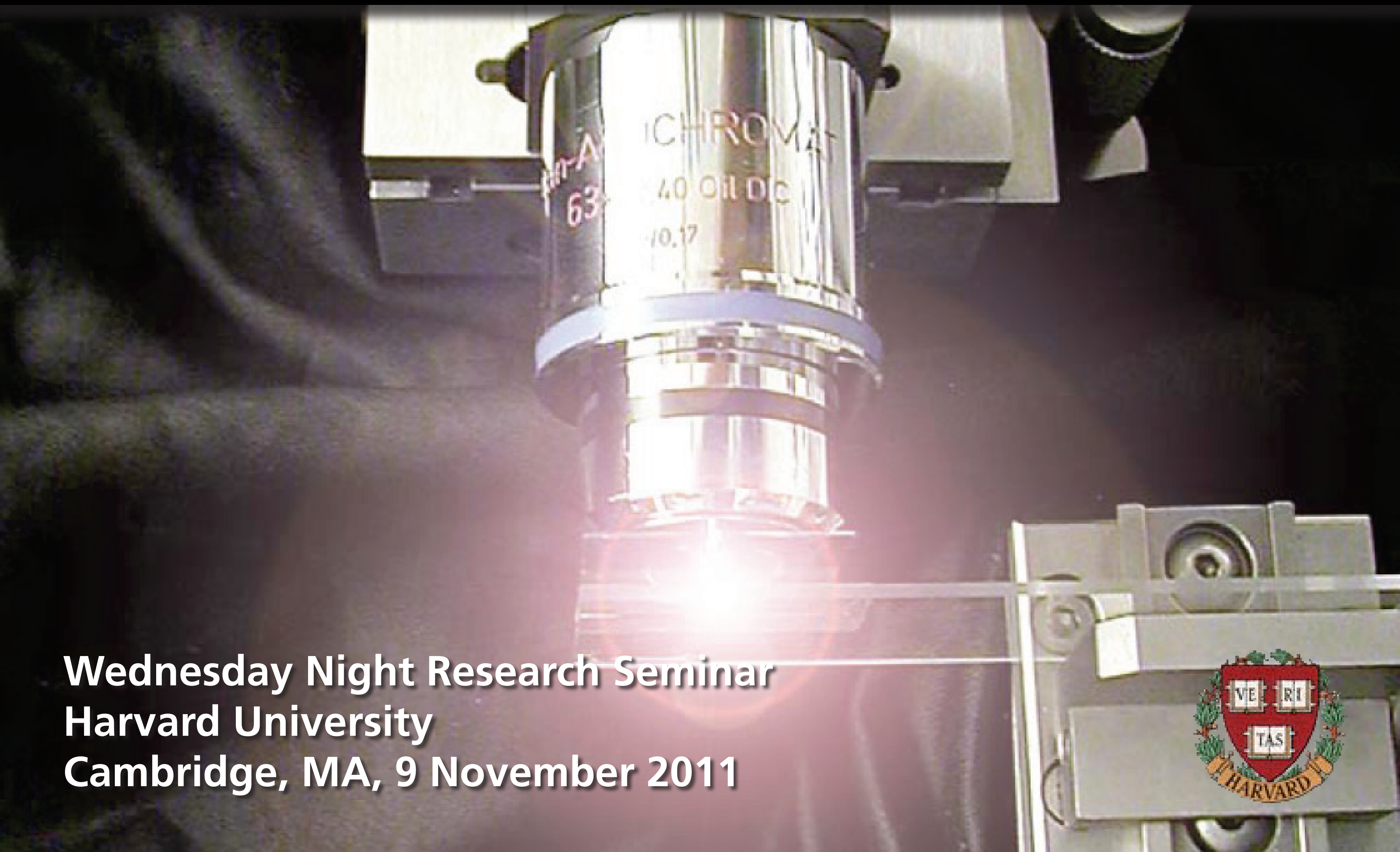
Manipulating Matter with Ultrashort Laser Pulses

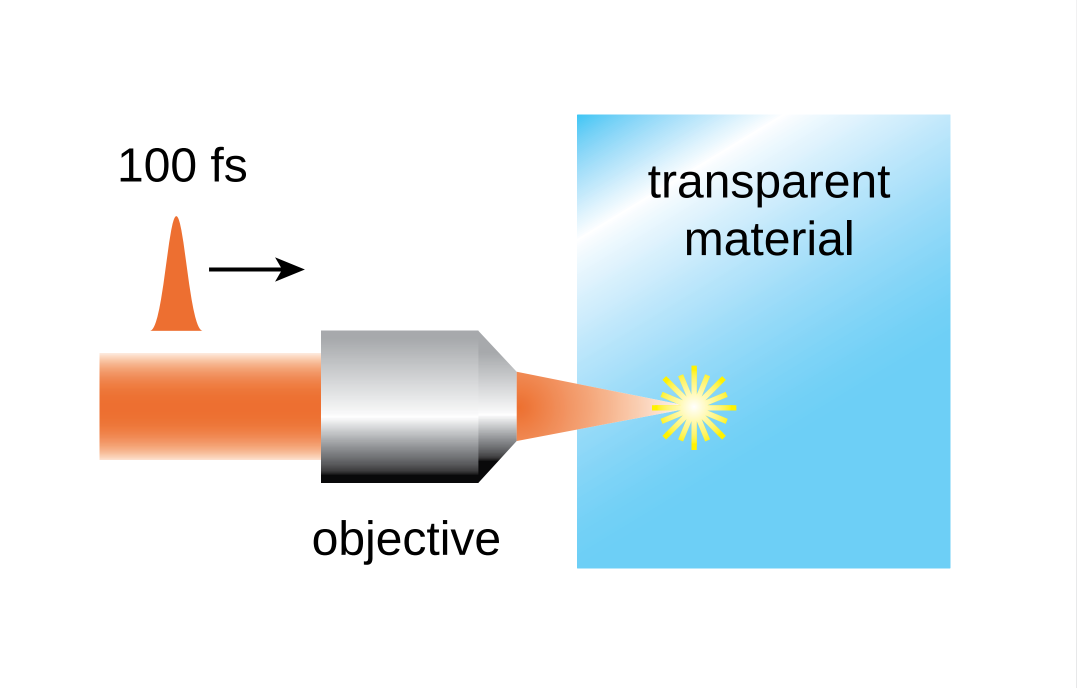


Wednesday Night Research Seminar
Harvard University
Cambridge, MA, 9 November 2011

Introduction

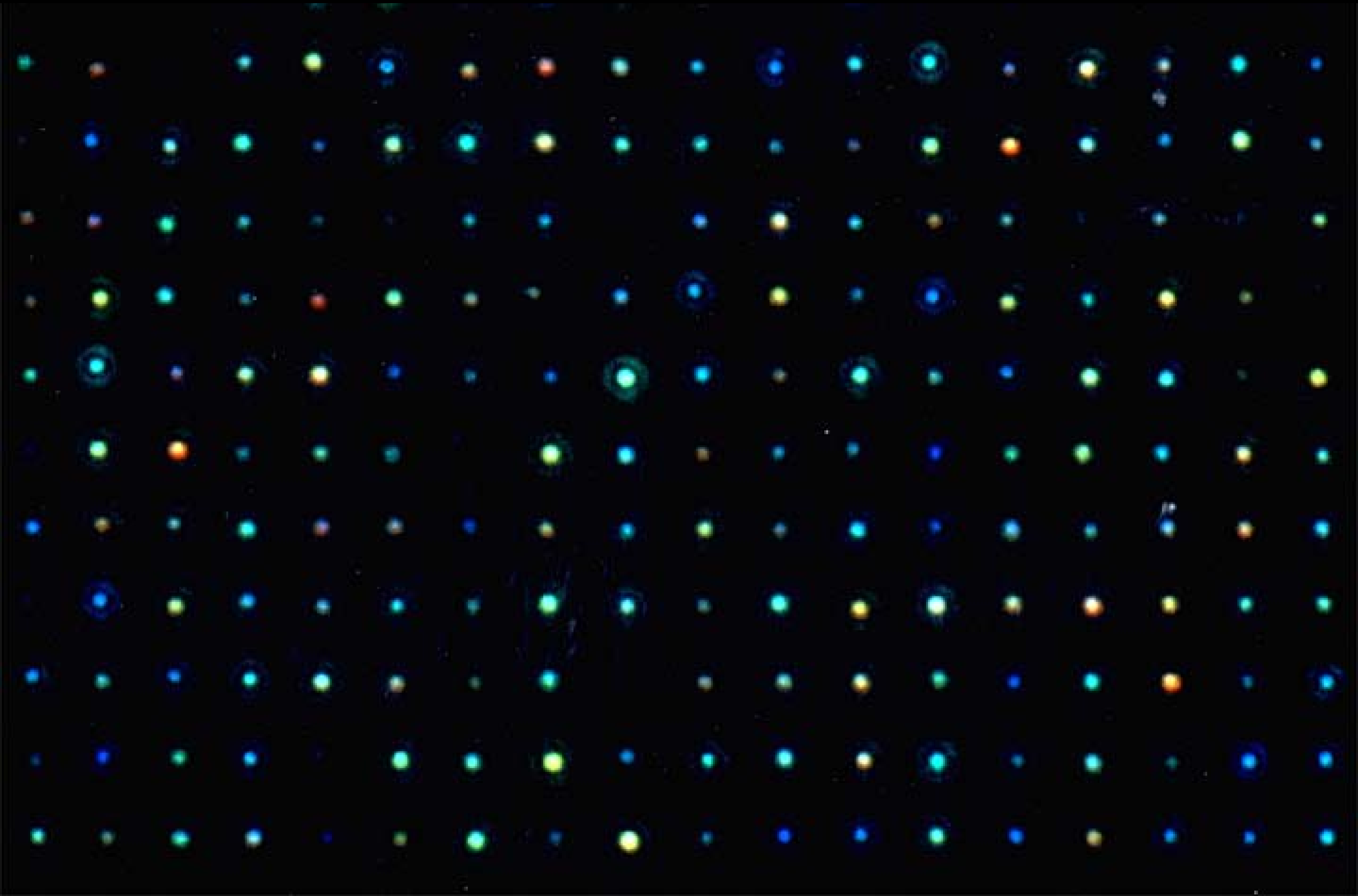
Introduction

focus laser beam inside material



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

Introduction

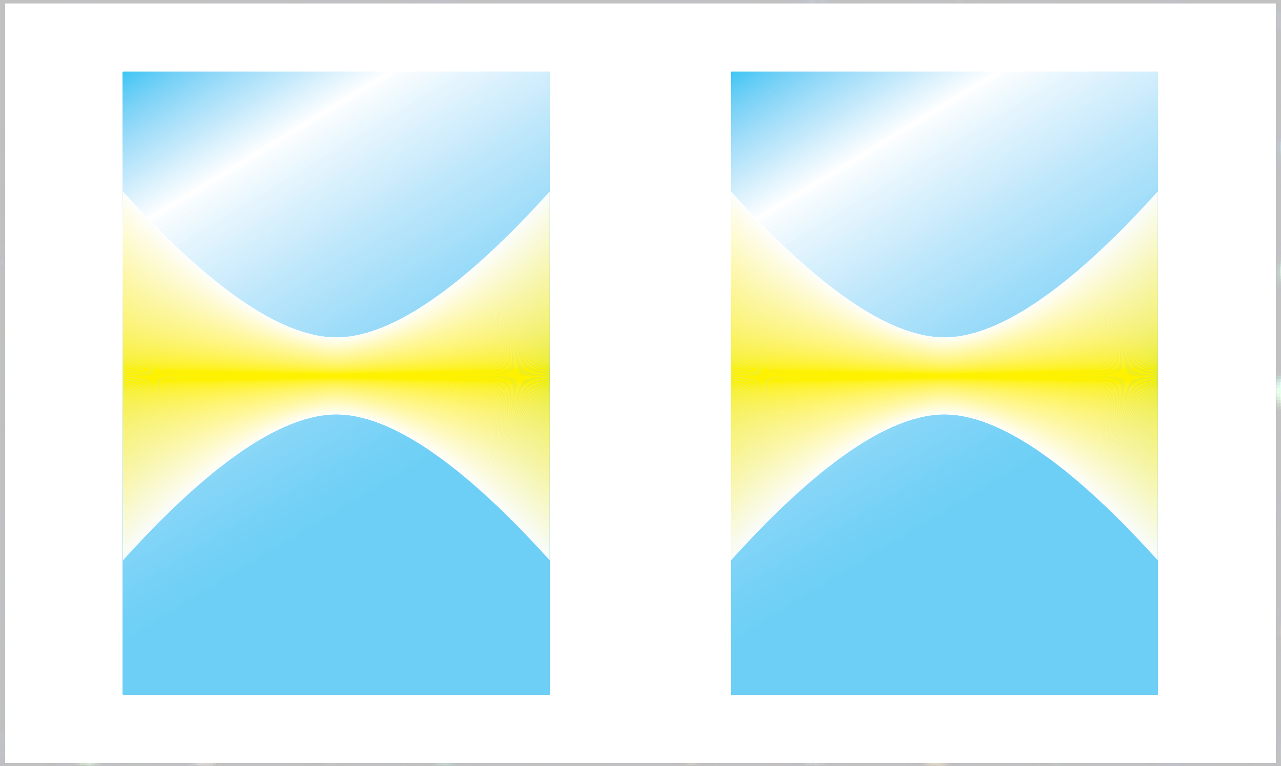


Introduction

photon energy < bandgap ⟶ nonlinear interaction

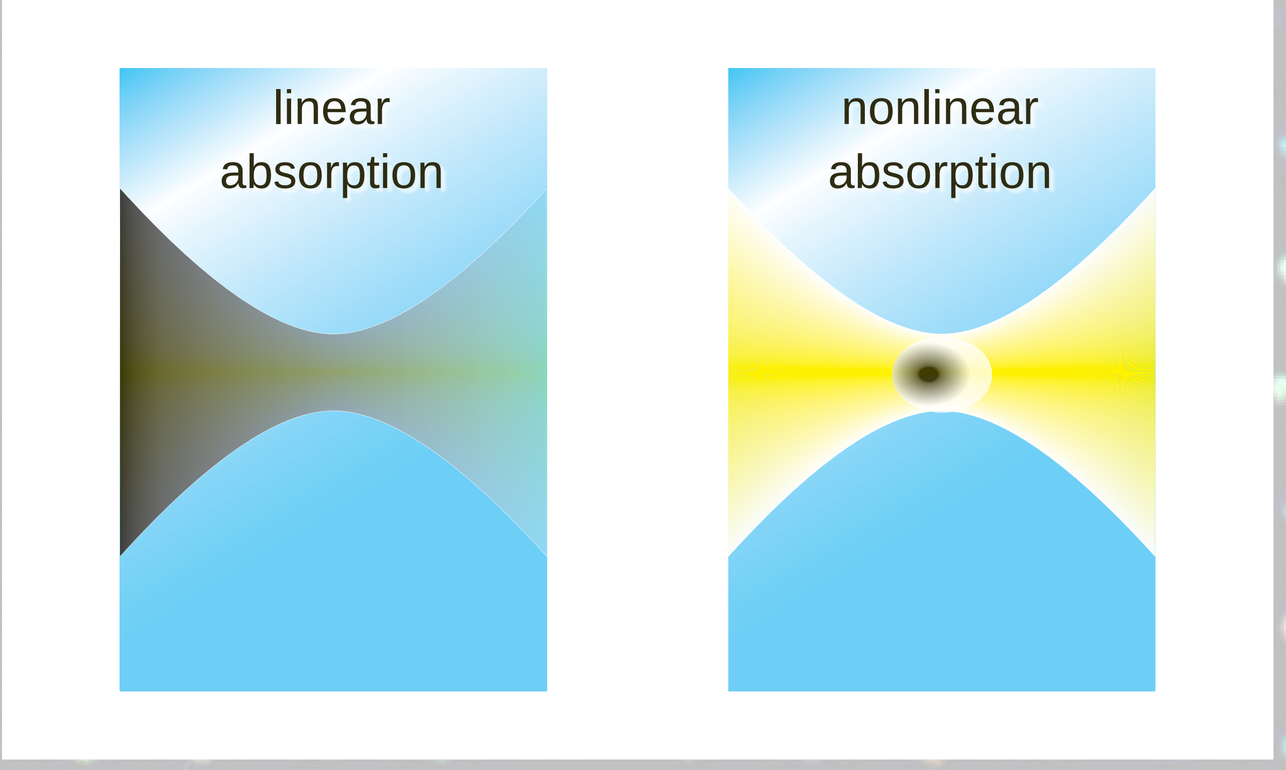
Introduction

nonlinear interaction provides bulk confinement



Introduction

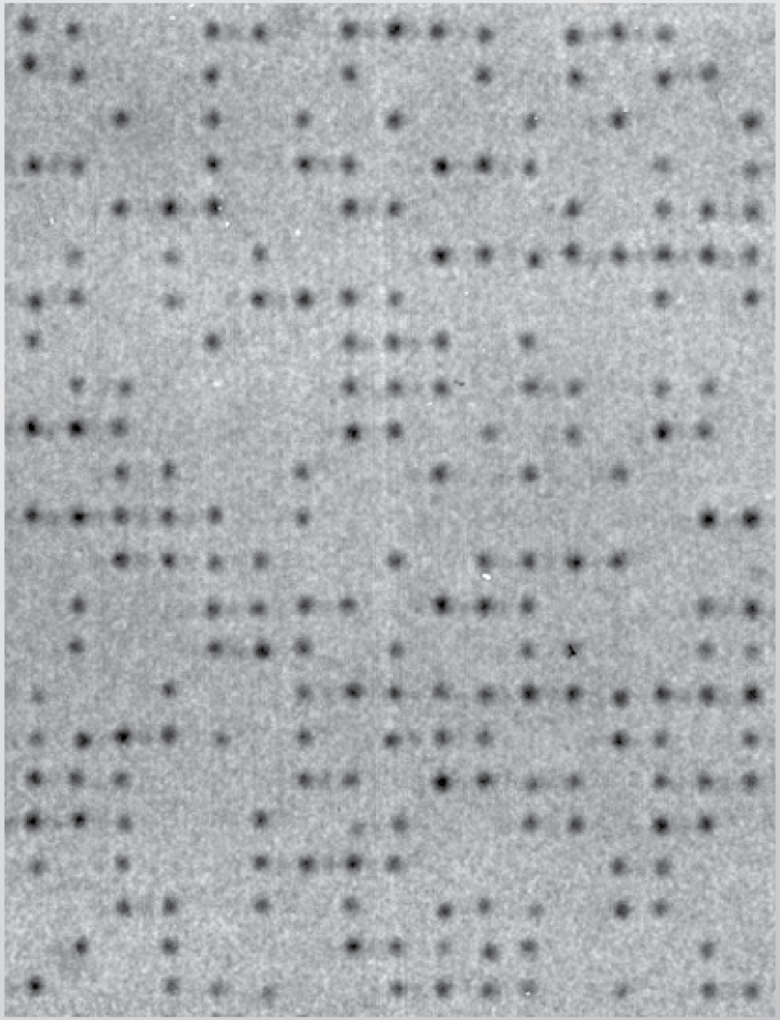
nonlinear interaction provides bulk confinement



Femtosecond micromachining

Some applications:

- data storage
- waveguides
- microfluidics

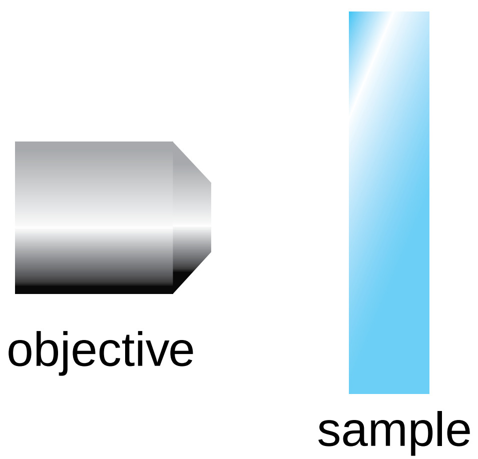


Outline

- femtosecond micromachining
- low-energy machining
- applications

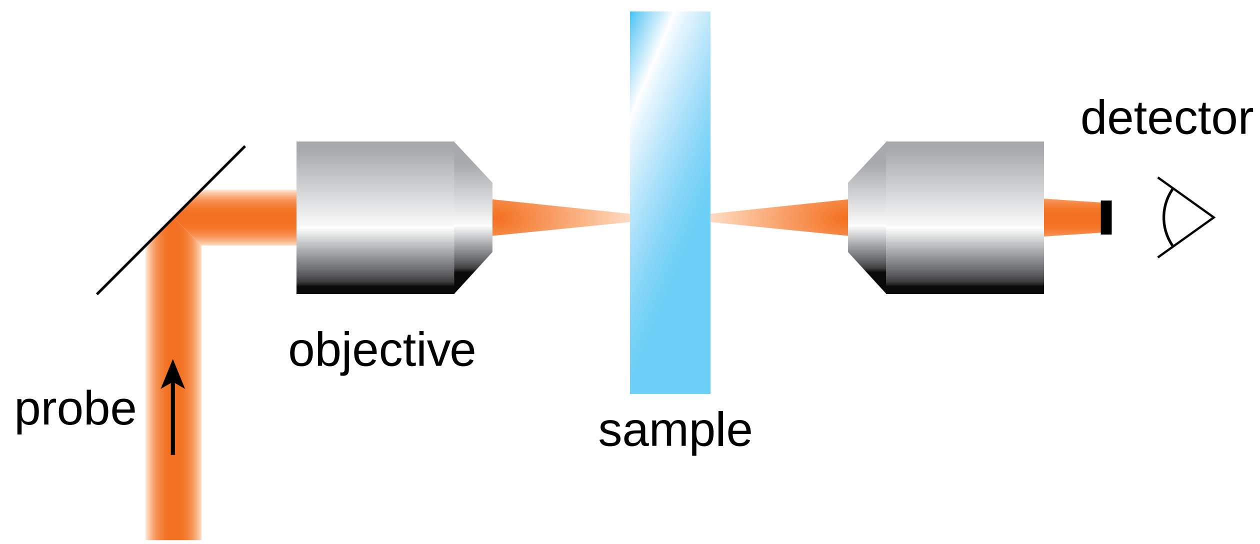
Femtosecond micromachining

Dark-field scattering



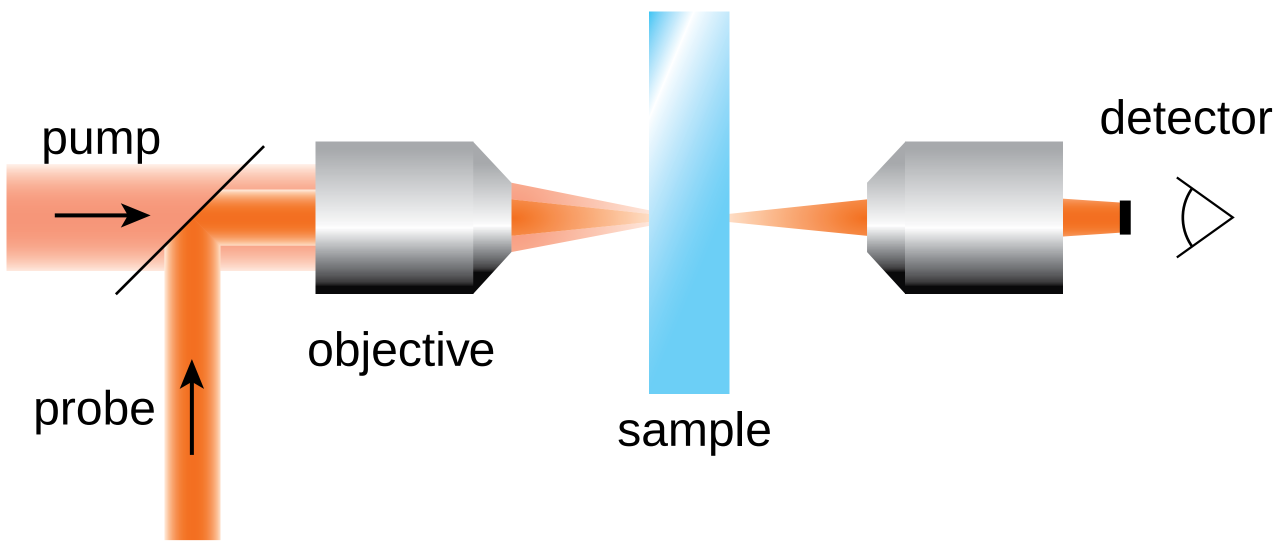
Femtosecond micromachining

block probe beam…



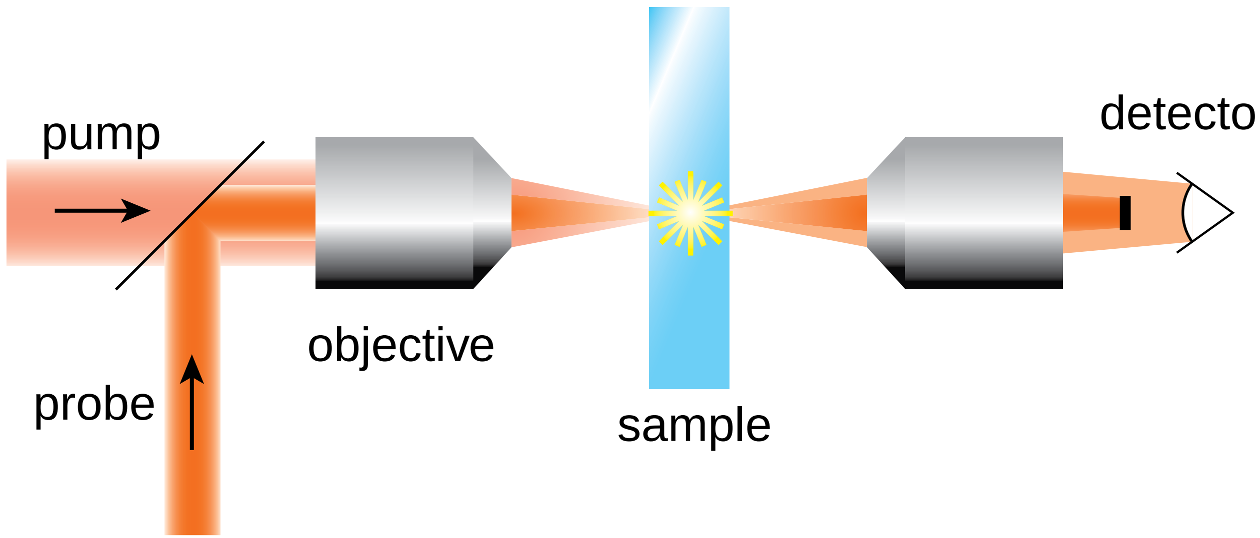
Femtosecond micromachining

… bring in pump beam…



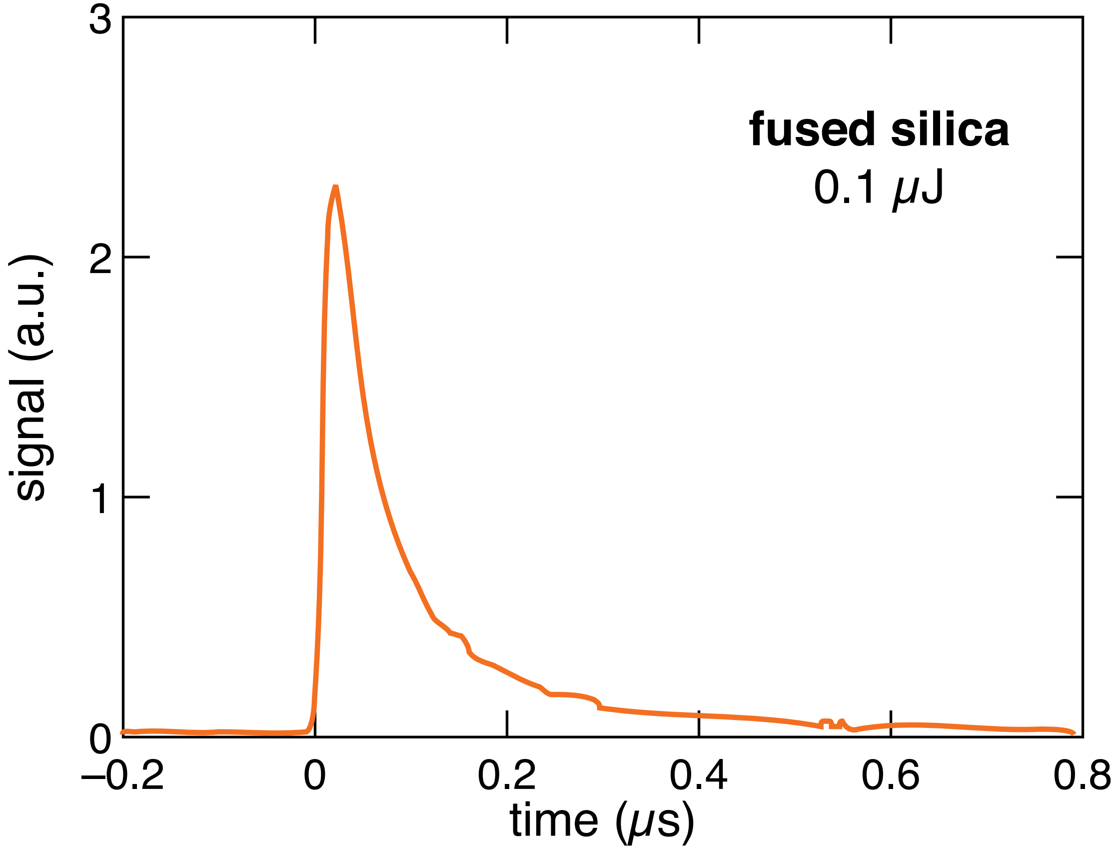
Femtosecond micromachining

... damage scatters probe beam



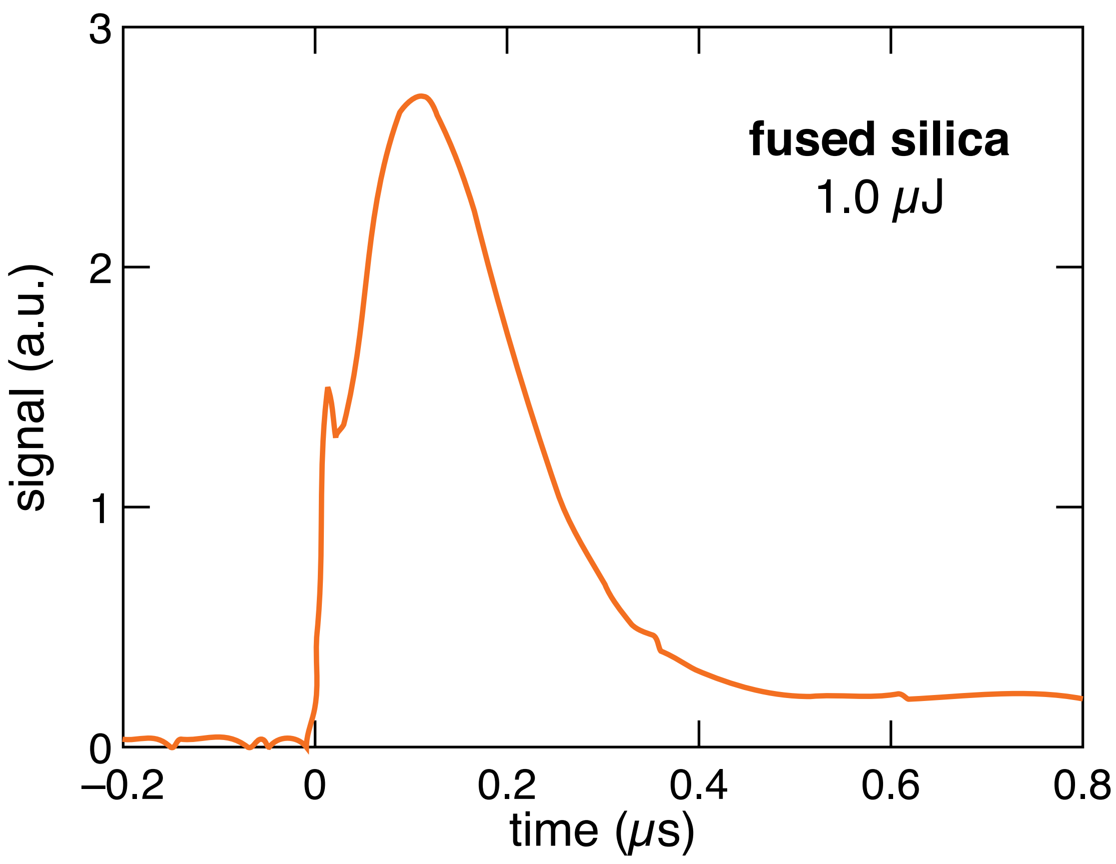
Femtosecond micromachining

scattered signal



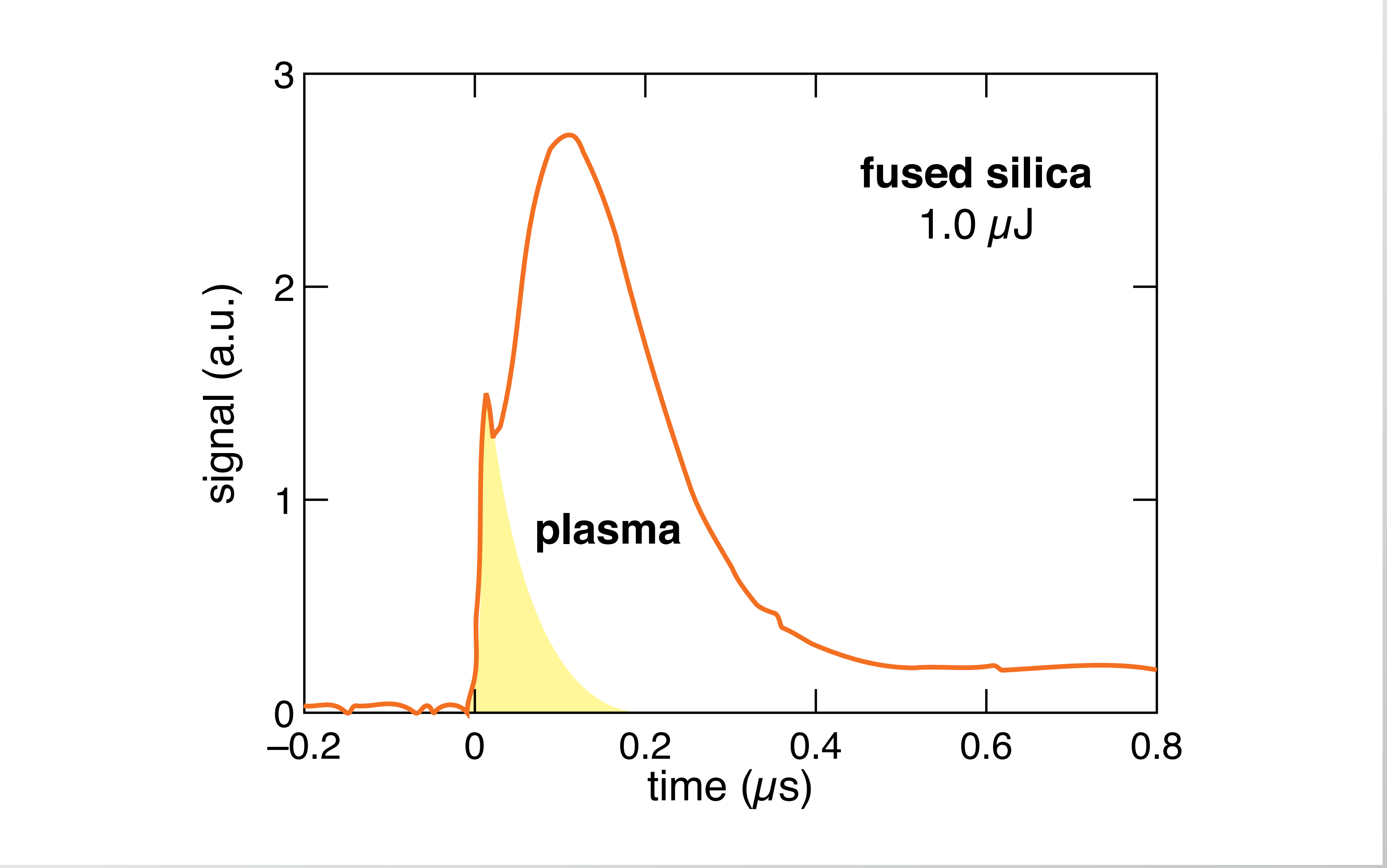
Femtosecond micromachining

scattered signal



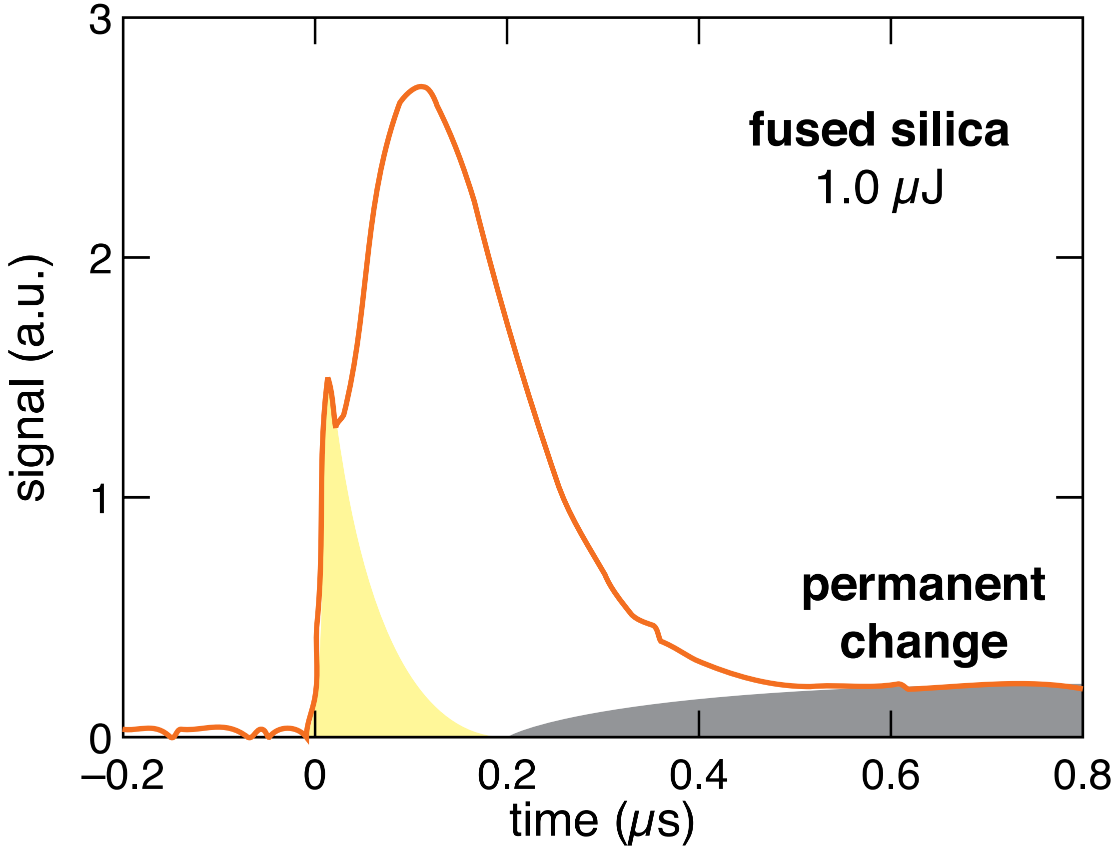
Femtosecond micromachining

scattered signal



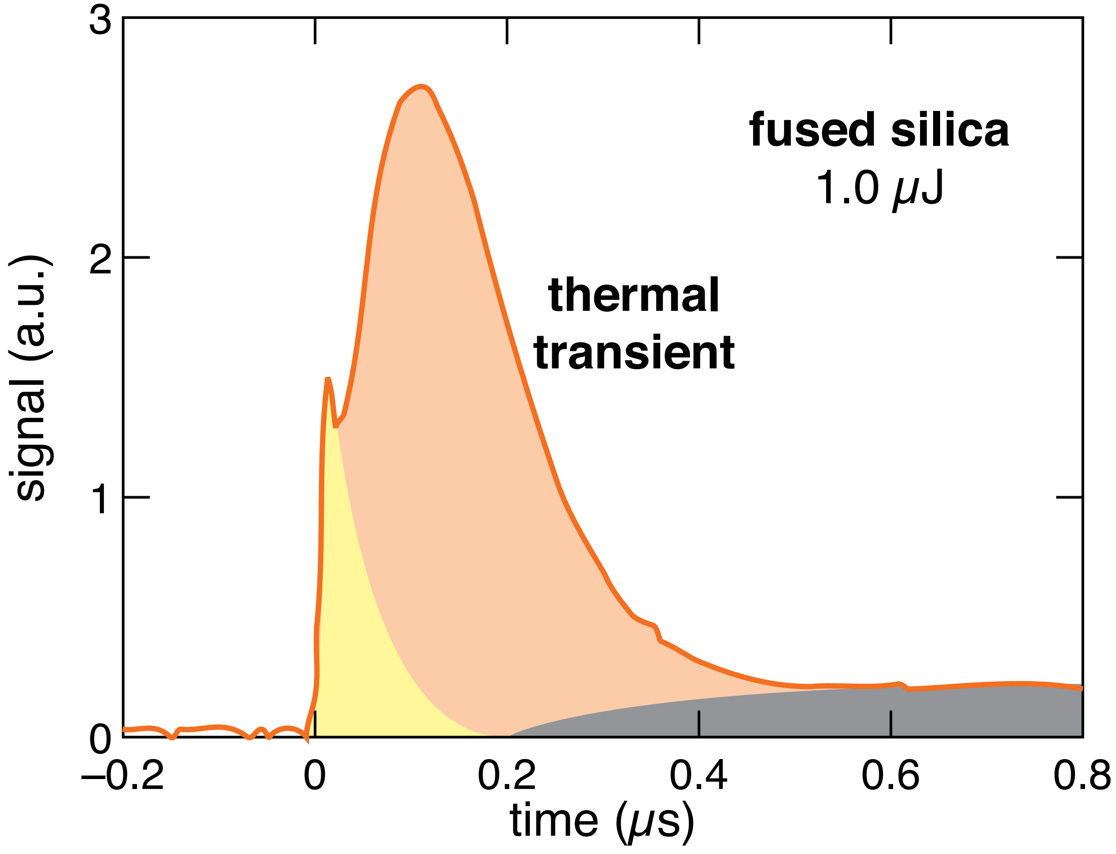
Femtosecond micromachining

scattered signal



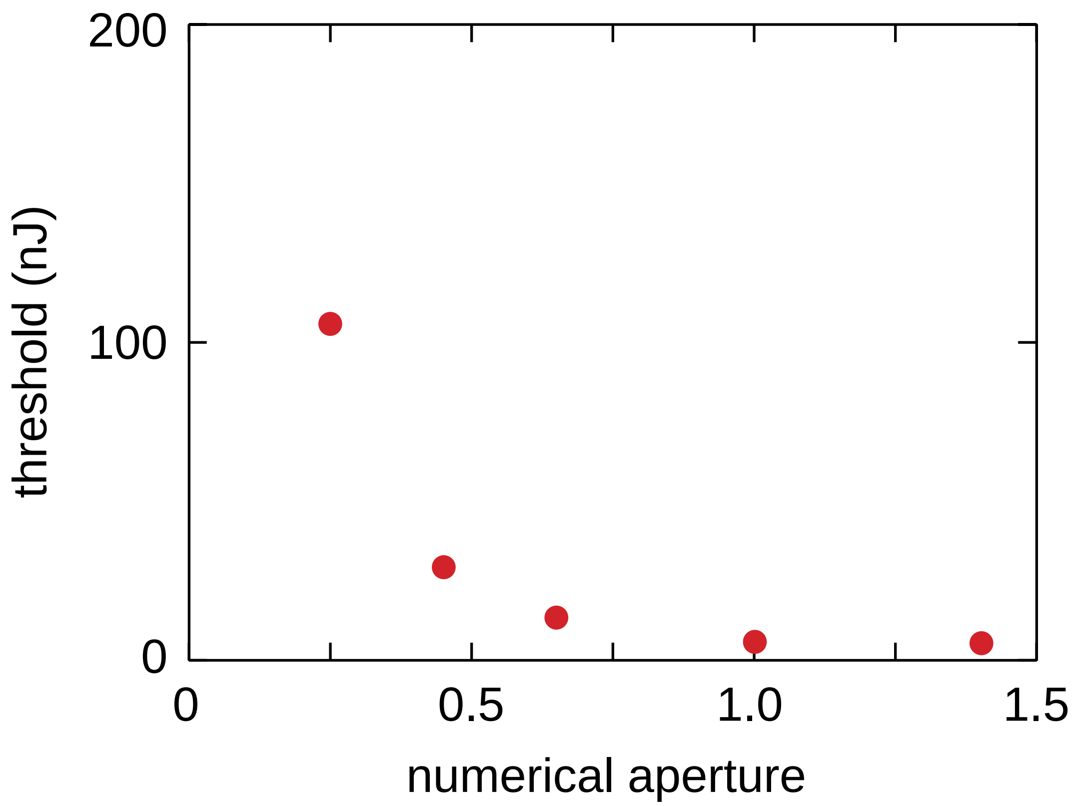
Femtosecond micromachining

scattered signal



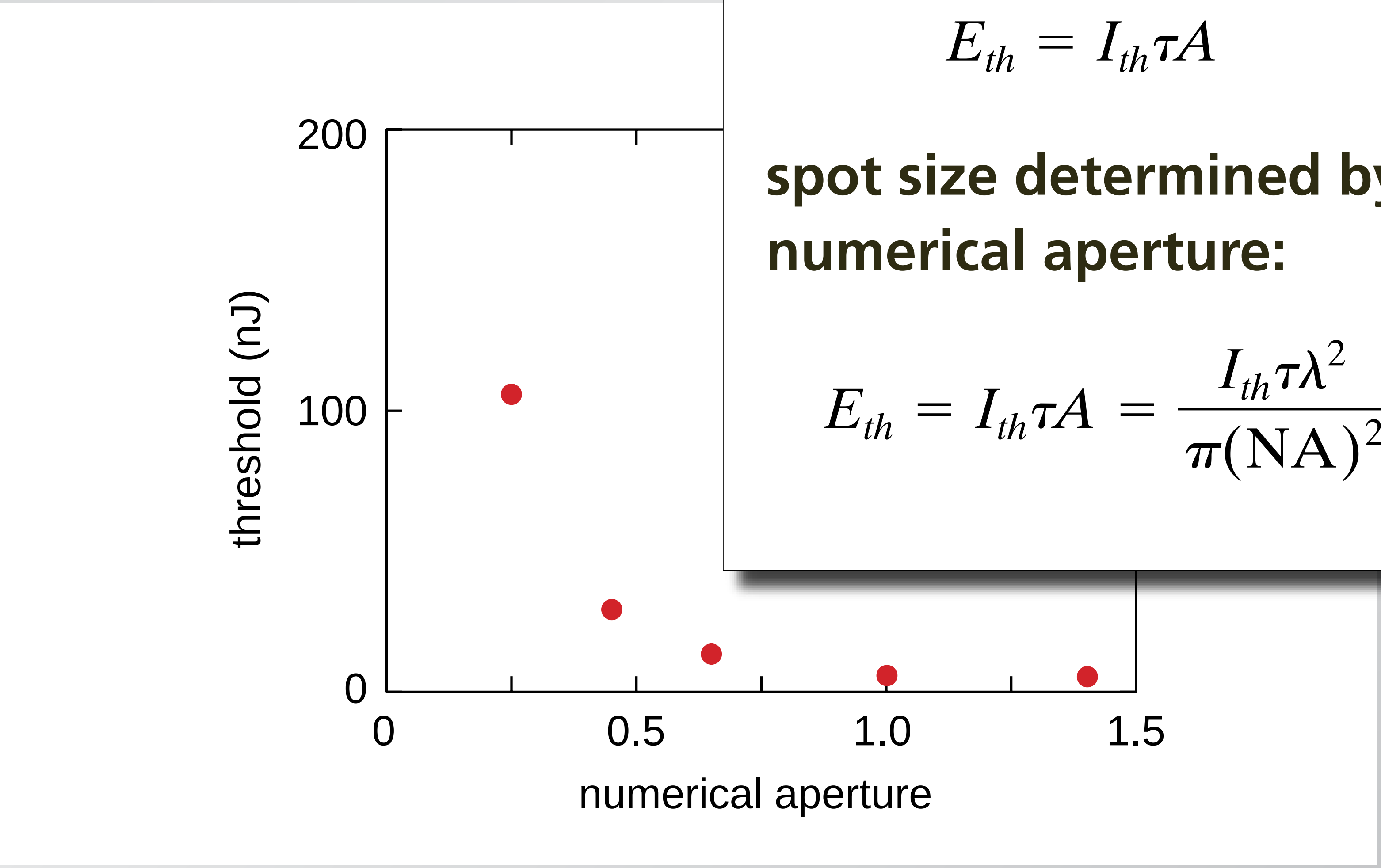
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

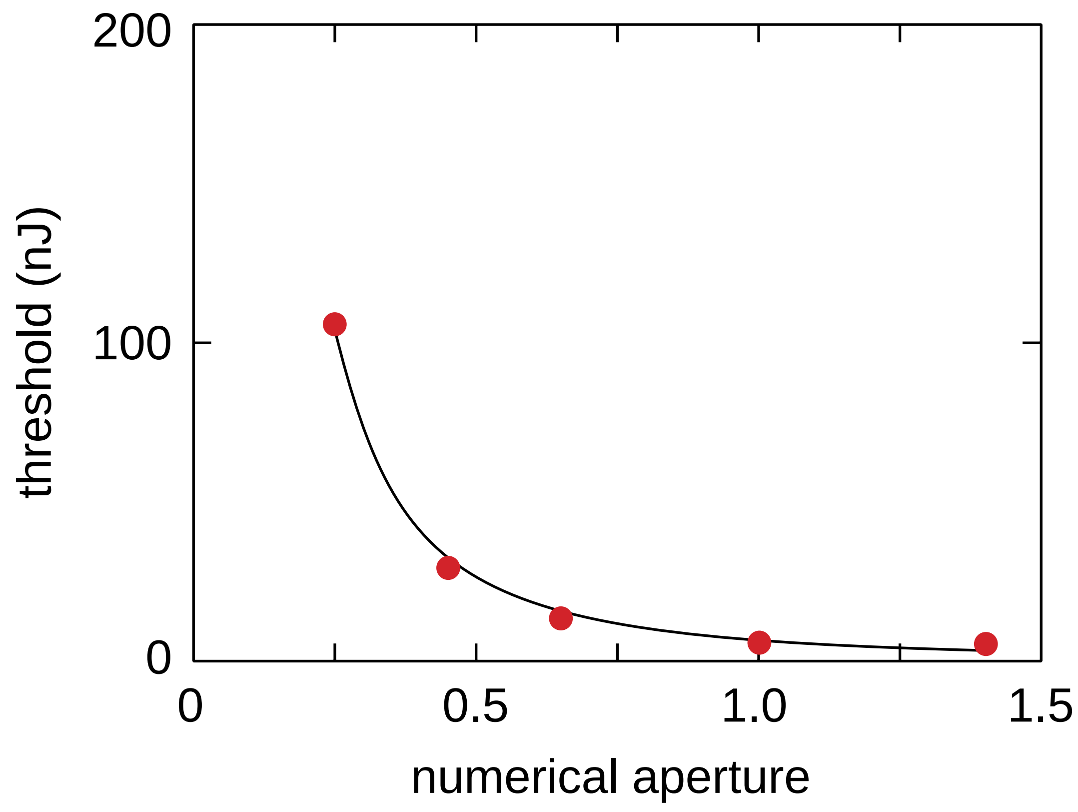
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

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

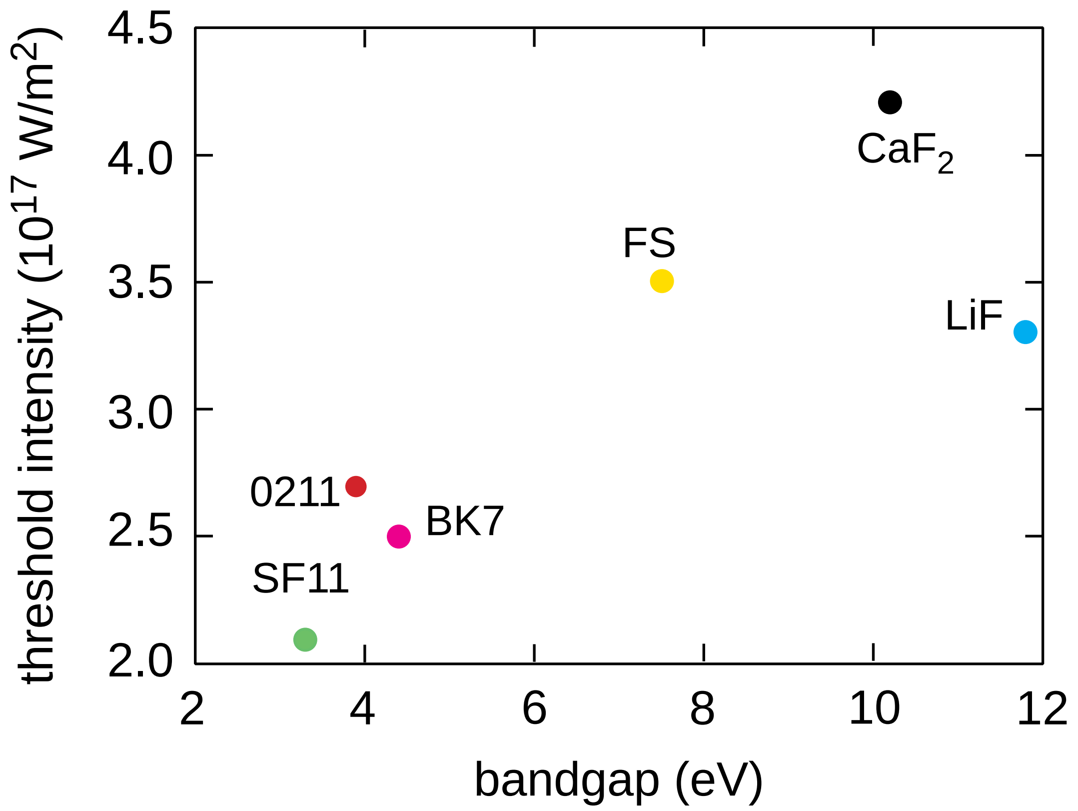
Femtosecond micromachining

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



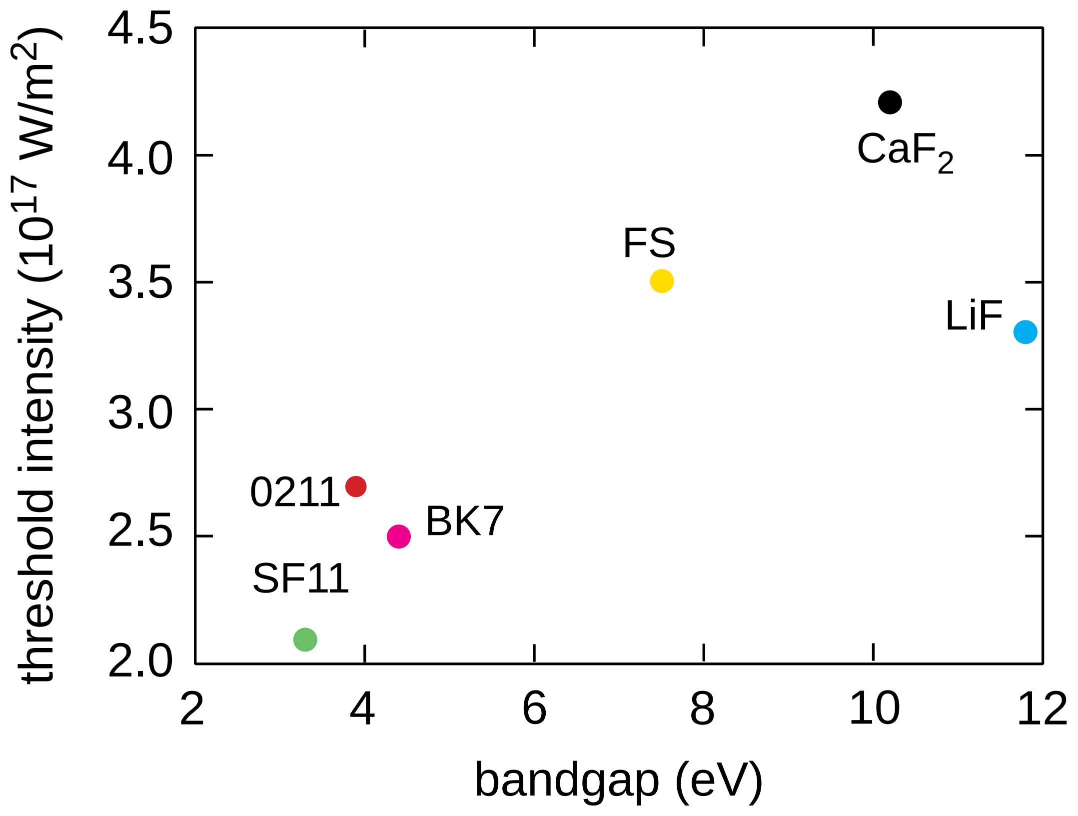
Femtosecond micromachining

vary material…



Femtosecond micromachining

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



Femtosecond micromachining

what prevents damage at low NA?

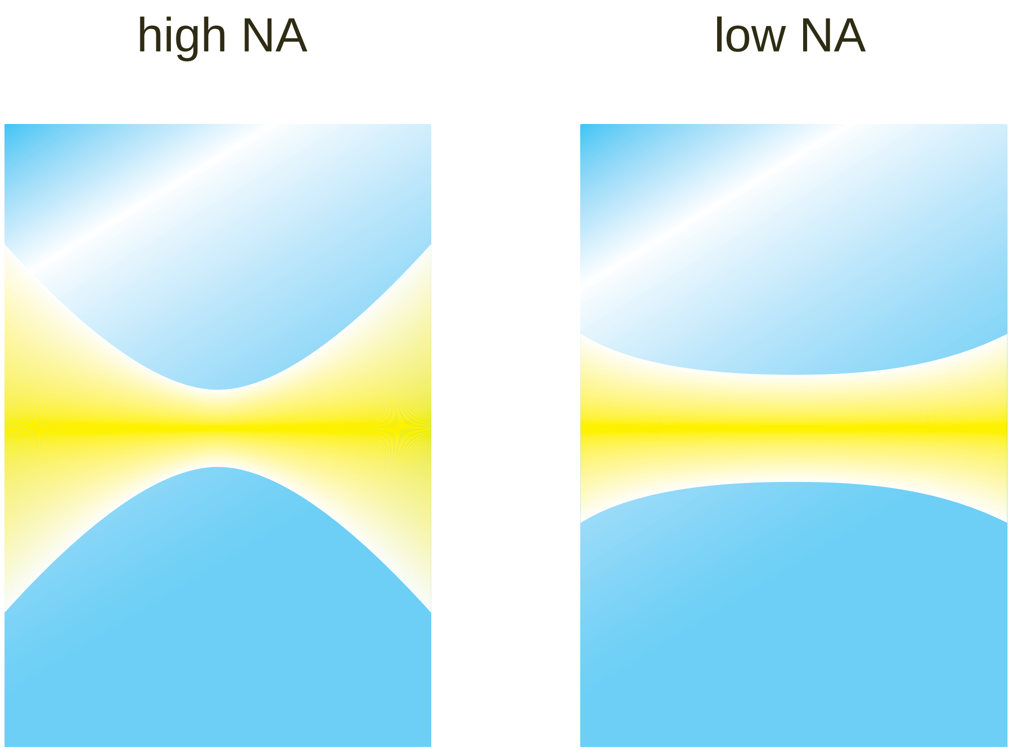
Femtosecond micromachining

Competing nonlinear effects:

- multiphoton absorption
- supercontinuum generation
- self-focusing

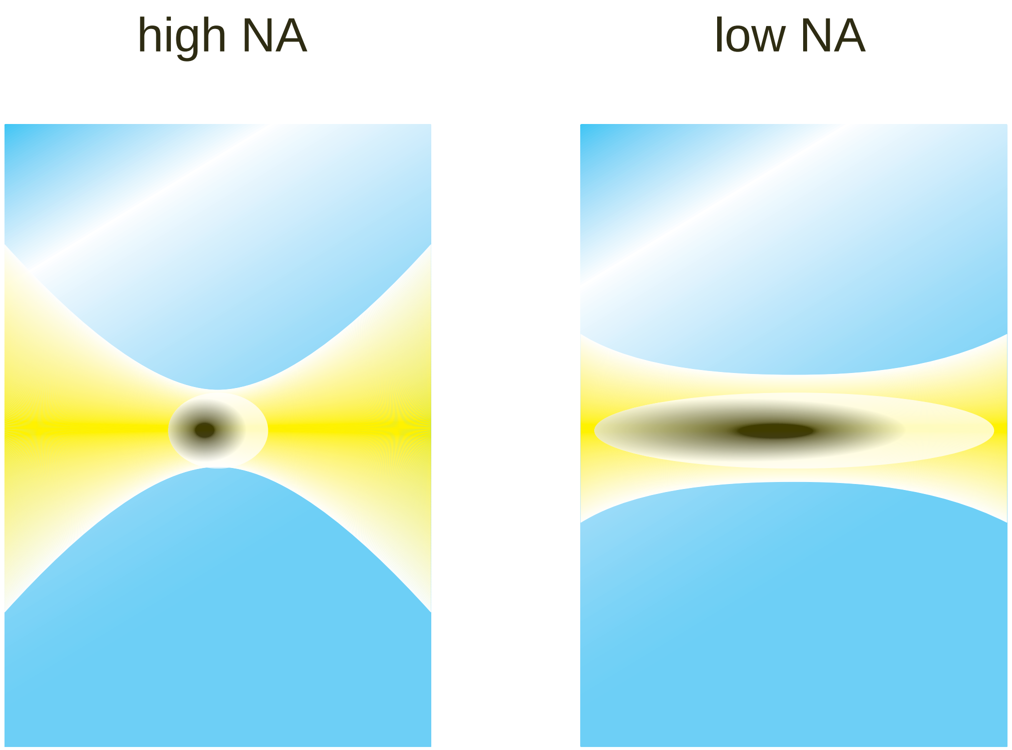
Femtosecond micromachining

why the difference?



Femtosecond micromachining

very different confocal length/interaction length

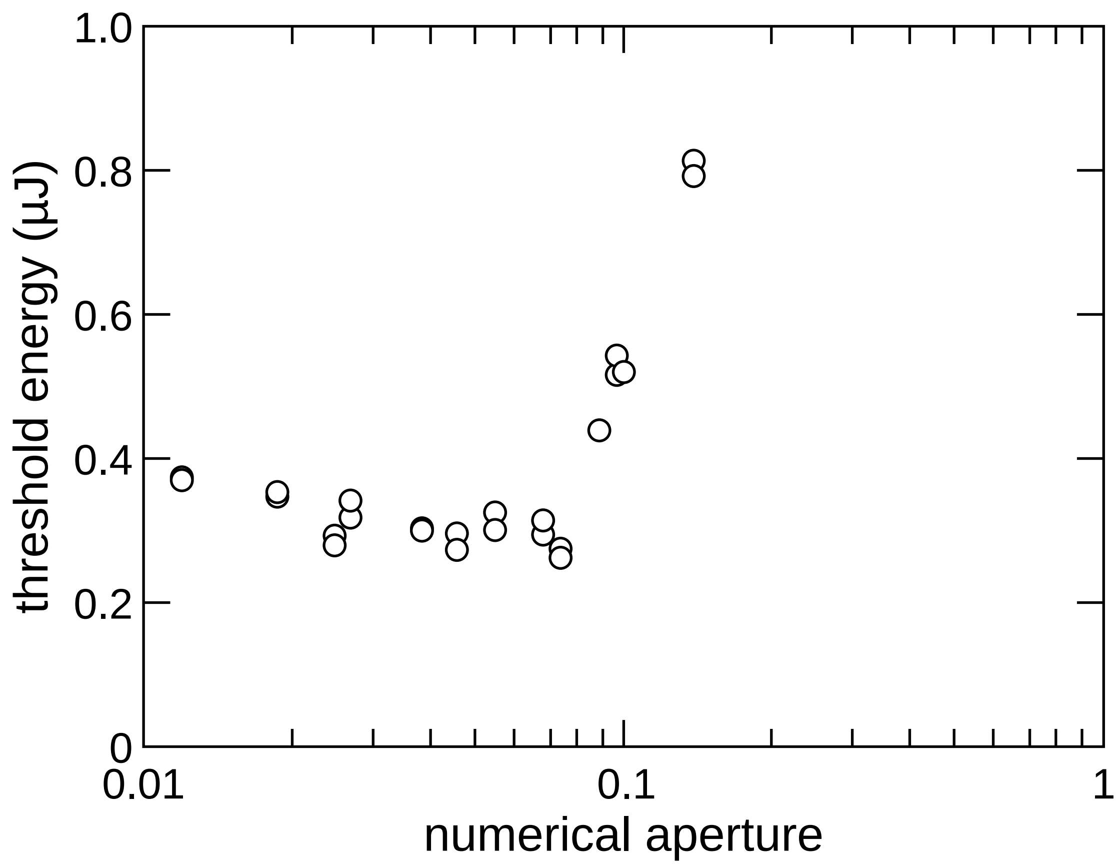


Femtosecond micromachining

high NA: interaction length too short for self-focusing

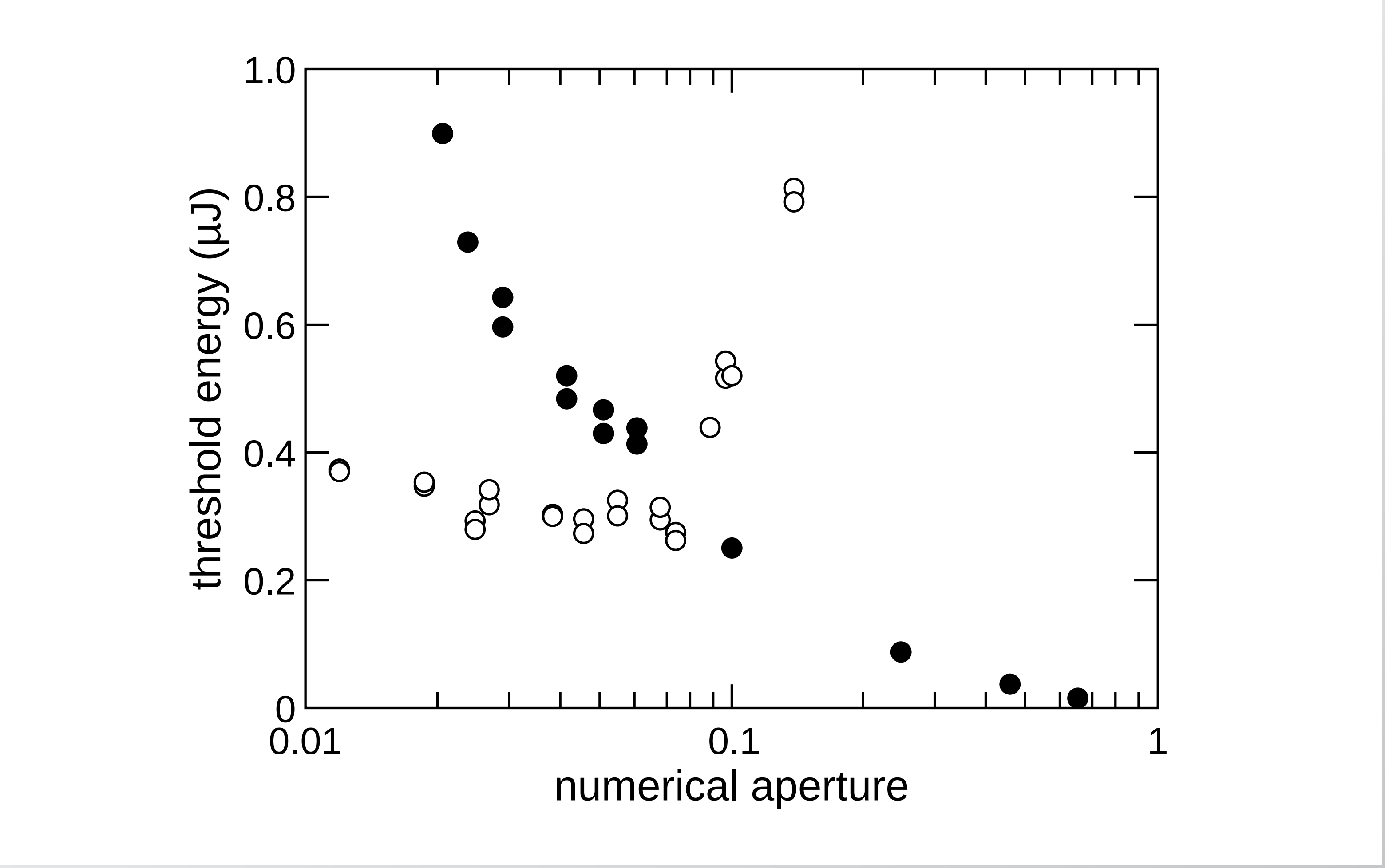
Femtosecond micromachining

threshold for supercontinuum generation



Femtosecond micromachining

threshold for damage



Femtosecond micromachining

Points to keep in mind:

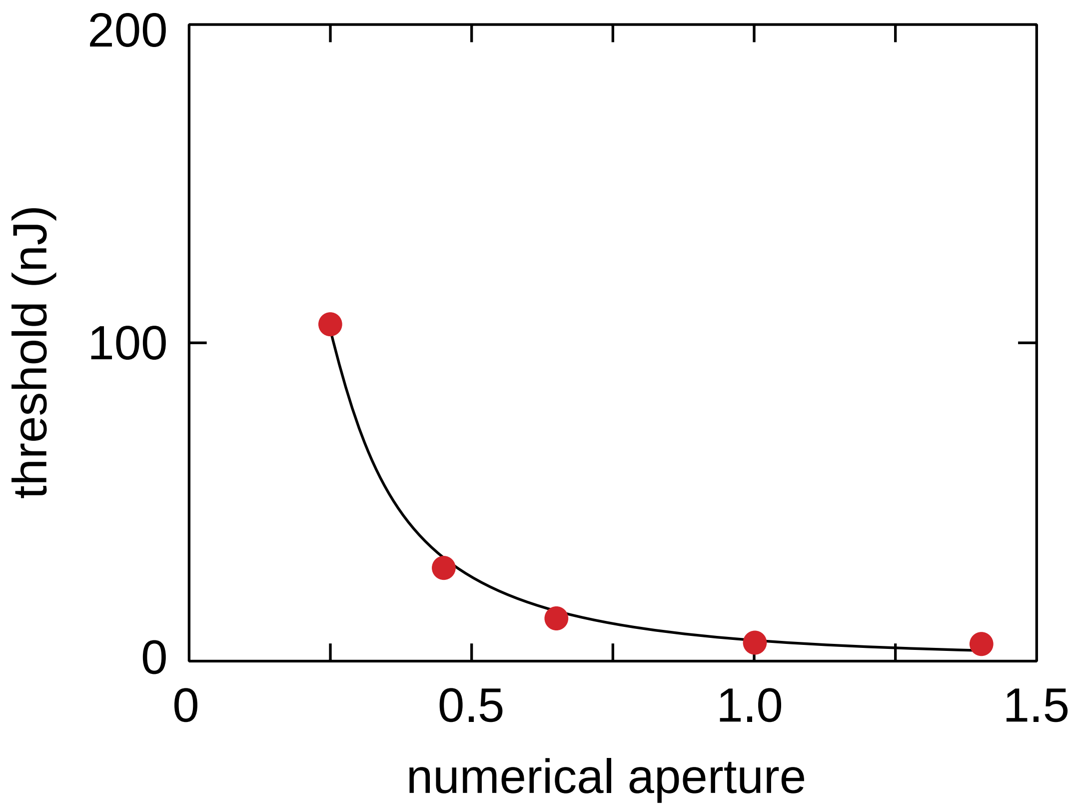
- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

Outline

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

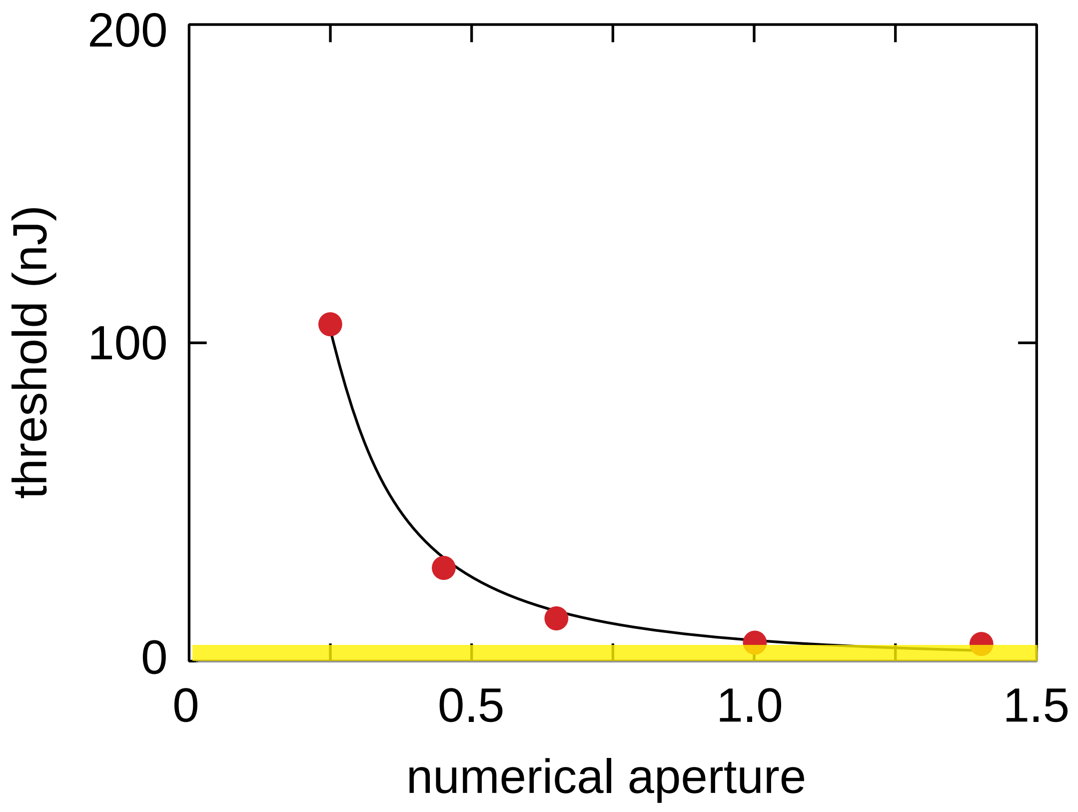
Low-energy machining

threshold decreases with increasing numerical aperture



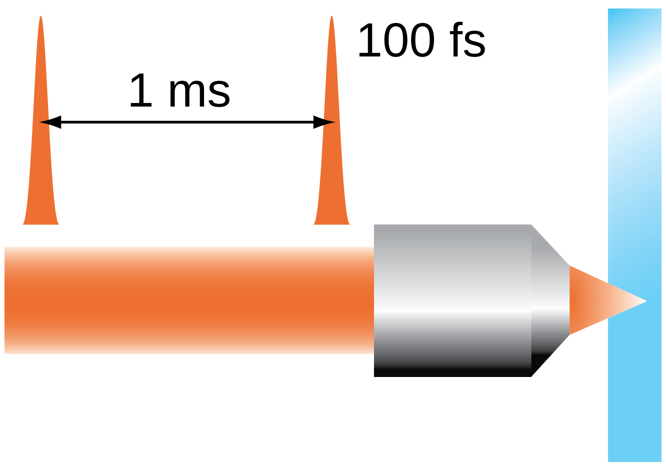
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

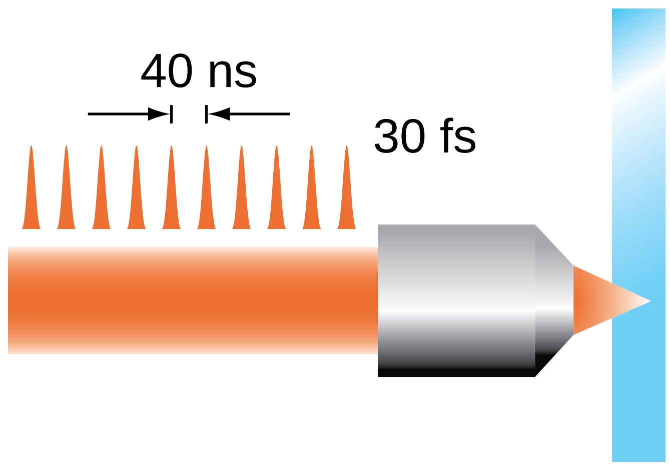
amplified laser: 1 kHz, 1 mJ



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

Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



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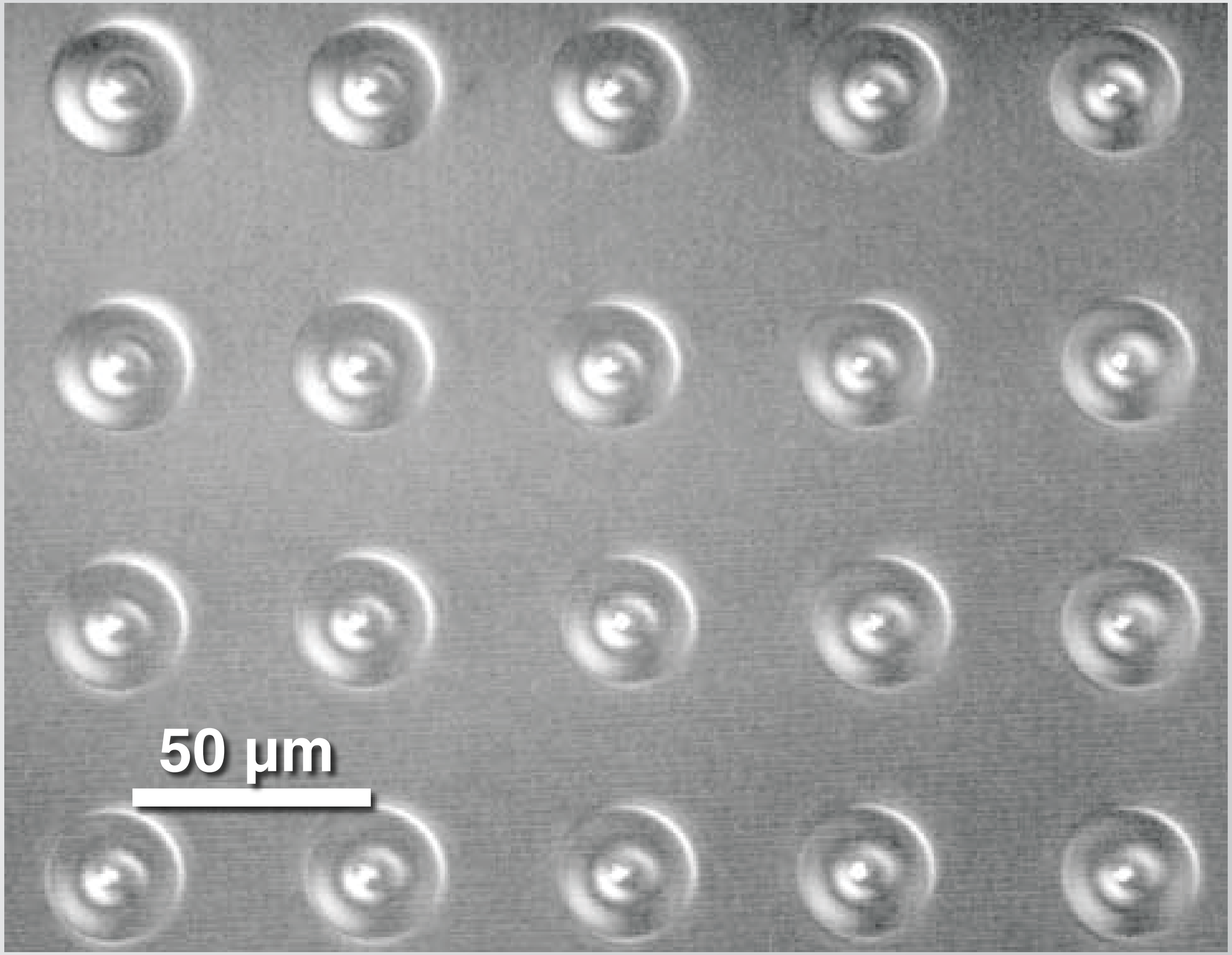
Low-energy machining



Low-energy machining

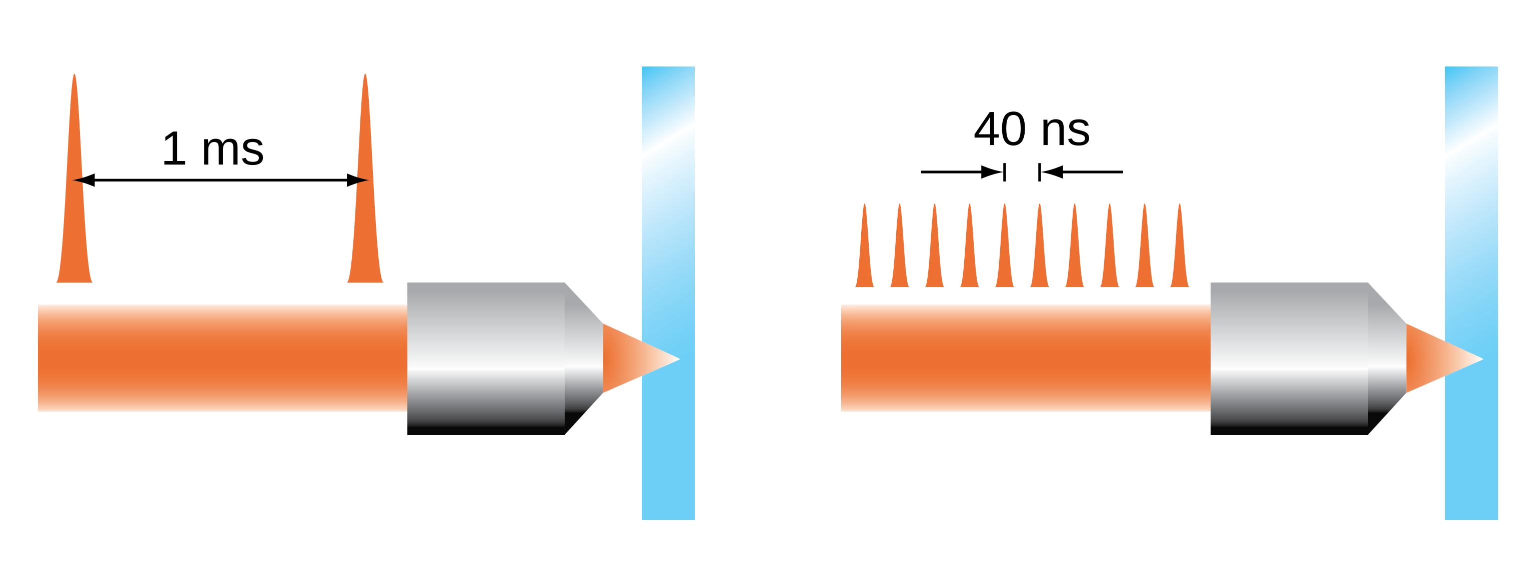
High repetition-rate micromachining:

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

Low-energy machining

amplified laser

oscillator

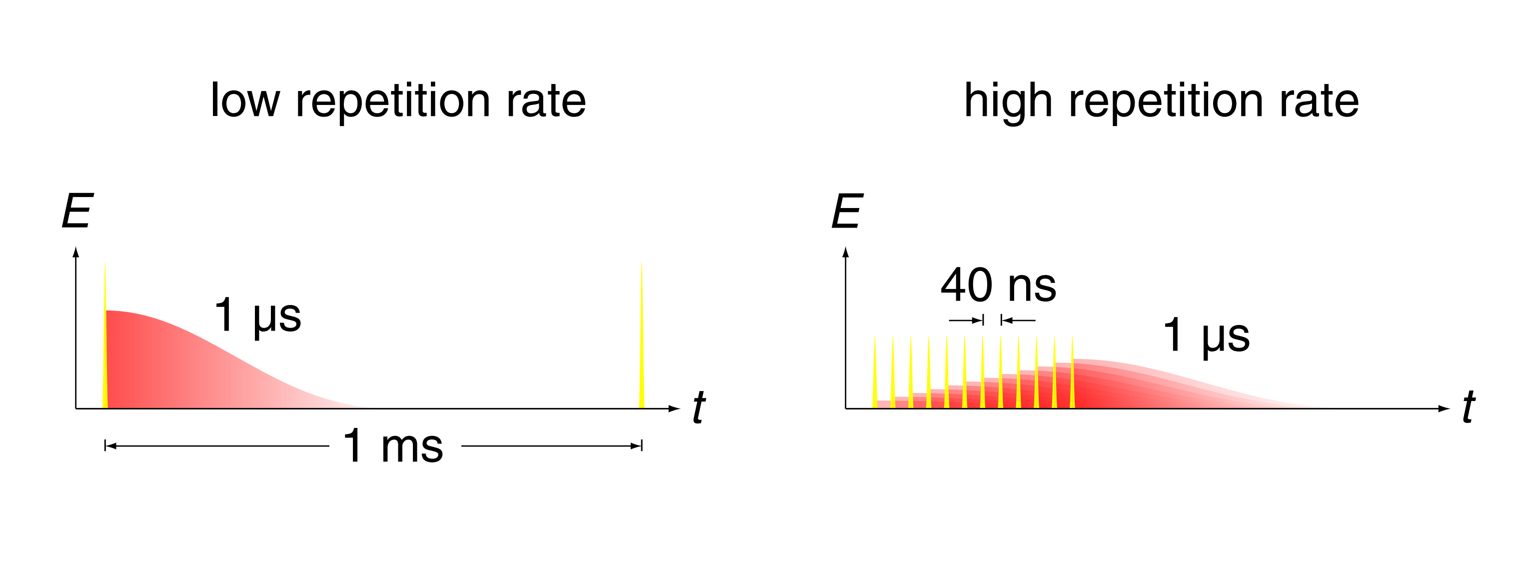


repetitive

cumulative

Low-energy machining

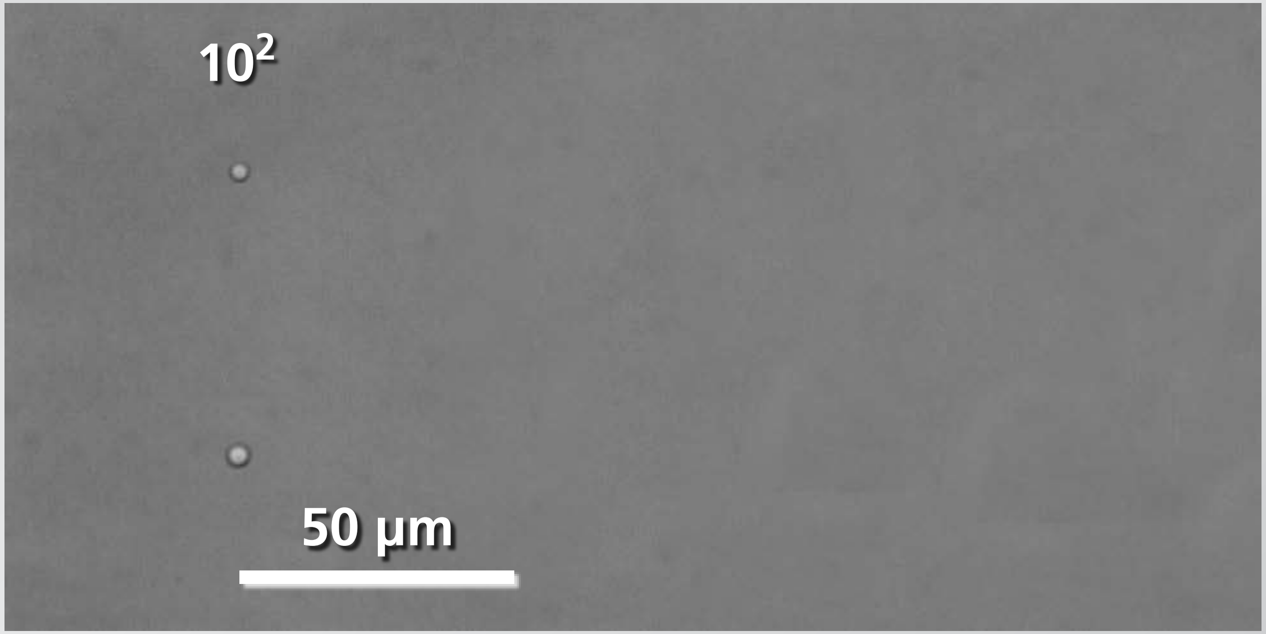
amplified laser | **oscillator**



repetitive | **cumulative**

Low-energy machining

the longer the irradiation…



Low-energy machining

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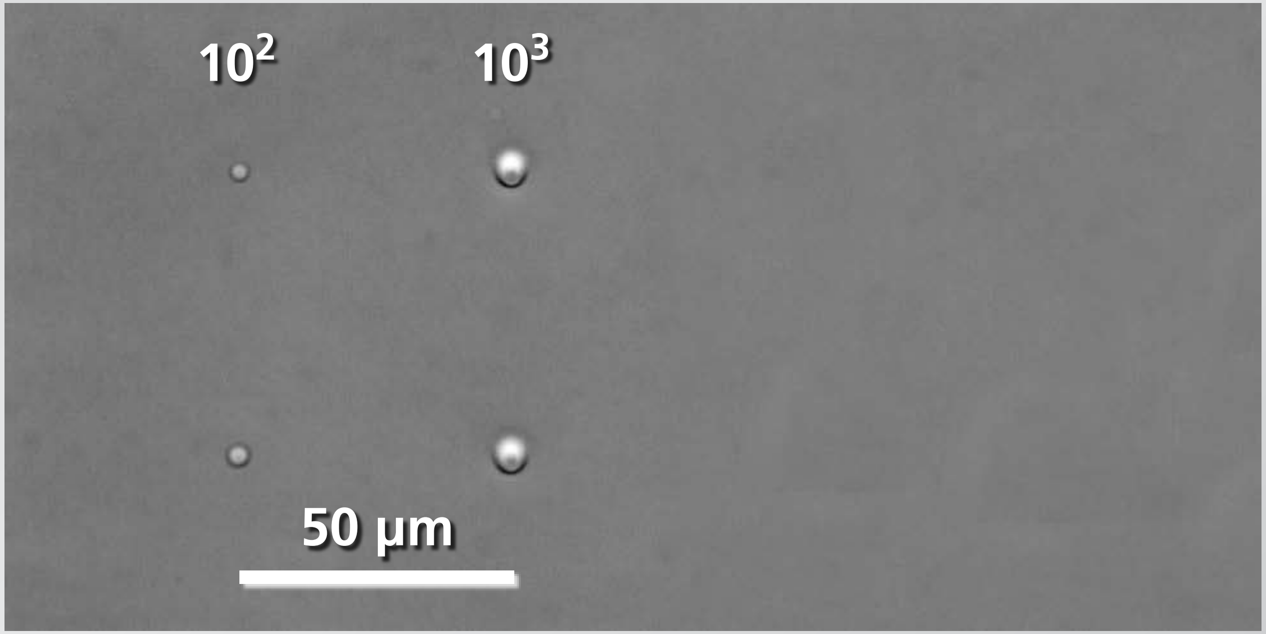

Low-energy machining

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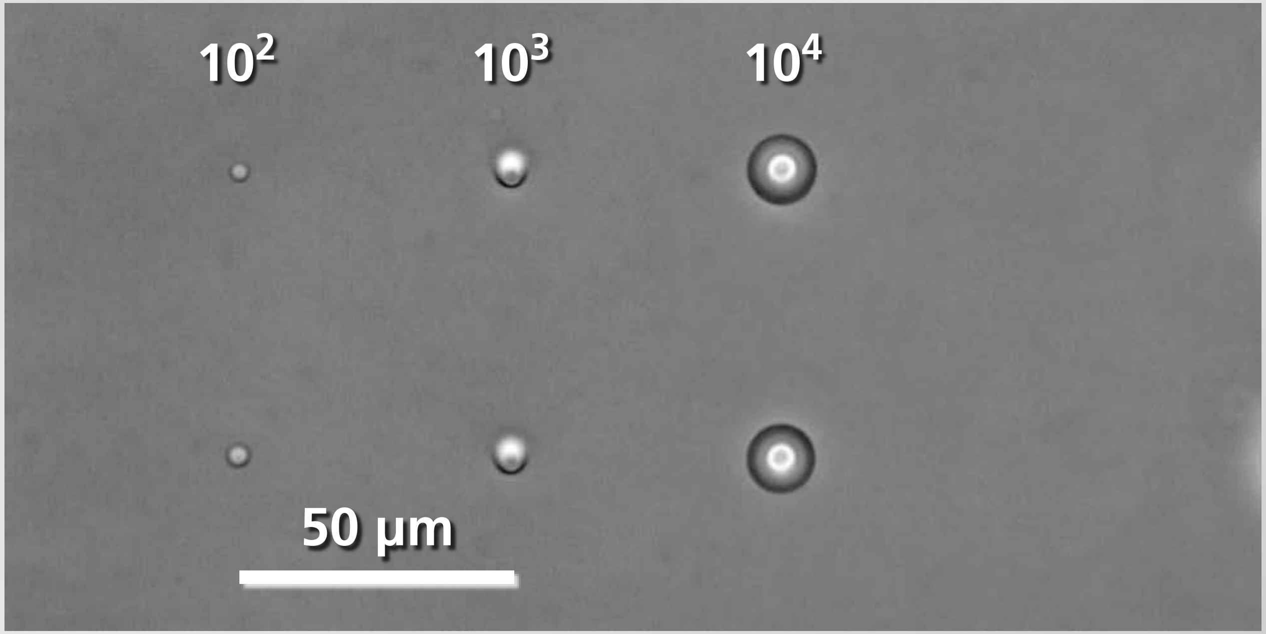
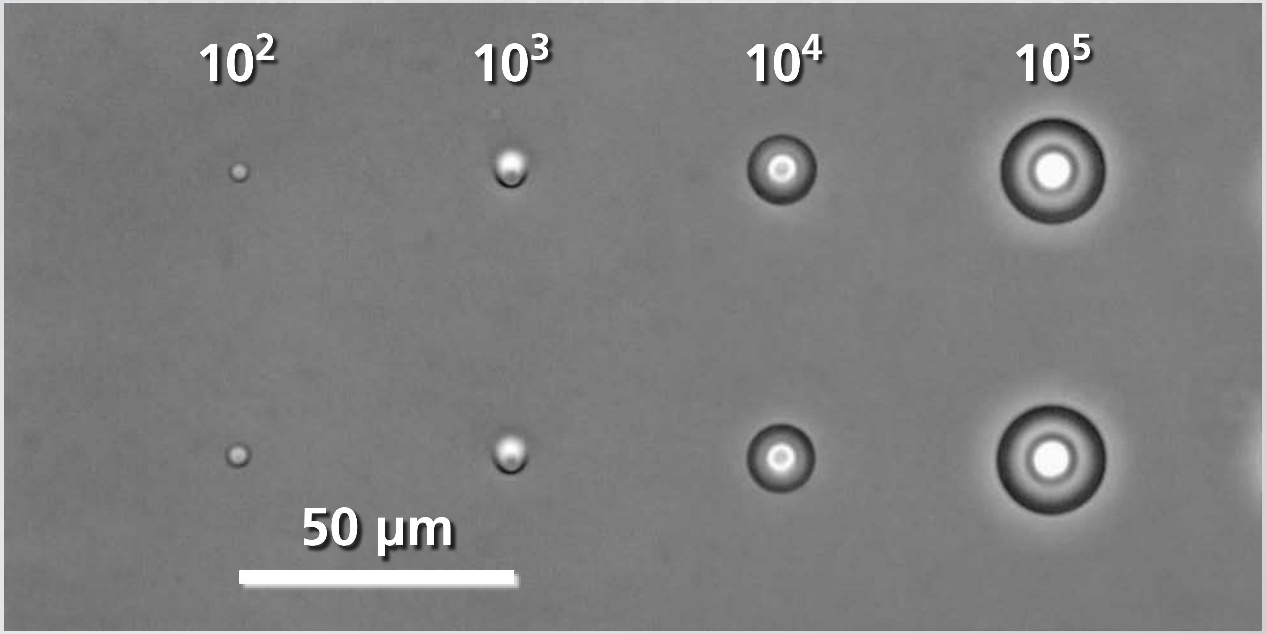


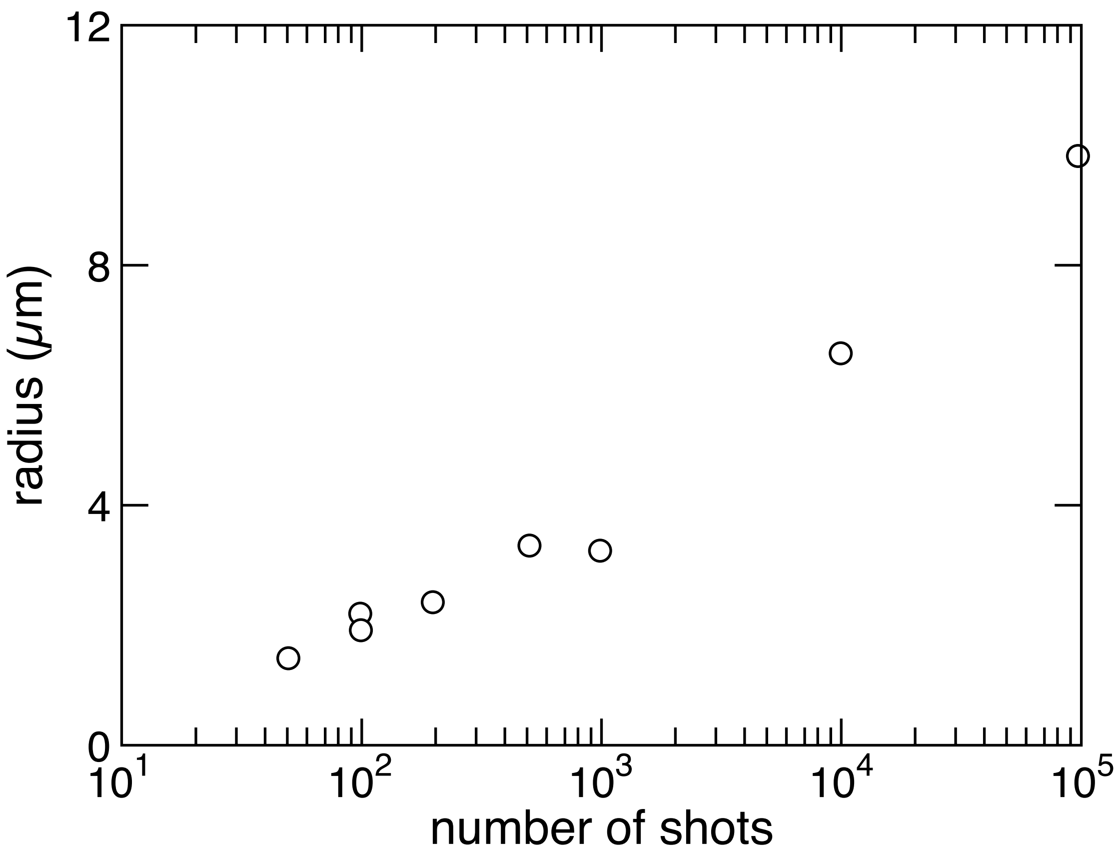
Low-energy machining

the longer the irradiation…



… the larger the radius

Low-energy machining



Low-energy machining

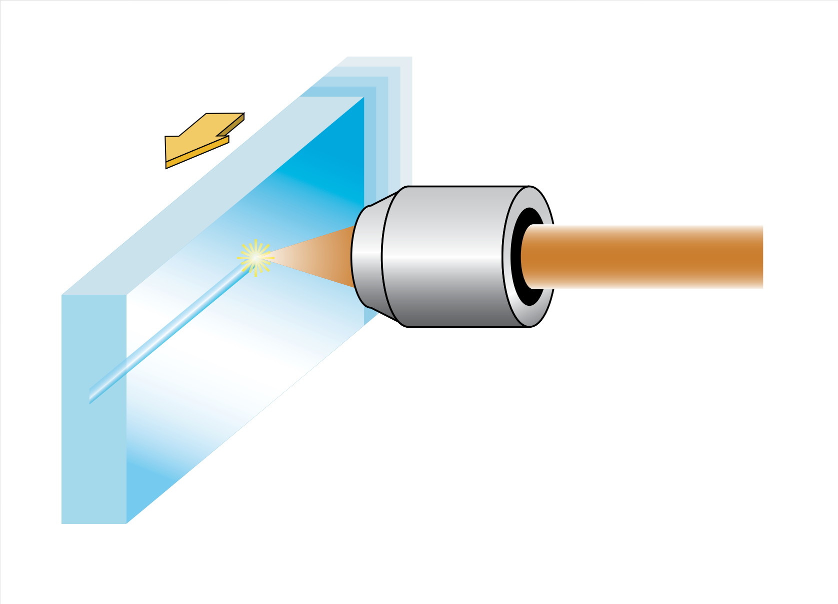
at high-rep rate: internal "point-source of heat"

Outline

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

Low-energy machining

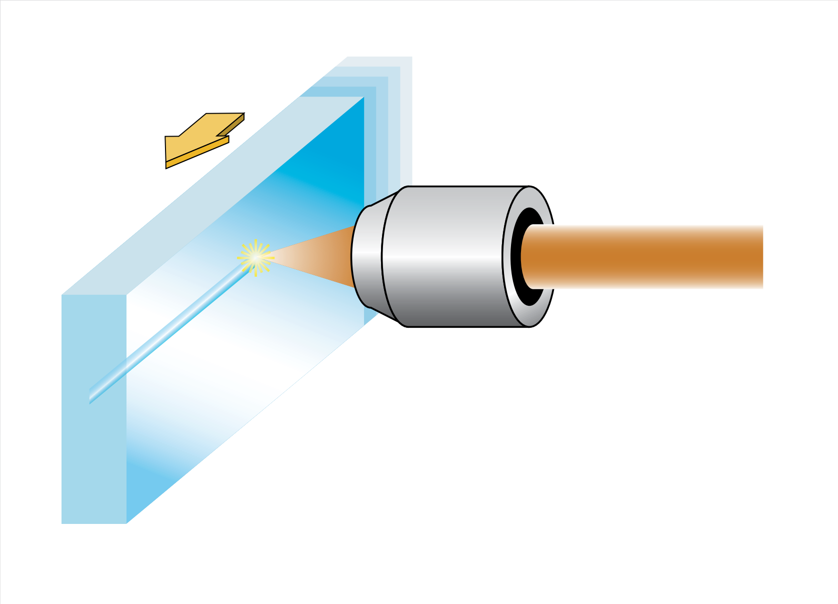
waveguide micromachining

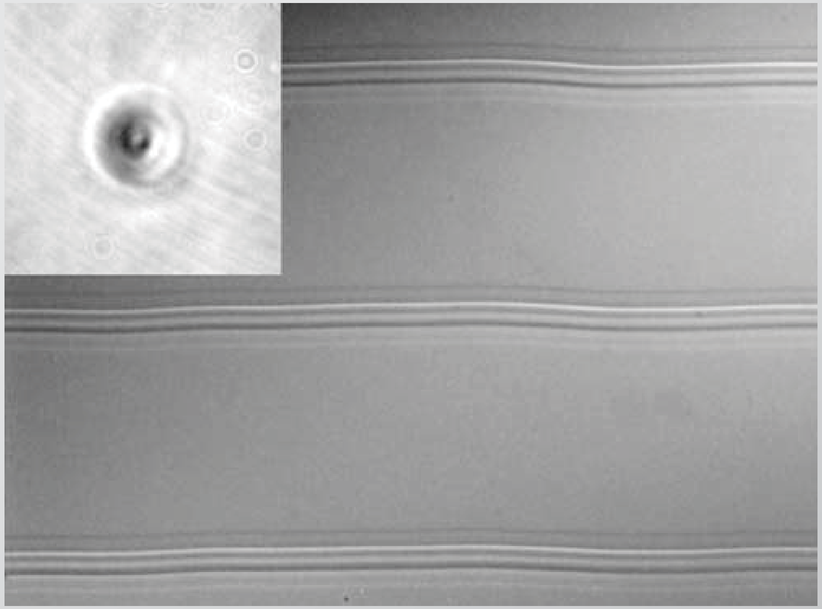


Opt. Lett. **26**, 93 (2001)

Low-energy machining

waveguide micromachining

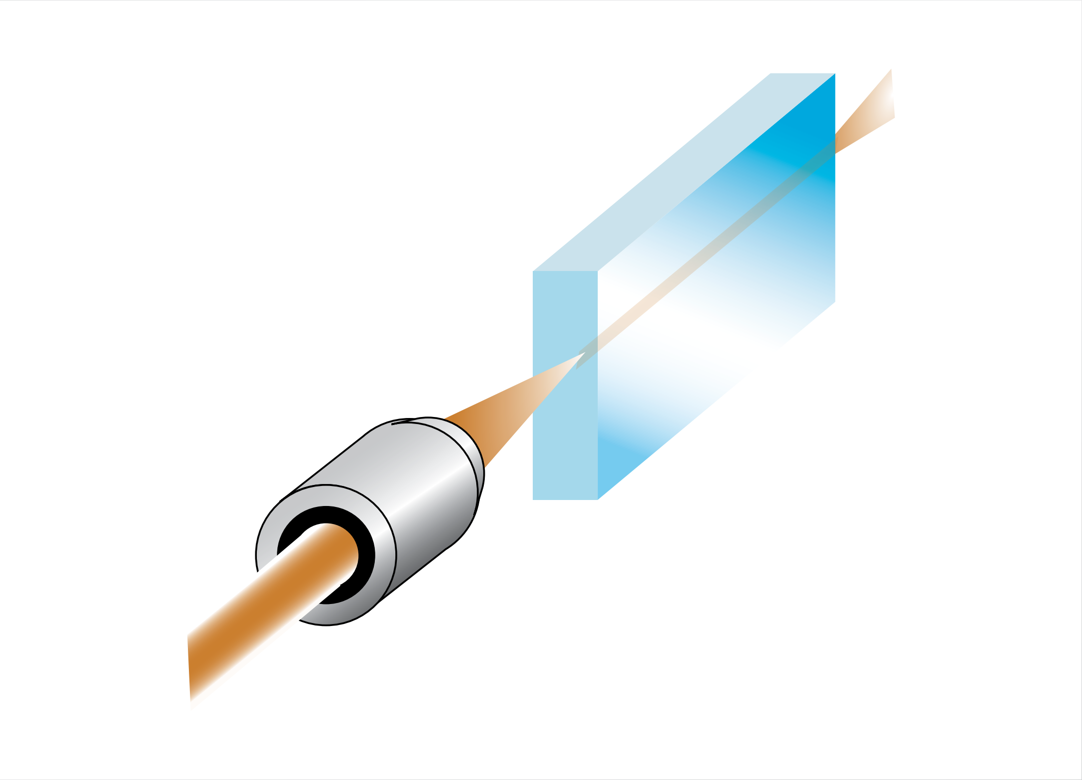




Opt. Lett. **26**, 93 (2001)

Low-energy machining

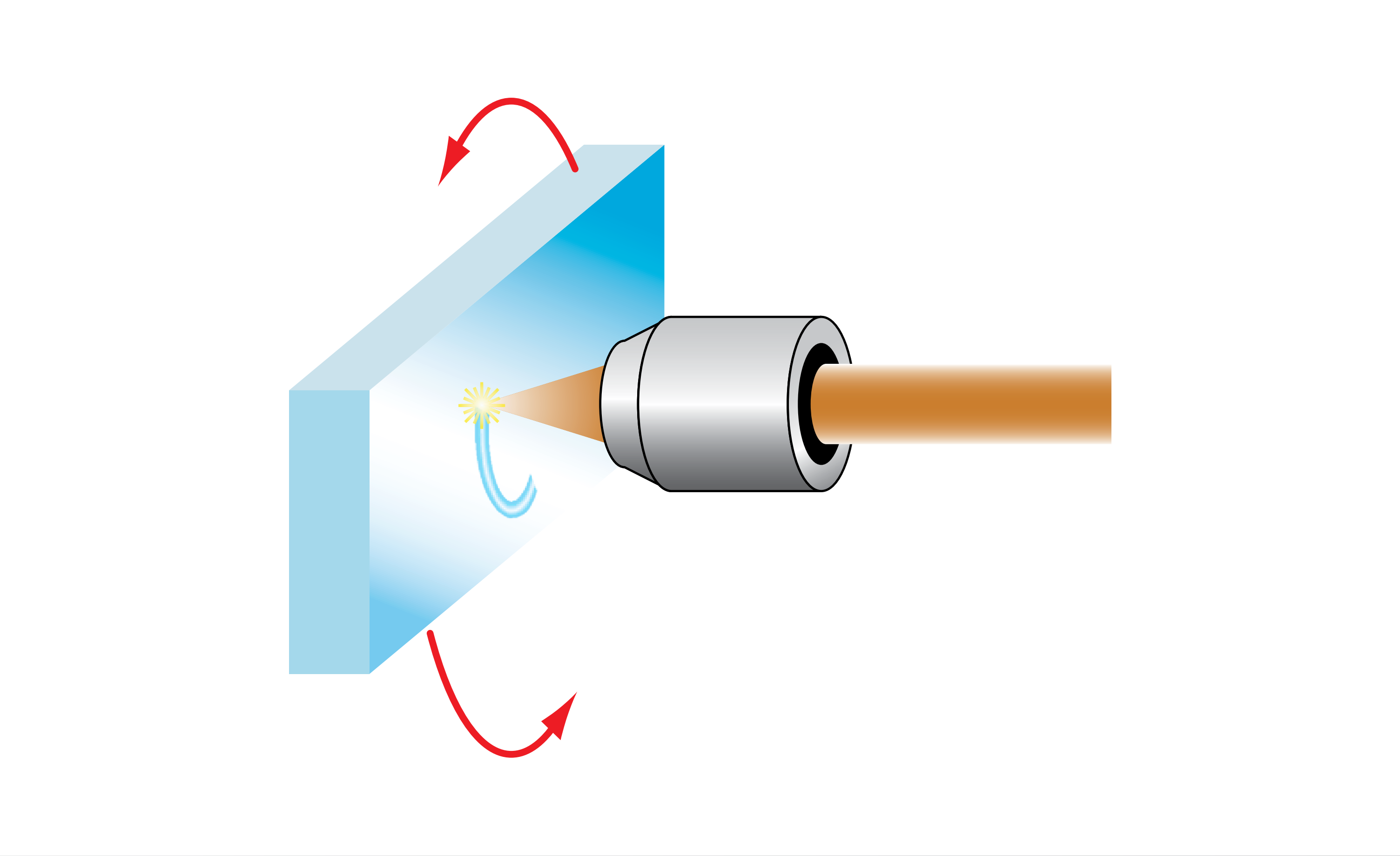
structures guide light



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

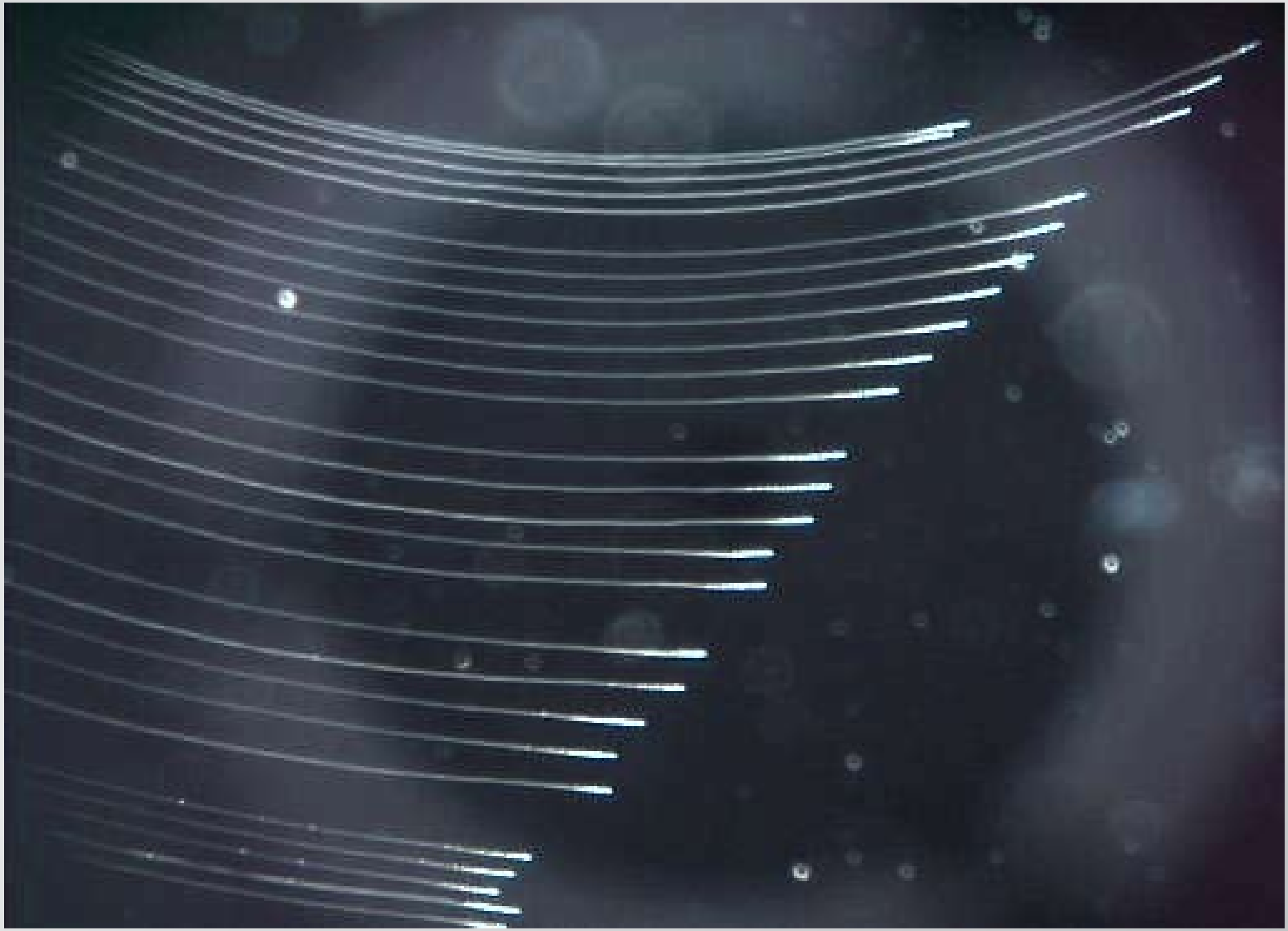
Applications

curved waveguides



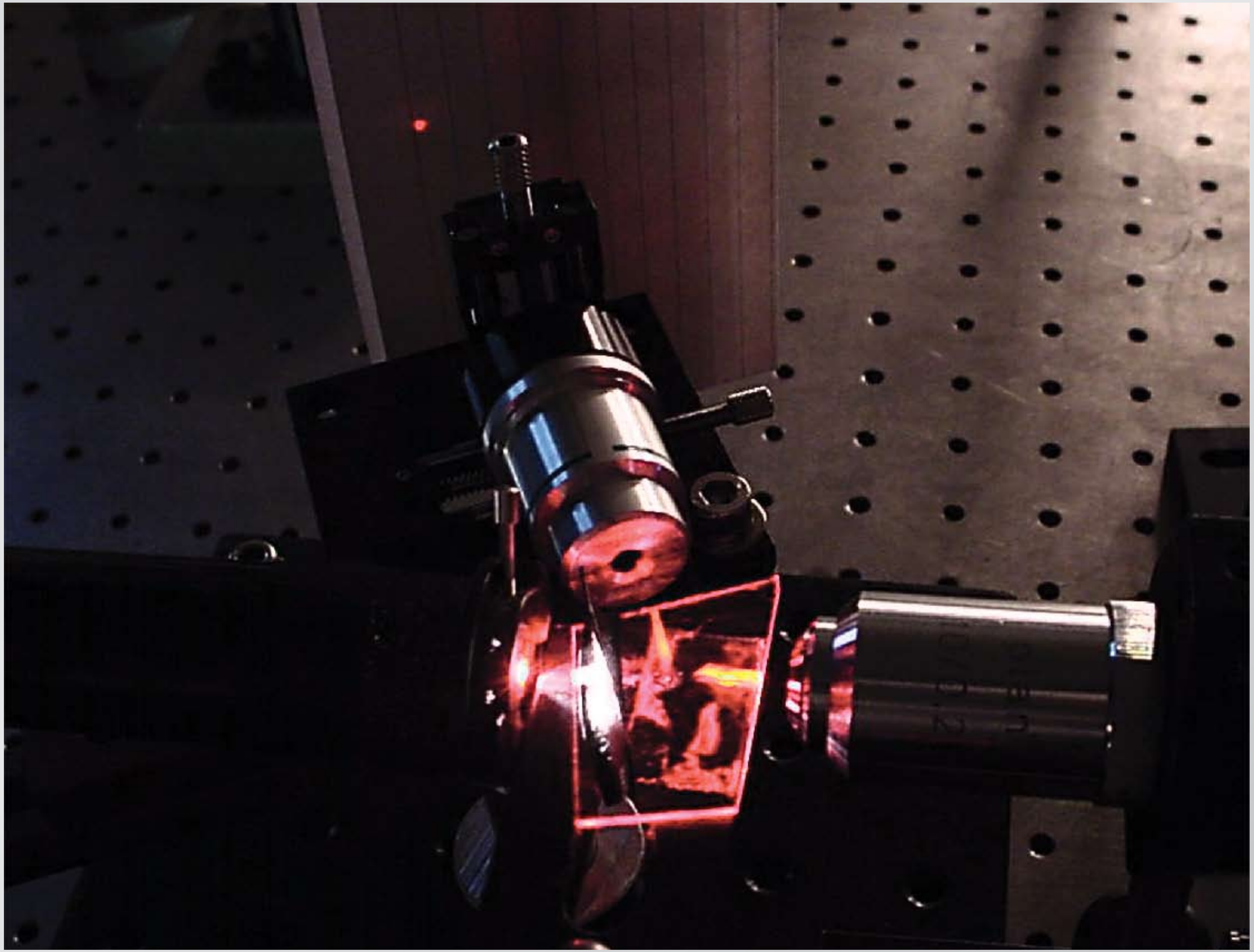
Applications

curved waveguides



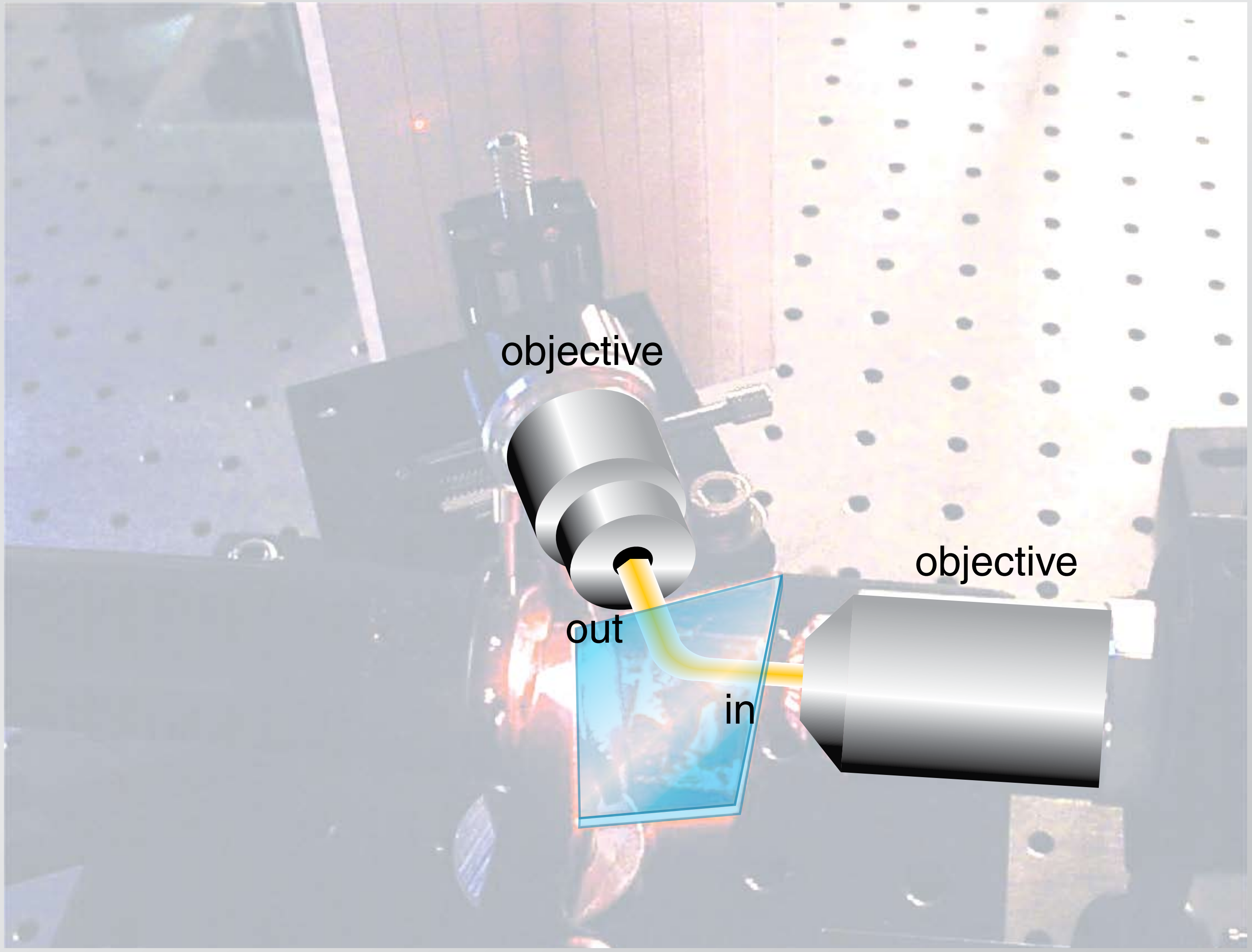
Applications

curved waveguides



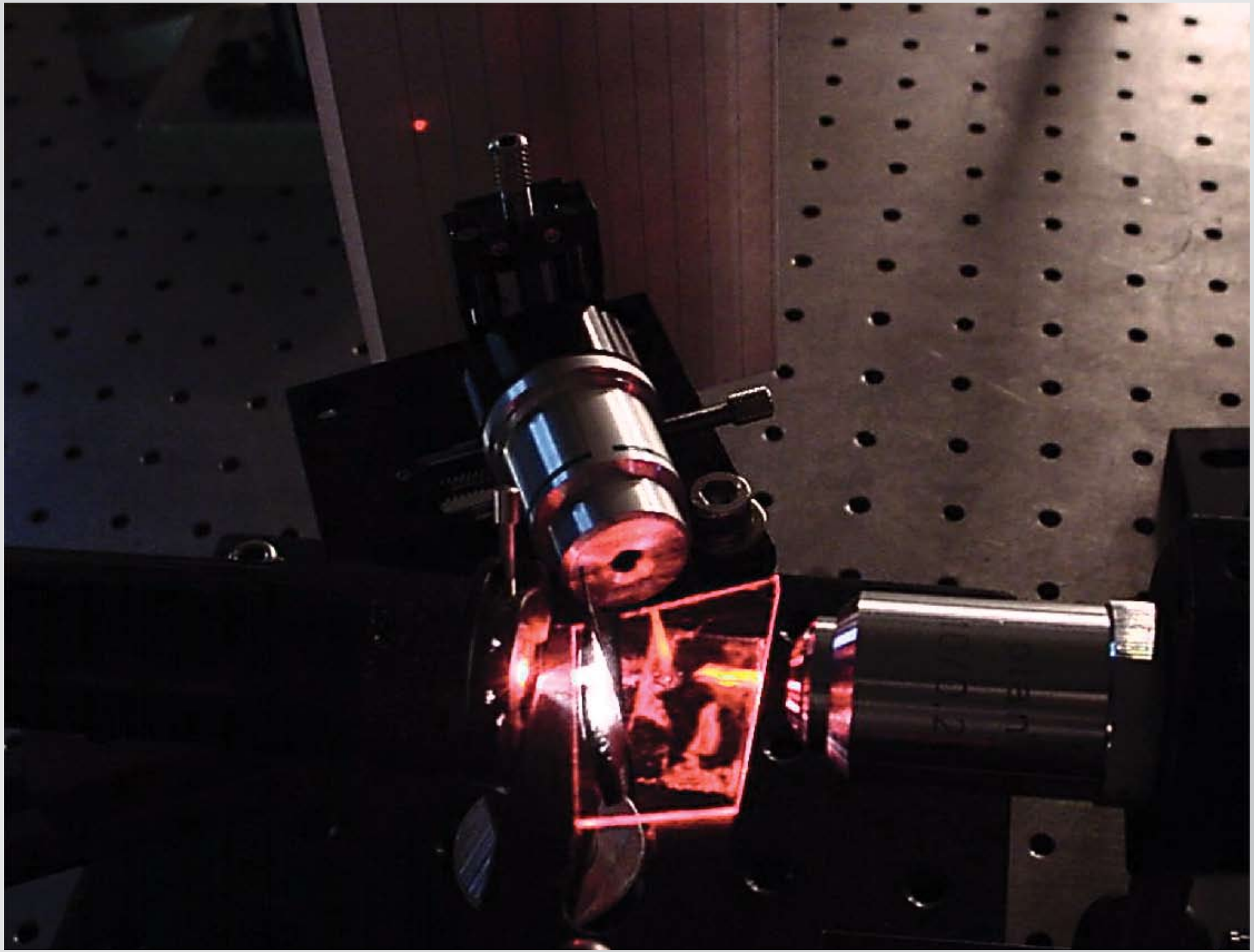
Applications

curved waveguides



Applications

curved waveguides



Applications

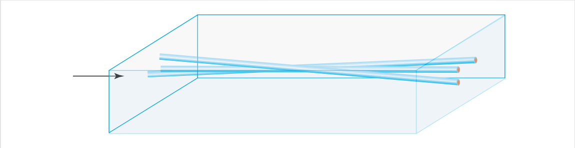
photonic fabrication techniques

	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

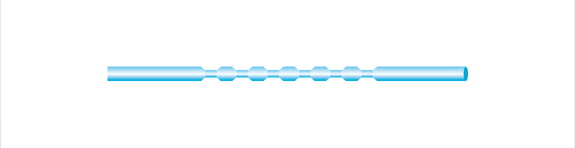
Applications

photonic devices

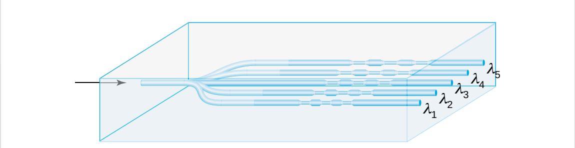
3D splitter



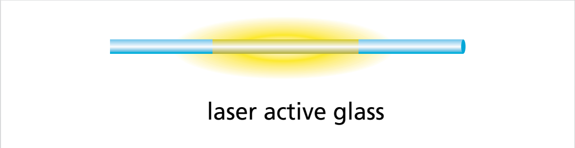
Bragg grating



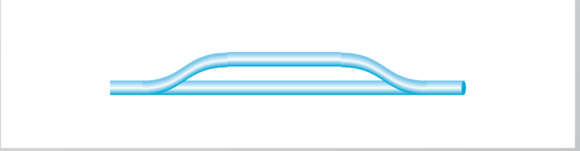
demultiplexer



amplifier

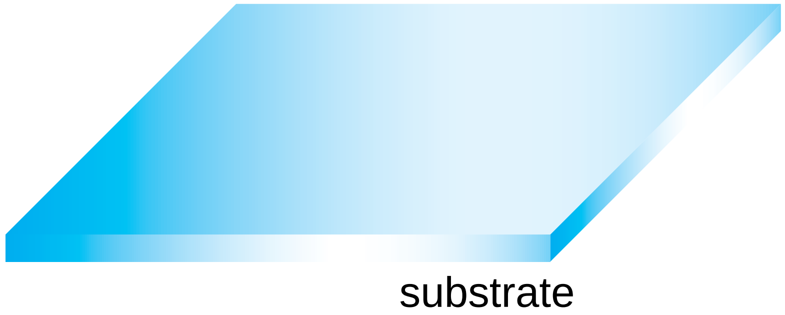


interferometer



Applications

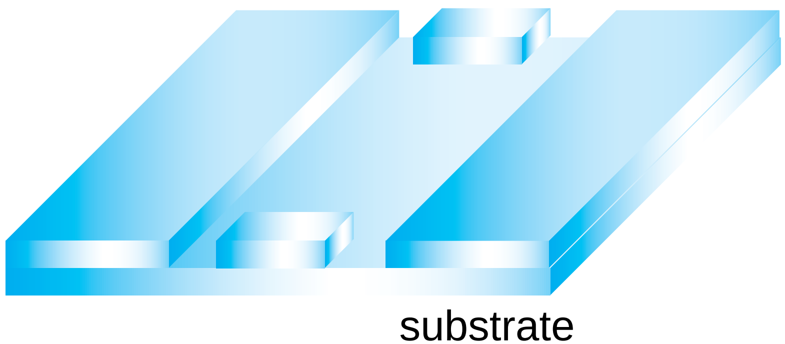
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor



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Applications

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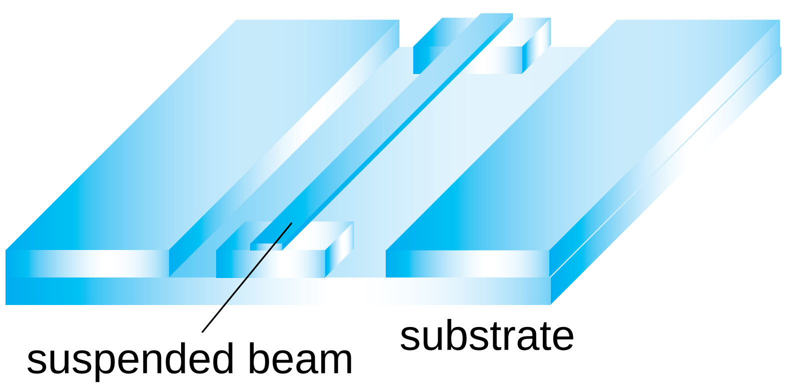

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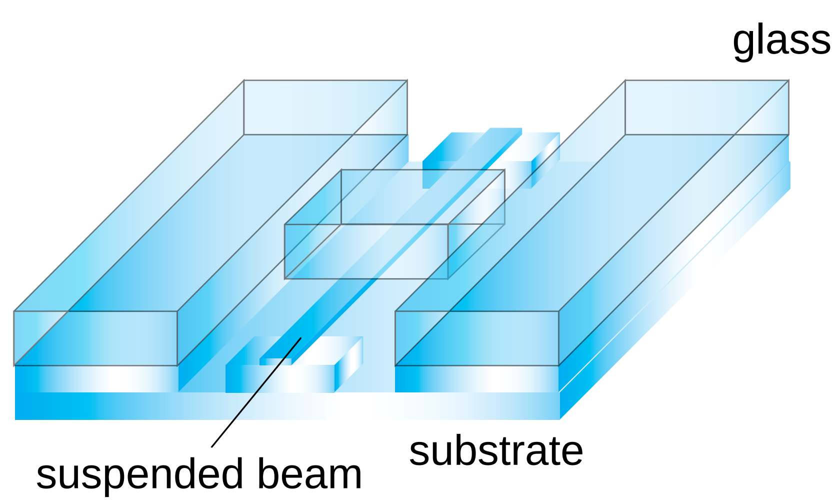

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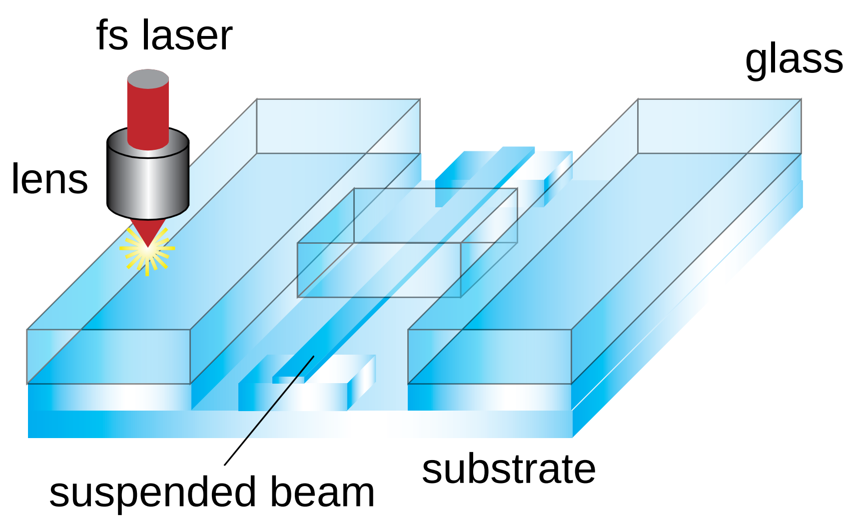

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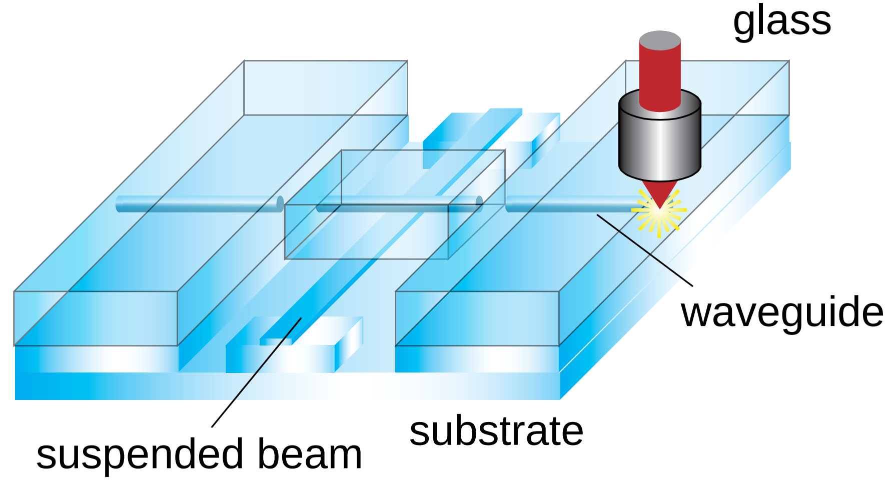

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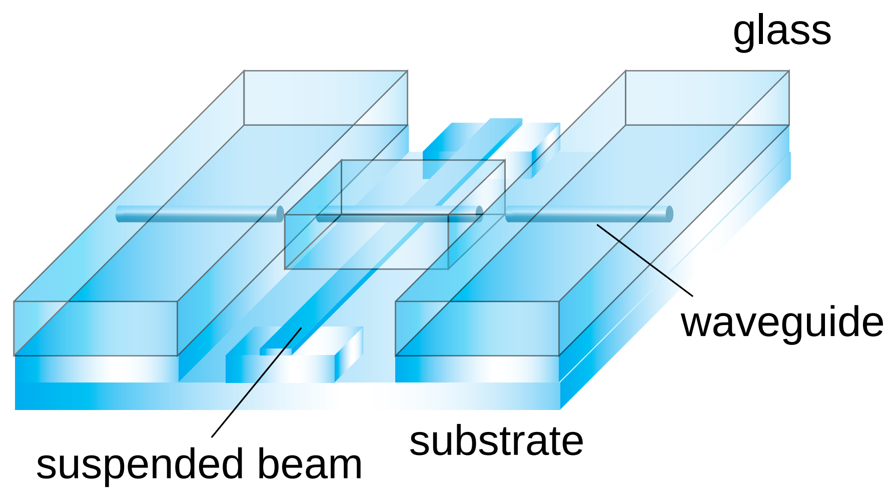

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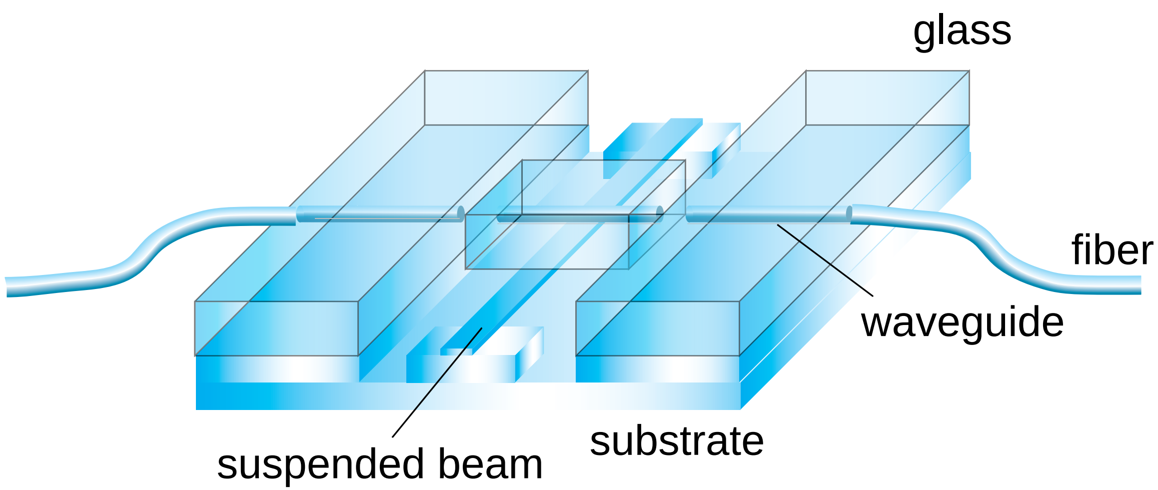

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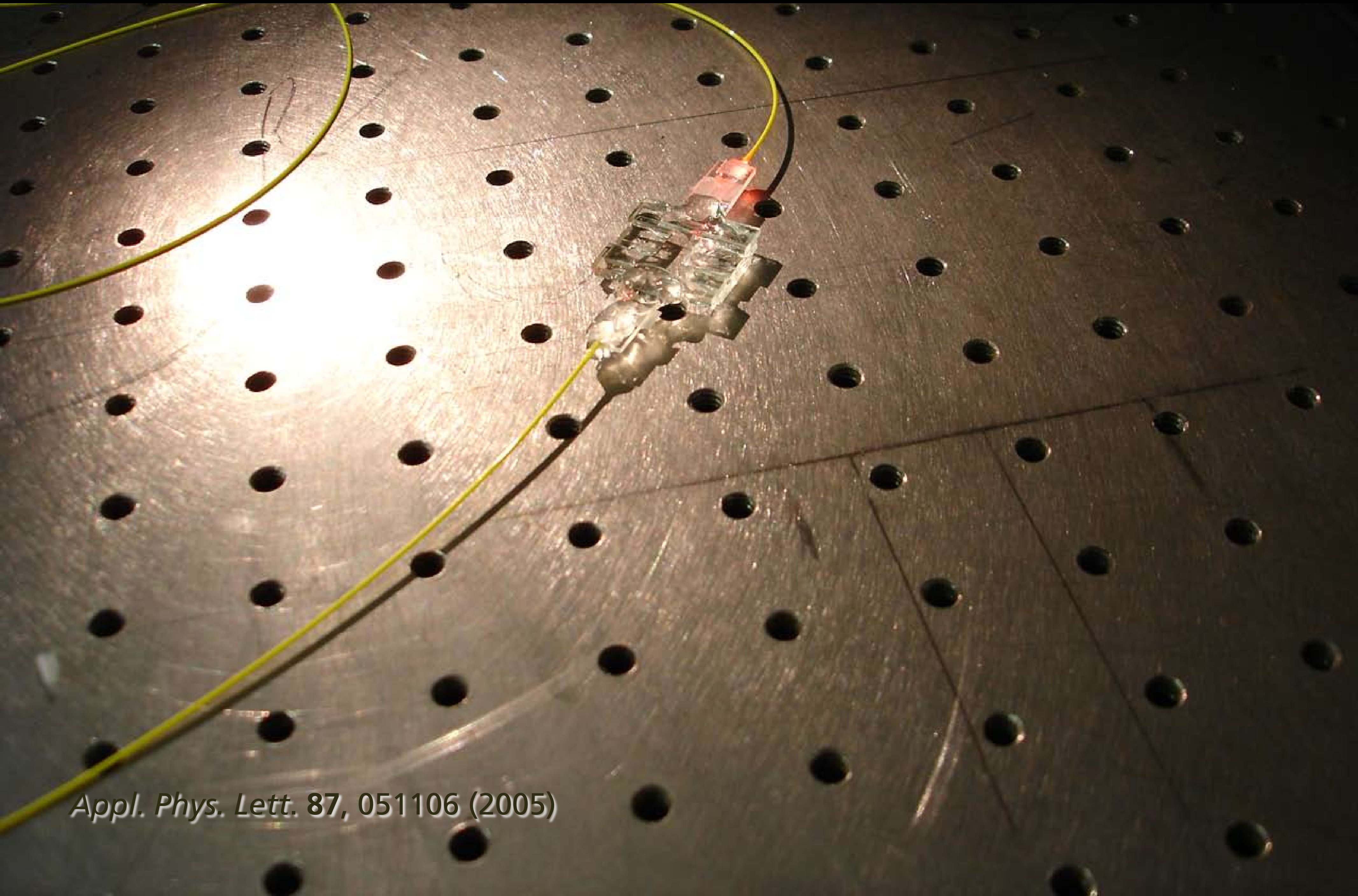
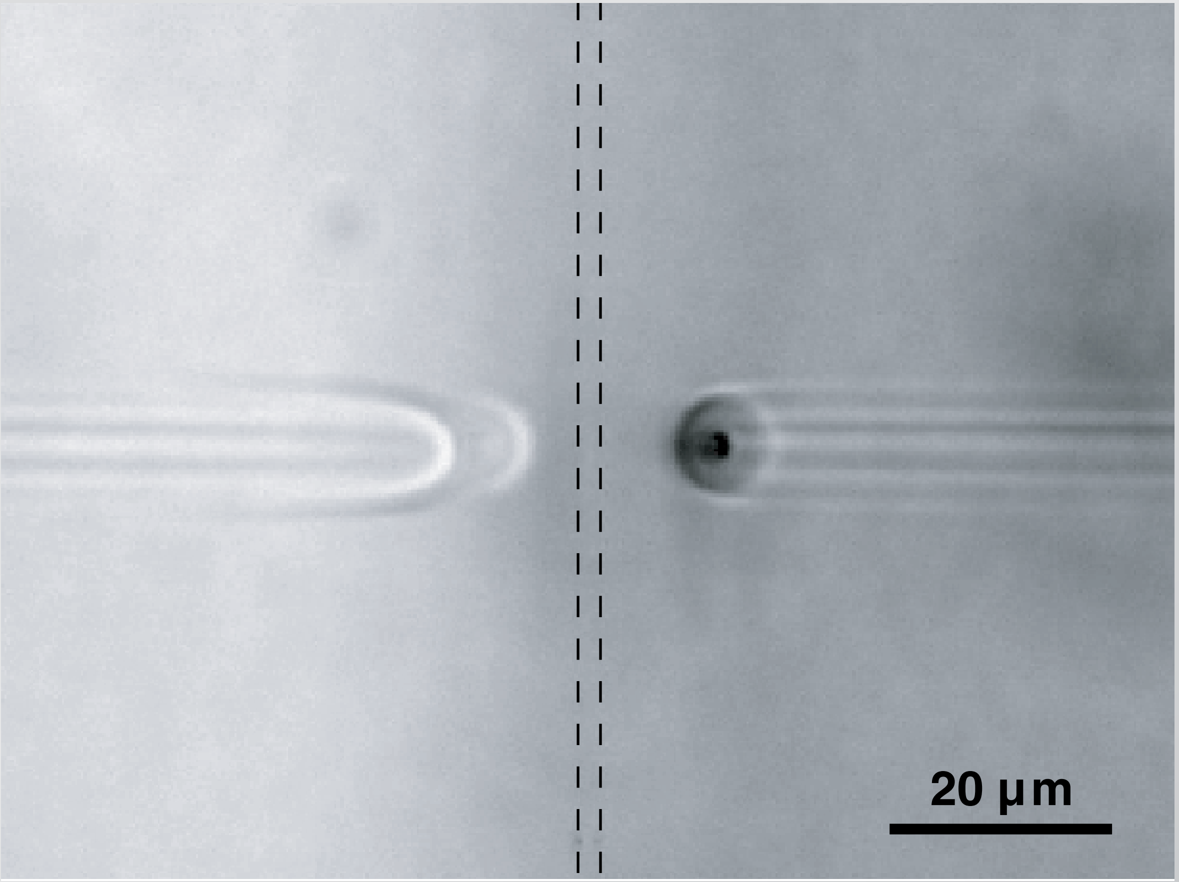
Applications



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

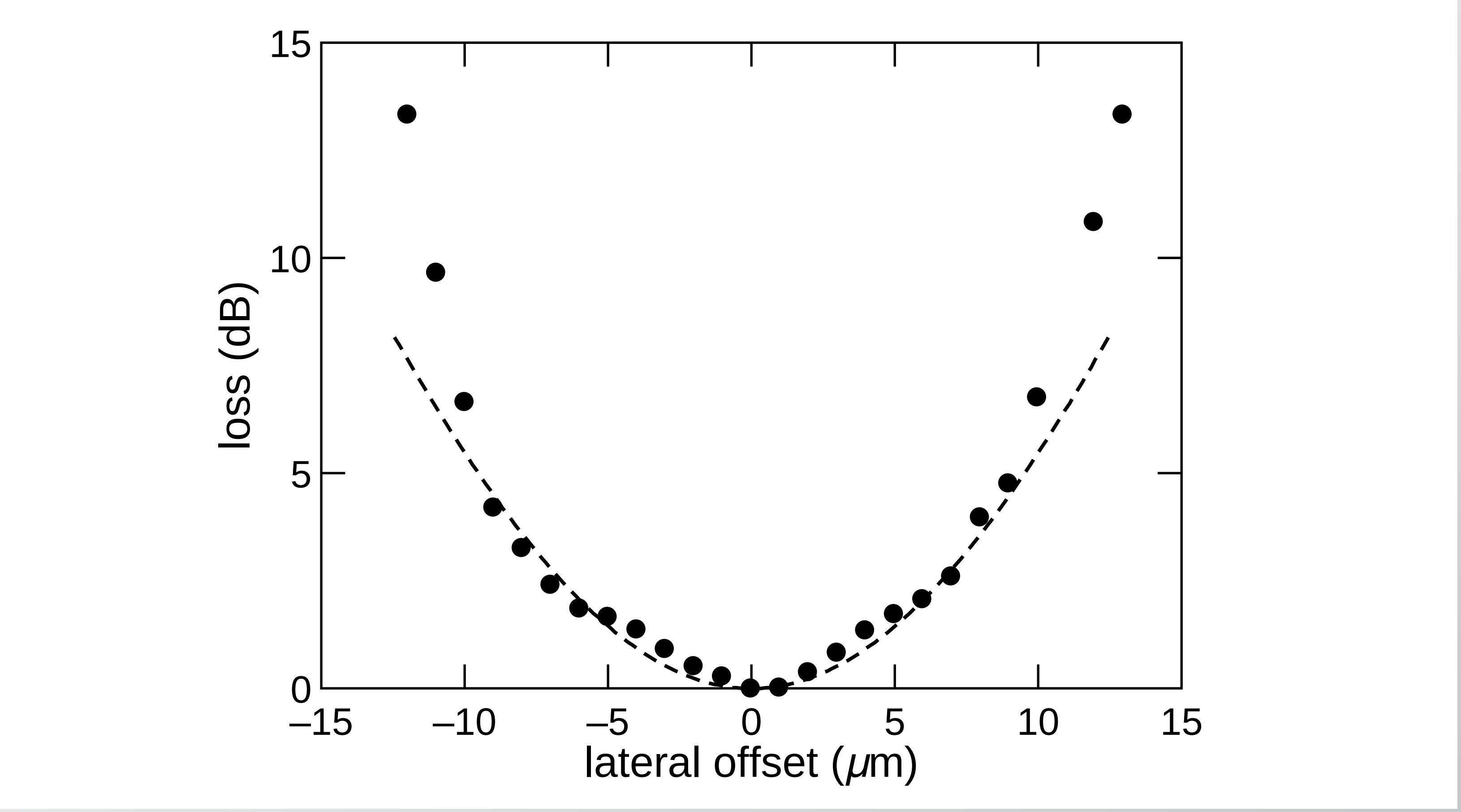
sensor gap



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

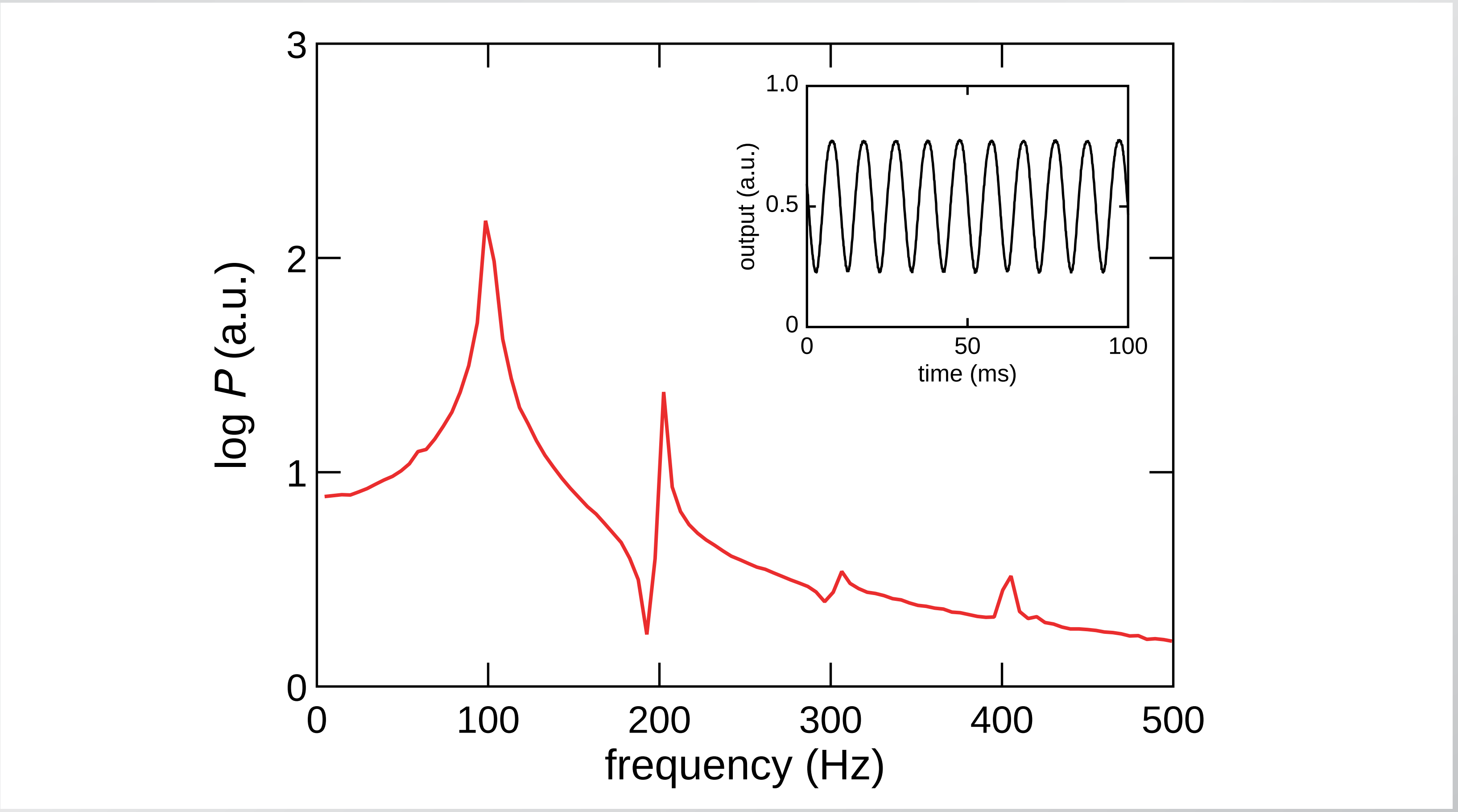
calibration



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

sensor response to 100 Hz acoustic wave



Appl. Phys. Lett. **87**, 051106 (2005)

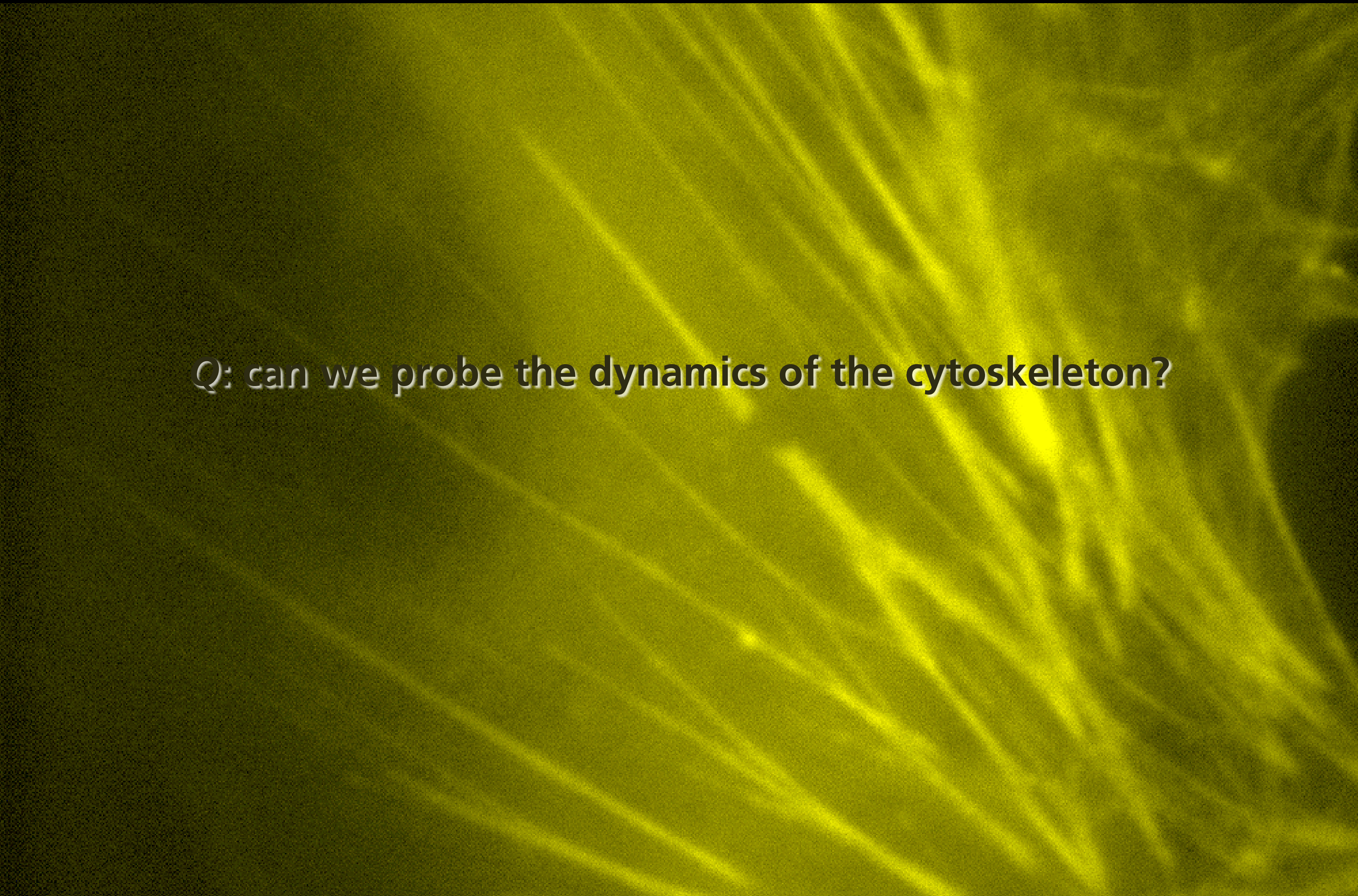
Applications

ideal tool for ablating (living) tissue

Applications

- standard biochemical tools: species selective
- fs laser “nanosurgery”: site specific

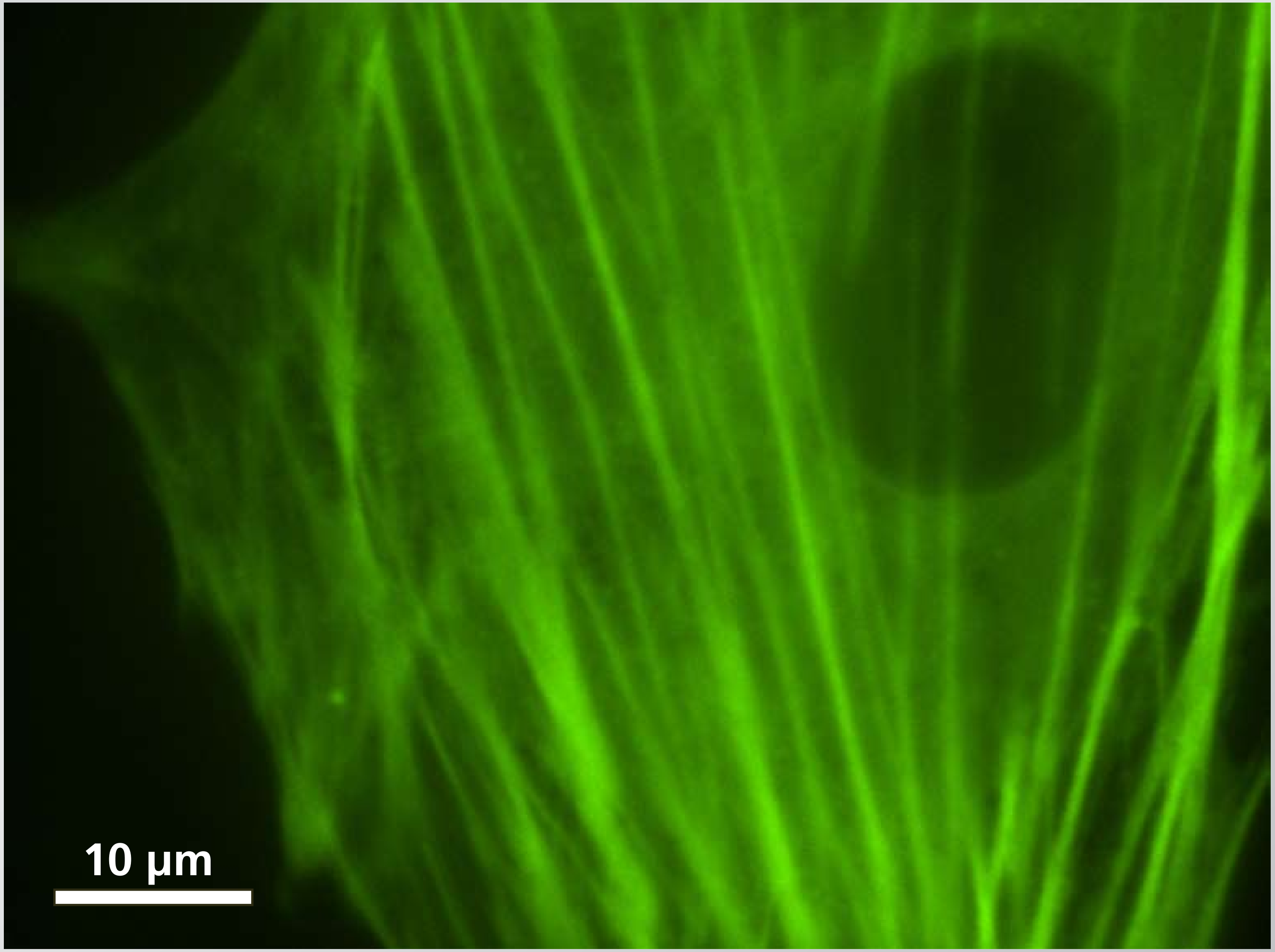
Applications



Q: can we probe the dynamics of the cytoskeleton?

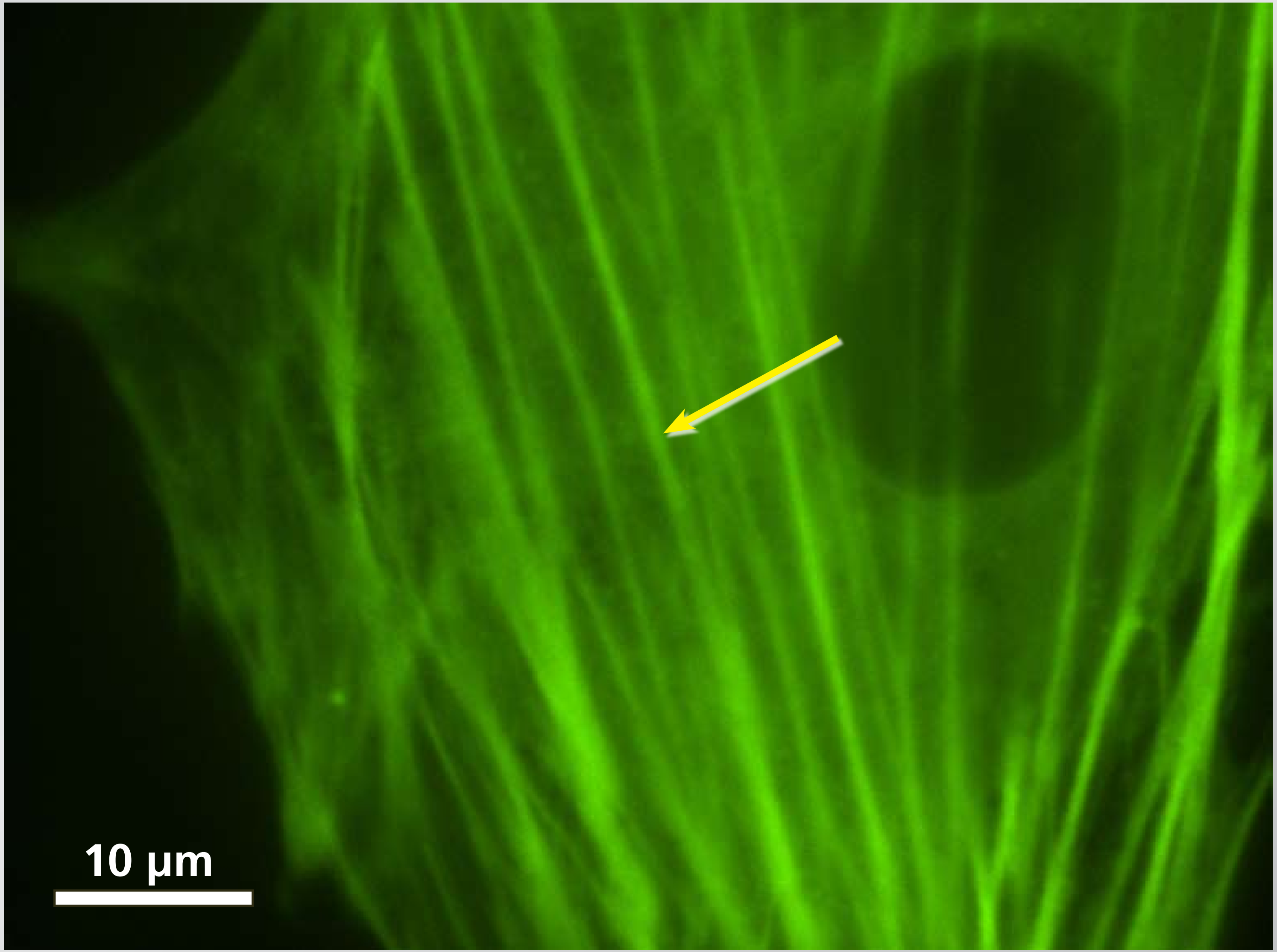
Applications

actin fiber network of a live cell



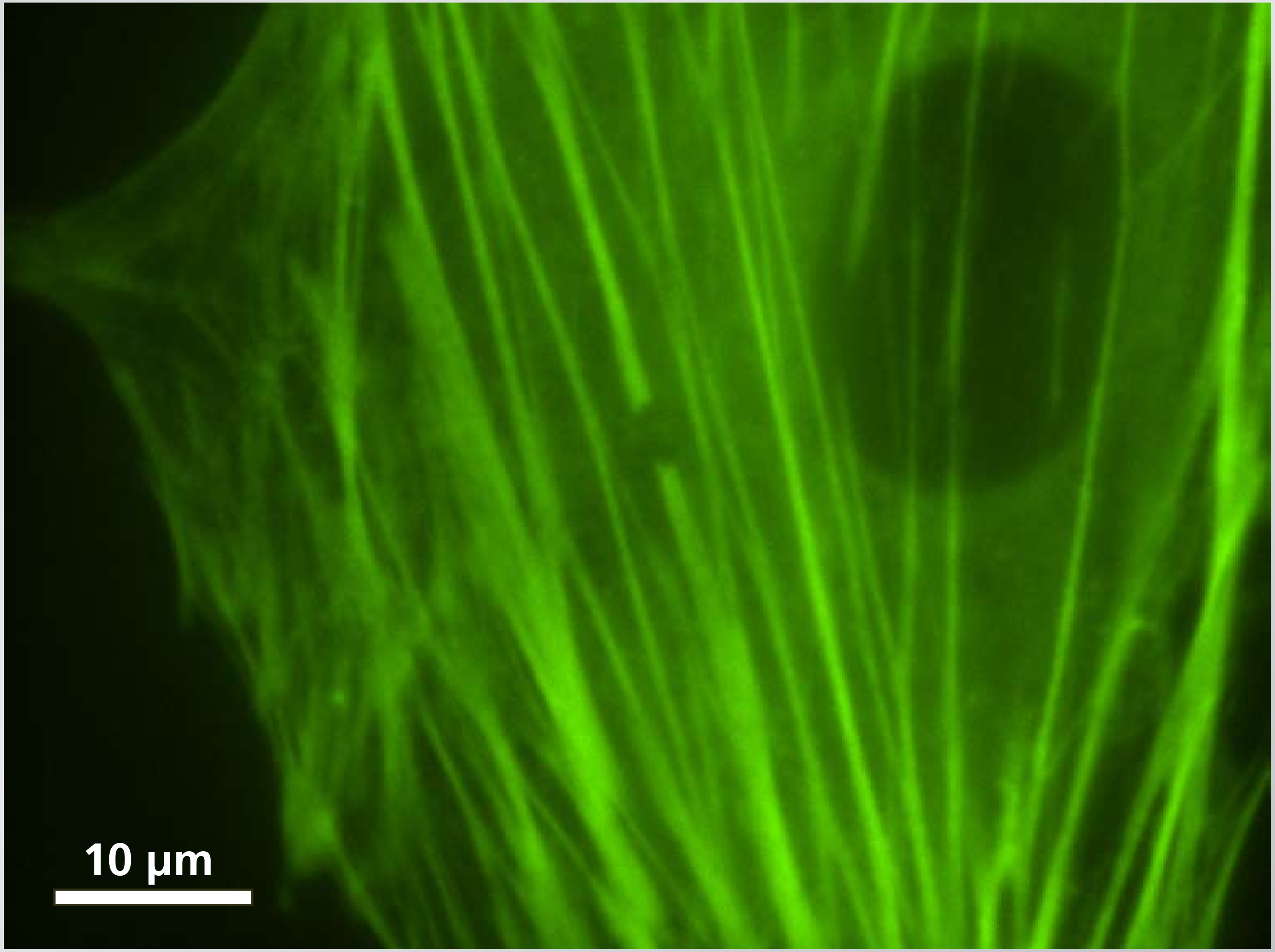
Applications

cut a single fiber bundle



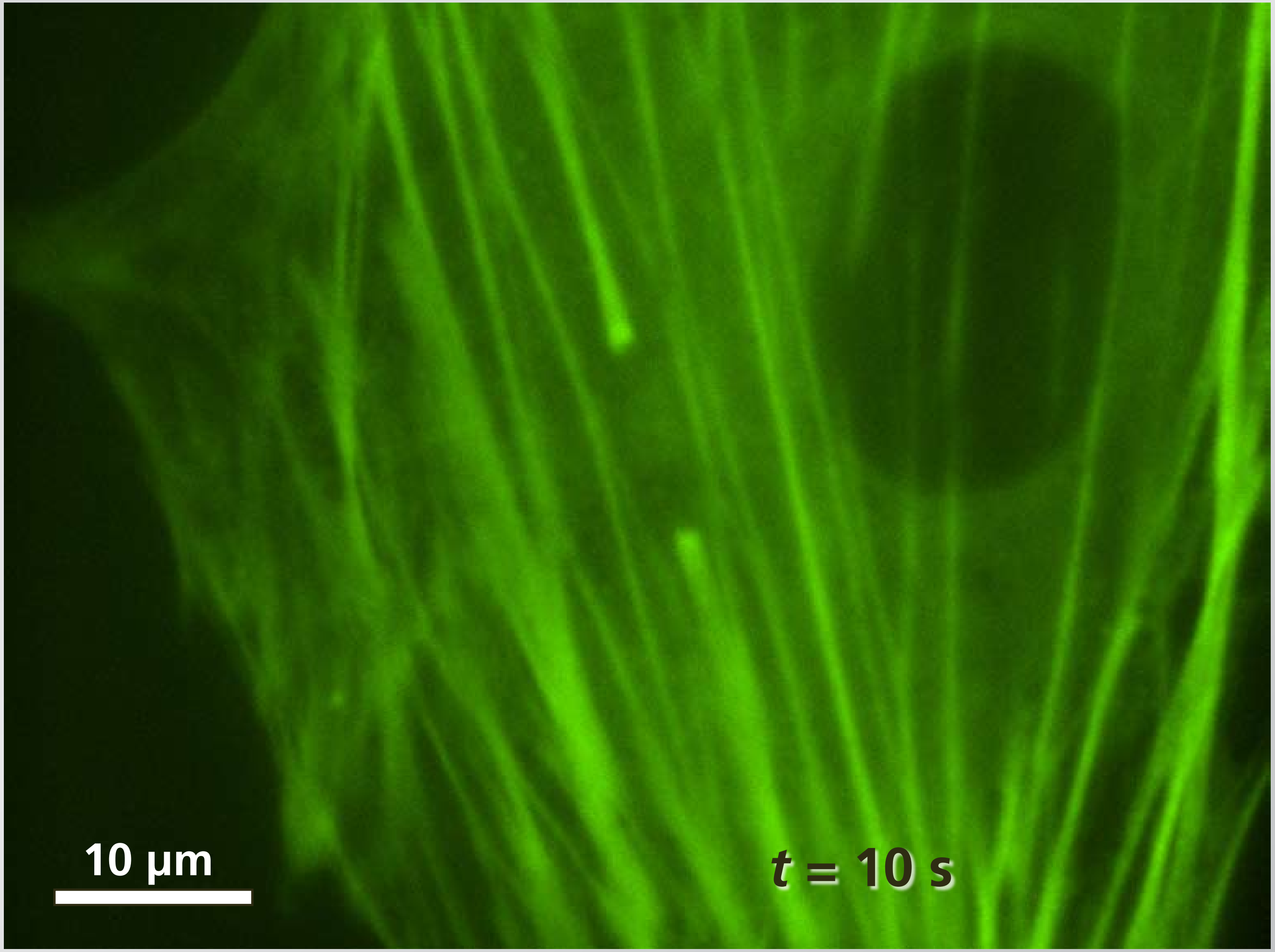
Applications

cut a single fiber bundle



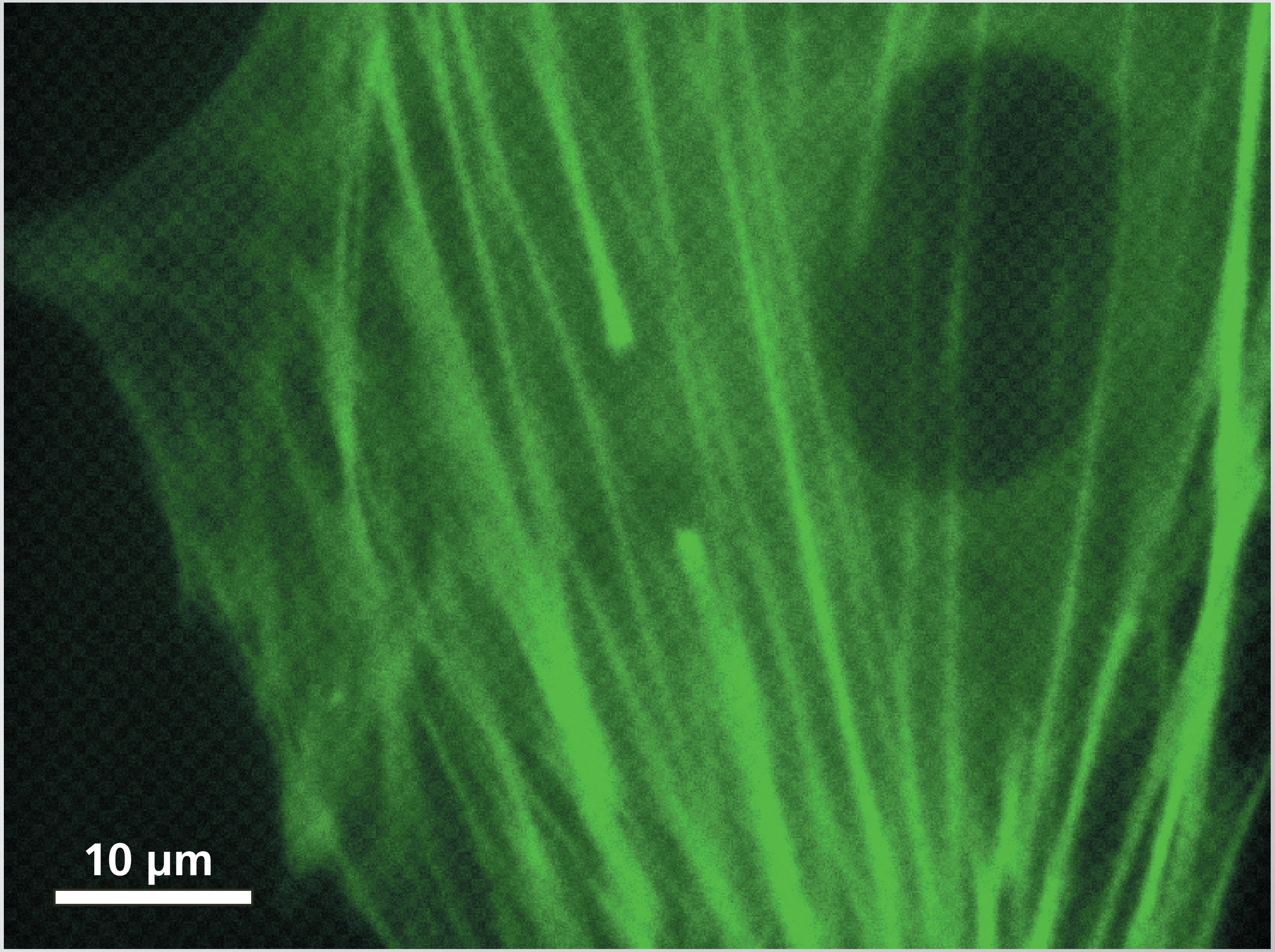
Applications

gap widens with time



Applications

dynamics provides information on *in vivo* mechanics



Summary

great tool for

- “wiring light”
- micromanipulating the machinery of life

Summary

- important parameters: focusing, energy, repetition rate
- nearly material independent
- two regimes: low and high repetition rate
- high-repetition rate (thermal) machining fast, convenient

Funding:

Army Research Office
National Science Foundation

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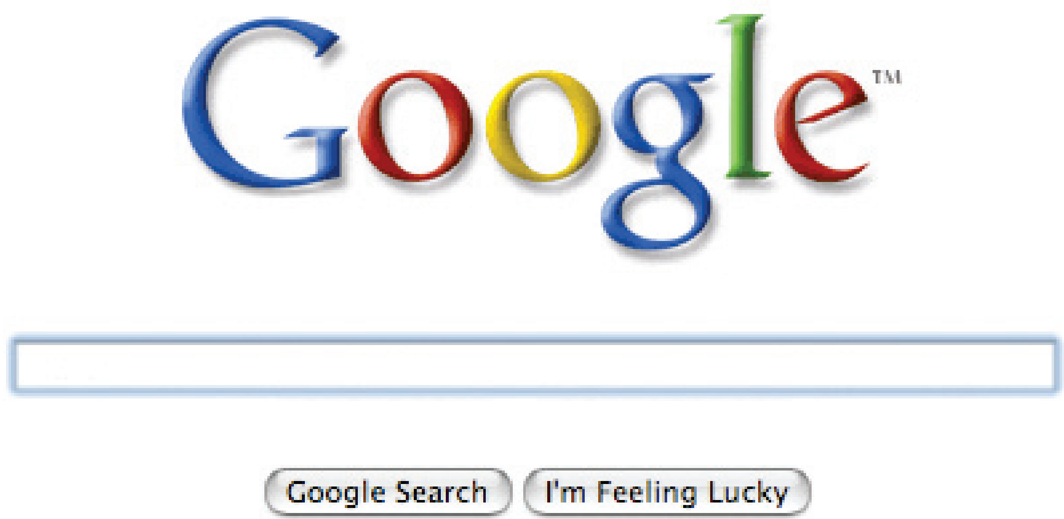
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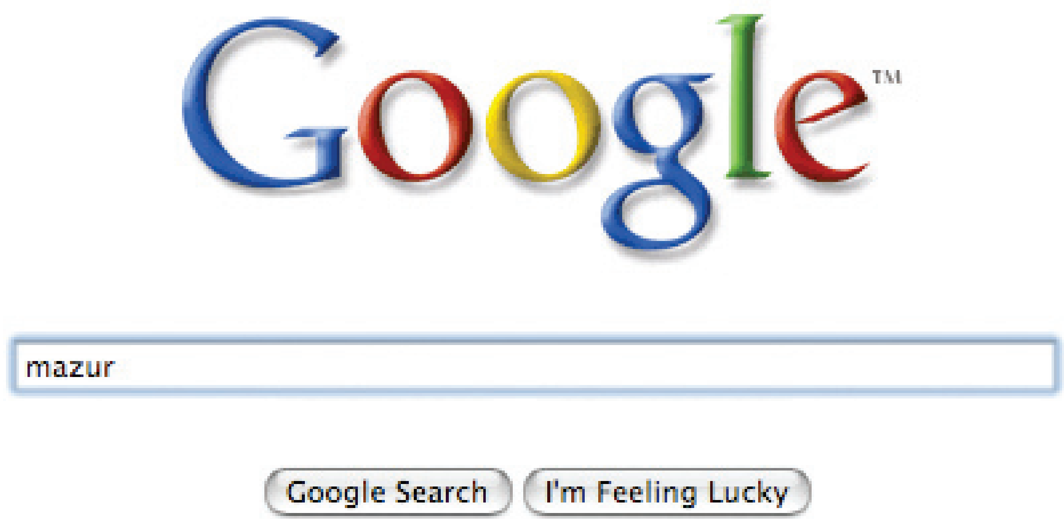
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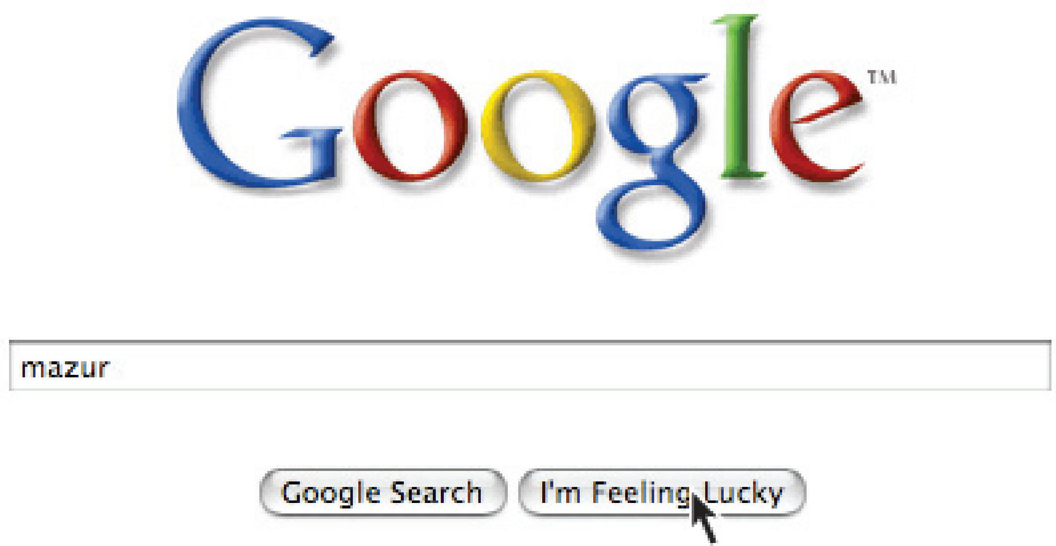
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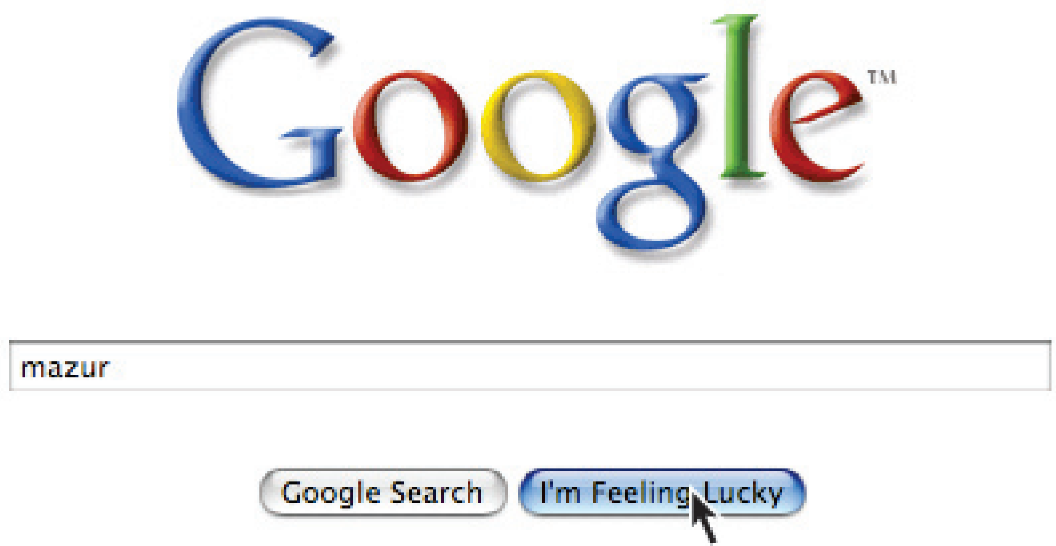
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