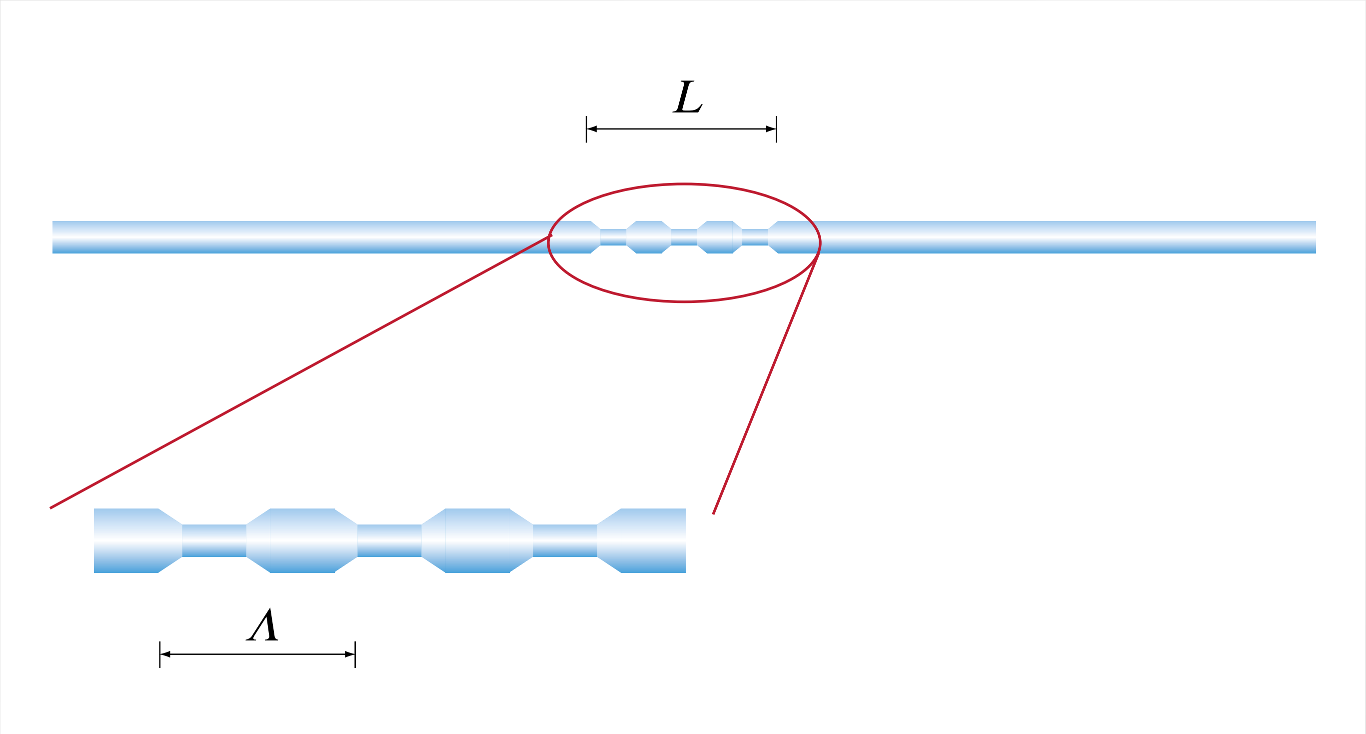


Bragg grating



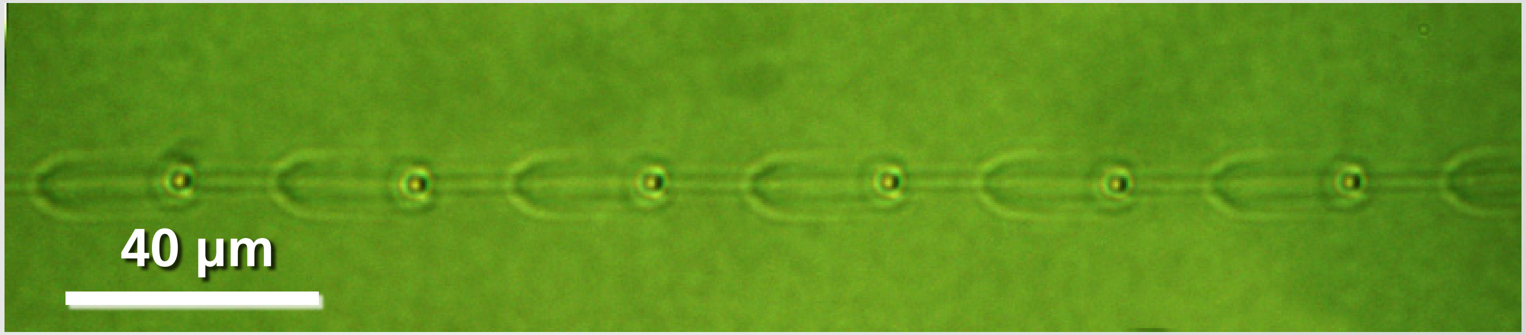
Photonic applications

Bragg grating



Photonic applications

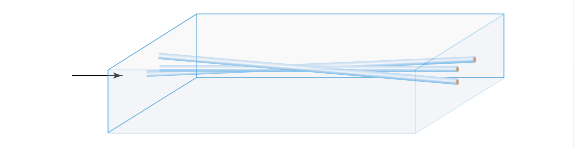
Bragg grating



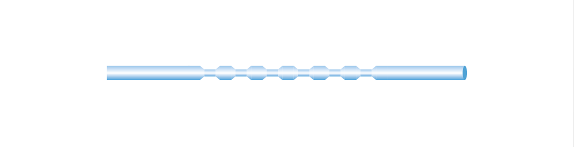
Photonic applications

photonic devices

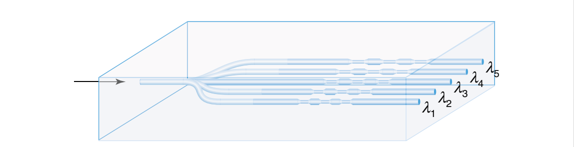
3D splitter



Bragg grating



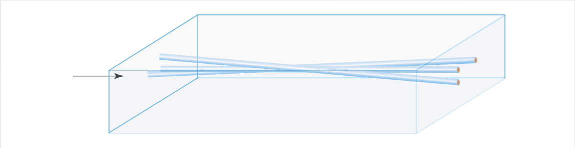
demultiplexer



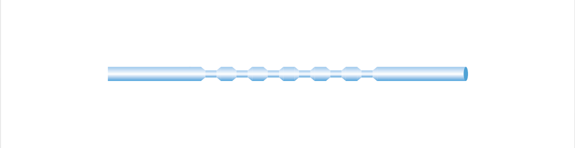
Photonic applications

photonic devices

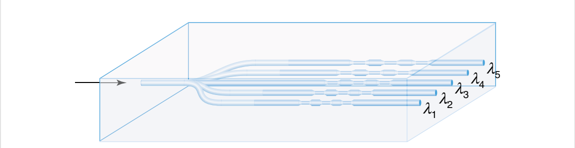
3D splitter



Bragg grating



demultiplexer

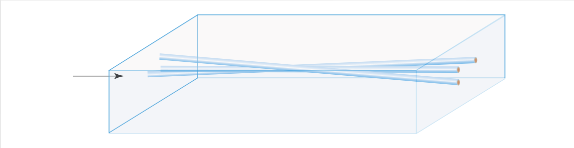


amplifier

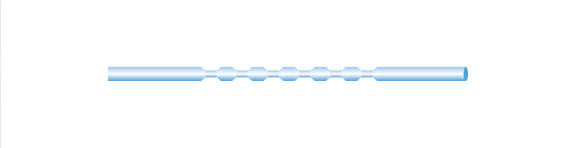
Photonic applications

photonic devices

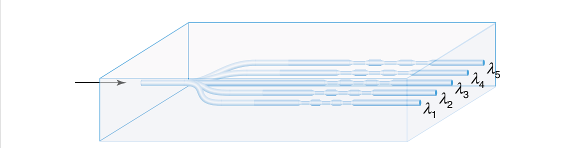
3D splitter



Bragg grating

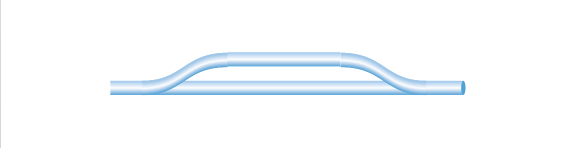


demultiplexer



amplifier

interferometer



Summary

- two regimes: low and high repetition rate
- high-repetition rate (thermal) machining fast, convenient
- many devices already realized

Conclusion

major step towards realization of optical integrated circuits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