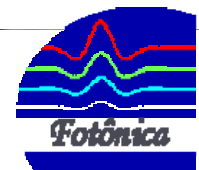


Femtosecond laser microfabrication in polymers

Prof. Dr. Cleber R. Mendonca



University of Sao Paulo - Brazil



students 77.000
52.000 undergrad.
25.000 grad.
employers 15.000
professors 6.000

- Sao Paulo
- Sao Carlos (9.000)
- Ribeirao Preto

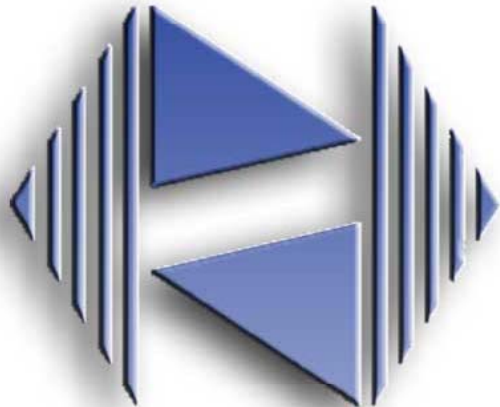




University of Sao Paulo, Sao Carlos



Instituto de Física de São Carlos



Professors: 72

Employers: 173
(technical and administration)

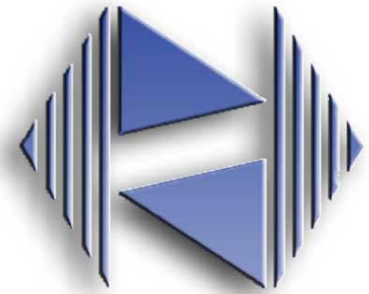
Students: 600 (undergrad)
105 (master)
170 (phD)

Several research areas in Physics
and Material Sciences





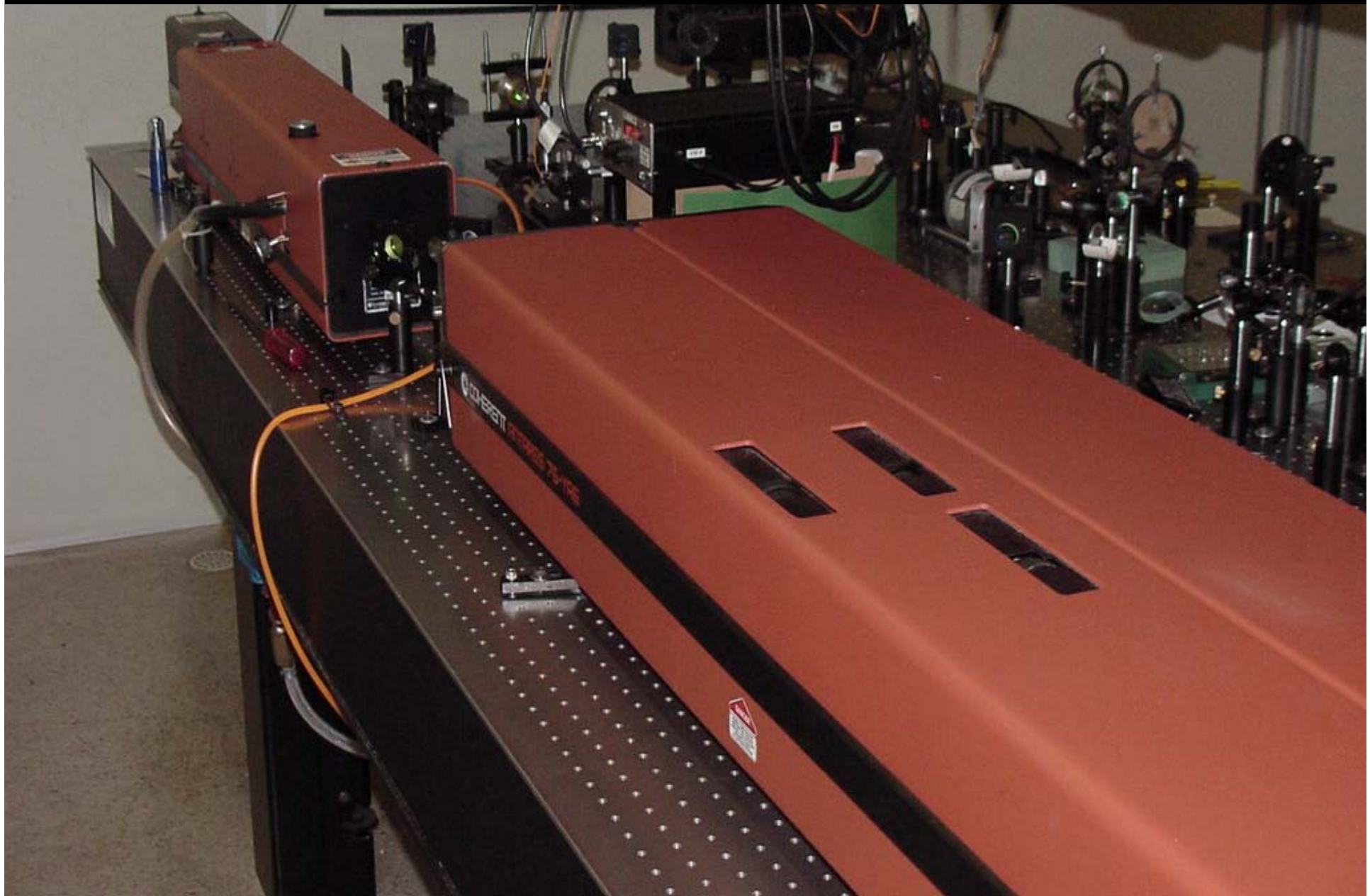
Photonics Groups



research areas

- study of optical nonlinearities in organic materials
- optical storage and surface relief gratings in azopolymers
- coherent control of light matter interaction
- fs-laser microfabrication

70 ps Q-switch/modelocked laser (532/1064 nm)



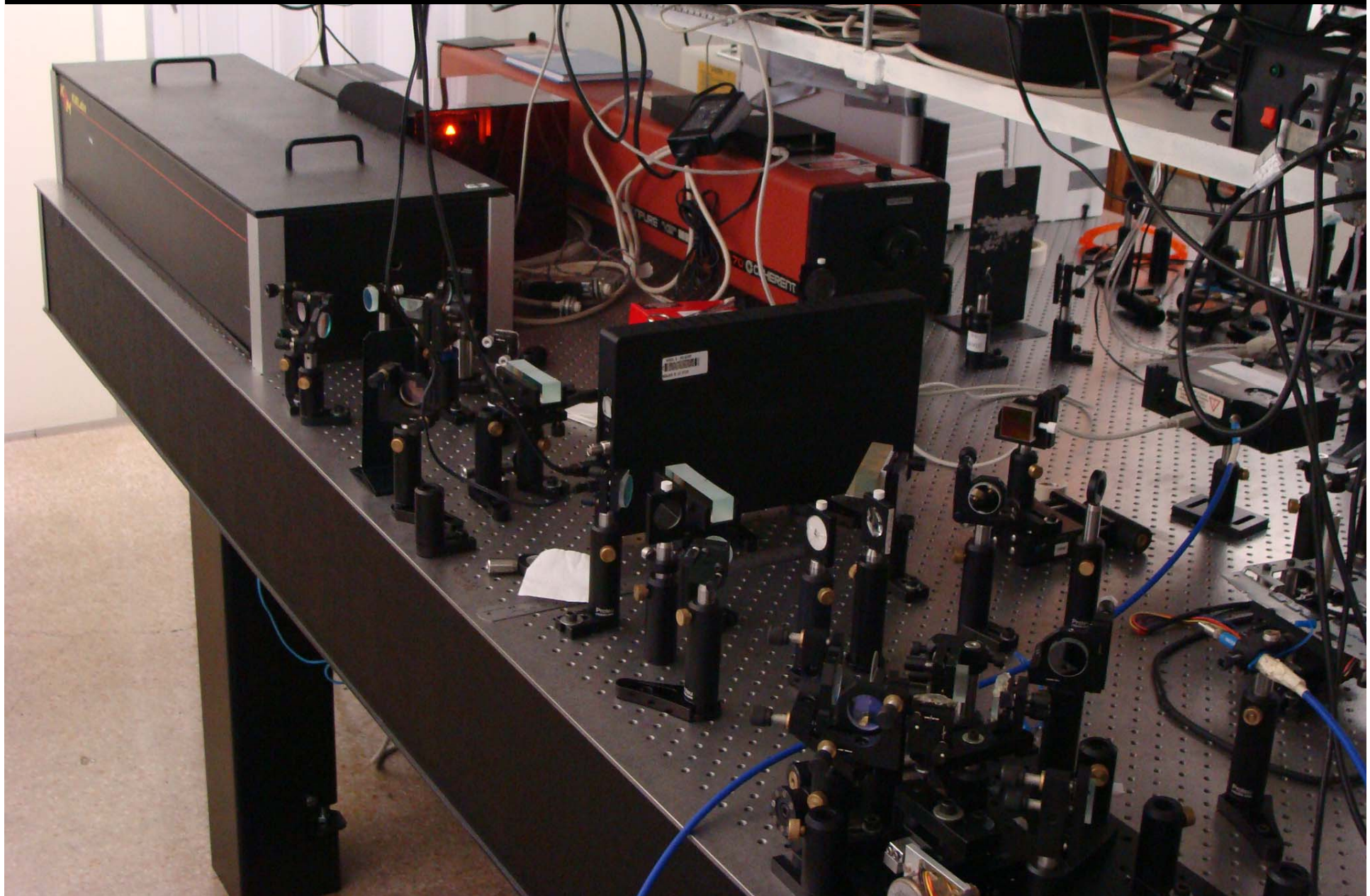
150 fs Ti:sapphire amplifier



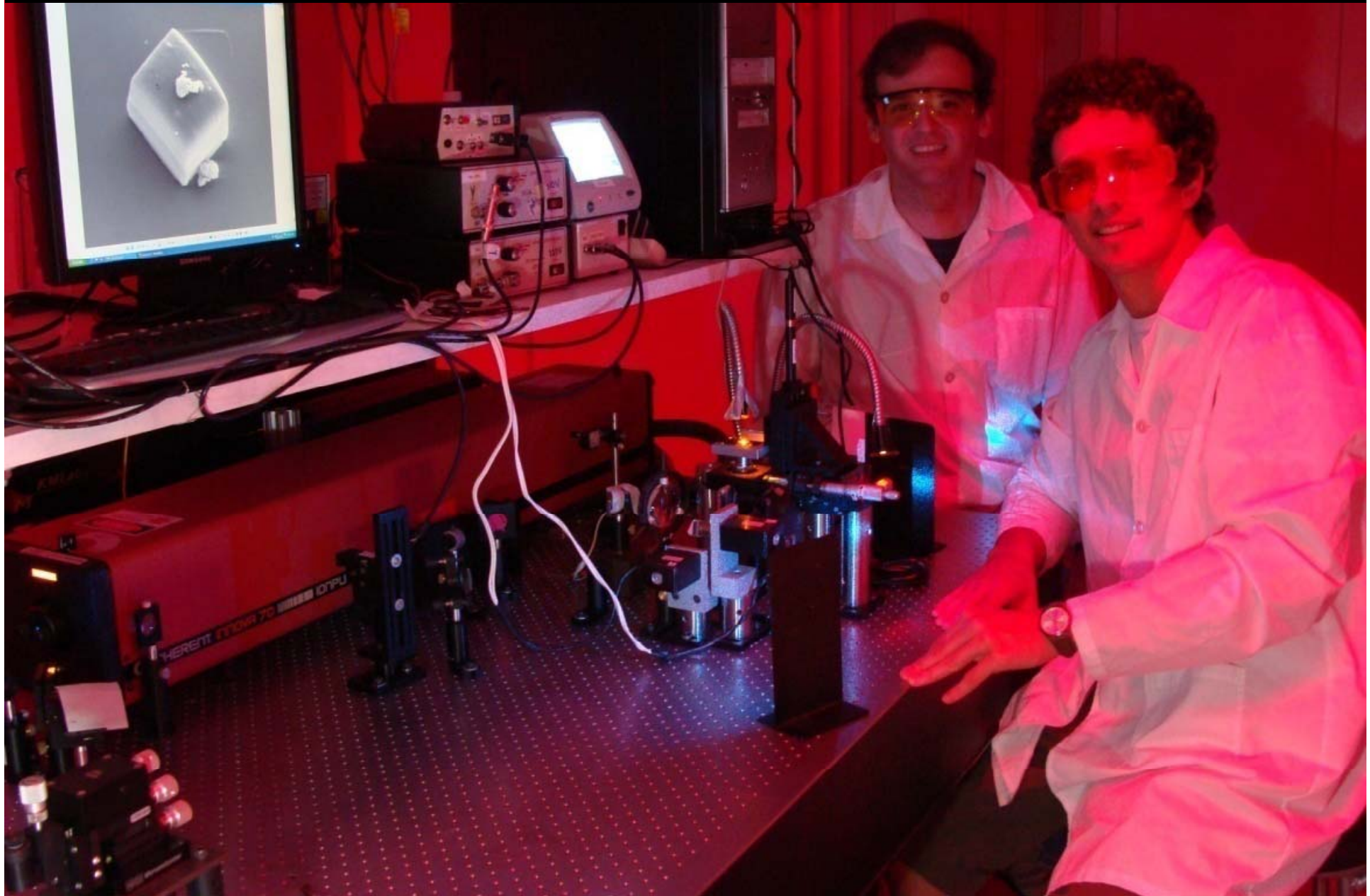
40 fs Ti:sapphire amplifier



20 fs laser oscillator

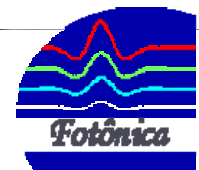


microfabrication laboratory



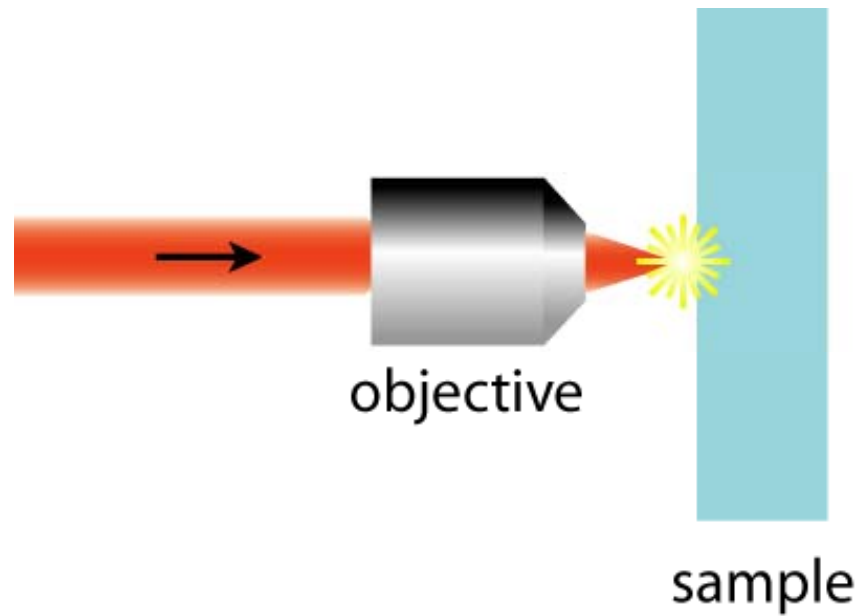
Femtosecond laser microfabrication in polymers

Prof. Dr. Cleber R. Mendonca

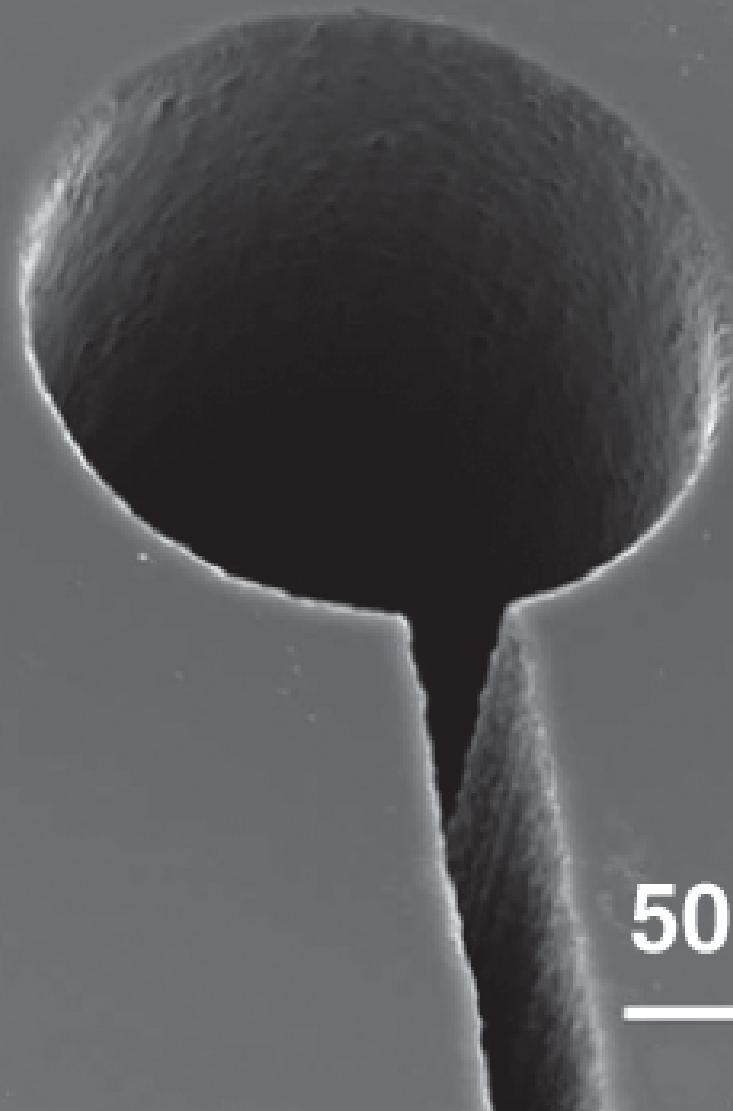


laser microfabrication

focus laser beam on material's surface



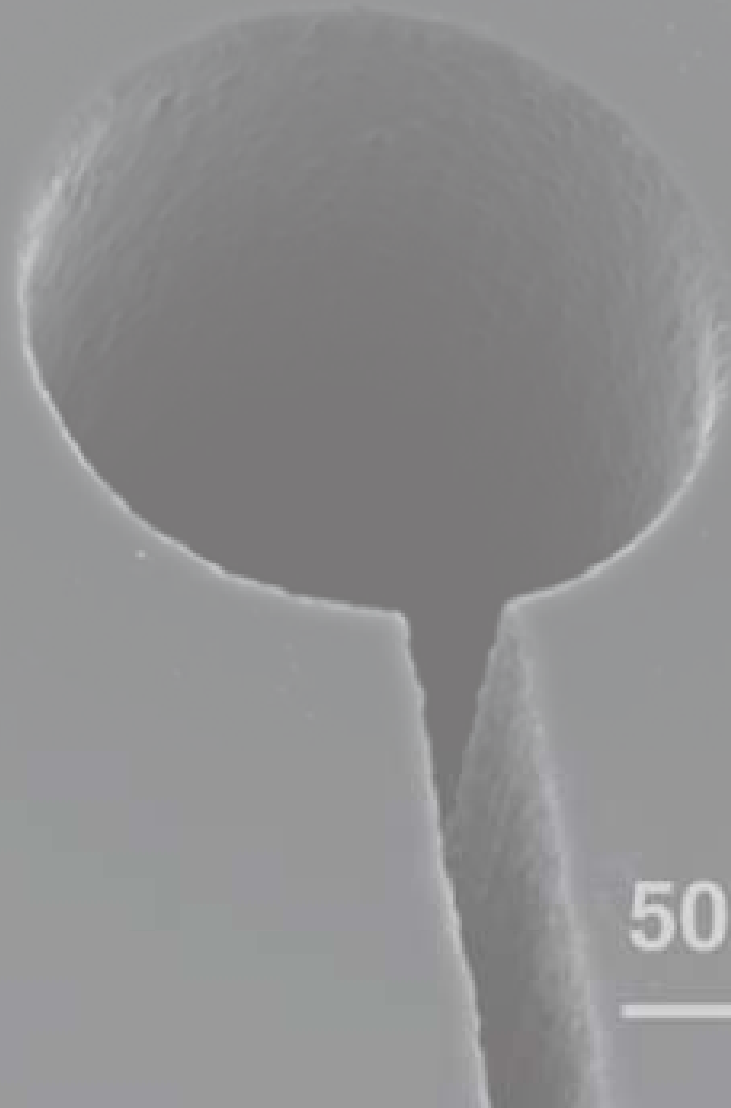
laser microfabrication



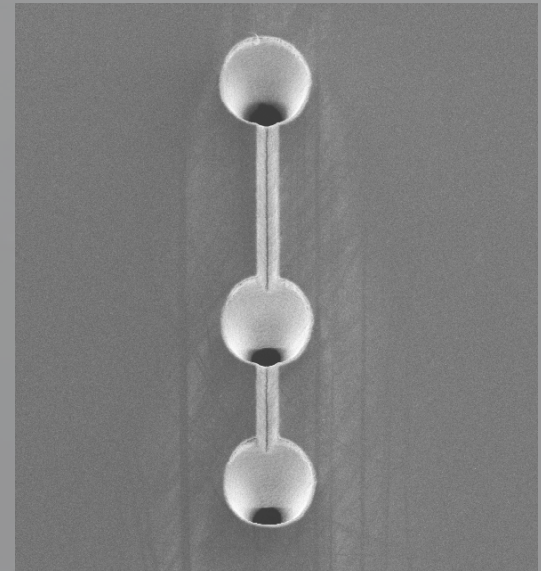
50 μm



laser microfabrication



50 μm

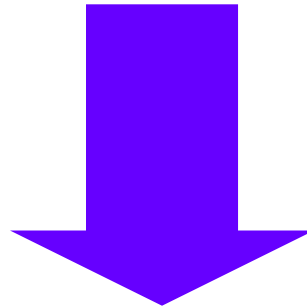


laser microfabrication

surface microstructuring

fs-micromachining

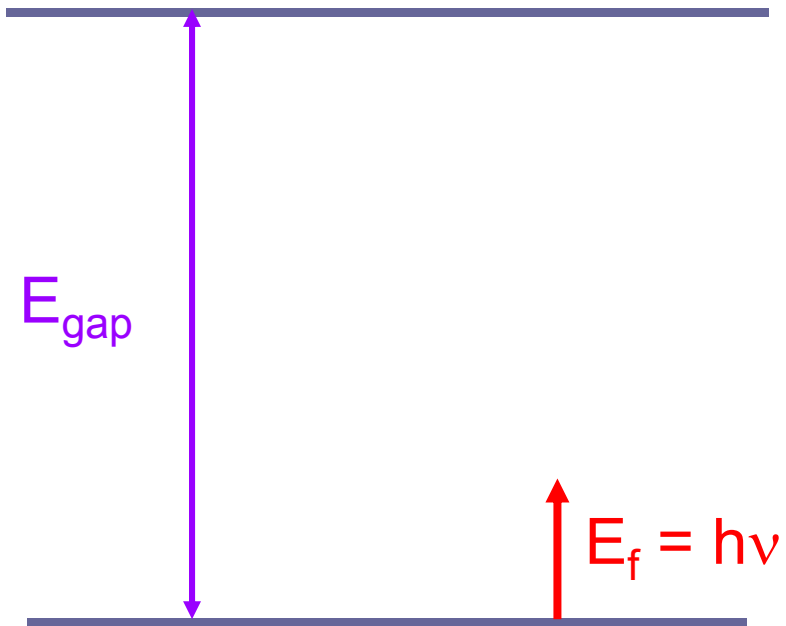
photon energy < bandgap



nonlinear interaction

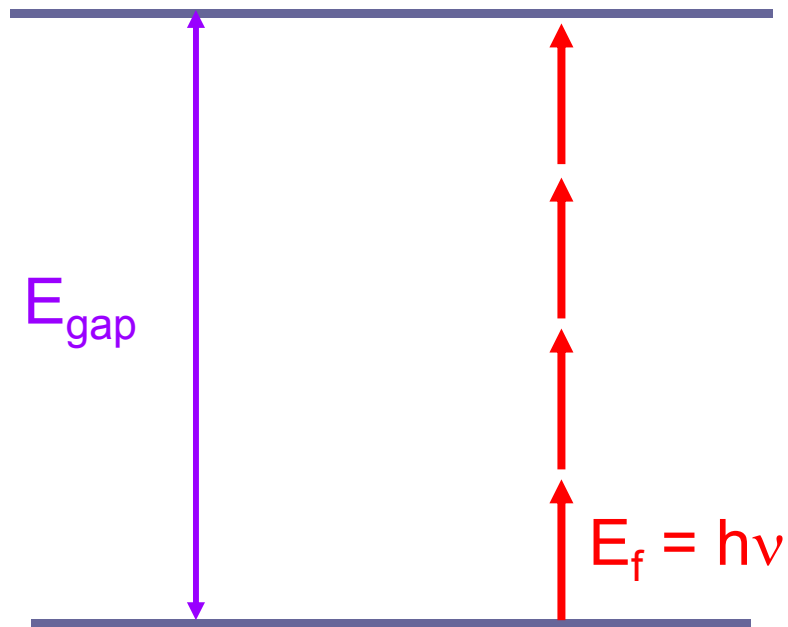
fs-micromachining

nonlinear interaction



fs-micromachining

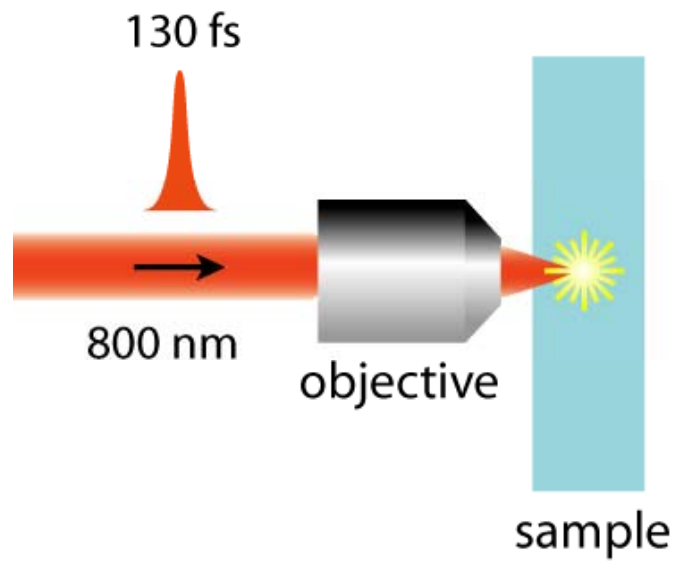
nonlinear interaction



multiphoton absorption

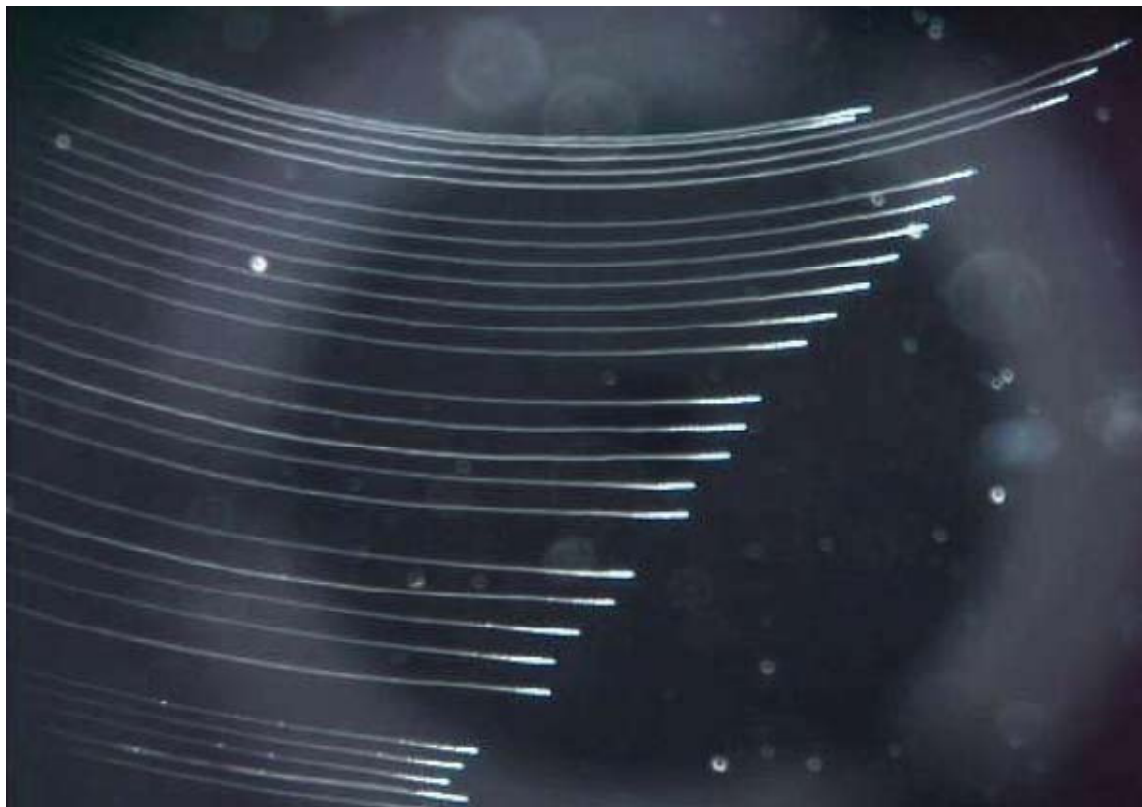
fs-laser microfabrication

focus laser beam inside material



fs-laser microfabrication

curved waveguides inside glass



fs-micromachining

it is important to understand the nonlinear interaction, as well as the nonlinear response of materials

Outline

introduction

fs-micromachining

- microstructuring MEH-PPV

- waveguides in azopolymers

- micromachining living cells

- superhydrophobic surfaces

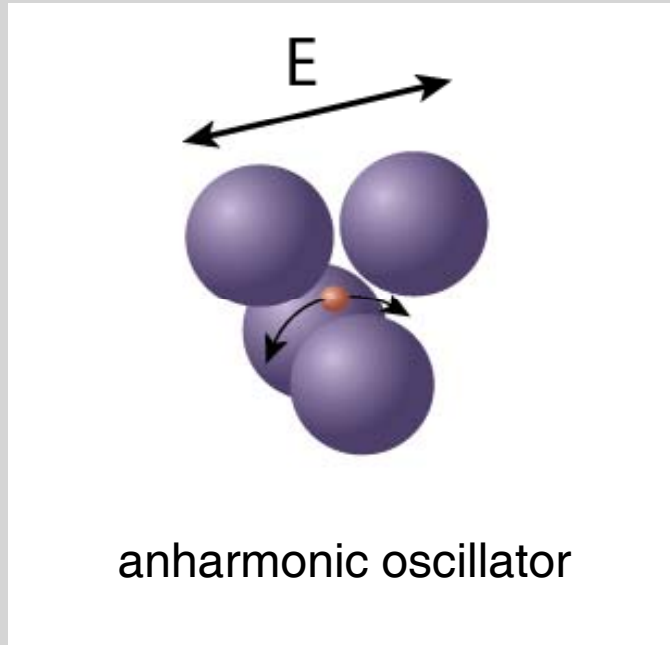
two-photon polymerization

- birefringent microstructures

- fluorescent microstructures

- optical circuiting

Nonlinear Optics



high light intensity

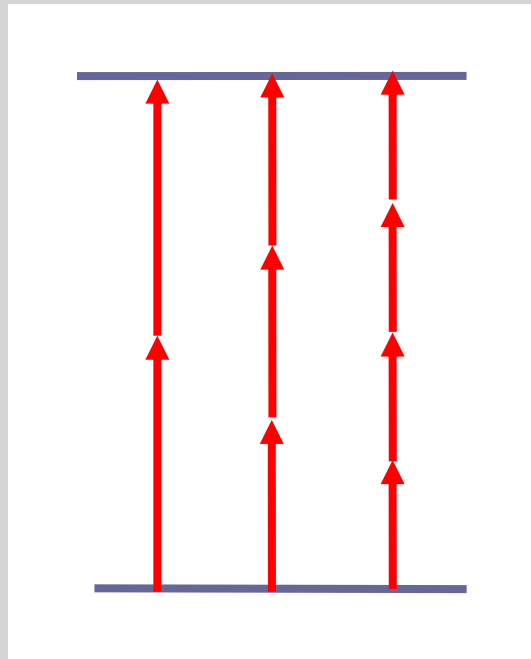
$$E_{\text{rad.}} \sim E_{\text{inter.}}$$

nonlinear polarization response

$$P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots$$

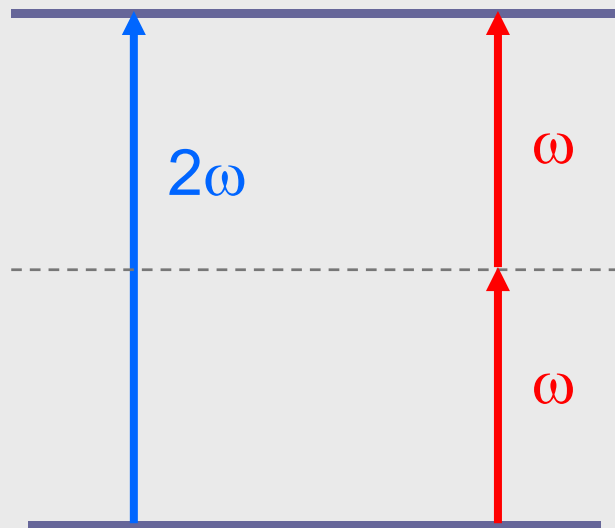
Multi-photon absorption

$$\chi^{(3)}, \chi^{(5)}, \chi^{(7)}, \dots$$



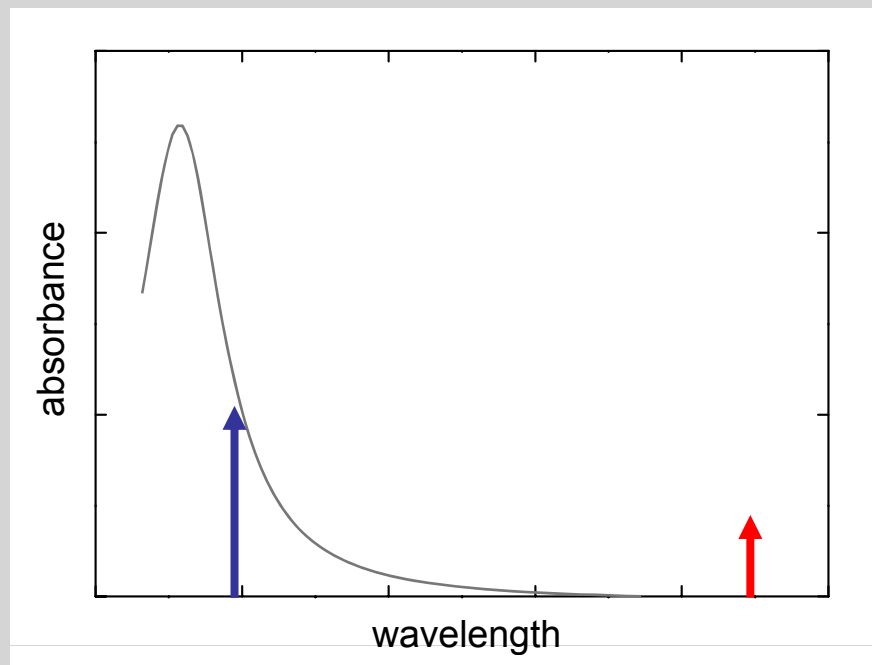
$$\alpha = \alpha_0 + \beta I + \alpha_3 I^2 + \alpha_4 I^3 + \alpha_5 I^4 + \dots$$

Two-photon absorption



$$\alpha = \alpha_0 + \beta I$$

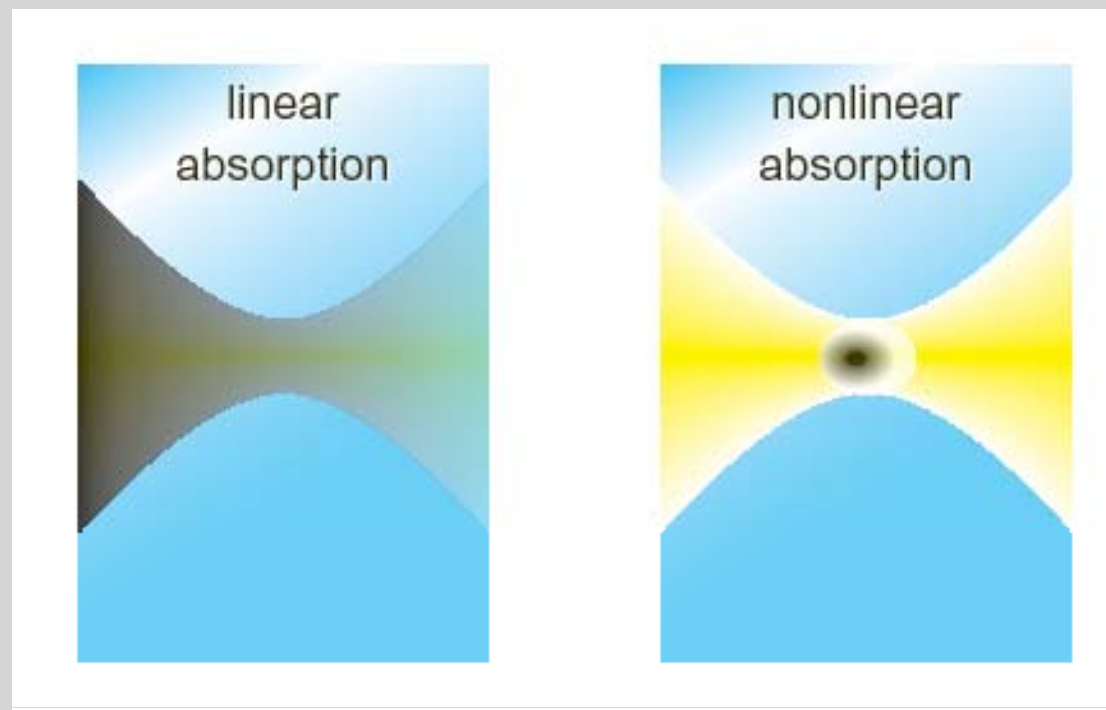
Third order processes $\chi^{(3)}$



Two-photon absorption

Nonlinear interaction provides spatial confinement of the excitation

fs-microfabrication



$$\alpha = \alpha_0$$

$$\alpha = \alpha_0 + \beta I$$

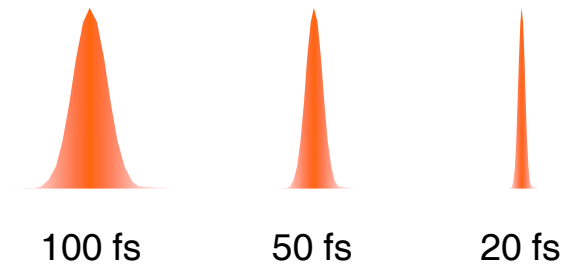
Two-photon absorption



spatial confinement of excitation

femtosecond pulses

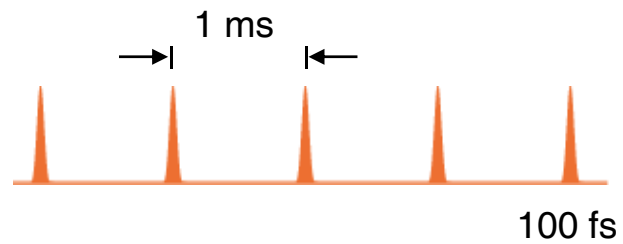
Ti:Sapphire lasers



$1 \text{ fs} = 10^{-15} \text{ s}$

Repetition rate

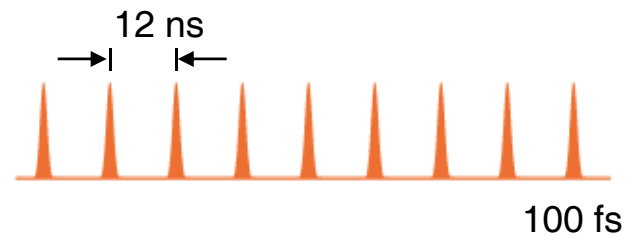
1 KHz



Energy

mJ

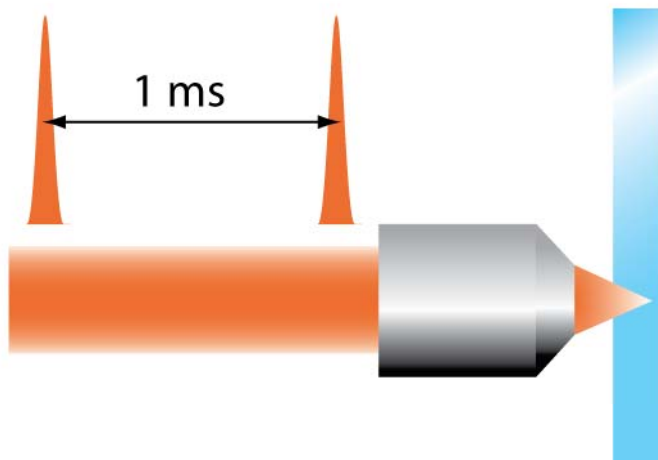
86 MHz



nJ

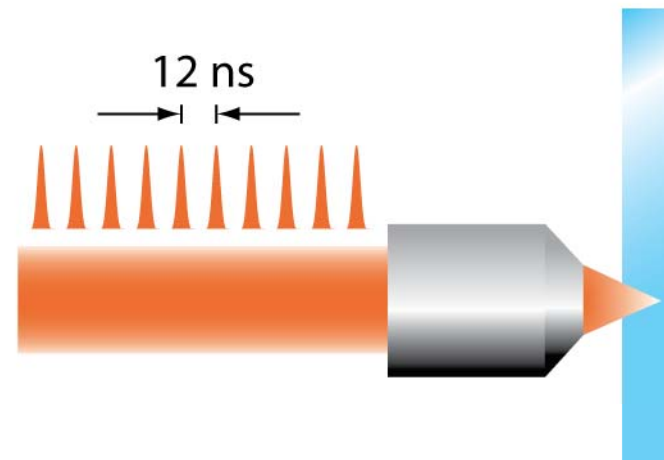
femtosecond pulses

amplified laser



repetitive

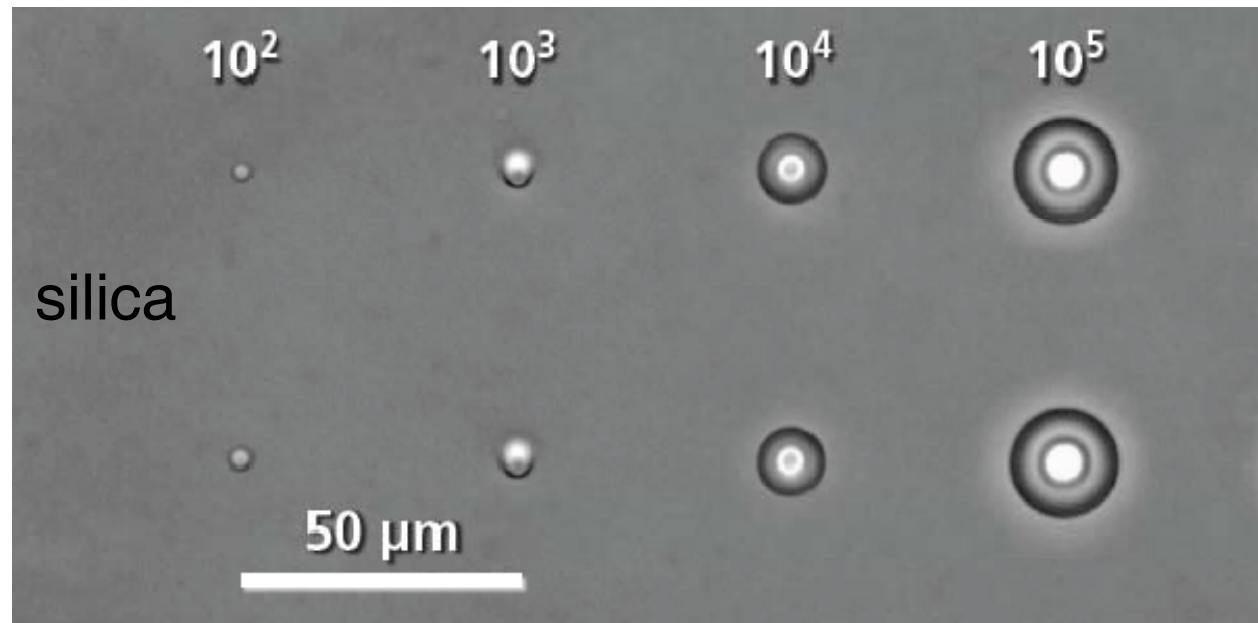
oscillator



cumulative

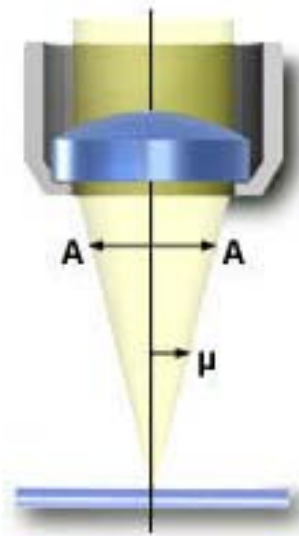
fs-micromachining

the longer the irradiation the longer the radius



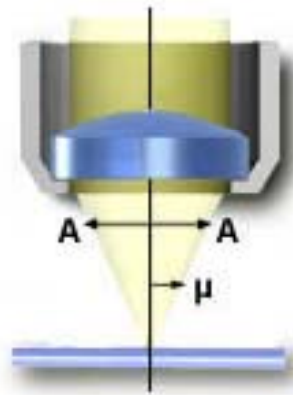
E. Mazur – Harvard University

fs-micromachining: focusing



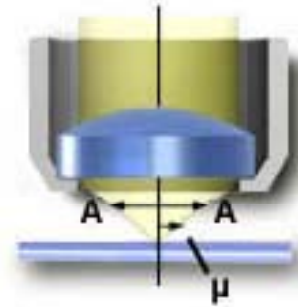
$$NA = 0.12$$

$$\mu = 7^\circ$$



$$NA = 0.34$$

$$\mu = 20^\circ$$

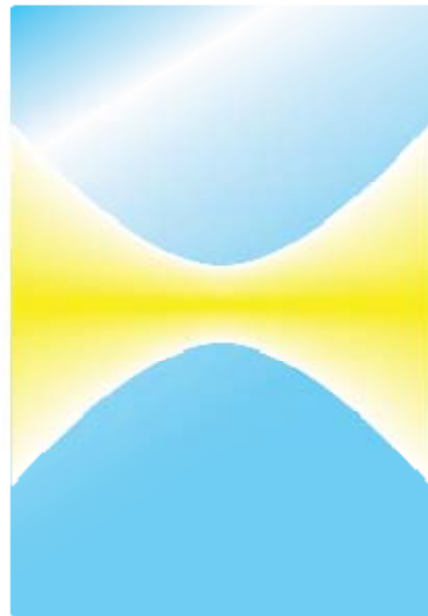


$$NA = 0.87$$

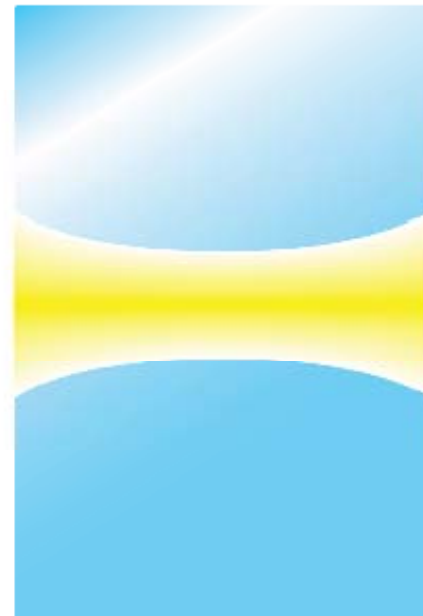
$$\mu = 60^\circ$$

what is the difference ?

high NA



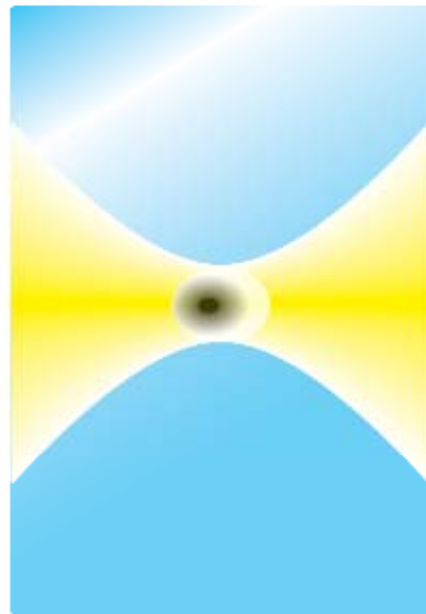
low NA



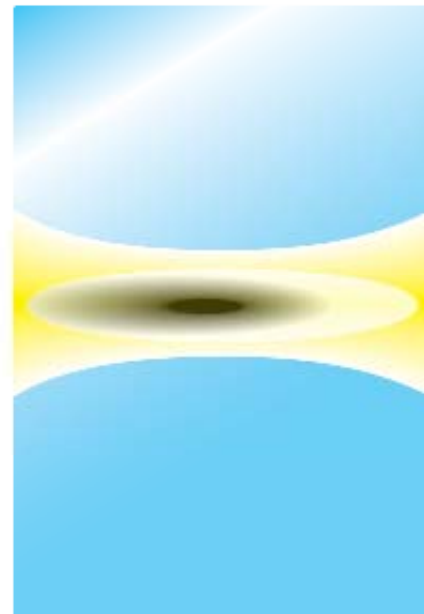
$$w_0 = \frac{\lambda}{\pi NA} \sqrt{1 - NA^2}$$

very different confocal length/interaction length

high NA



low NA



fs-micromachining

microfabrication can be controlled by

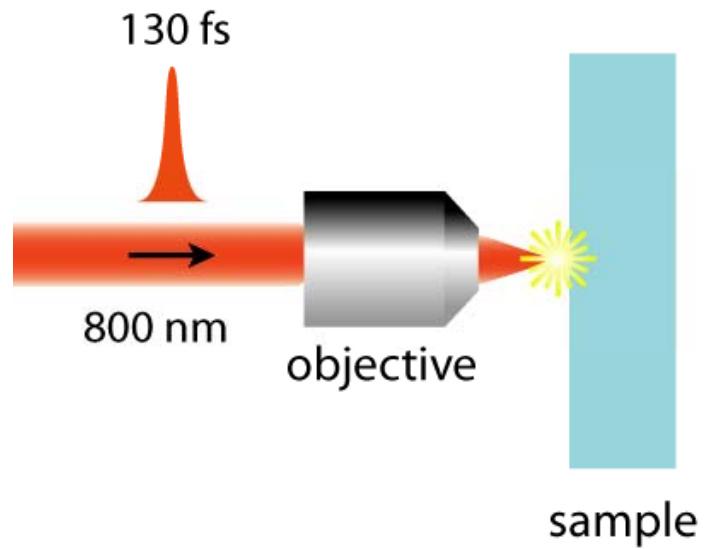
- objective NA
- number of pulses – scanning speed
- pulse energy

two main techniques

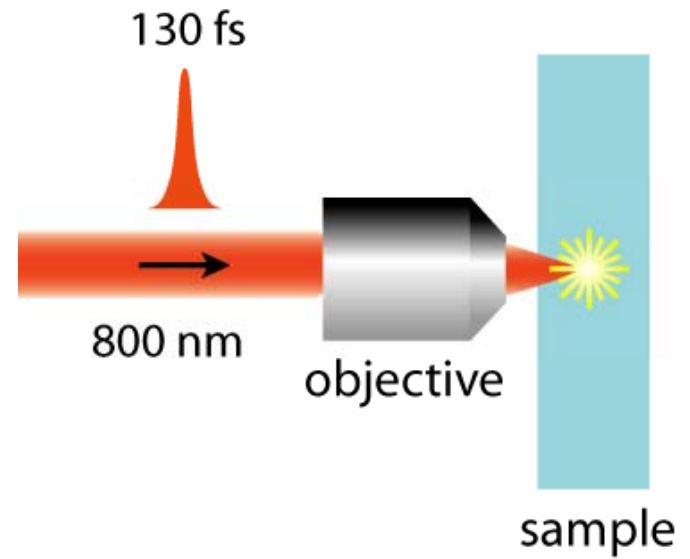
- fs-laser micromachining
- microfabrication via two-photon polymerization

fs-laser micromachining

Surface

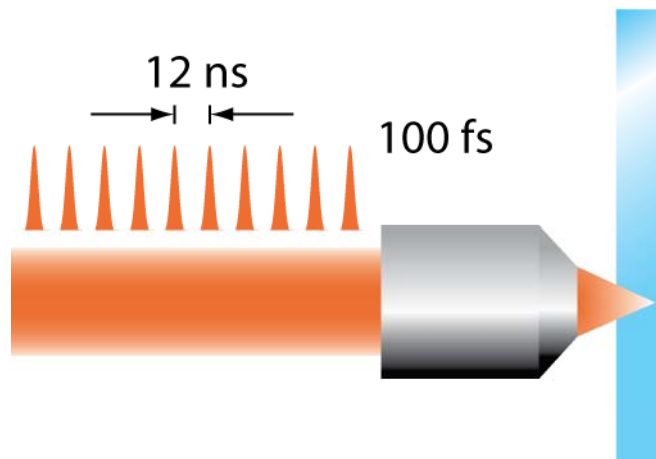


Volume



fs-pulses for micromachining polymers

Oscillator: 80 MHz, 5 nJ

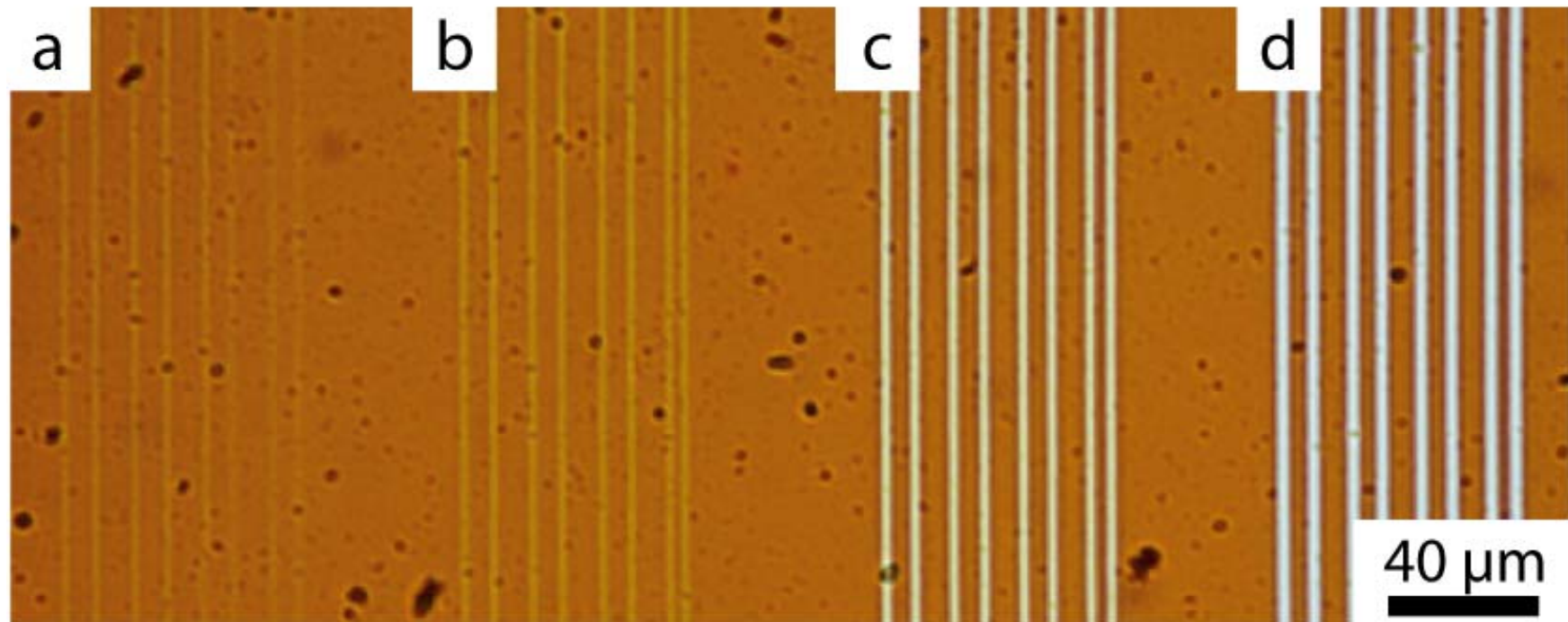


heat diffusion time: $t_{\text{diff}} \sim 1 \mu\text{s}$

cumulative

Micromachining the conductive polymer MEH-PPV

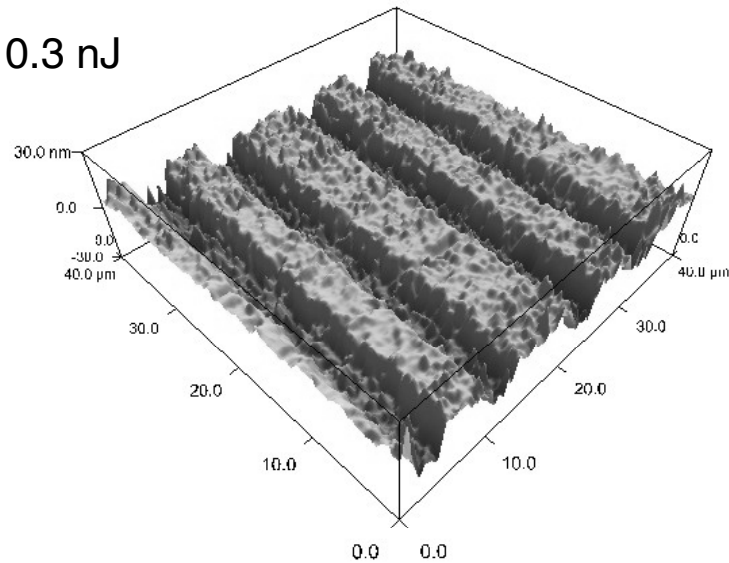
optical microscopy



a: 0.07 nJ
b: 0.14 nJ
c: 0.34 nJ
d: 0.68 nJ

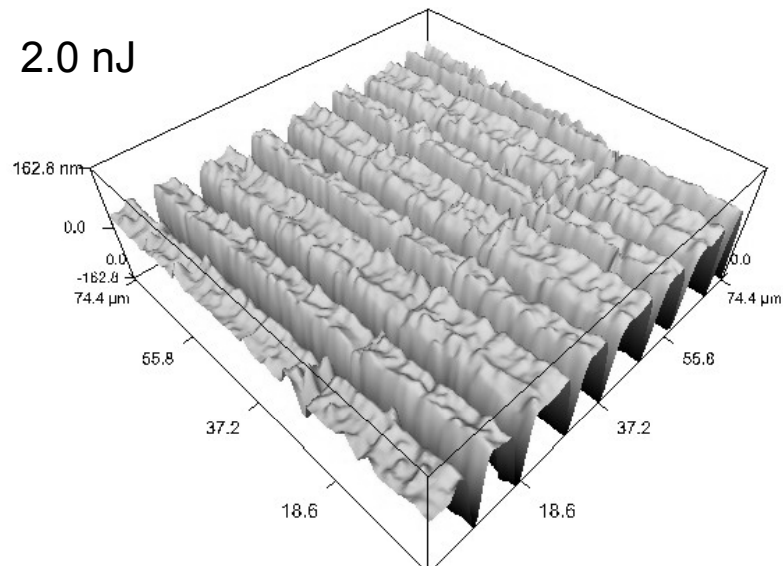
Micromachining the conductive polymer MEH-PPV

a 0.3 nJ

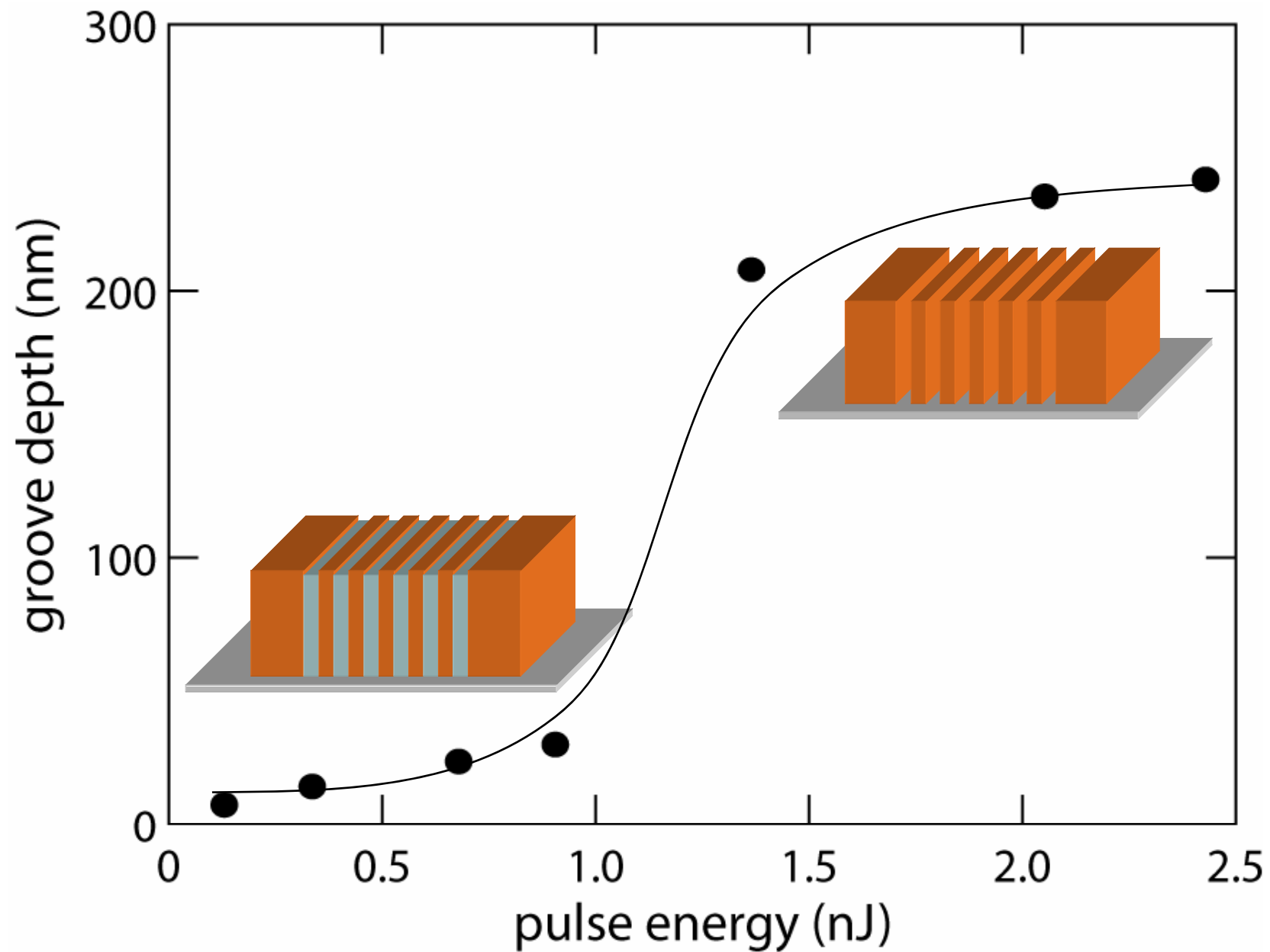


atomic force microscopy

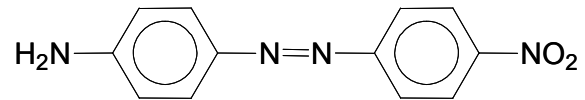
b 2.0 nJ



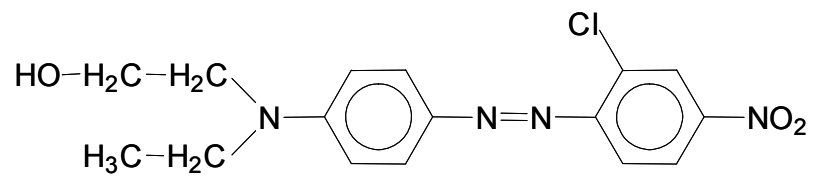
Micromachining the conductive polymer MEH-PPV



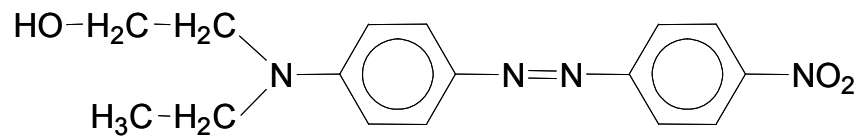
Waveguides in azo-polymers



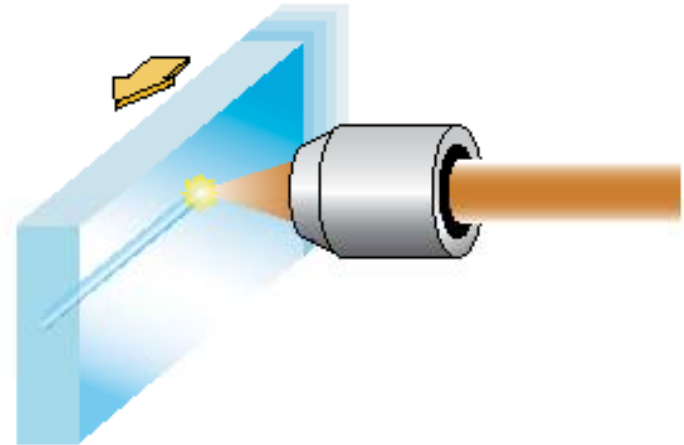
DO3



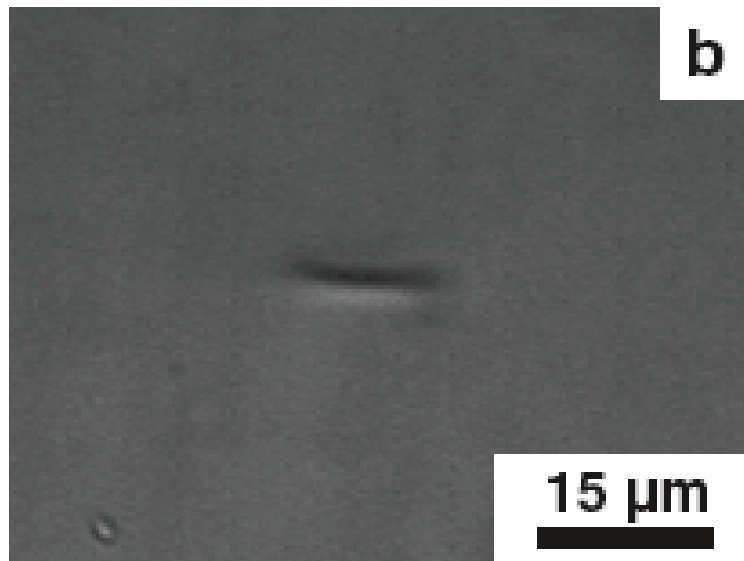
DR13



DR1



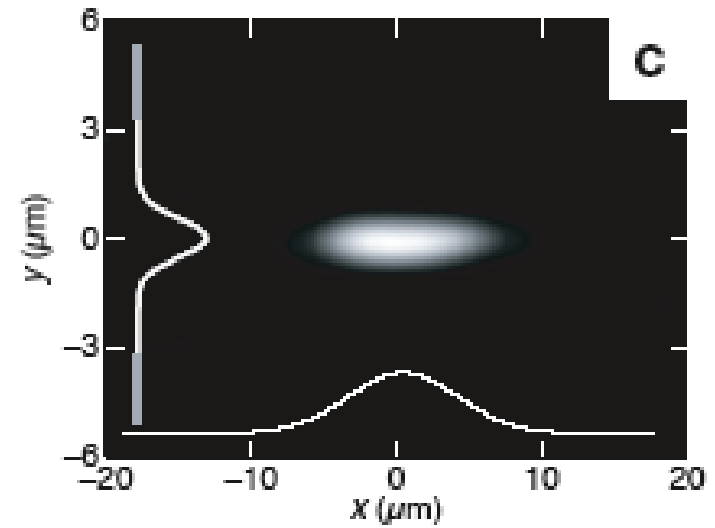
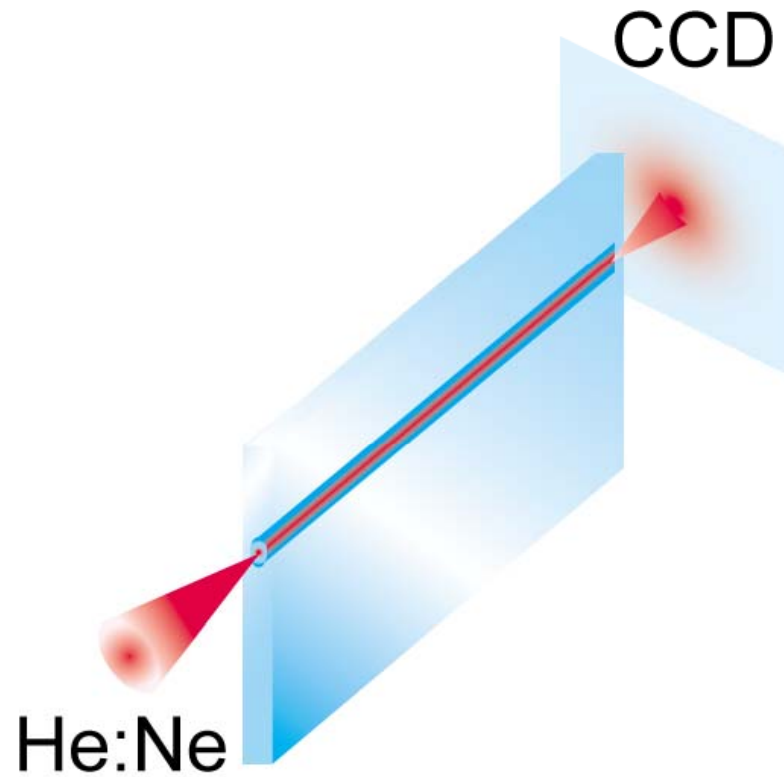
Waveguides in azo-polymers



(a) Optical microscope image of the waveguides micromachined (PMMA/DR1)

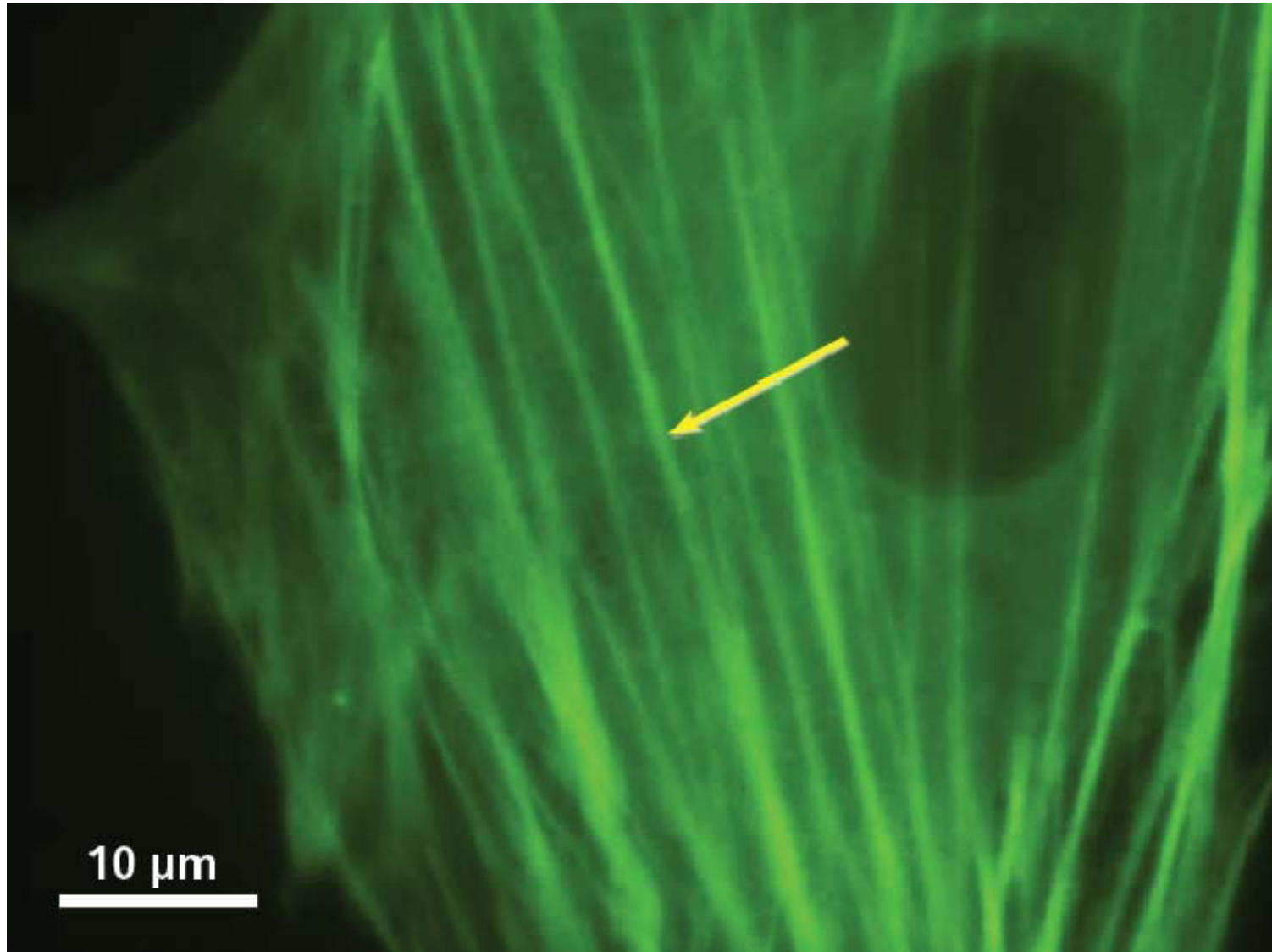
(b) Cross-sectional view of the waveguides

waveguides in azo-polymers



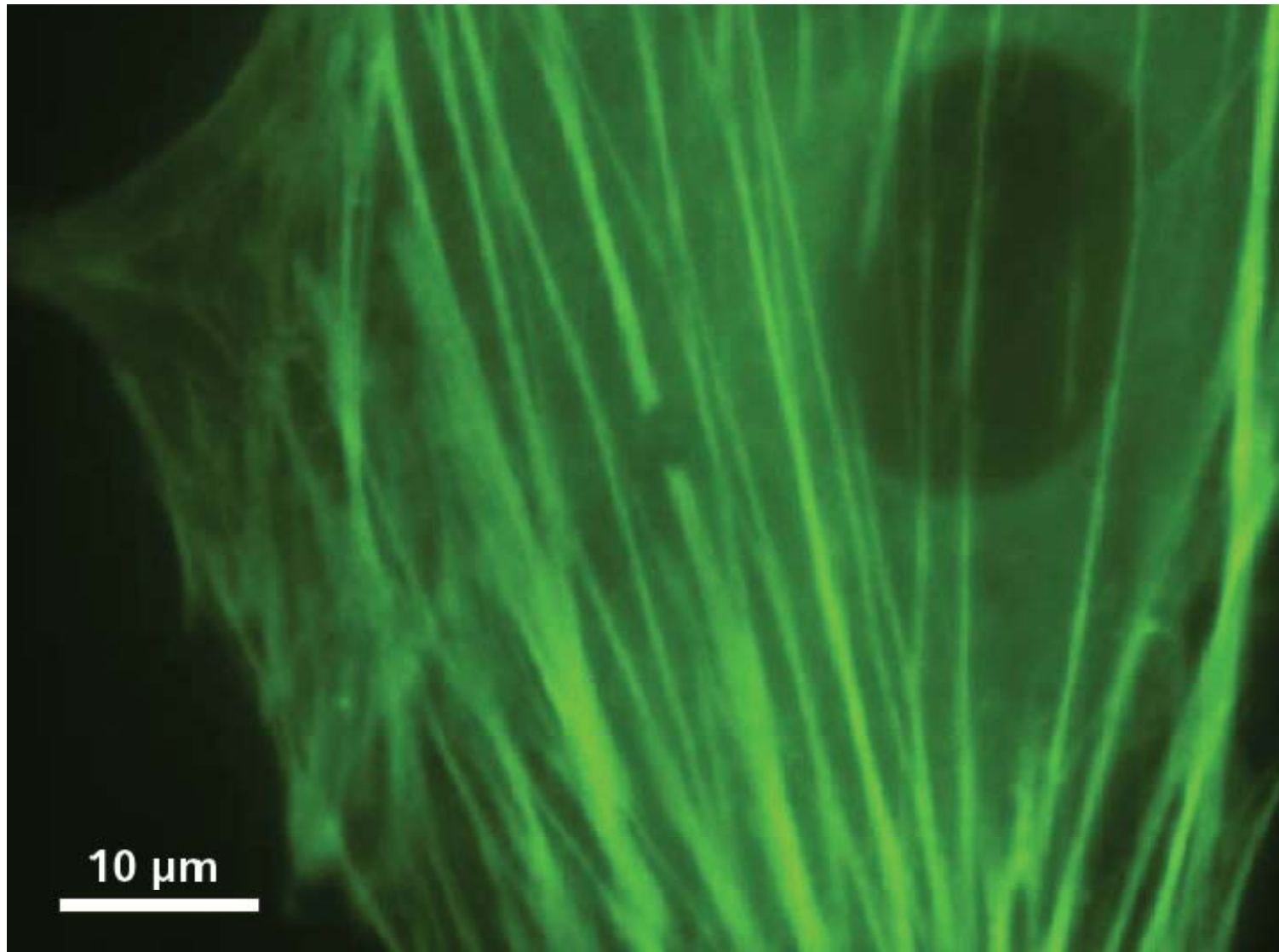
(c) Output image of the mode profile of 632.8-nm light coupled through the waveguide

Subcellular surgery



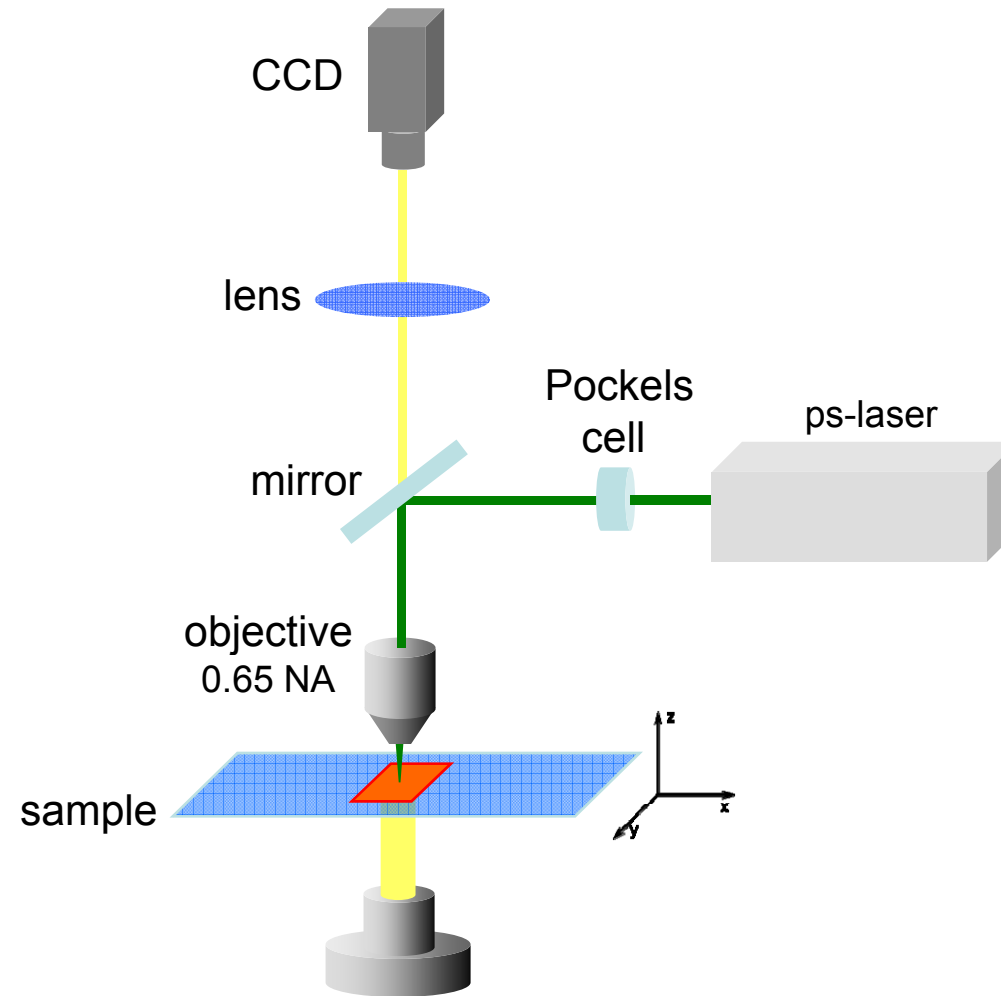
I. Maxwell, E. Mazur – Harvard University

Subcellular surgery

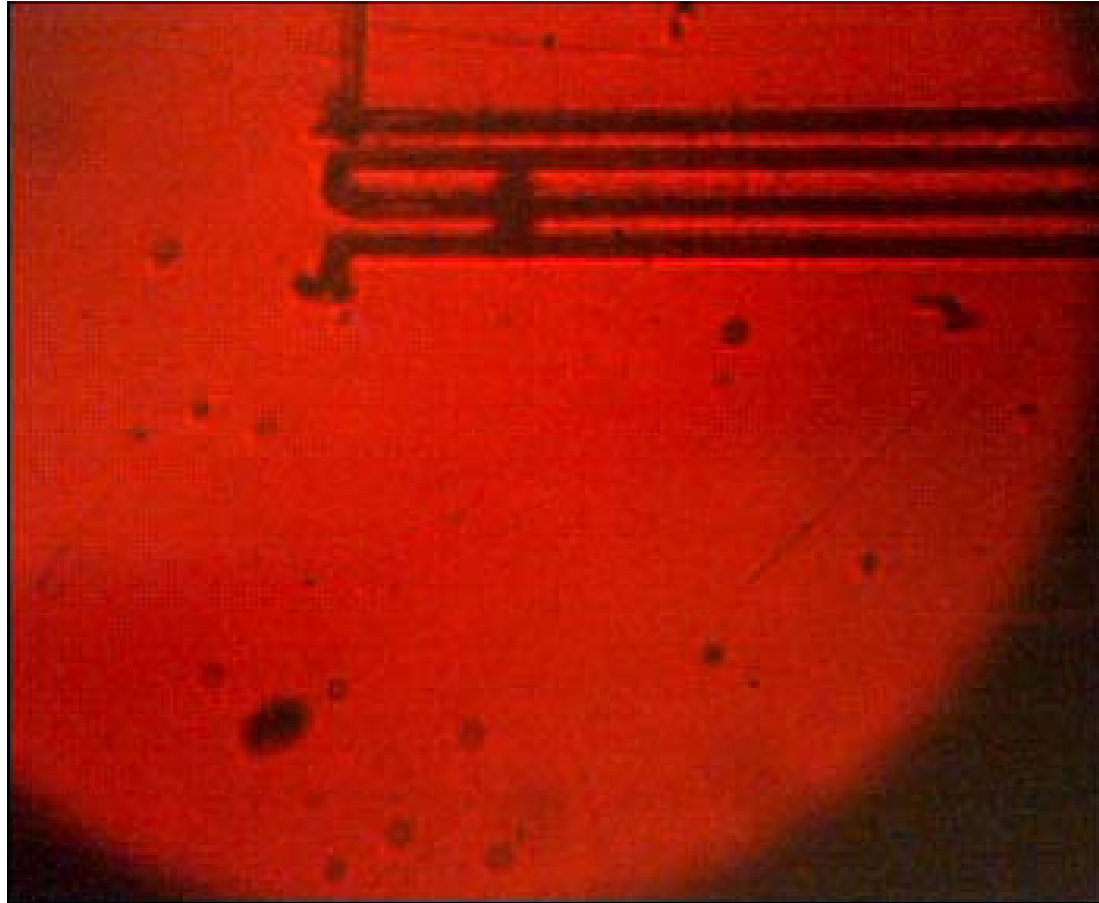


I. Maxwell, E. Mazur – Harvard University

microstructuring polymer: super hydrophobic surface

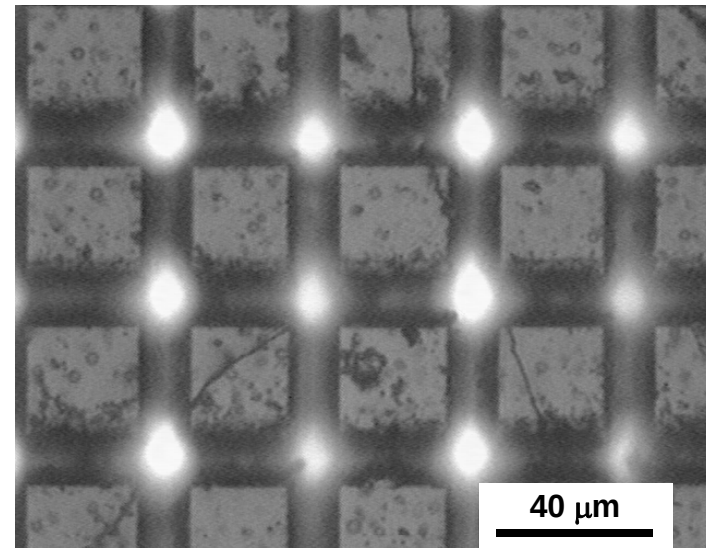
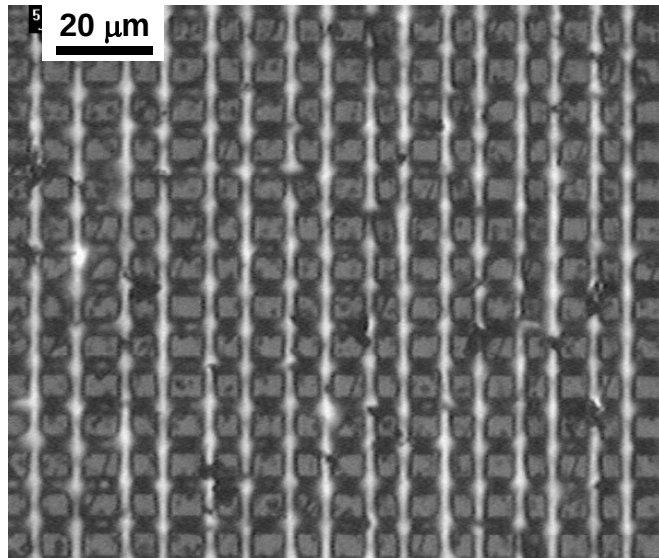


microstructuring polymer: super hydrophobic surface



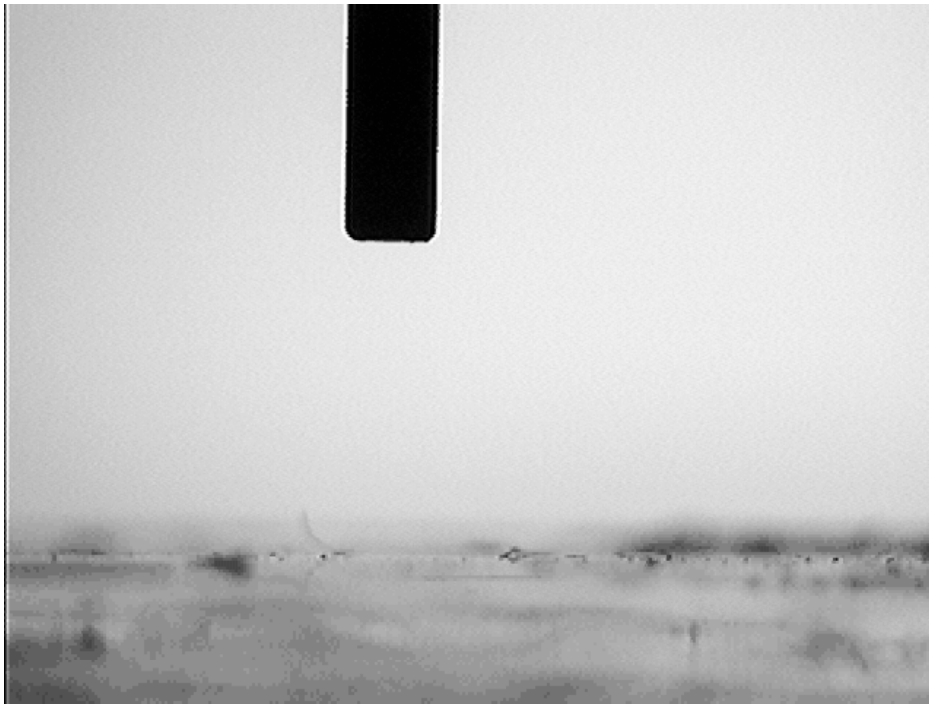
laser microfabrication: super hydrophobic surface

examples of fabricated surfaces

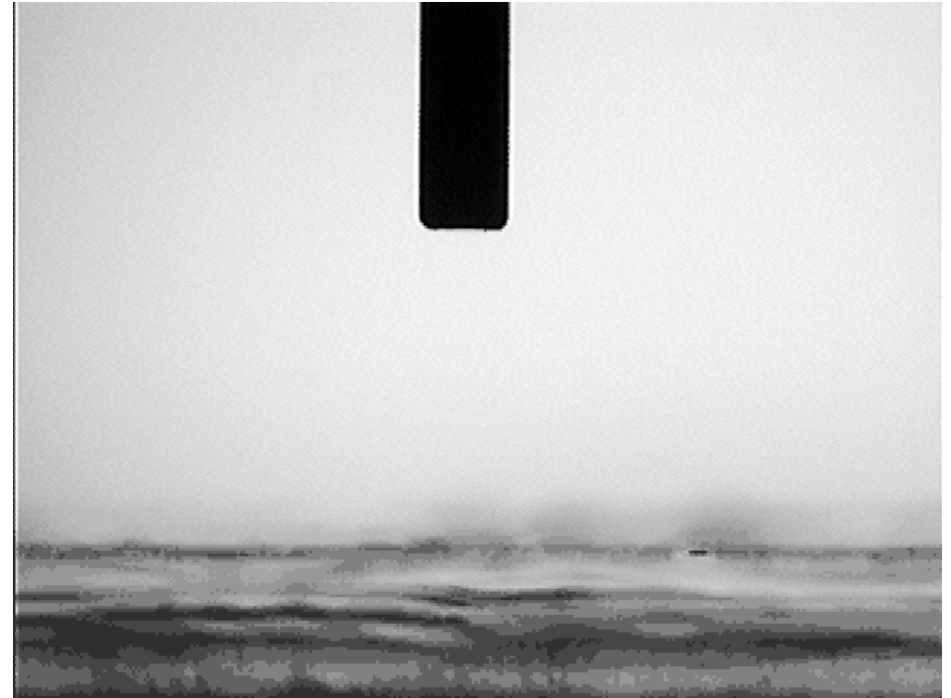


laser microfabrication: super hydrophobic surface

Superhydrophobic surfaces

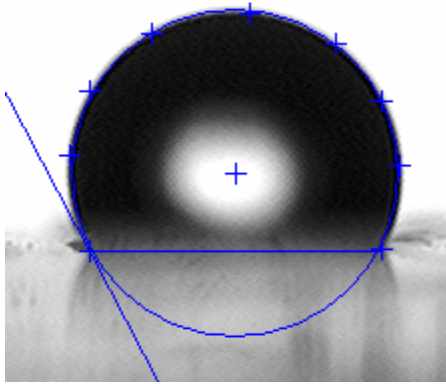


flat surface



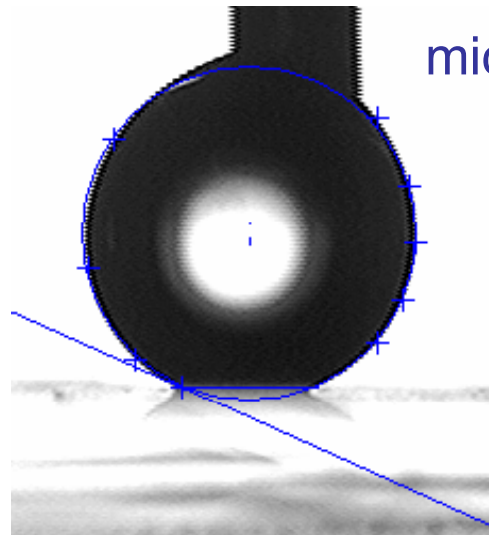
microstructured surface

microstructuring polymer



flat surface

$$\theta = 118^\circ$$



microstructured surface

$$\theta = 160^\circ$$

fs-laser microfabrication

Novel concept:

build a microstructure using fs-laser and nonlinear optical processes

two-photon polymerization

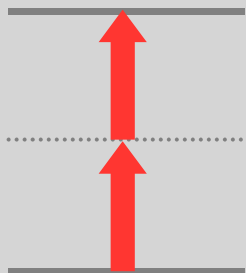
applications

- micromechanics
- waveguides
- microfluidics
- biology
- optical devices

Two-photon polymerization



Photoinitiator is excited by ***two-photon absorption***



$$R_{2PA} \propto I^2$$

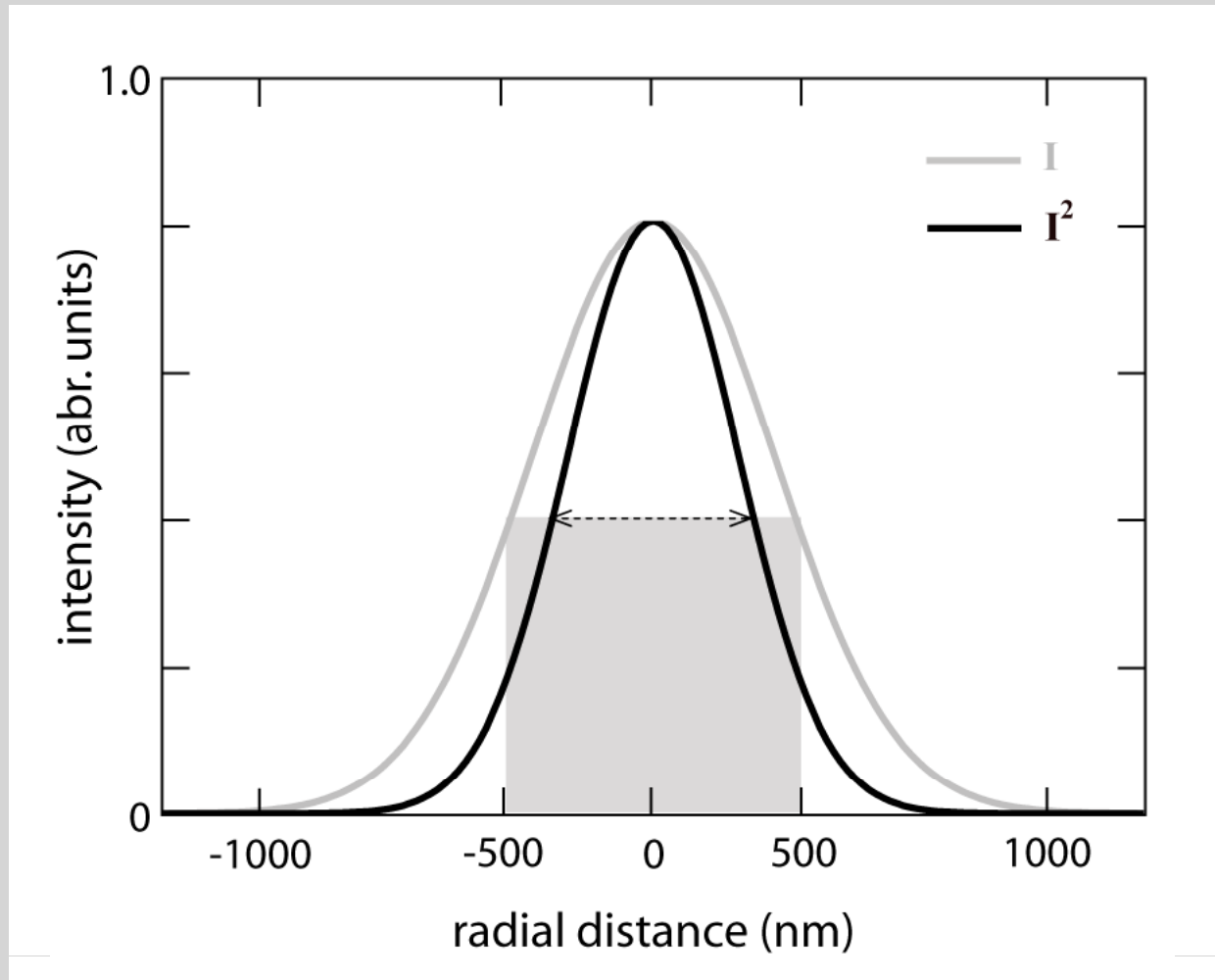
The polymerization is confined to the focal volume.



High spatial resolution

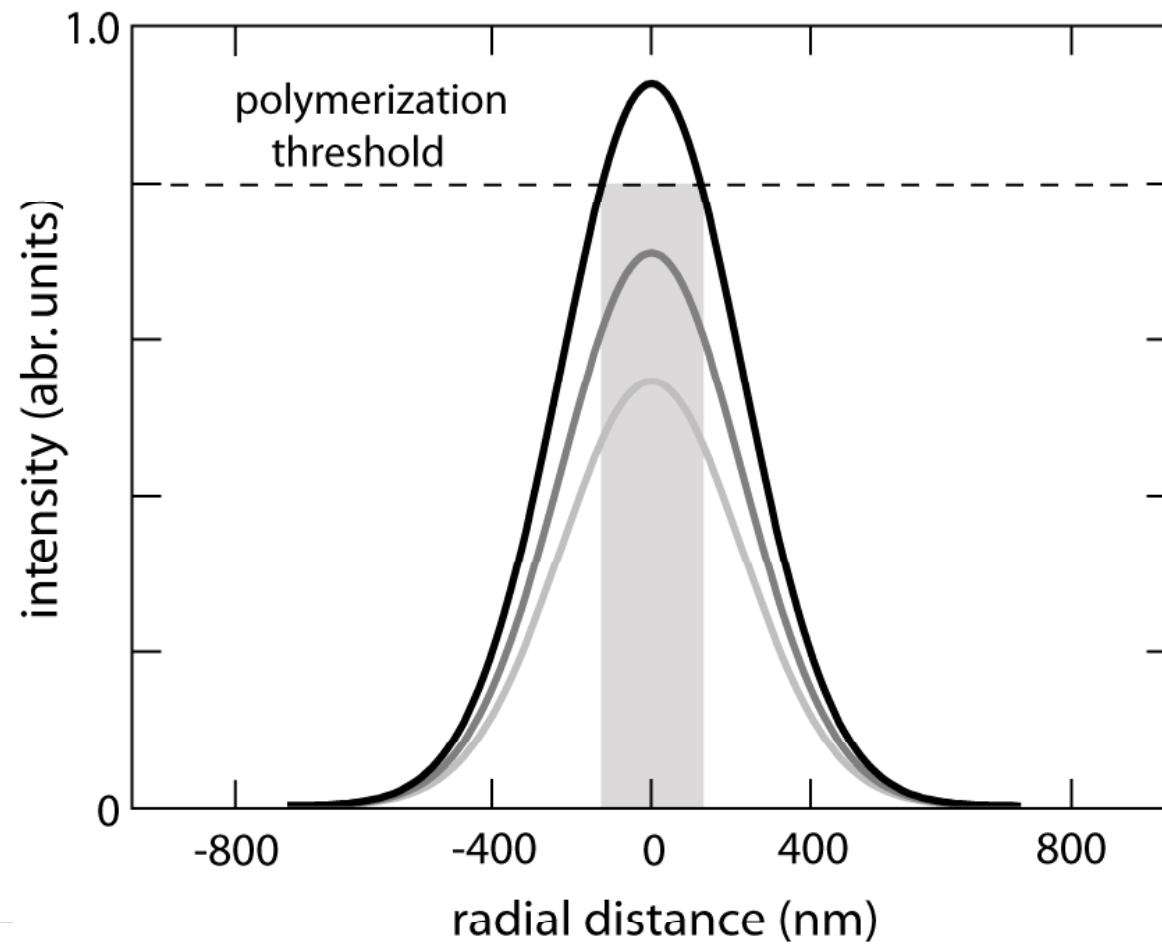


Two-photon polymerization



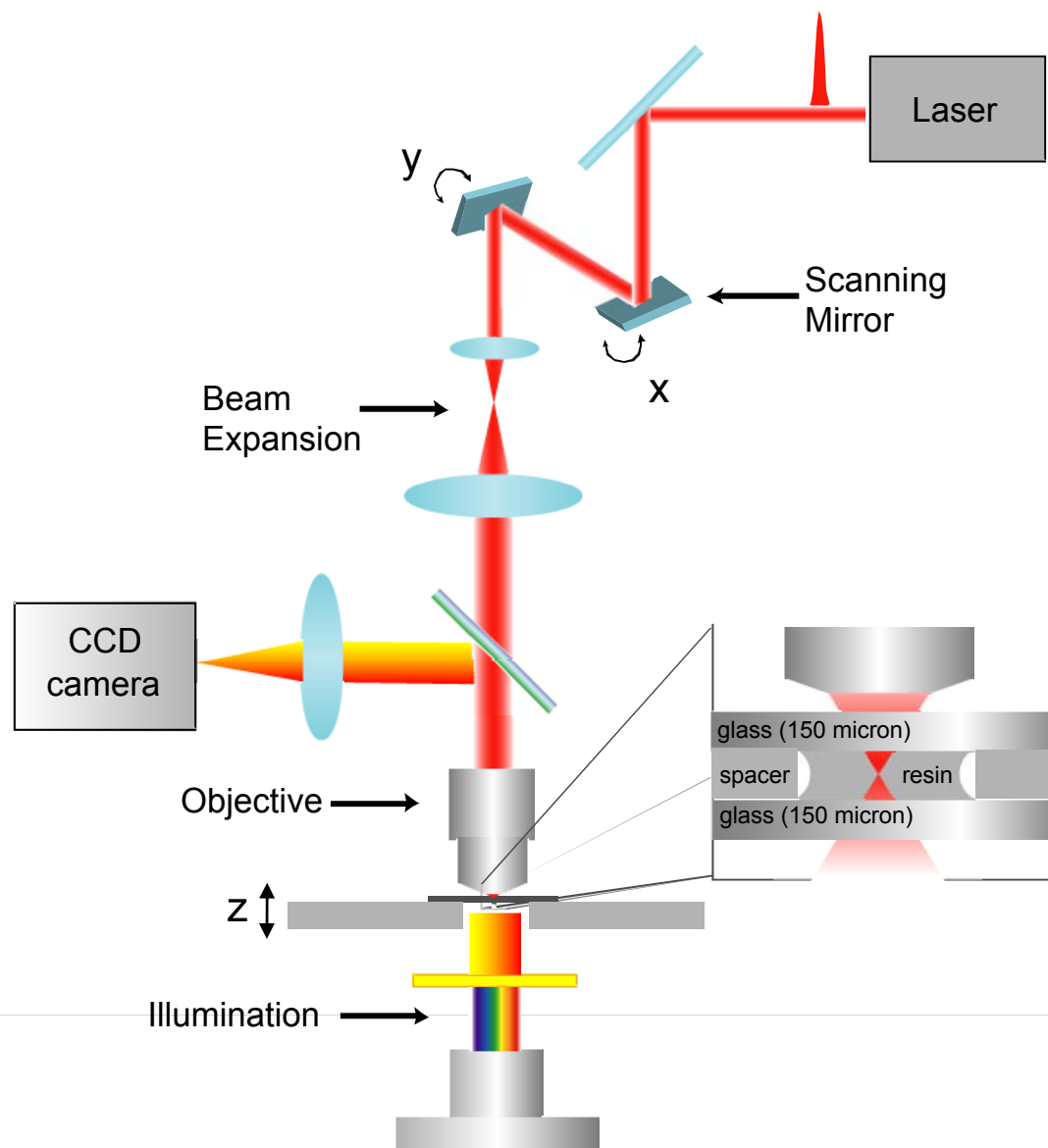
bellow the diffraction limit

Two-photon polymerization



even higher spatial resolution

Two-photon polymerization setup



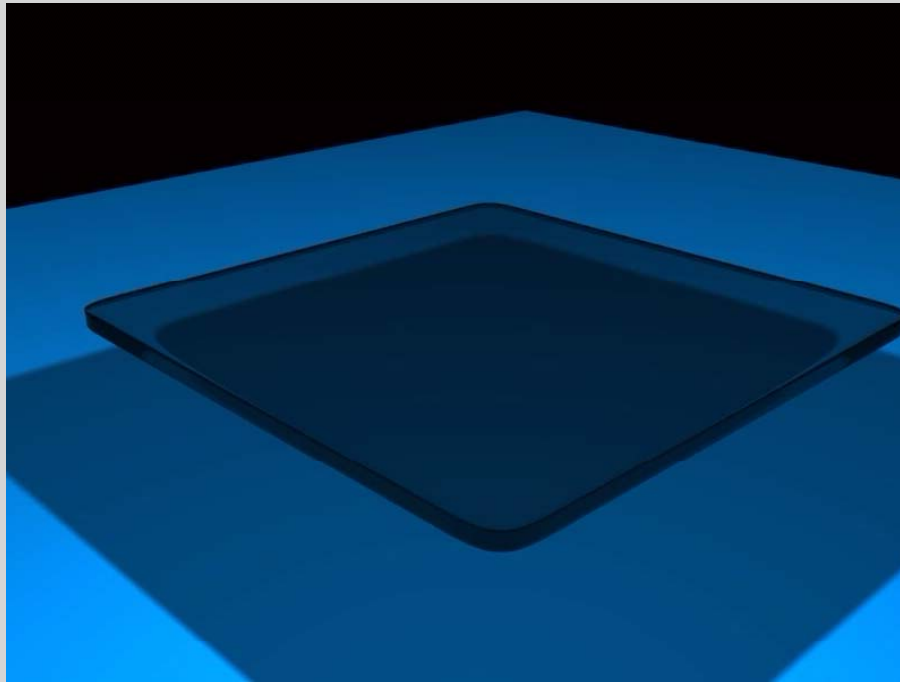
Ti:sapphire laser oscillator

- 130 fs
- 800 nm
- 76 MHz
- 20 mW

Objective

40 x
0.65 NA

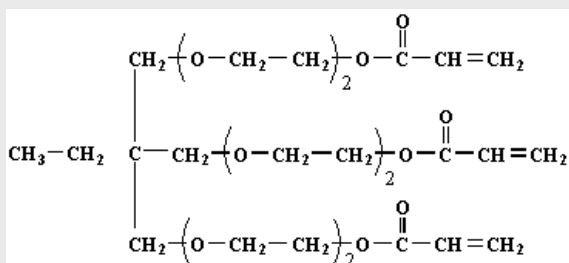
Two-photon polymerization



Resin preparation

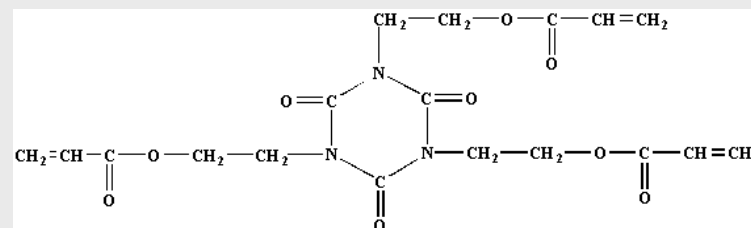
Monomers

Monomer A



reduces the shrinkage upon polymerization

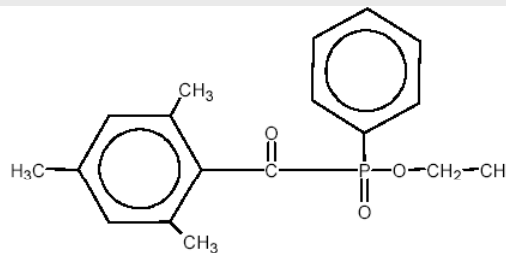
Monomer B



gives hardness to the polymeric structure

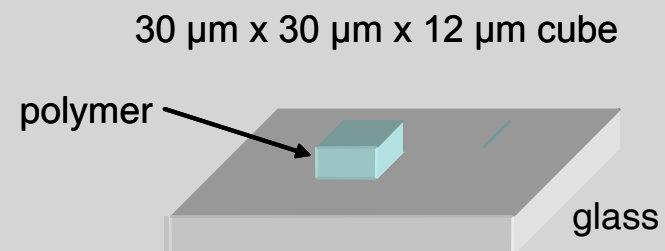
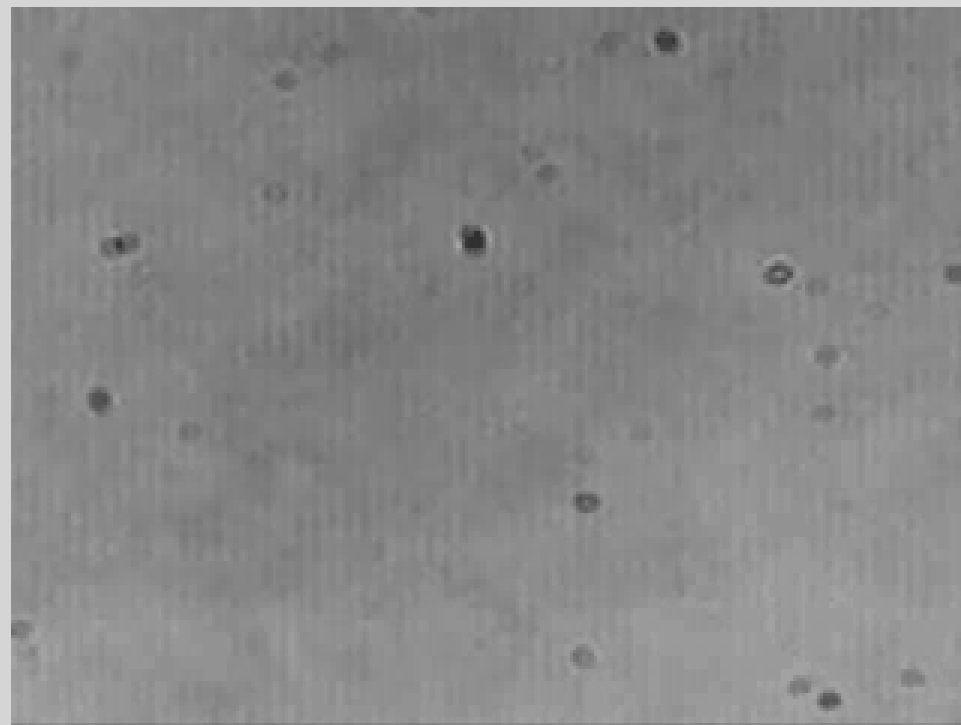
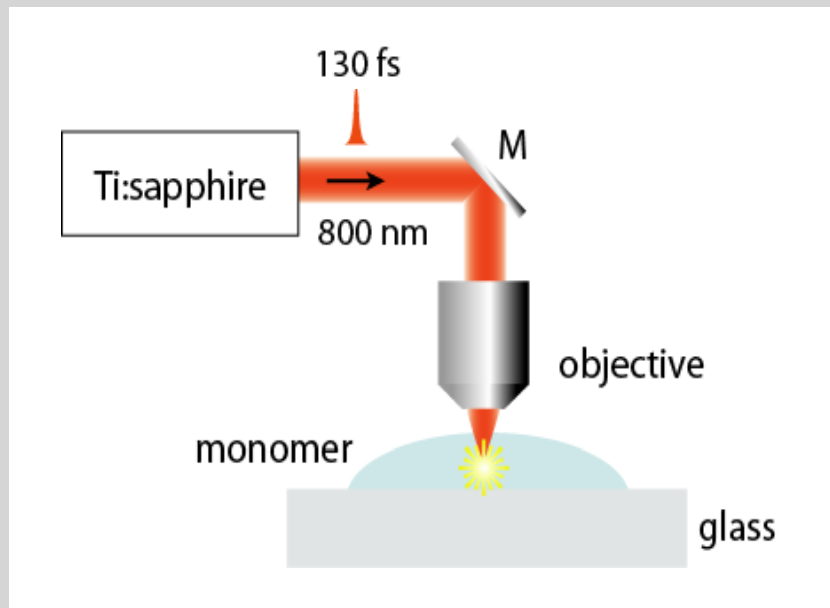
Photoinitiator

Lucirin TPO-L

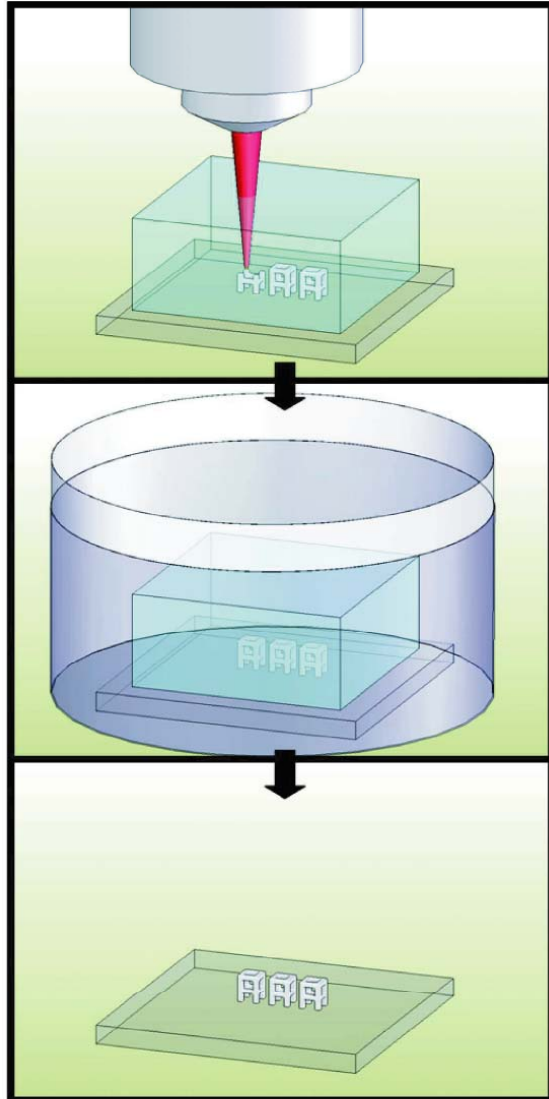


Appl. Phys. A, 90, 633–636 (2008)

Two-photon polymerization



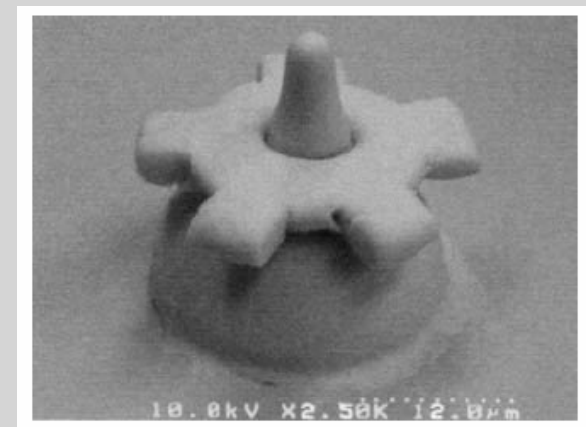
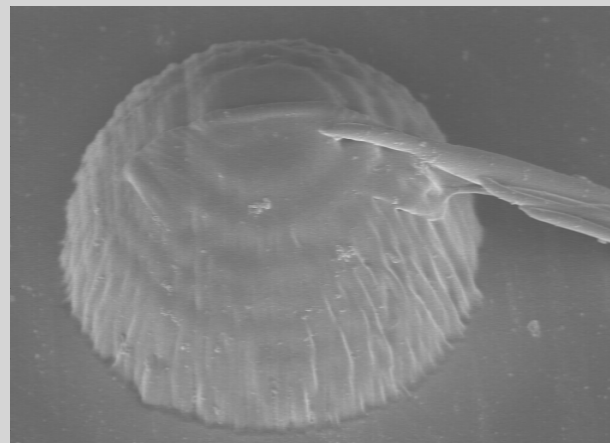
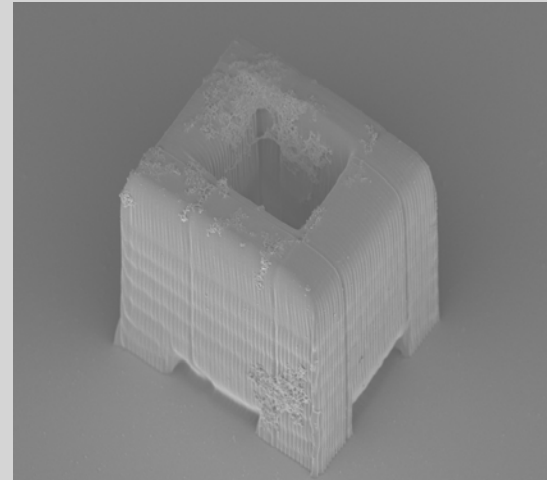
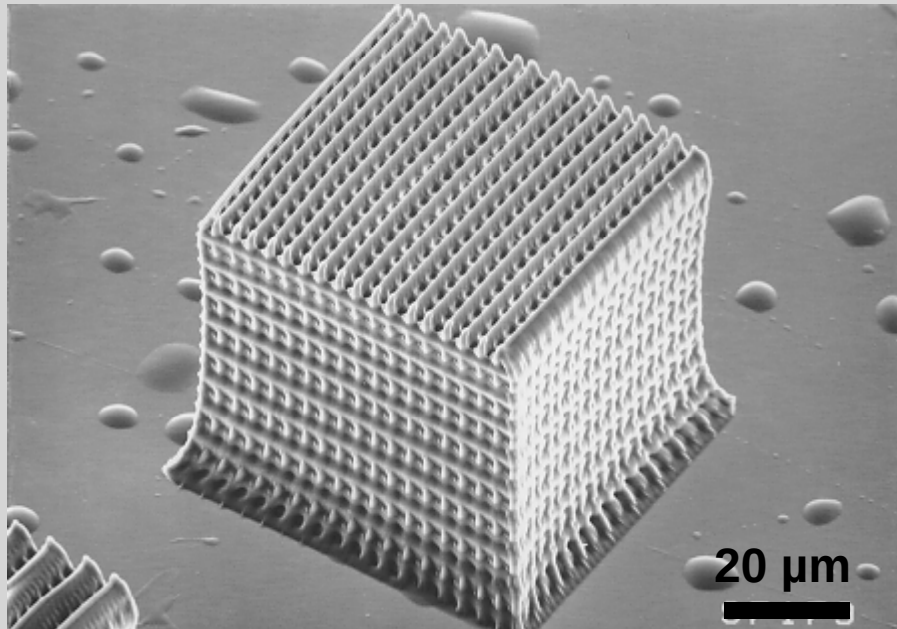
Two-photon polymerization



After the fabrication, the sample is immersed in ethanol to wash away any unsolidified resin and then dried

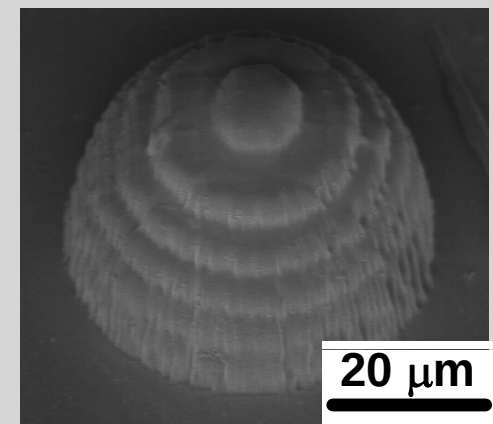
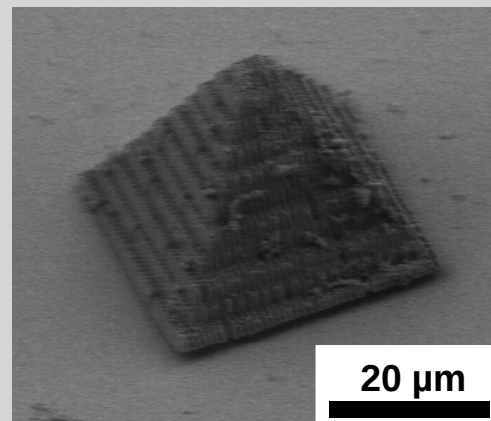
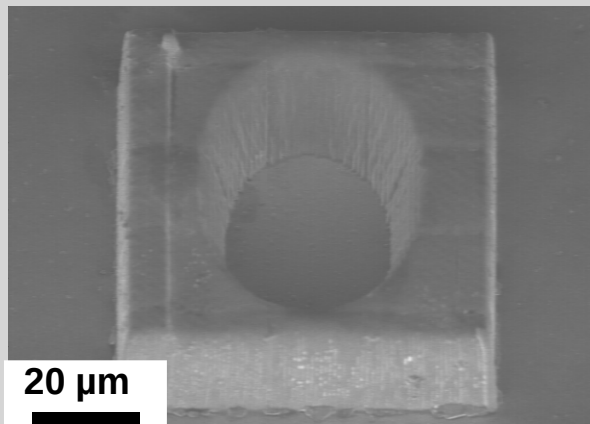
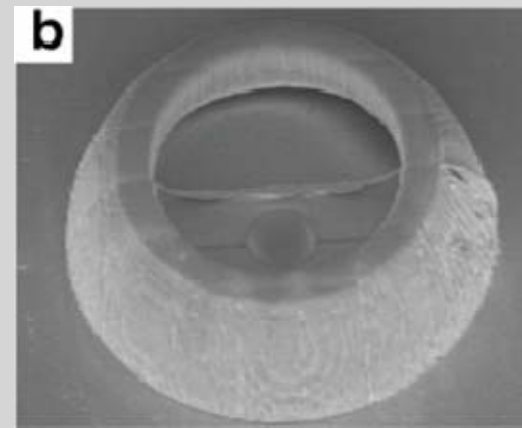
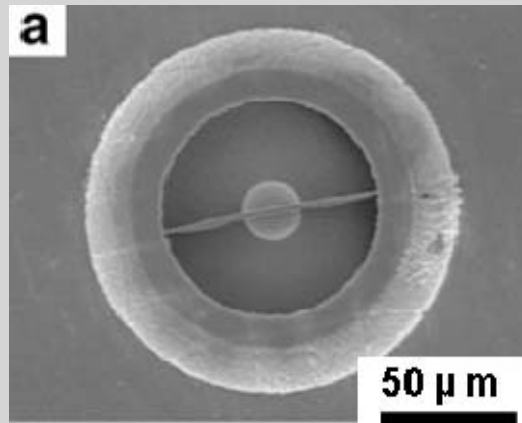
two-photon polymerization

photonic crystal – J. W. Perry

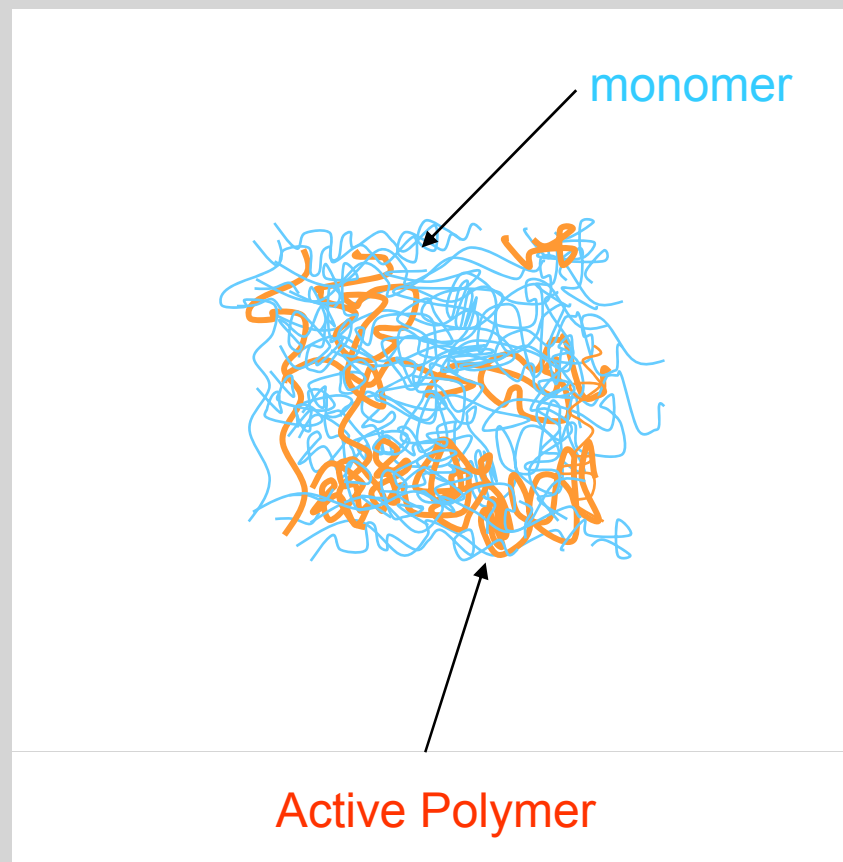
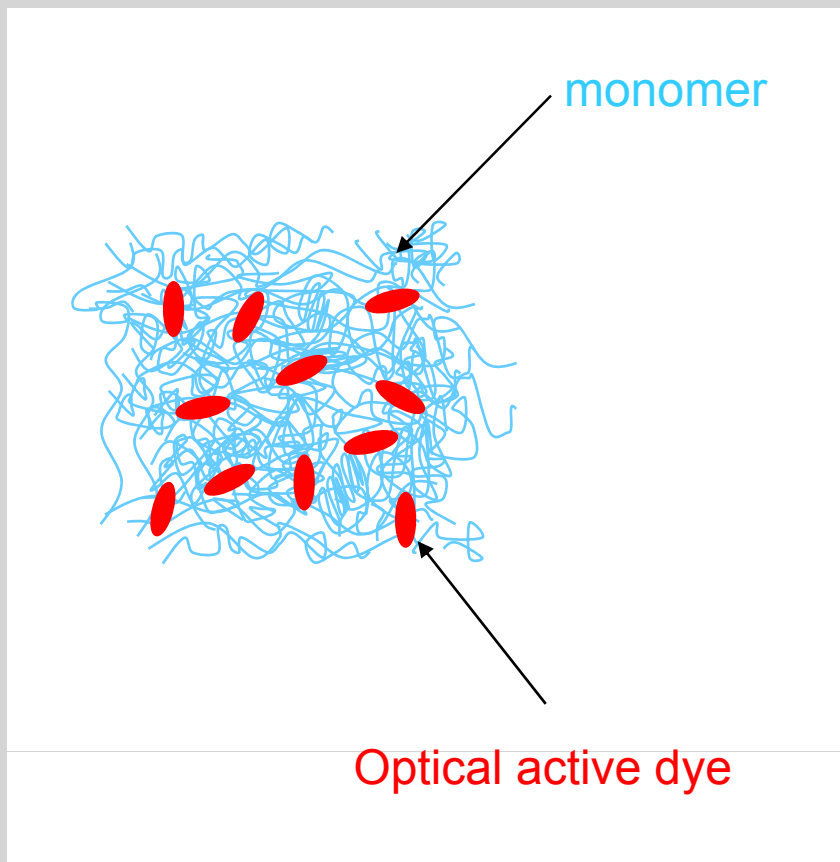


Two-photon polymerization

Microstructures fabricated by two-photon polymerization



Microstructures containing active compounds



Applications of two-photon polymerization

Optics and Photonics

Doping microstructures with organic molecules and metals

- fluorescence
- birefringence
- conductivity

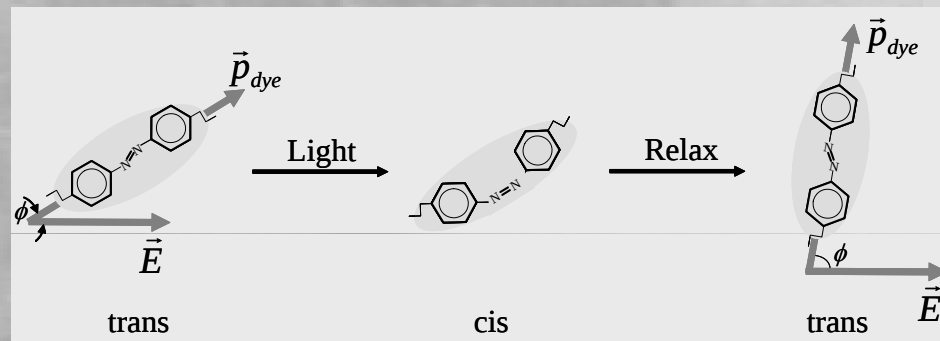
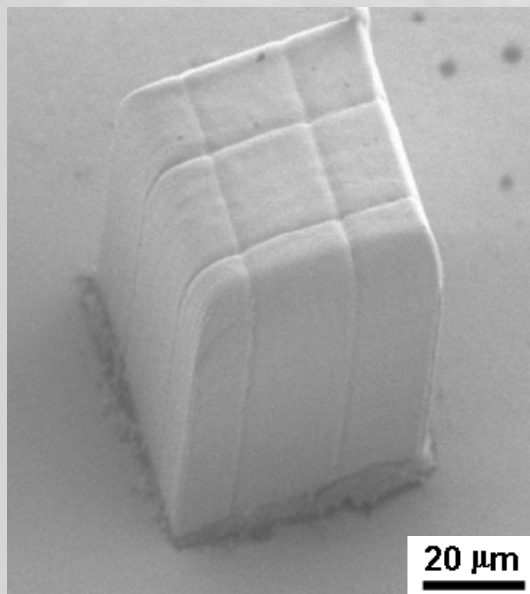
Bio-applications

Fabrication using bio-compatible resins to biological applications

- tissue engineering scaffolds
- fabrication of microneedle
- cell study

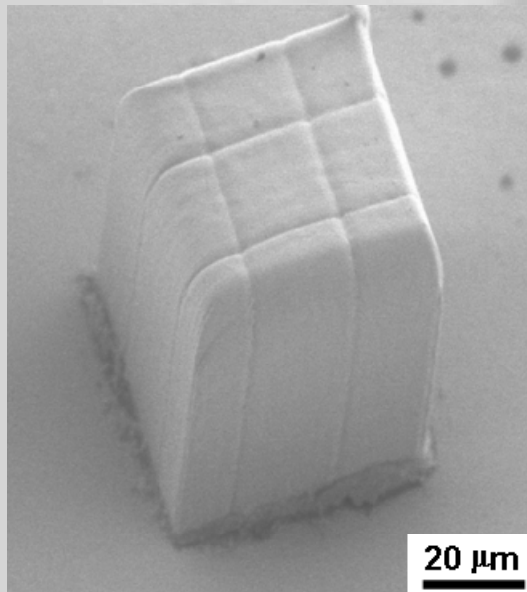
Other studies

- microstructures for optical storage – birefringence



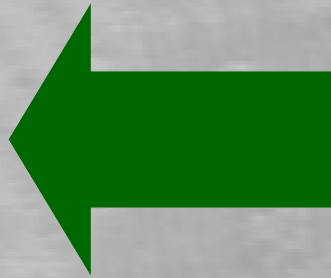
Other studies

- microstructures for optical storage – birefringence



Ar⁺ ion laser irradiation

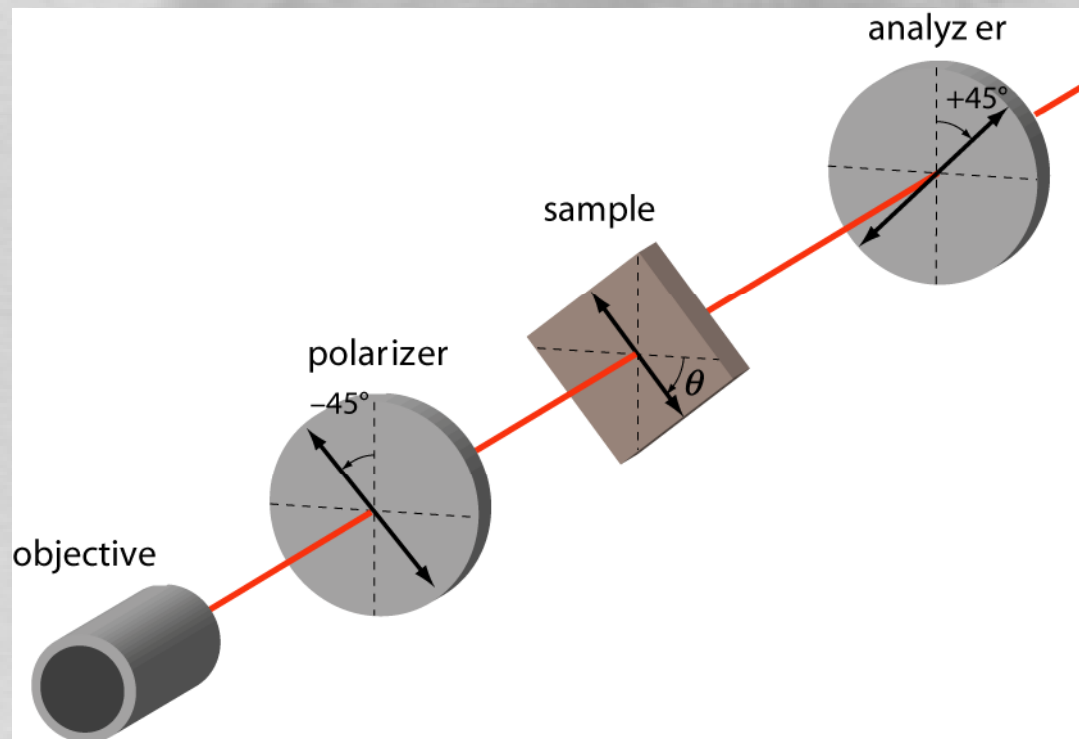
- 514.5 nm
- one minute
- intensity of 600 mW/cm²



Other studies

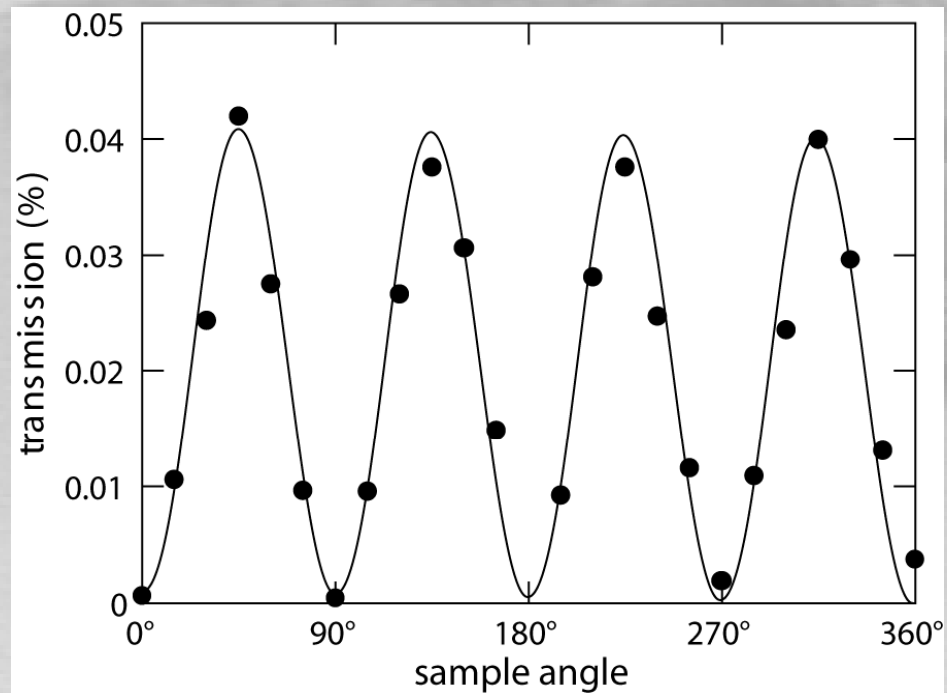
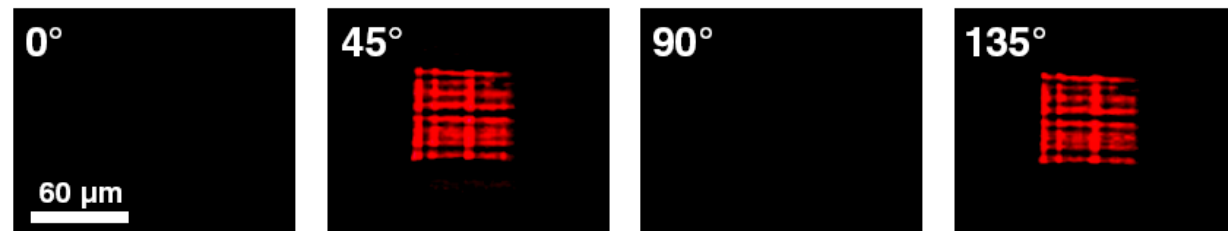
- microstructures for optical storage – birefringence

The sample was placed under an optical microscope between crossed polarizers and its angle was varied with respect to the polarizer angle



Other studies

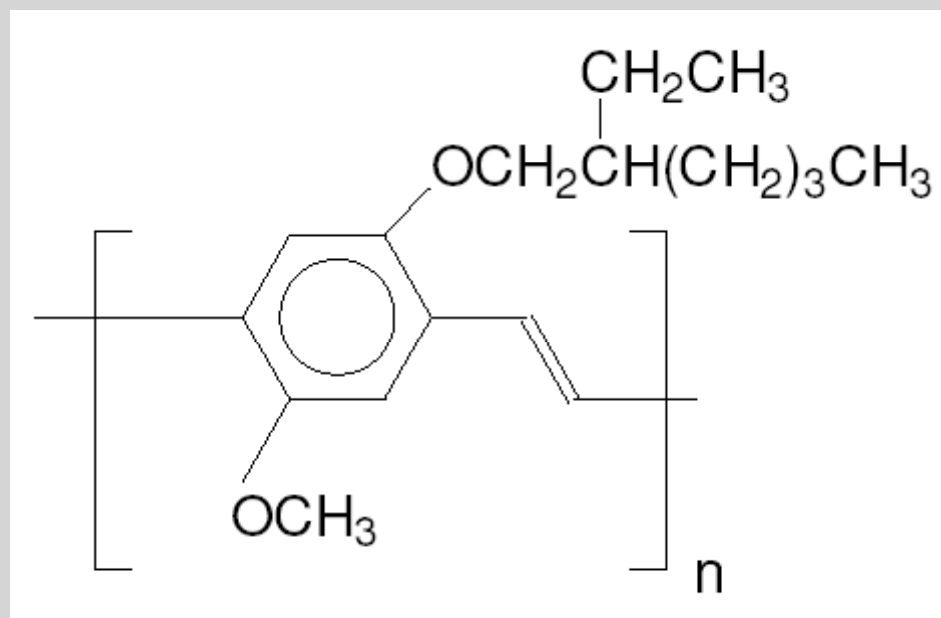
- microstructures for optical storage – birefringence



J. Appl. Phys., 102, 13109-1-13109-4 (2007)

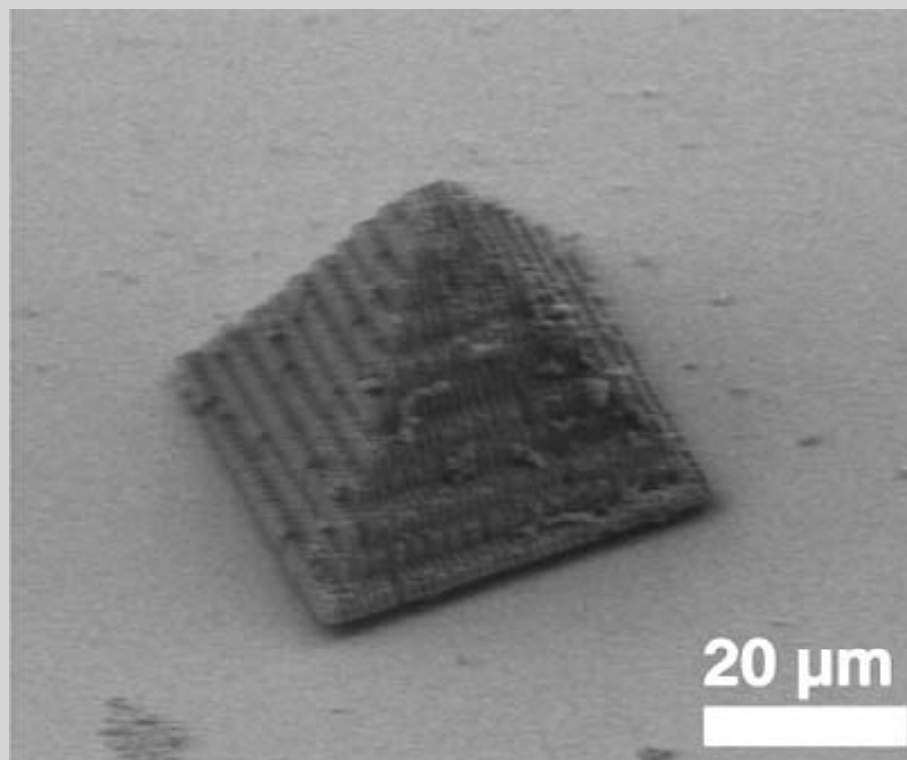
Microstructures containing MEH-PPV

MEH-PPV

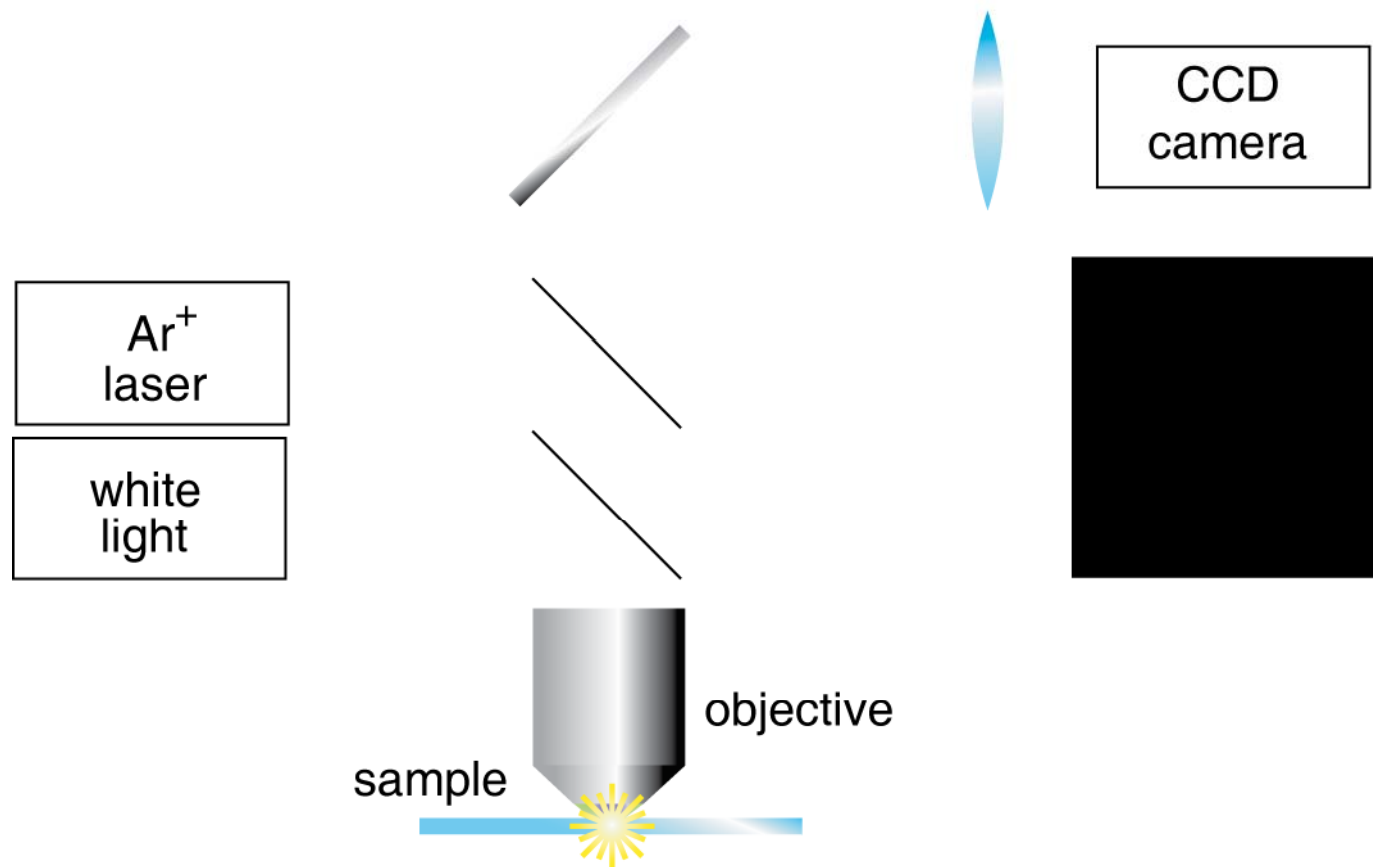


Fluorescence
Electro Luminescent
Conductive

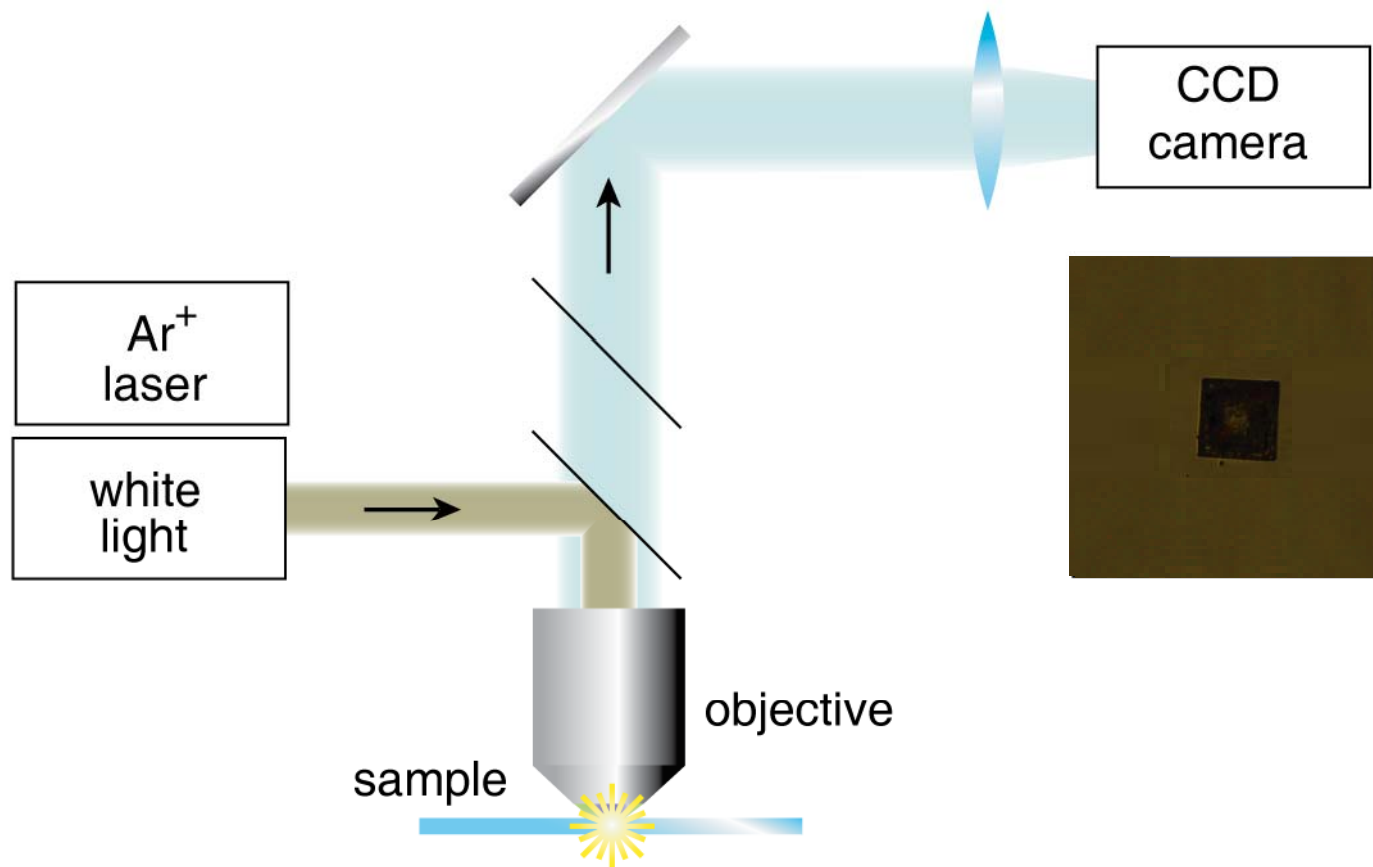
Microstructure containing MEH-PPV



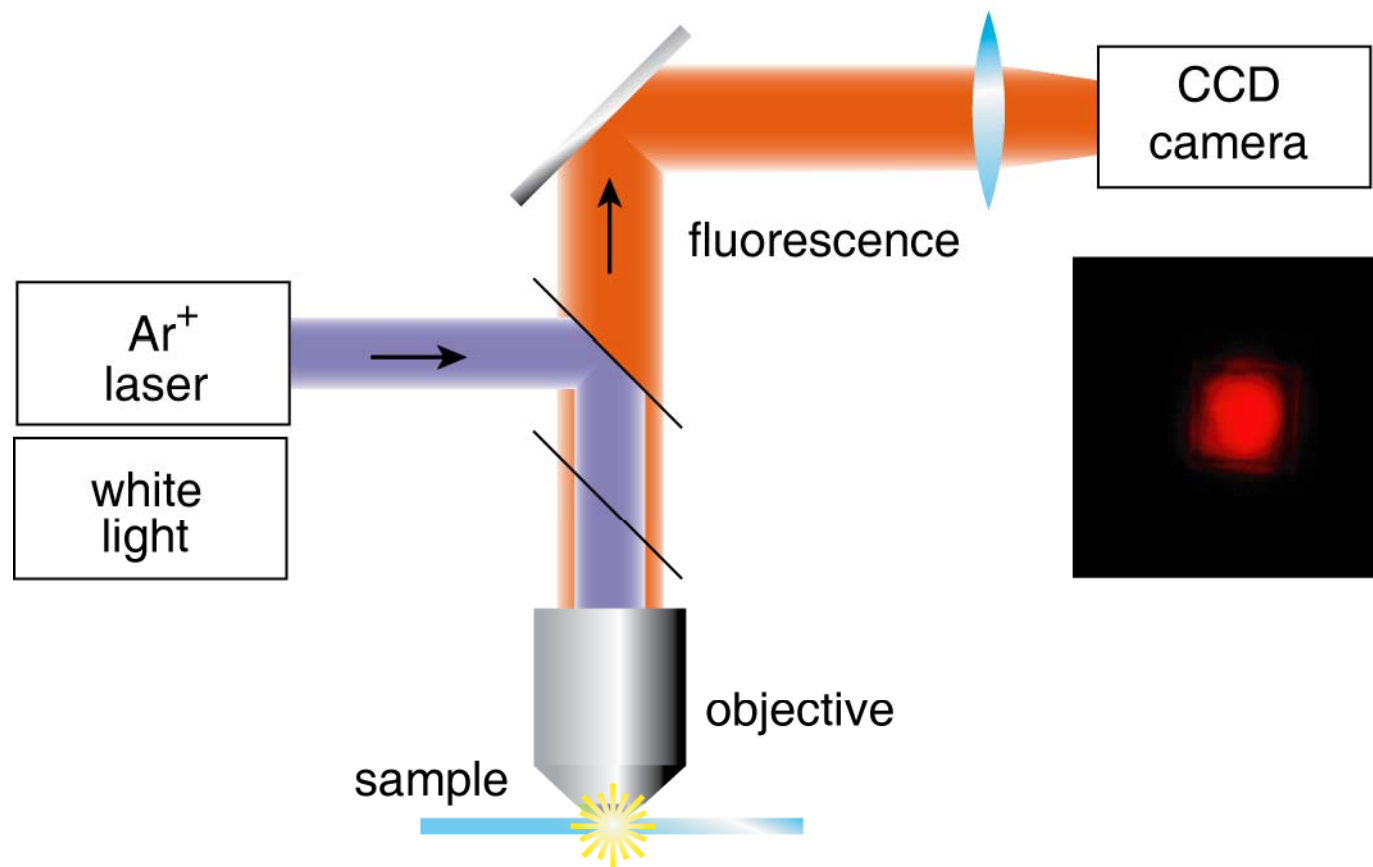
Microstructure containing MEH-PPV



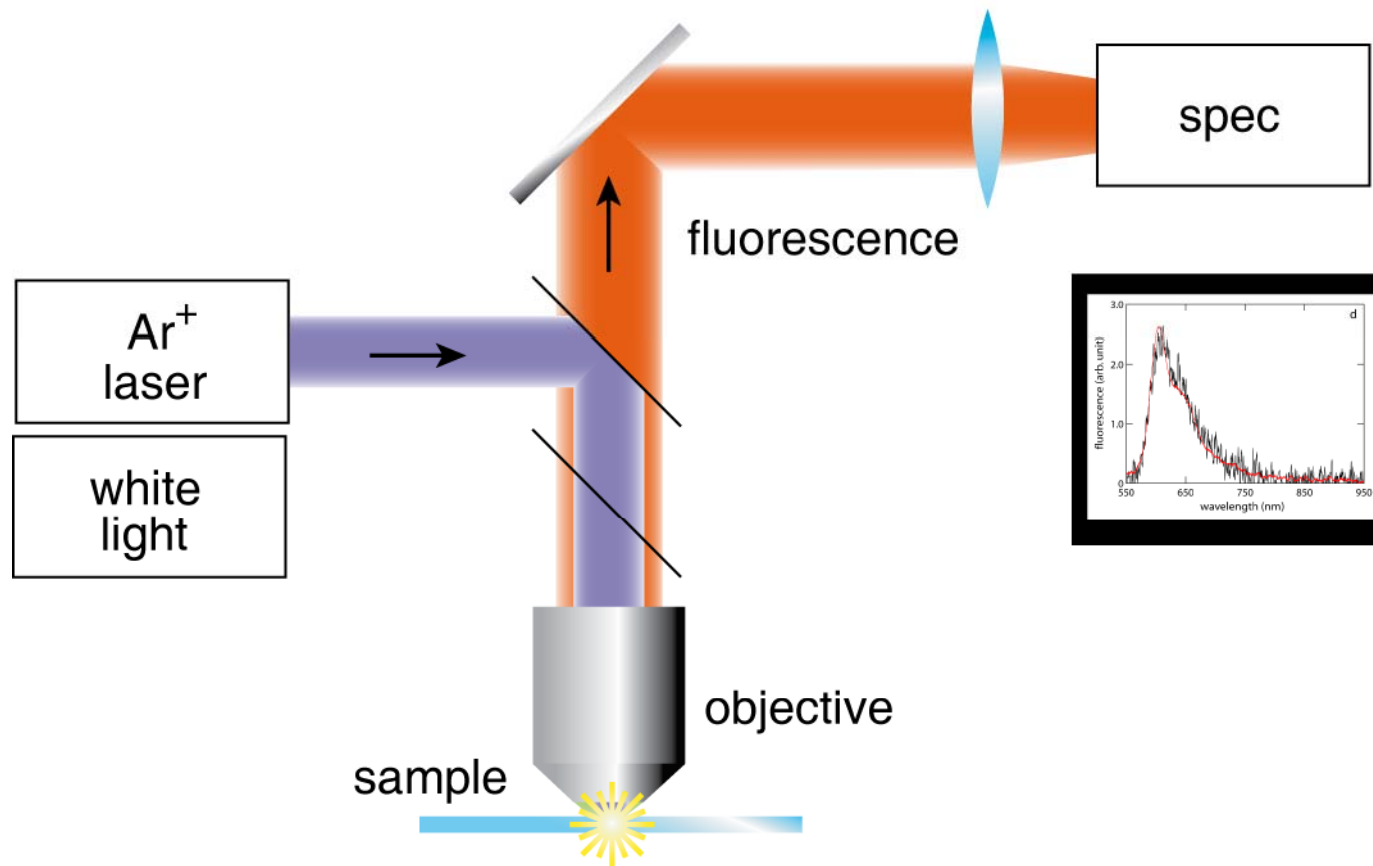
Microstructure containing MEH-PPV



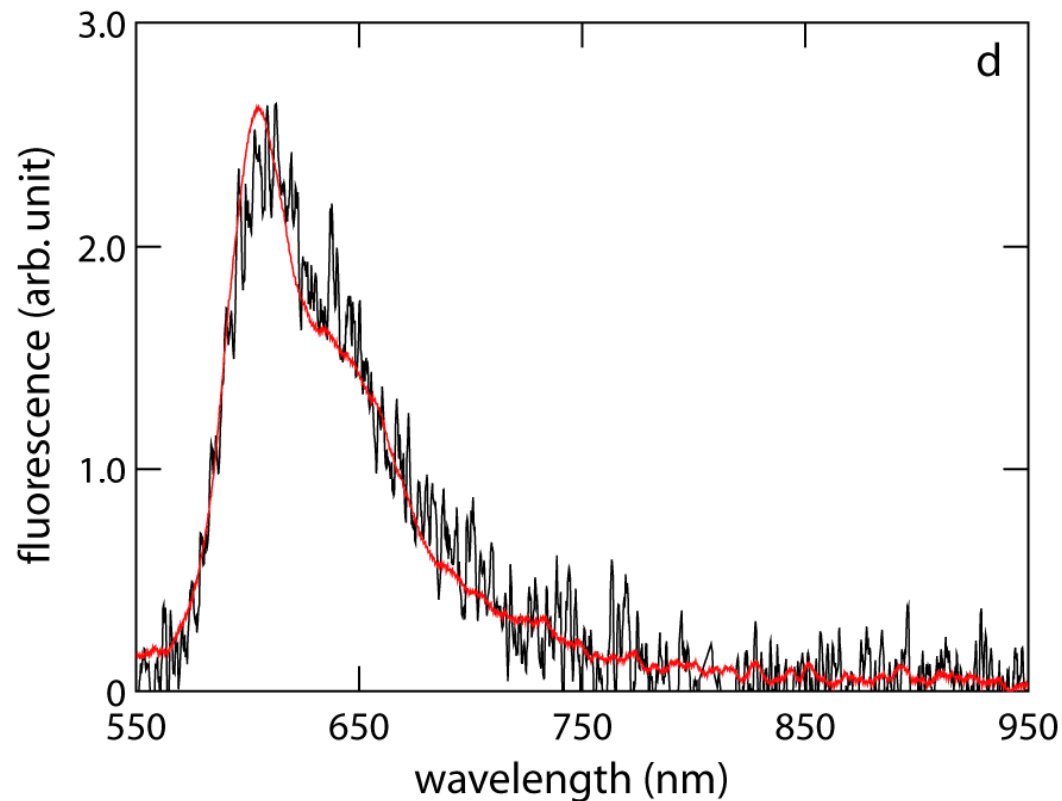
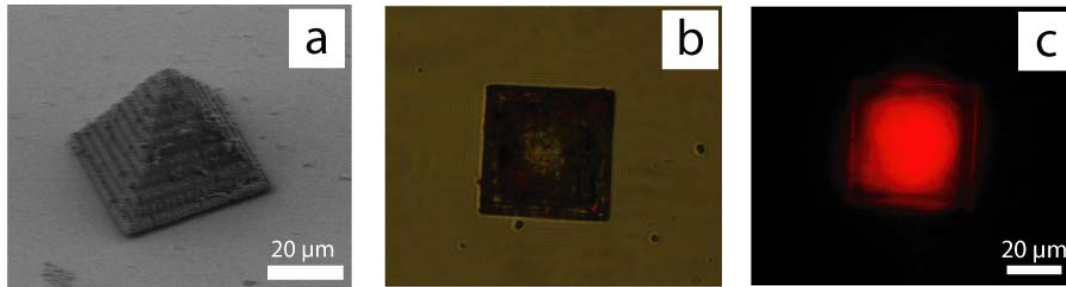
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV



Microstructure containing MEH-PPV

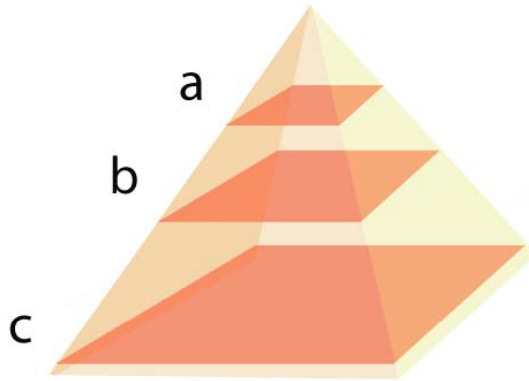


(a) Scanning electron microscopy

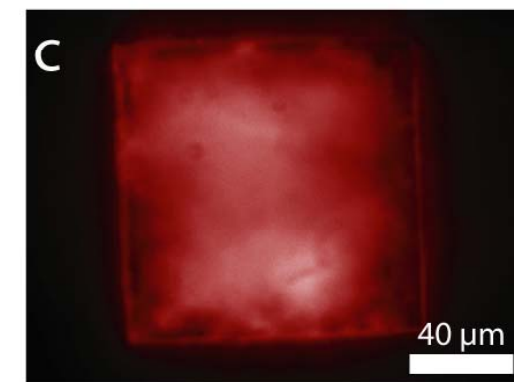
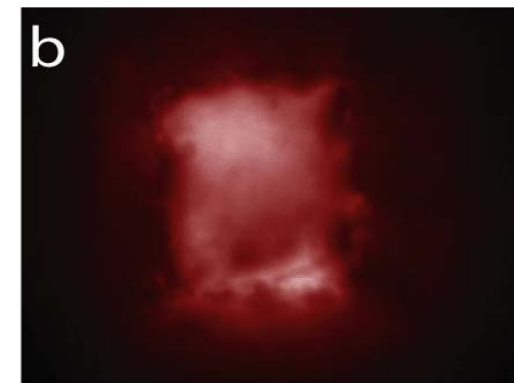
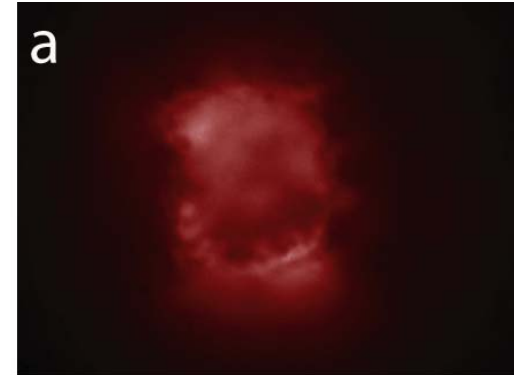
(b,c) Fluorescence microscopy of the microstructure with the excitation OFF (b) and ON (c)

(d) Emission of the microstructure (black line) and of a film with the same composition (red line)

Microstructure containing MEH-PPV



Fluorescent confocal microscopy images in planes separated by 16 μm in the pyramidal microstructure.



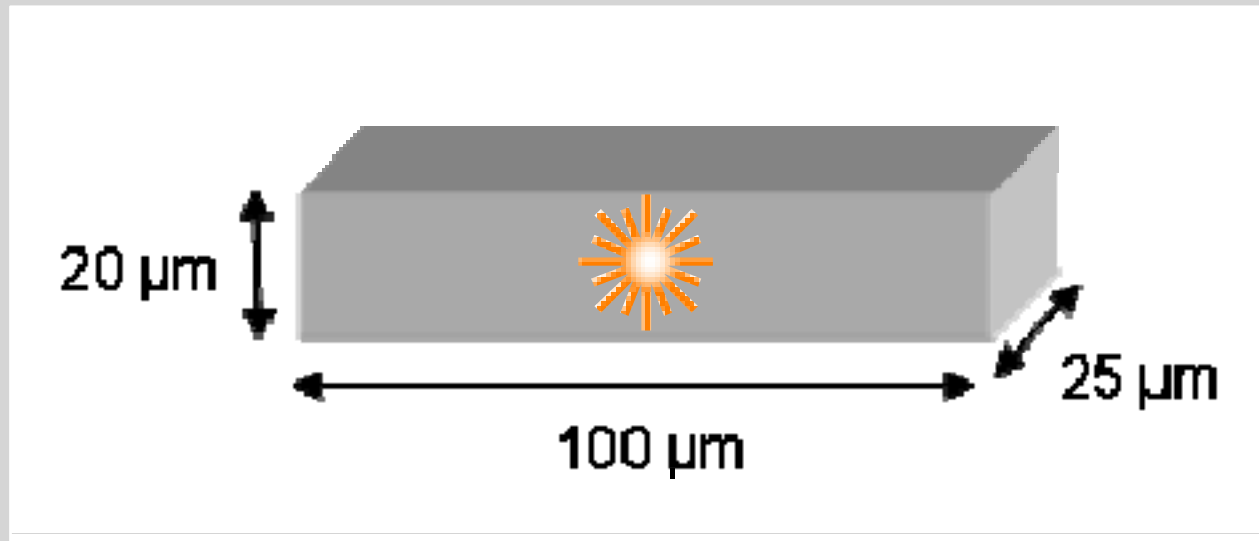
Microstructure containing MEH-PPV

Do we have waveguiding in the microstructure ?

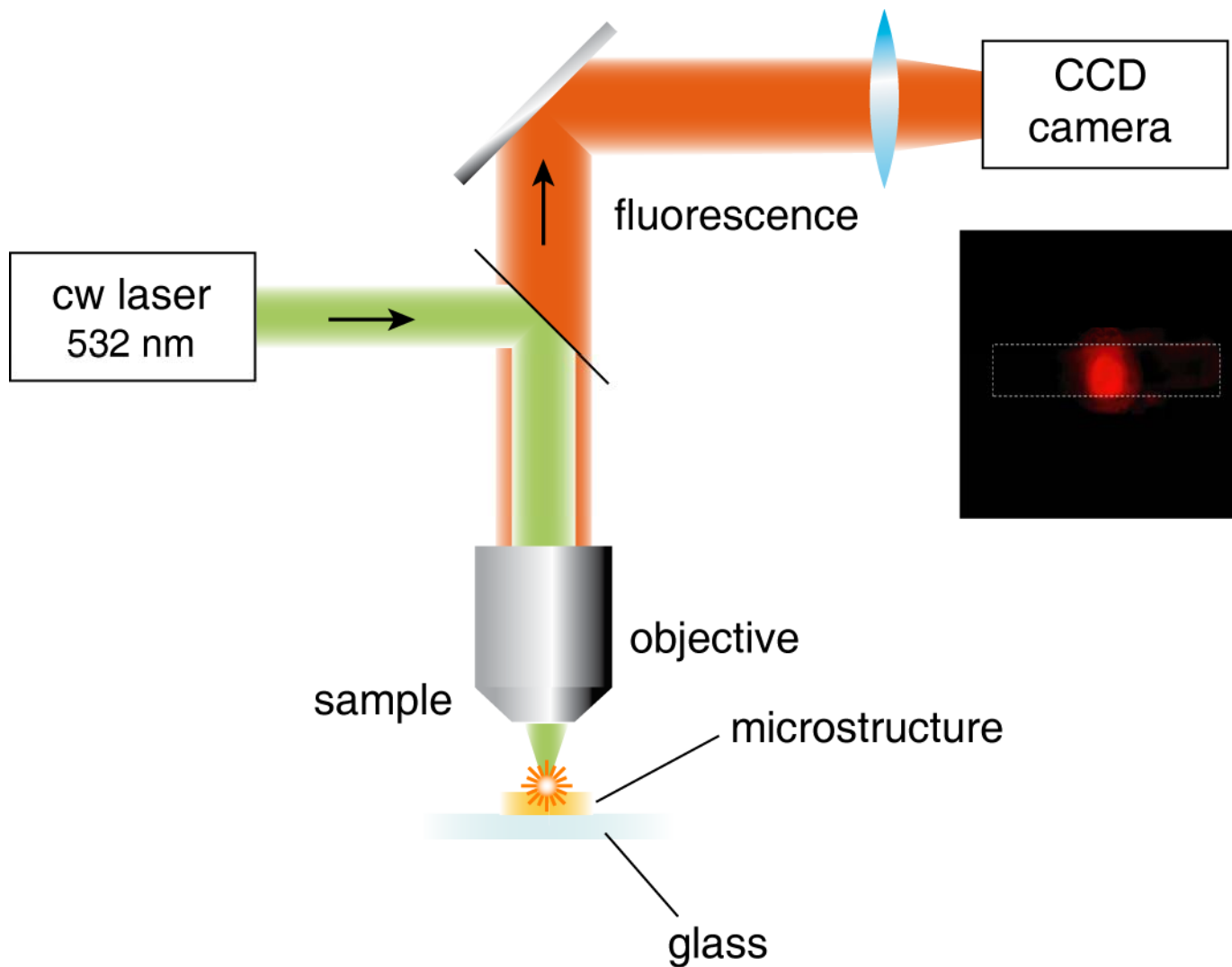


Microstructure containing MEH-PPV

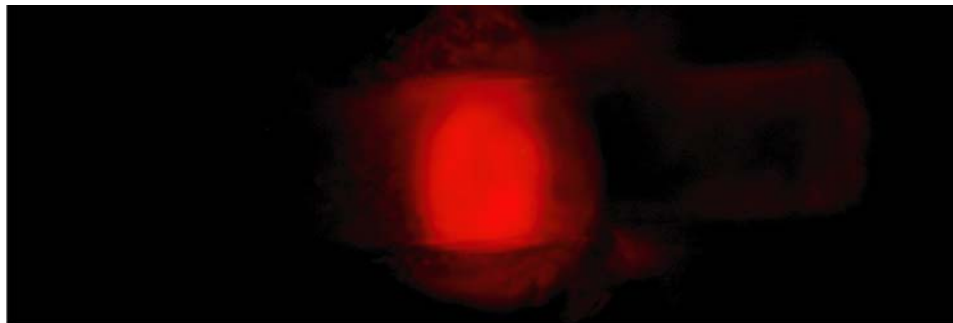
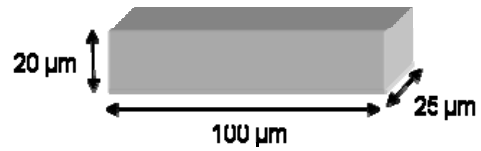
Do we have waveguiding in the microstructure ?



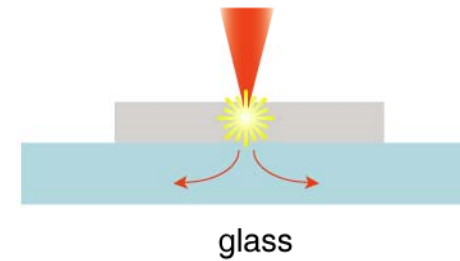
Microstructure containing MEH-PPV



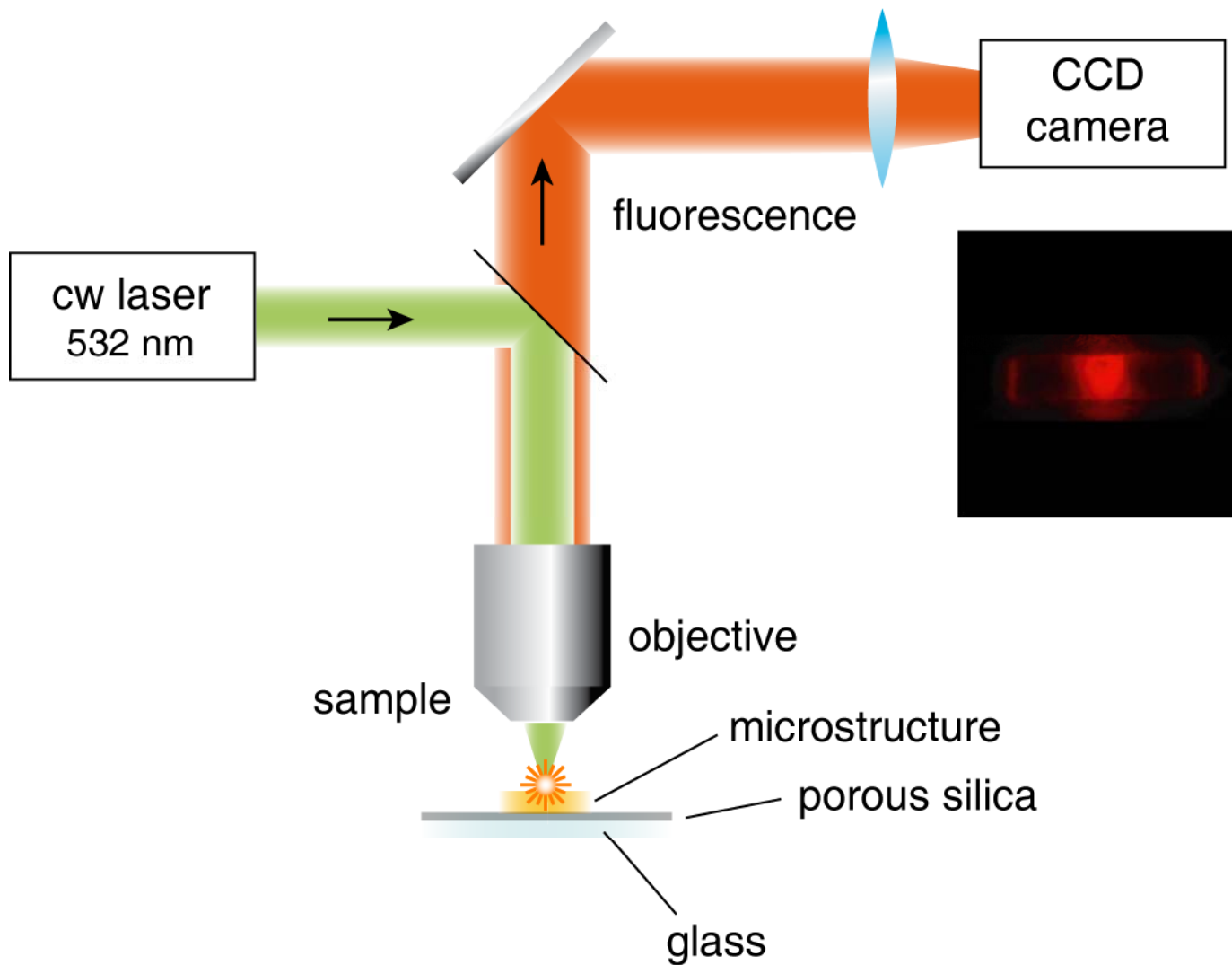
Microstructure containing MEH-PPV



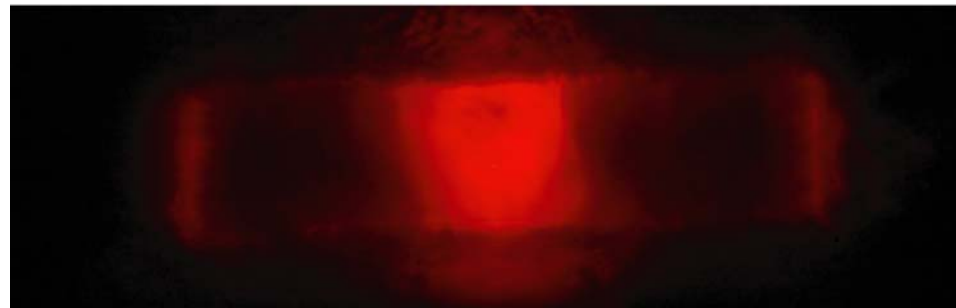
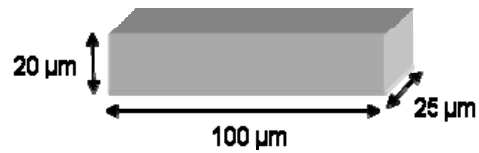
$20\ \mu\text{m}$ 



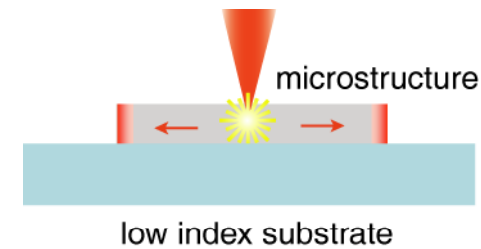
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV



$20\ \mu\text{m}$ 

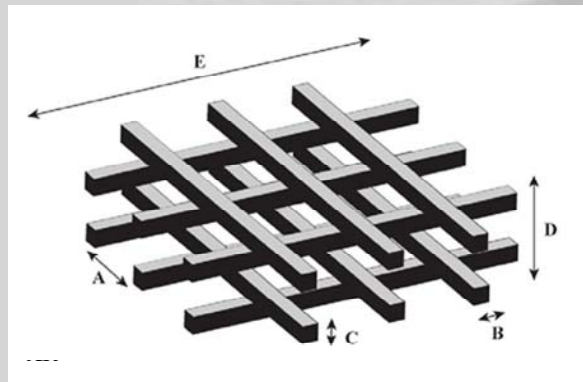


waveguiding of the microstructure fabricated on porous silica substrate ($n= 1.185$)

Applications: micro-laser; fluorescent microstructures; conductive microstructures

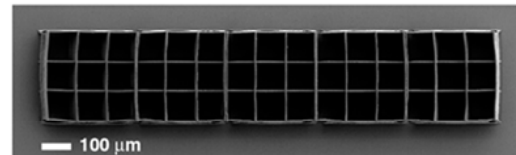
3D cell migration

- 3D cell migration studies in micro-scaffolds



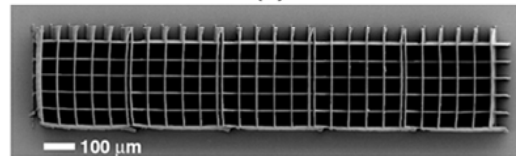
SEM of the scaffolds

110 μm pore size



(c)

52 μm pore size



(d)

Top view



(e)

(f)

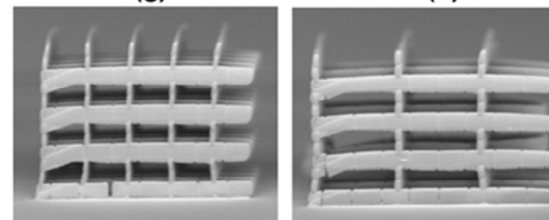
110, 52, 25, 12 μm pore size



(g)

(h)

Side view



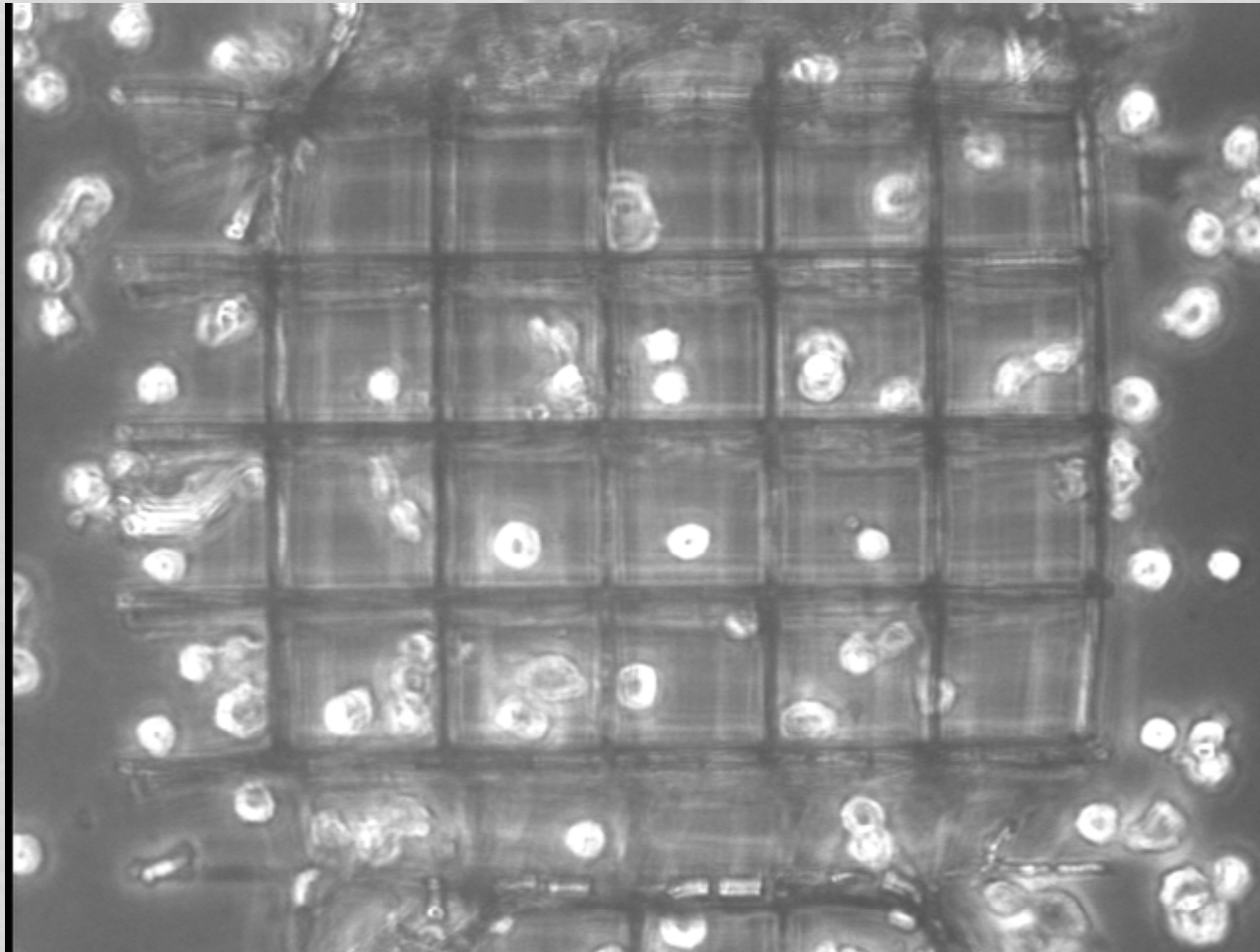
(i)

(j)

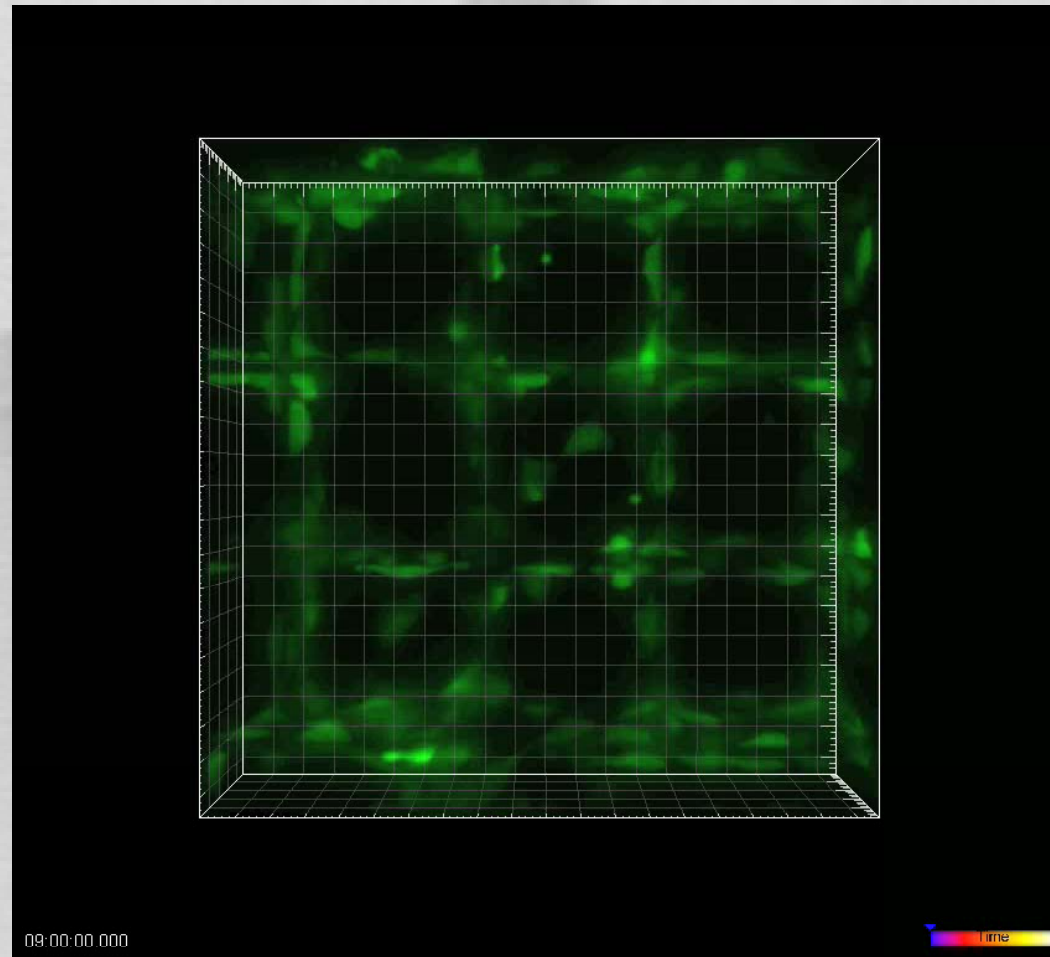
25, 52 μm pore size

3D cell migration

50 μm pore size

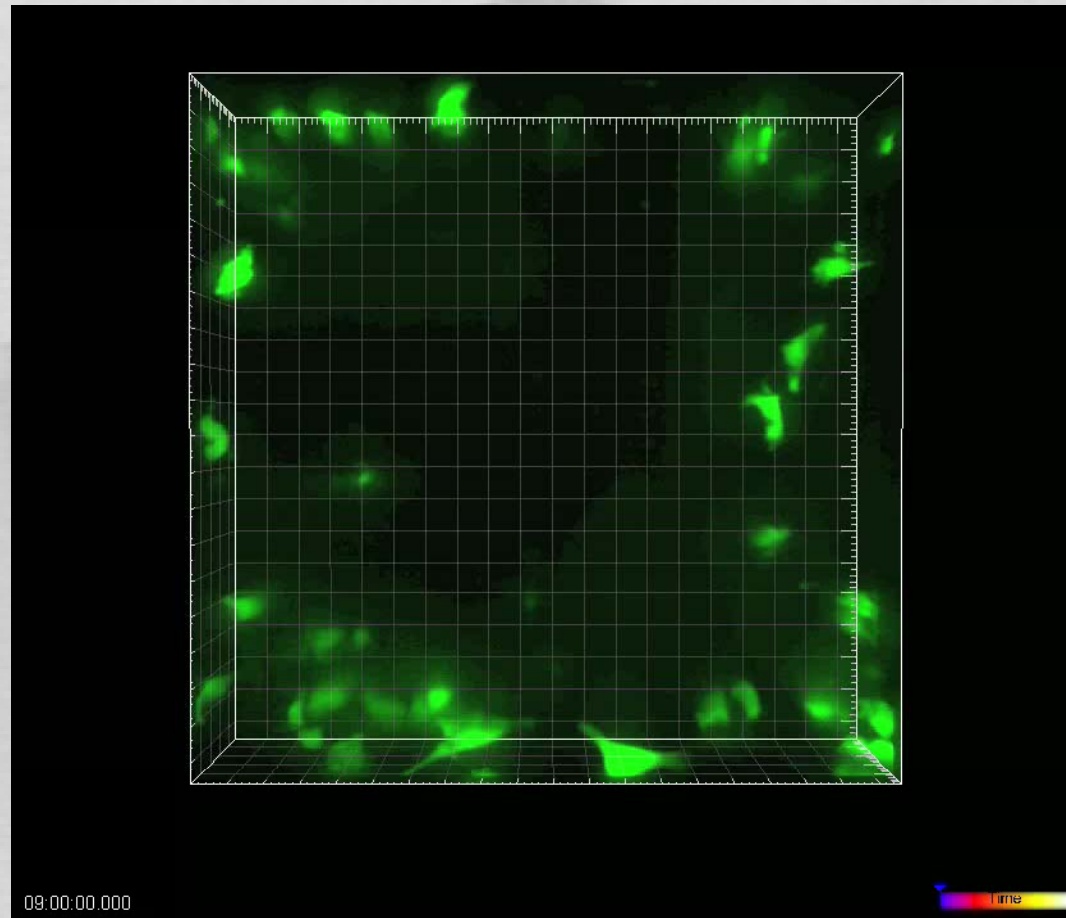


3D cell migration



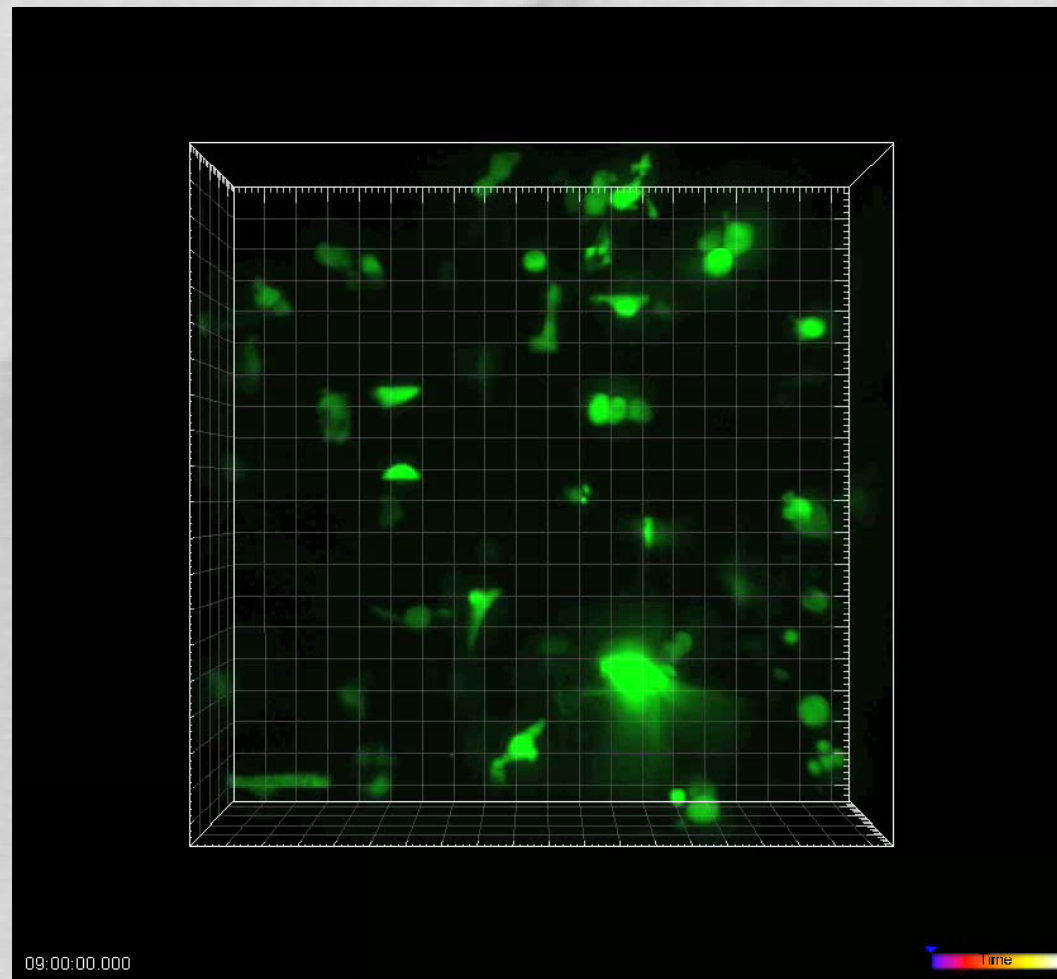
110 μm pore size

3D cell migration



12 μm pore size

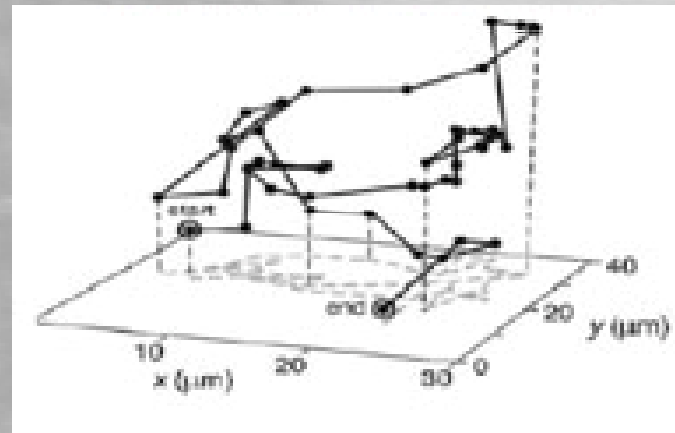
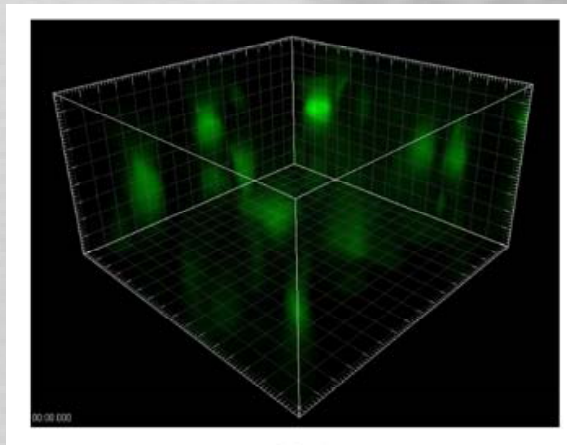
3D cell migration



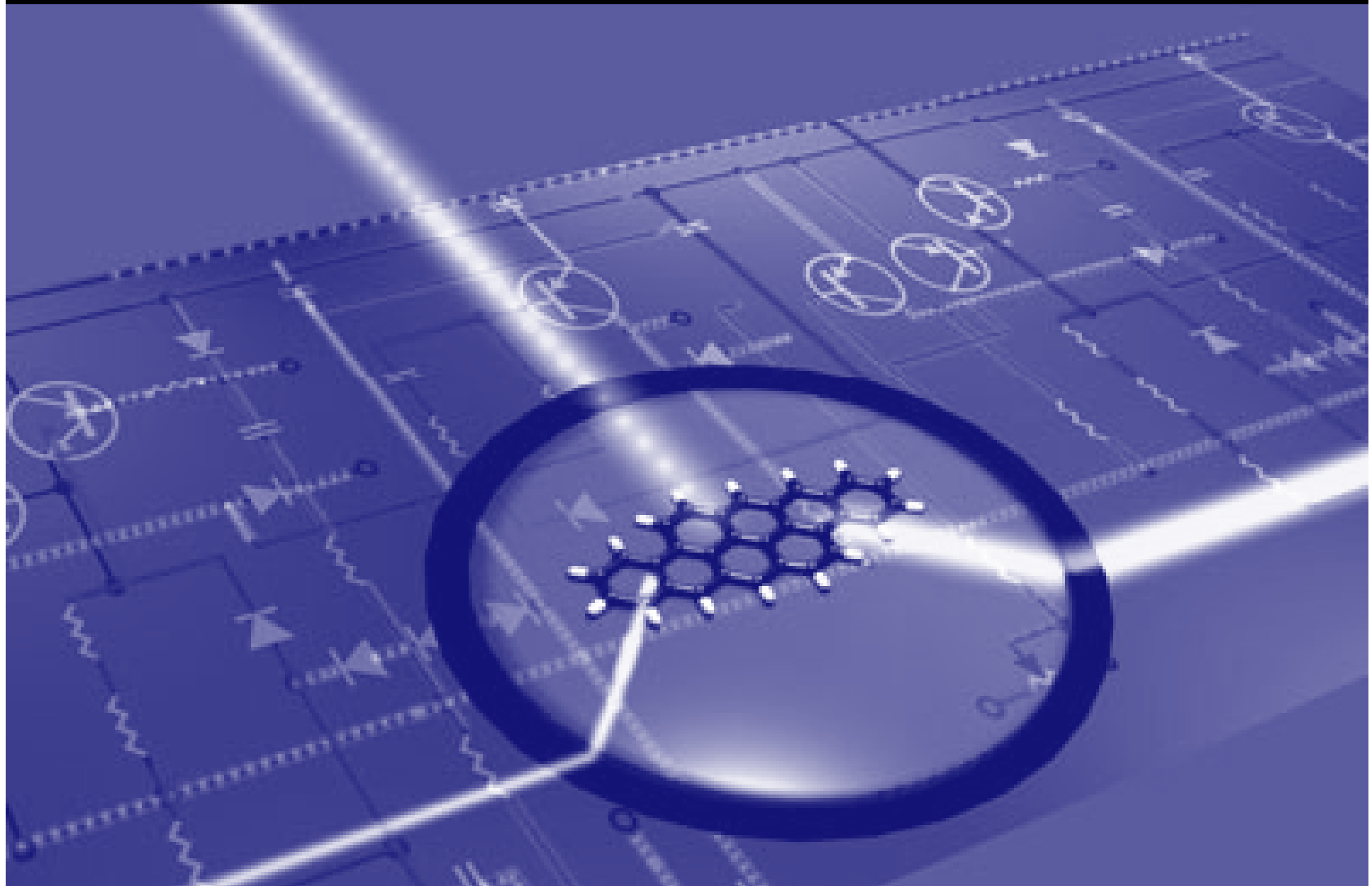
52 μm pore size

3D cell migration

- 3D cell migration studies in micro-scaffolds



Optical circuit



Optical circuit

- microfabrication
- silica nanowires
- coupling microstructures

50 μm



Silica nanowires

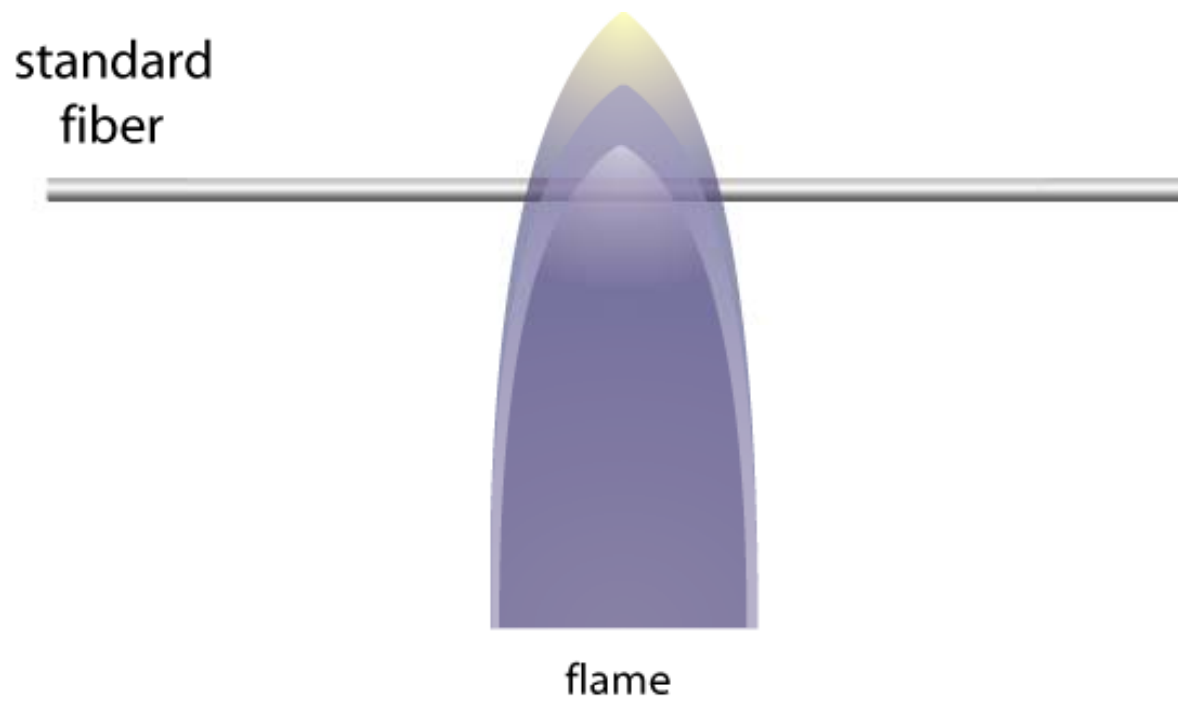
nanowires fabrication process

standard
fiber



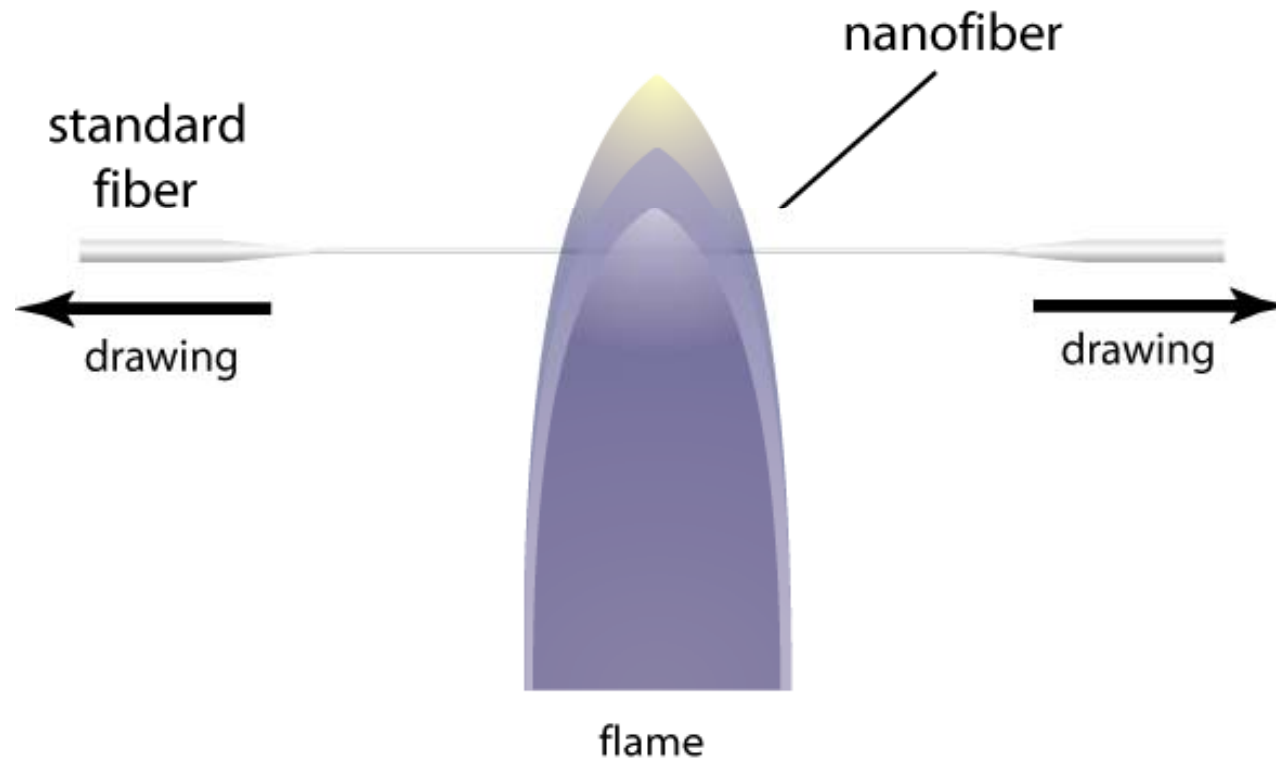
Silica nanowires

nanowires fabrication process



Silica nanowires

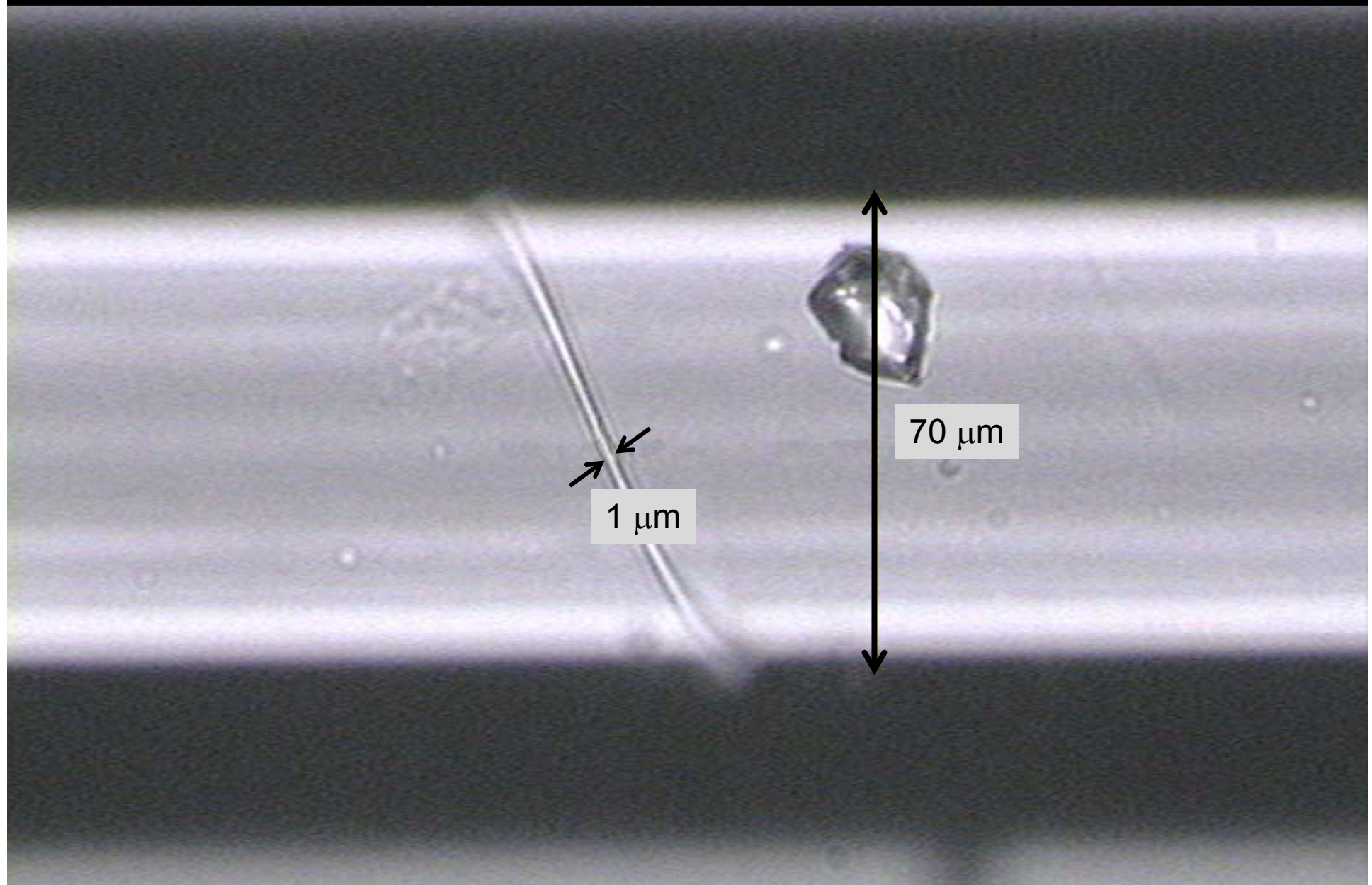
nanowires fabrication process



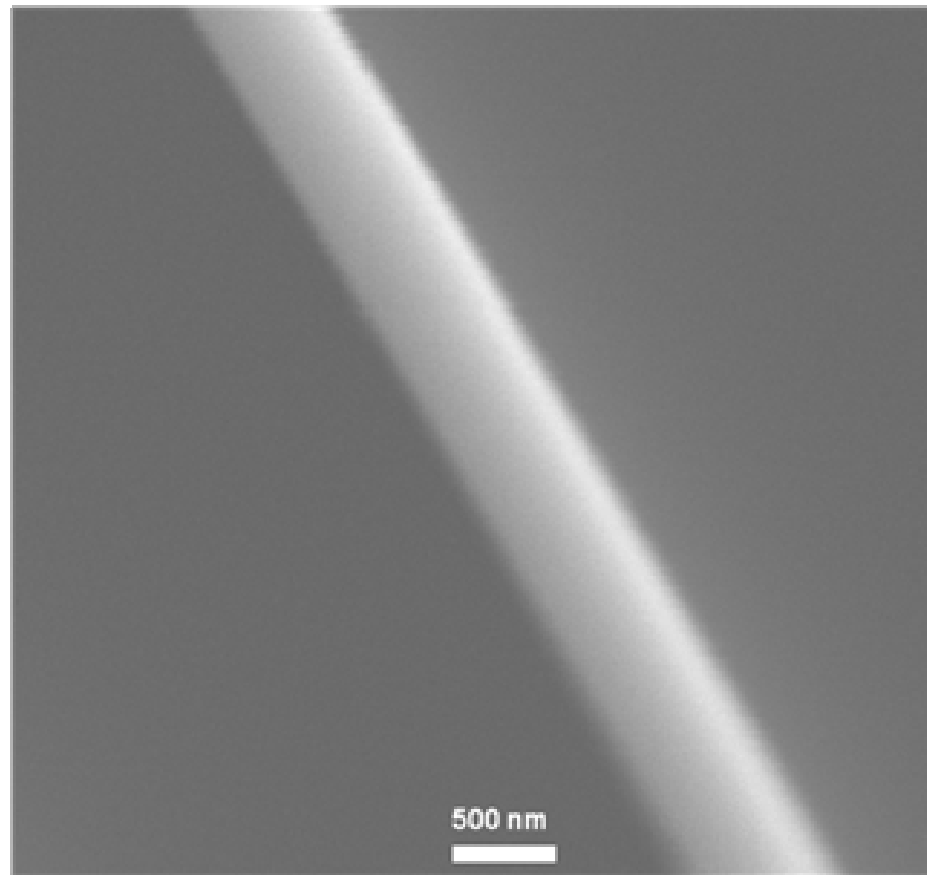
Silica nanowires



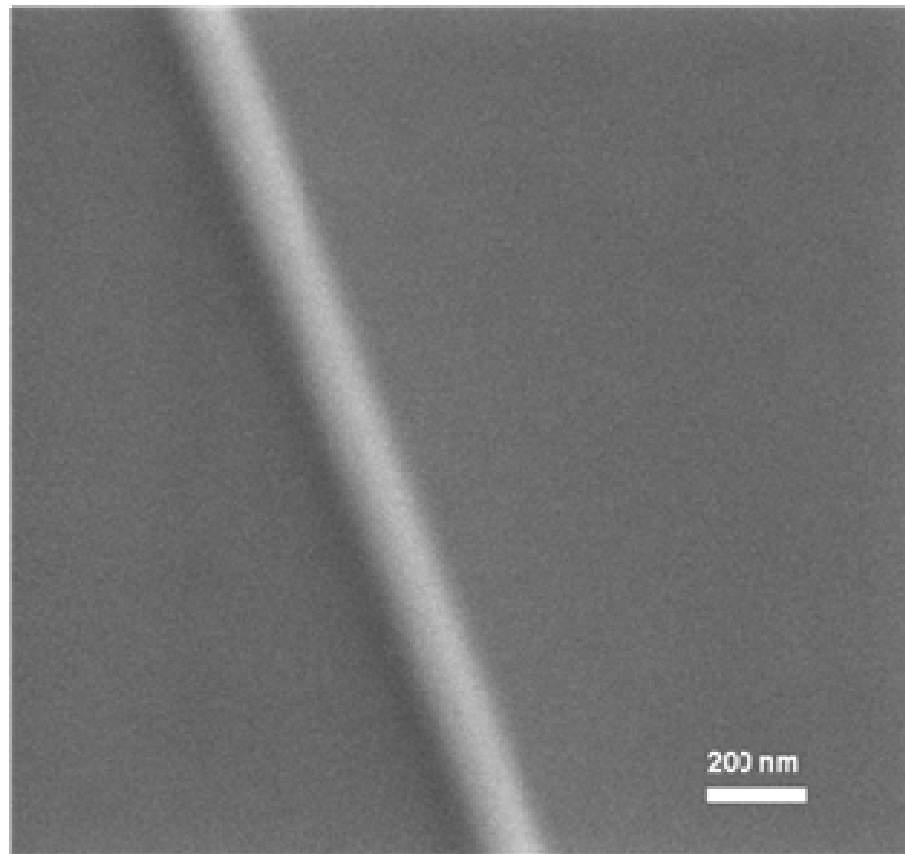
Silica nanowires



Silica nanowires

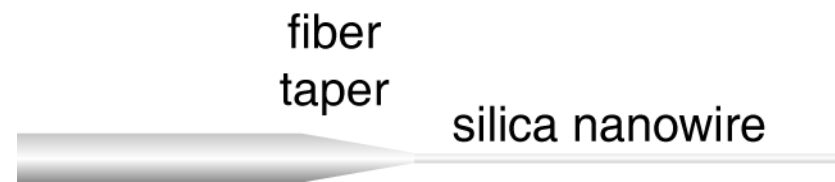


Silica nanowires



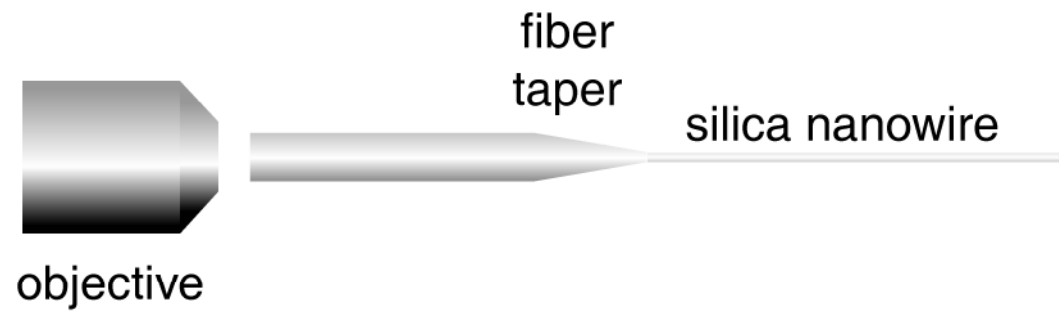
Silica nanowires

coupling light into nanowires



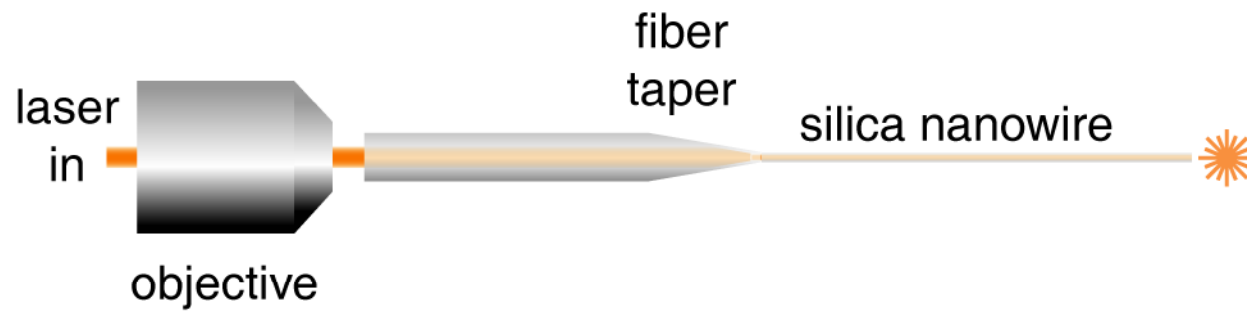
Silica nanowires

coupling light into nanowires



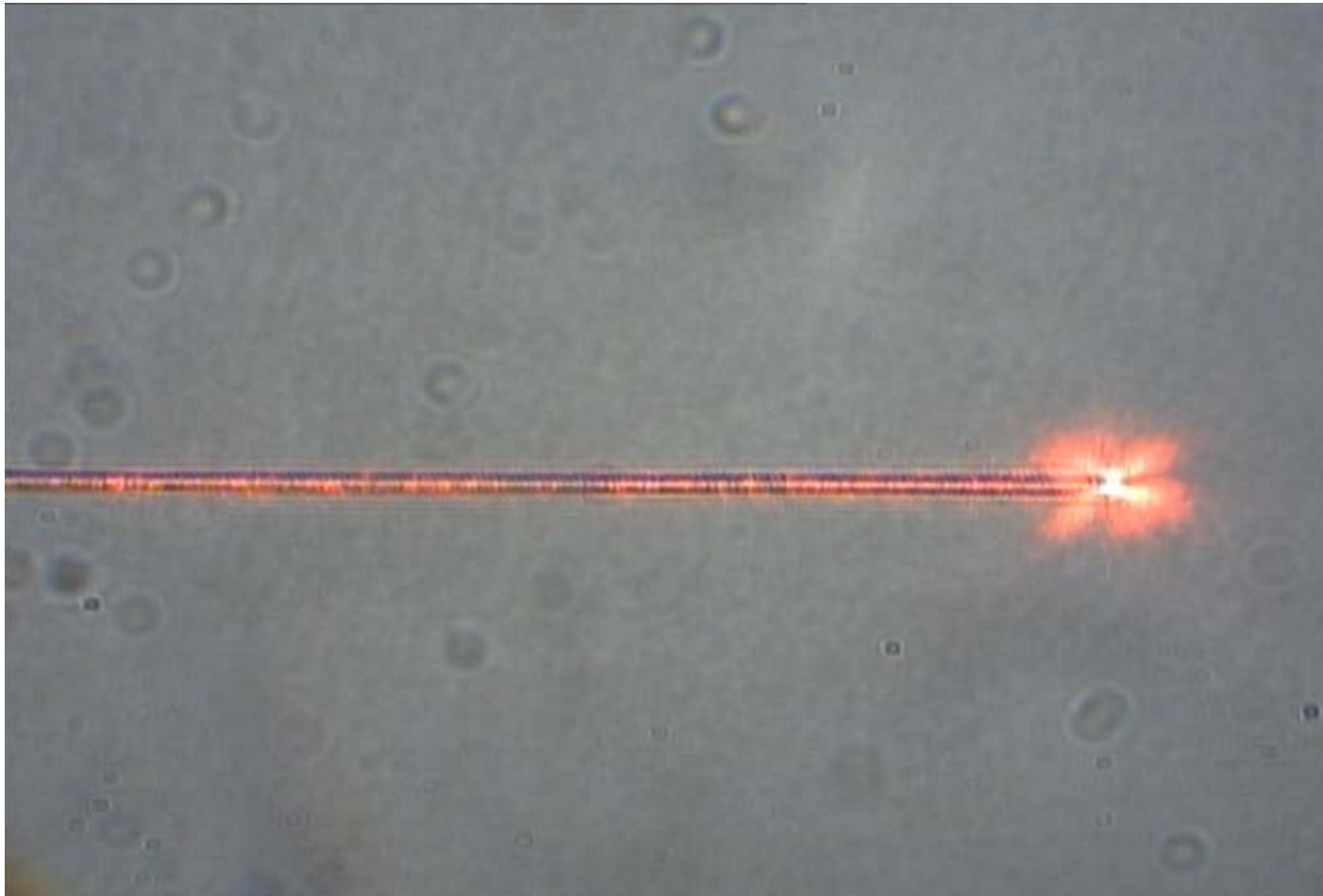
Silica nanowires

coupling light into nanowires



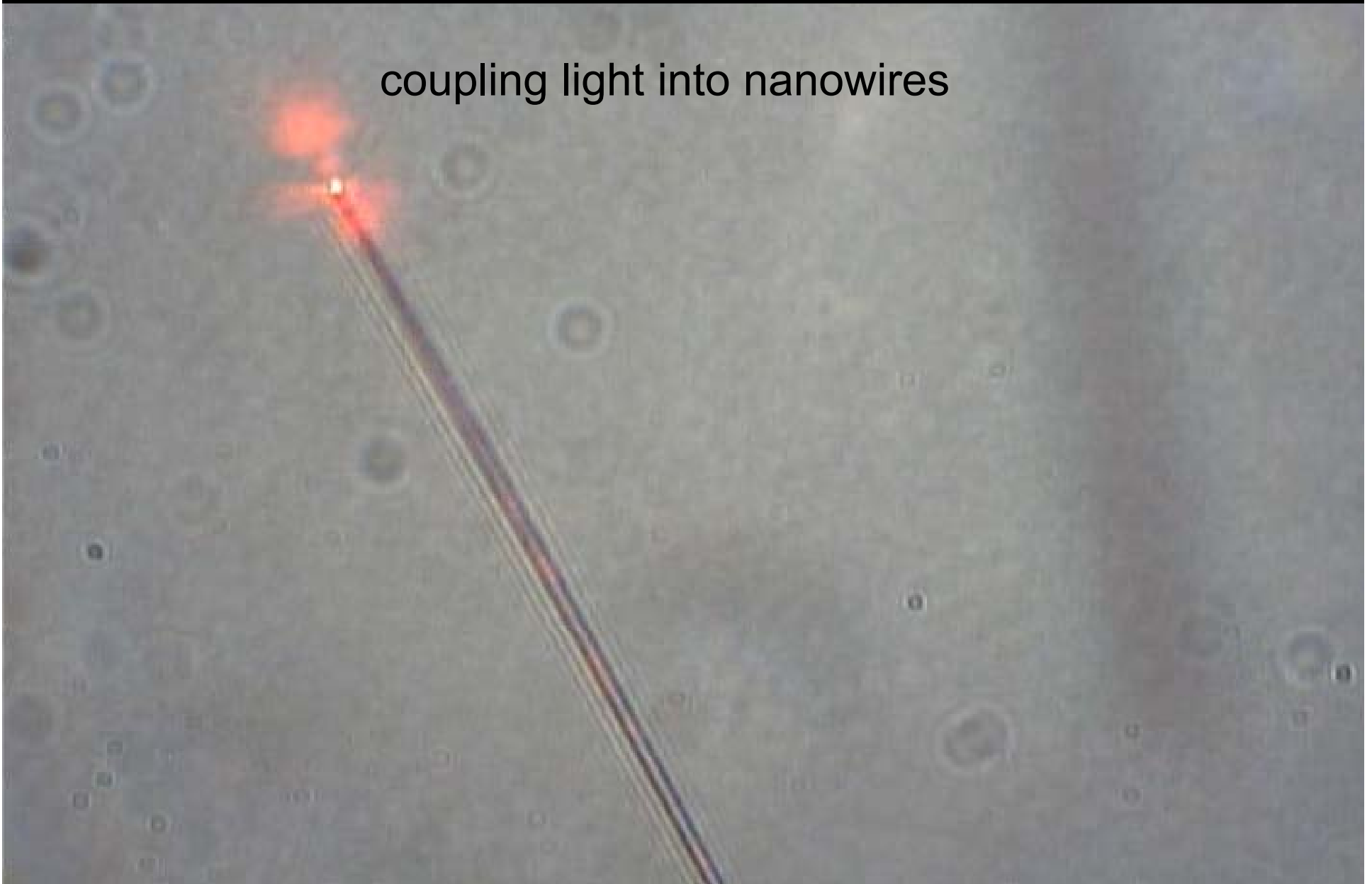
Silica nanowires

coupling light into nanowires



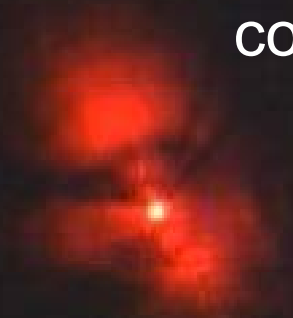
Silica nanowires

coupling light into nanowires



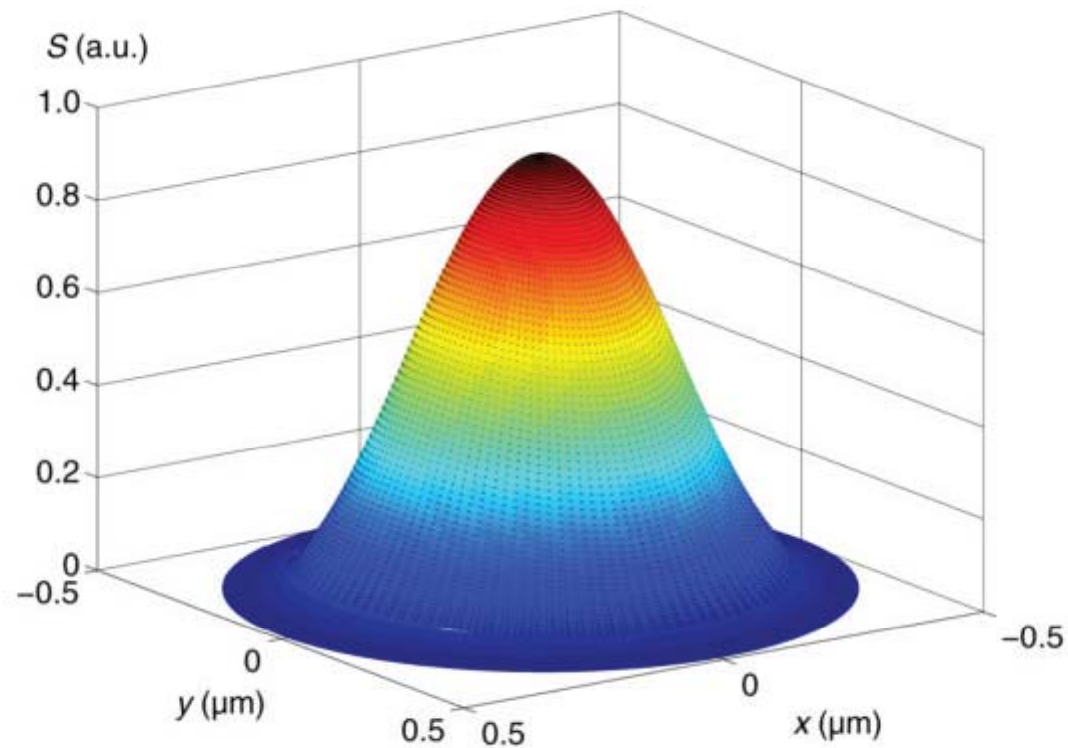
Silica nanowires

coupling light into nanowires



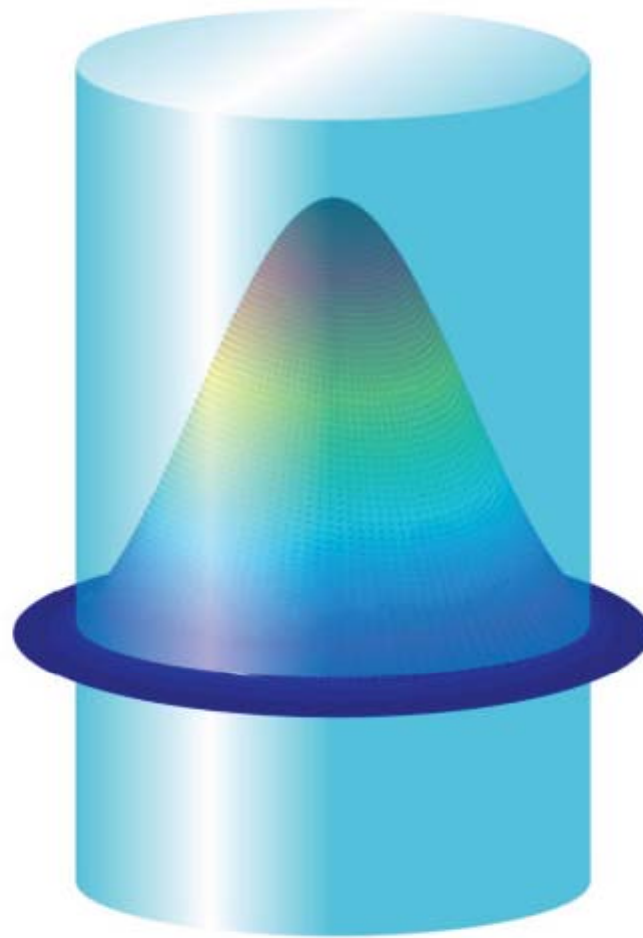
Silica nanowires

Poynting vector for 800 nm nanowires



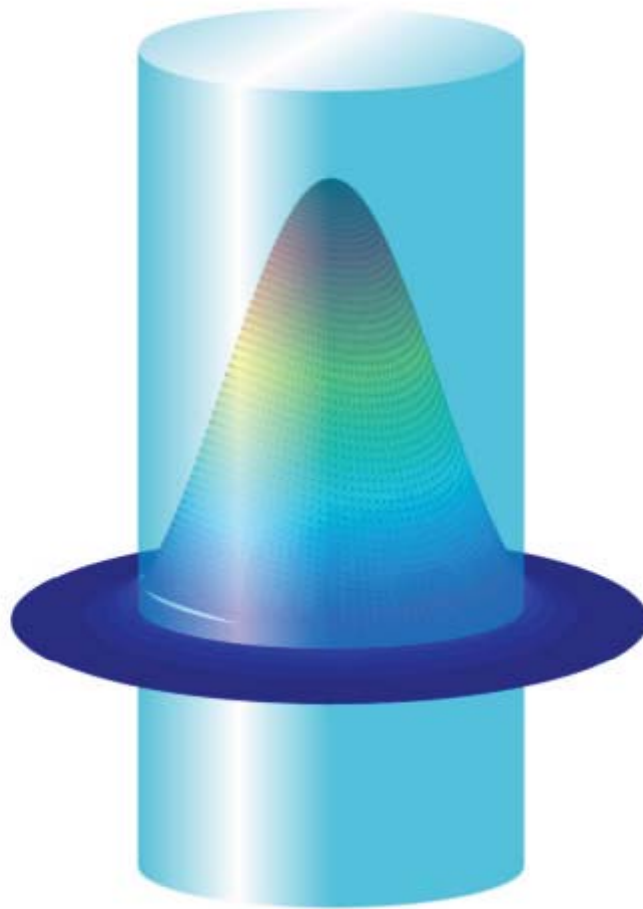
Silica nanowires

Poynting vector for 800 nm nanowires



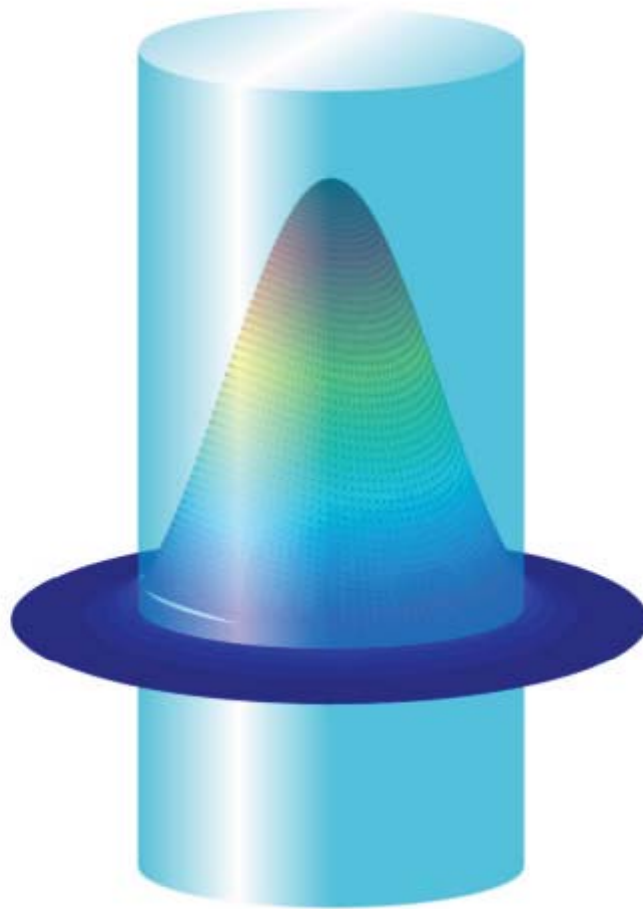
Silica nanowires

Poynting vector for 600 nm nanowires



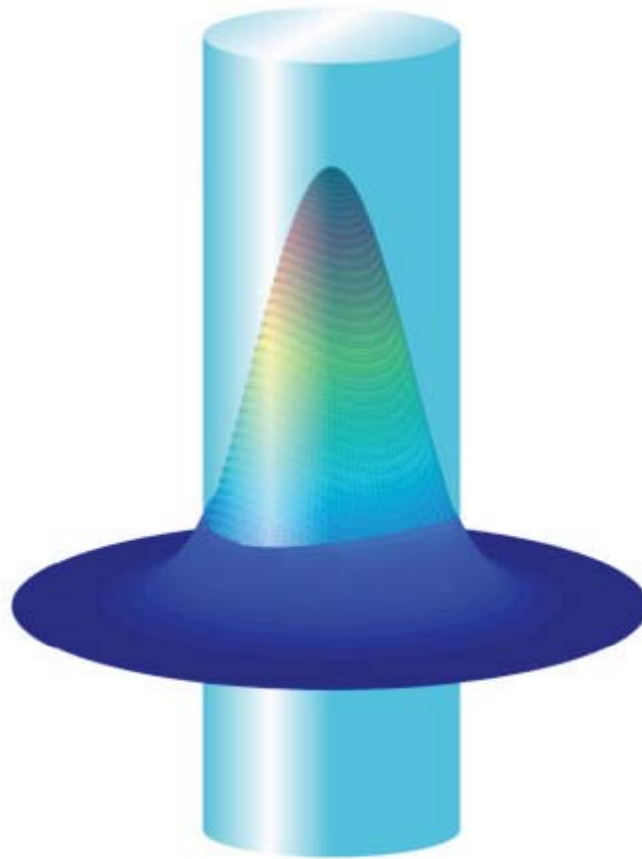
Silica nanowires

Poynting vector for 600 nm nanowires



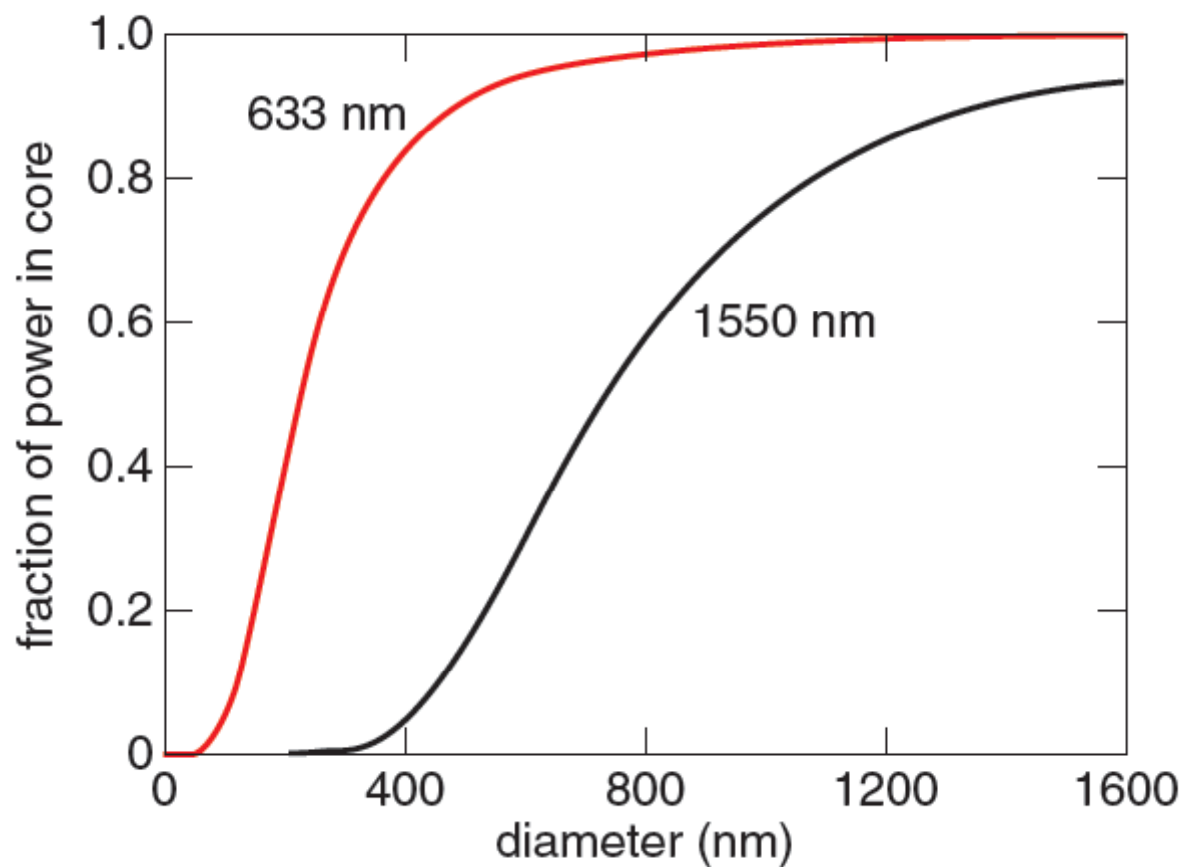
Silica nanowires

Poynting vector for 400 nm nanowires



Silica nanowires

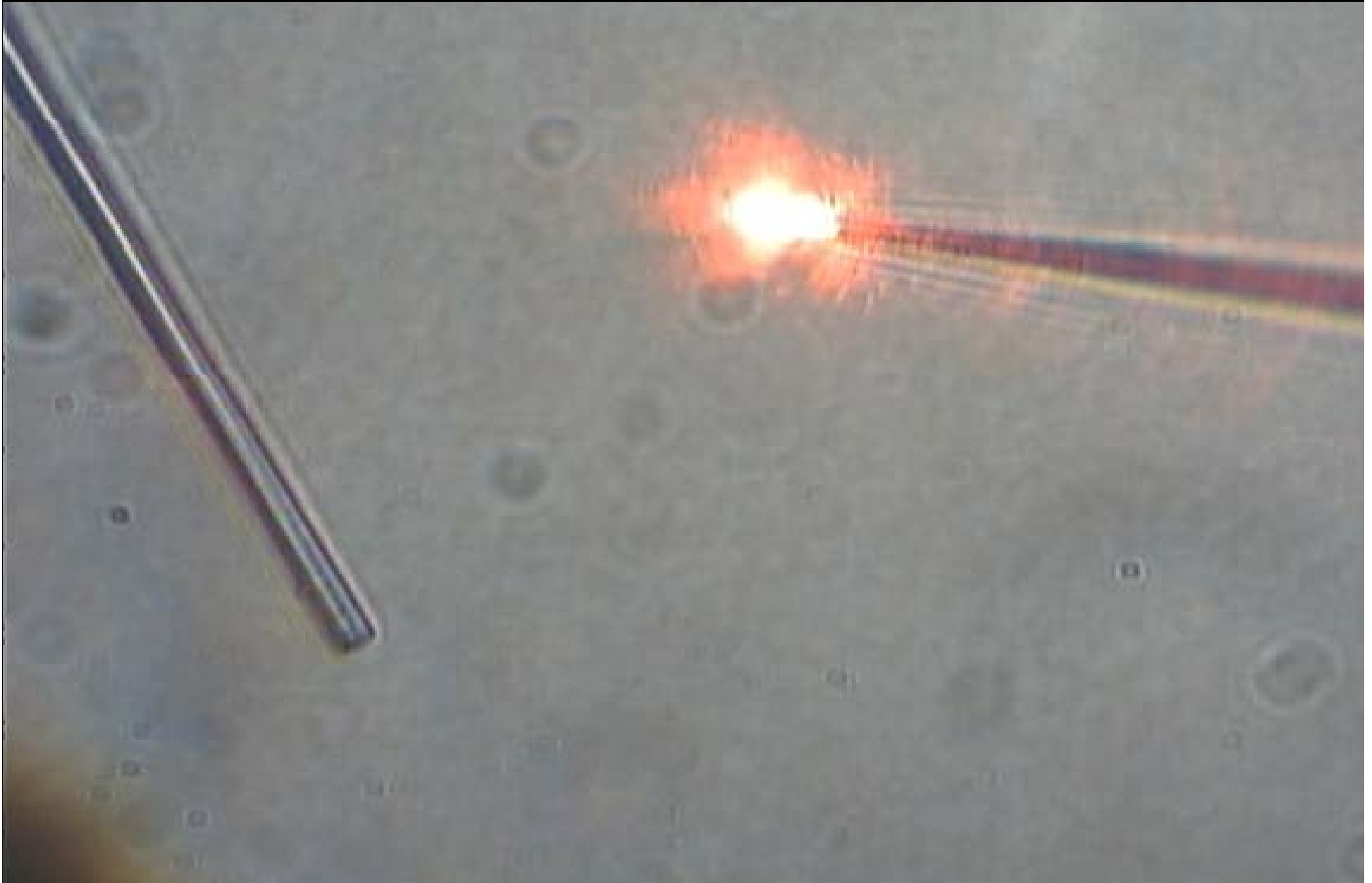
Power fraction in the core of the nanowires



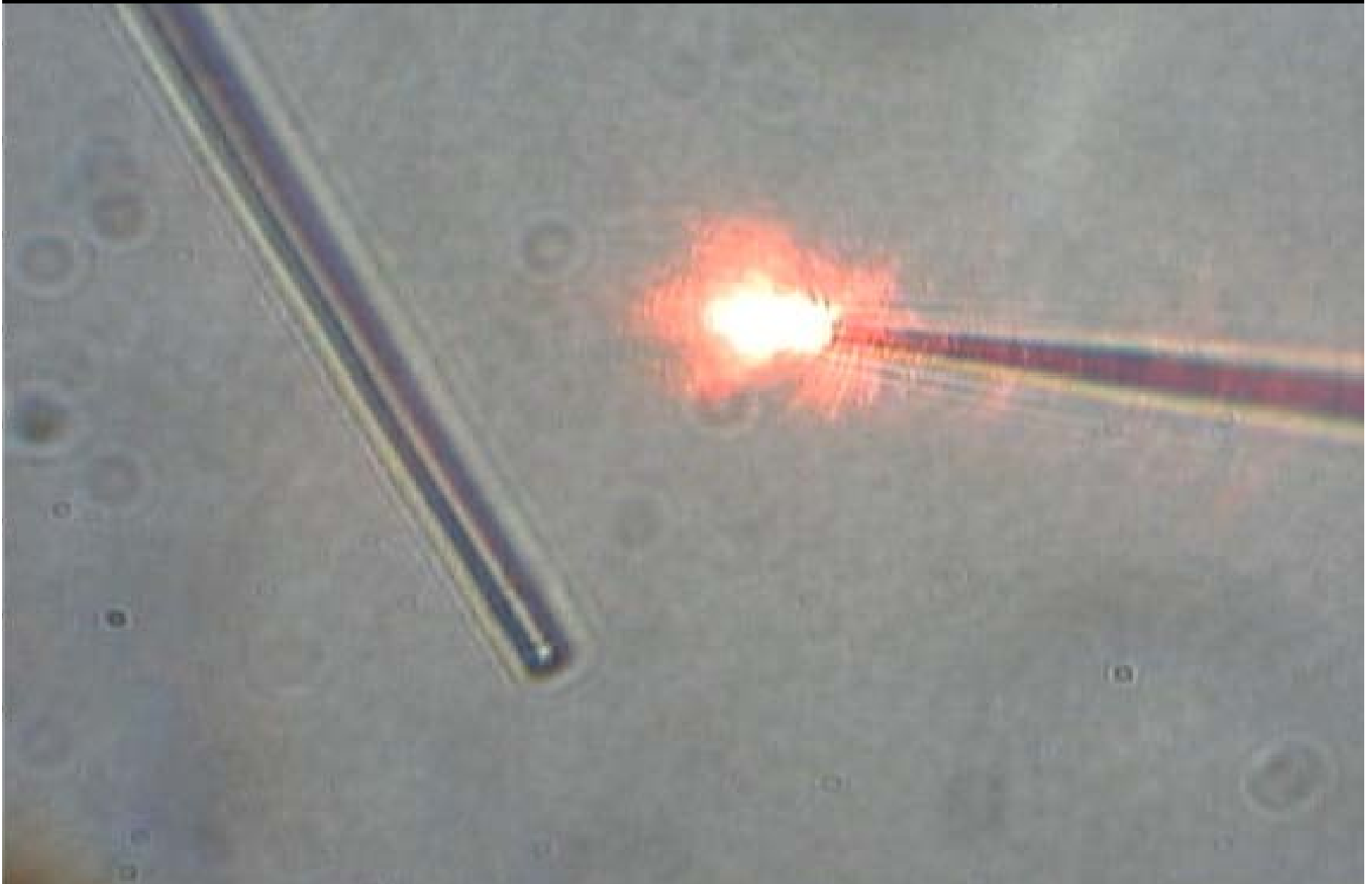
Silica nanowires

Manipulating the nanowires

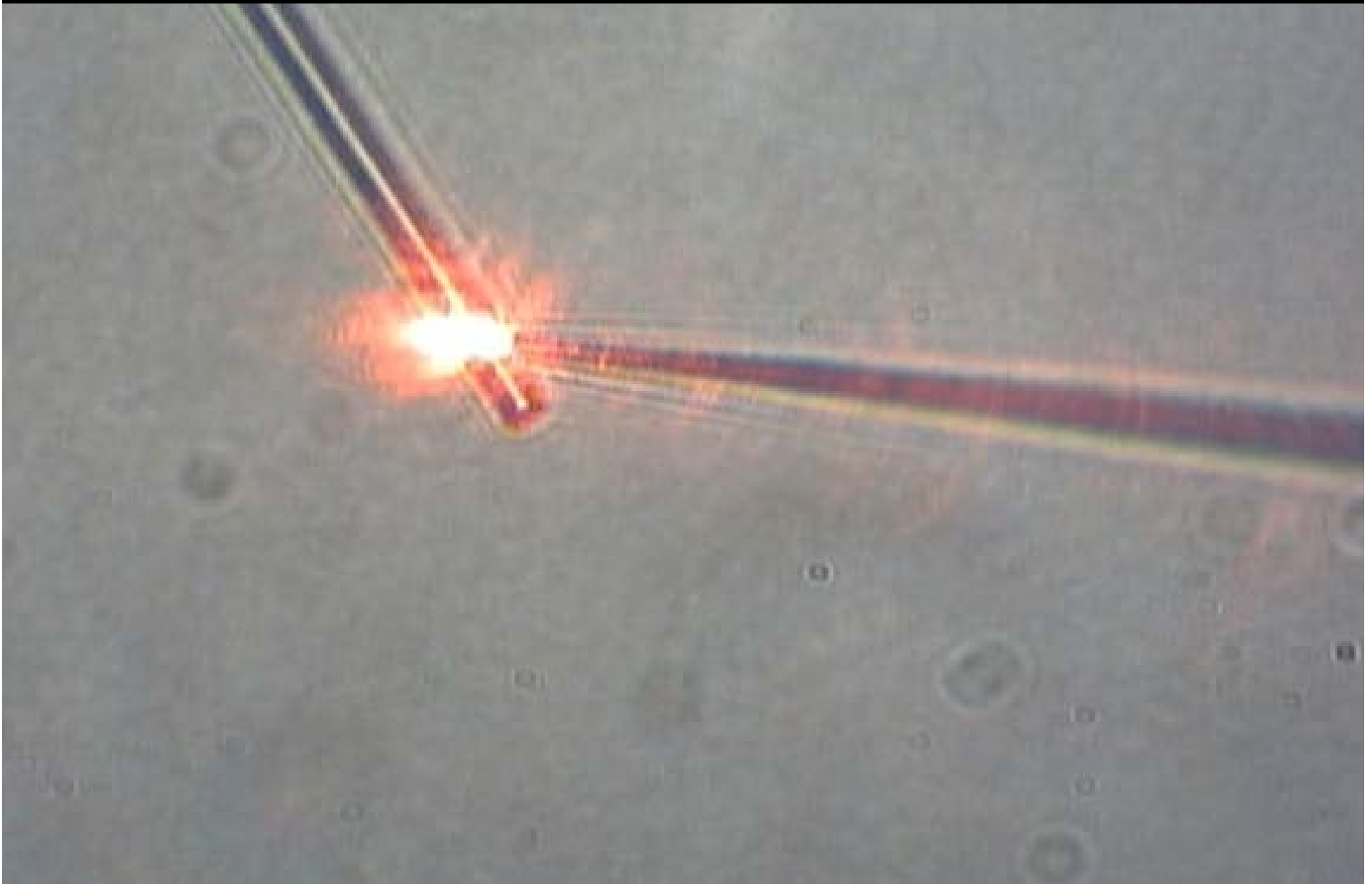
Silica nanowires



Silica nanowires

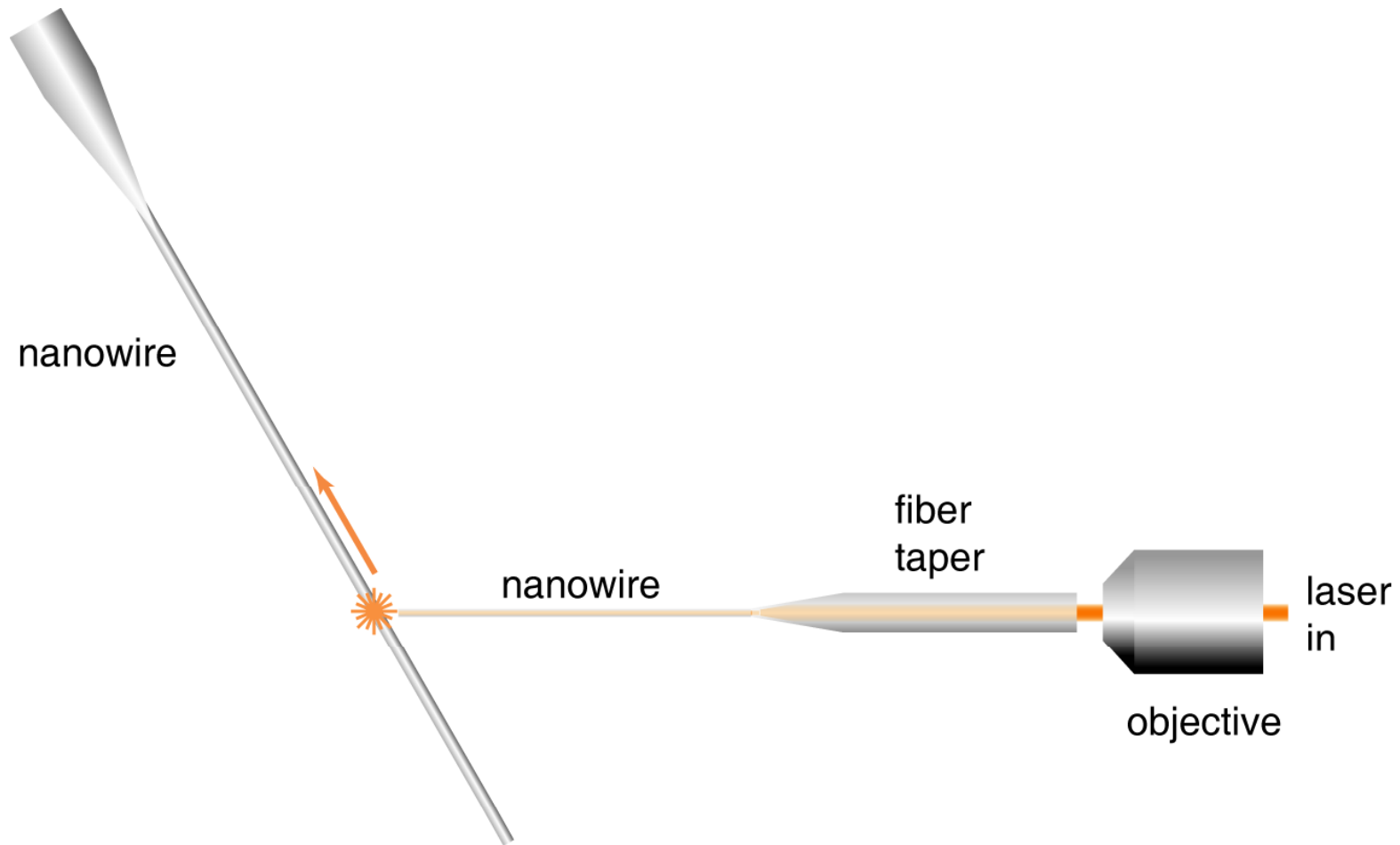


Silica nanowires



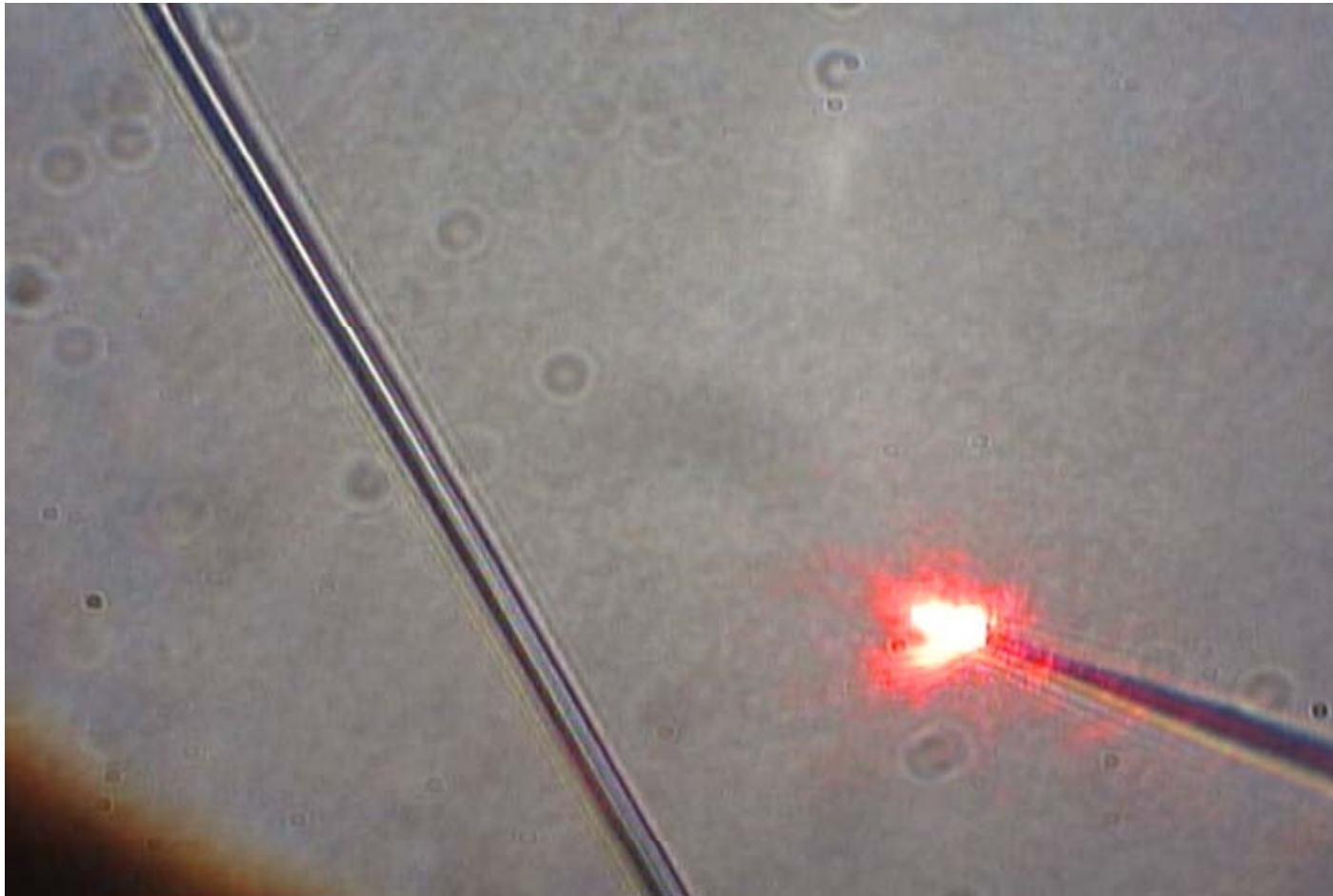
Silica nanowires

coupling light into nanowires



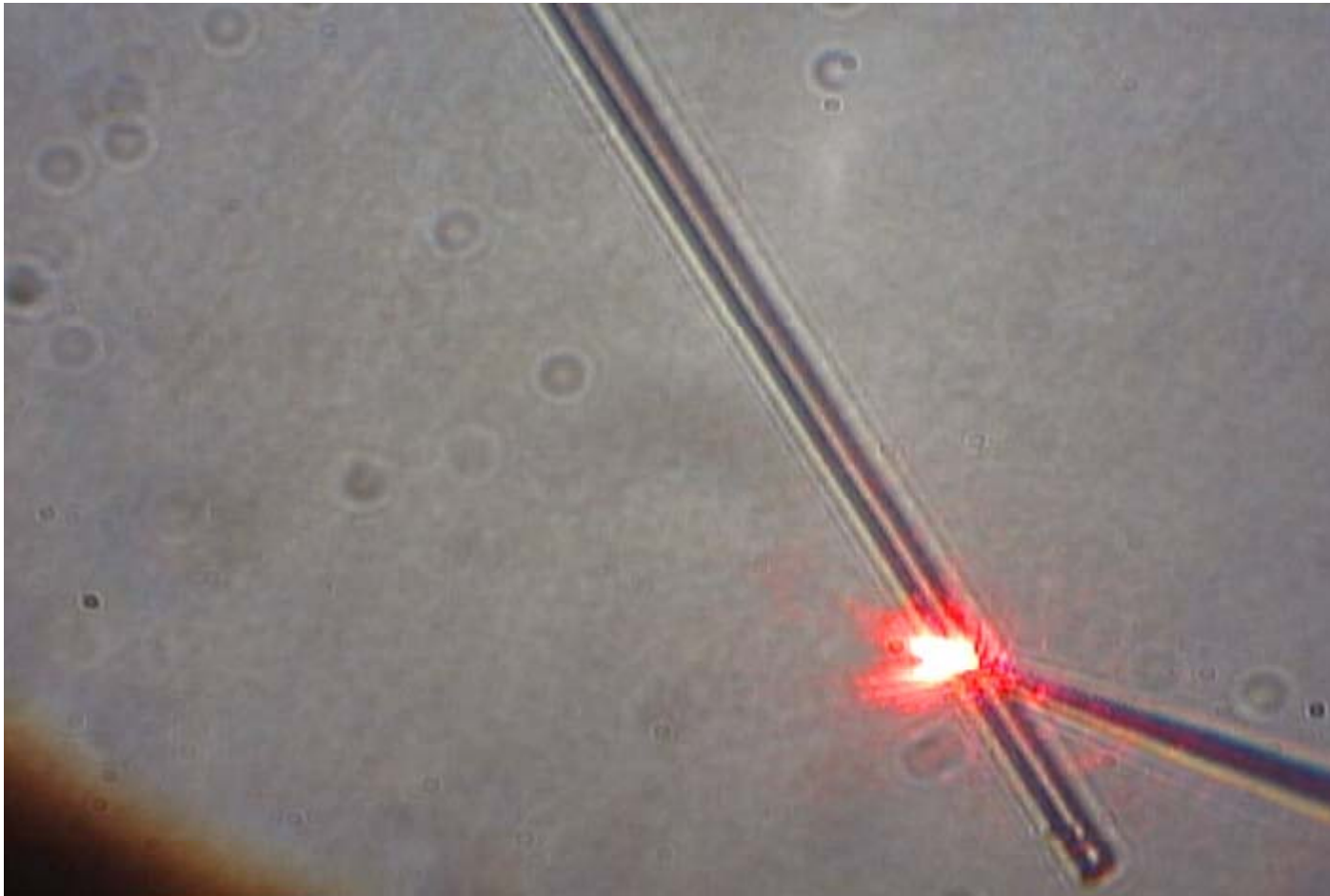
Silica nanowires

coupling light into nanowires



Silica nanowires

coupling light into nanowires

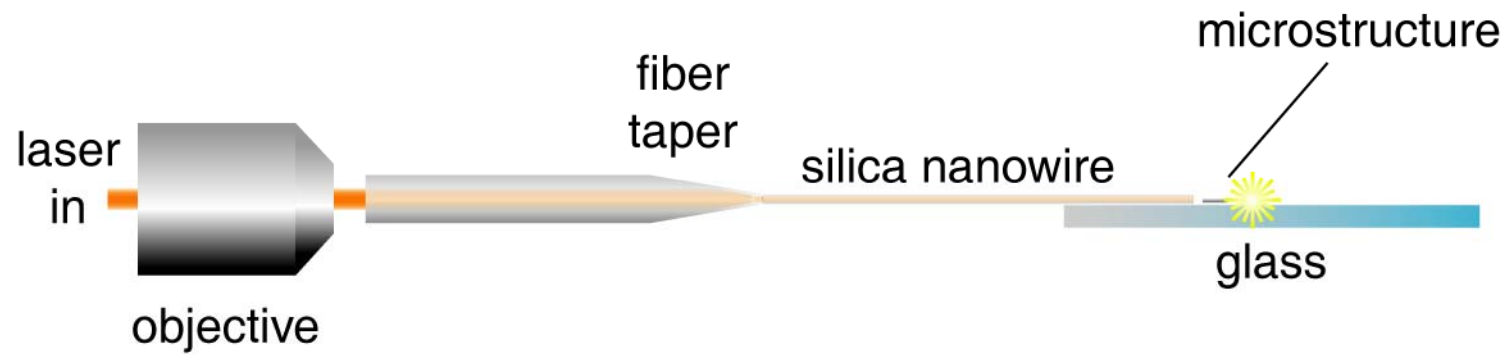


Outline

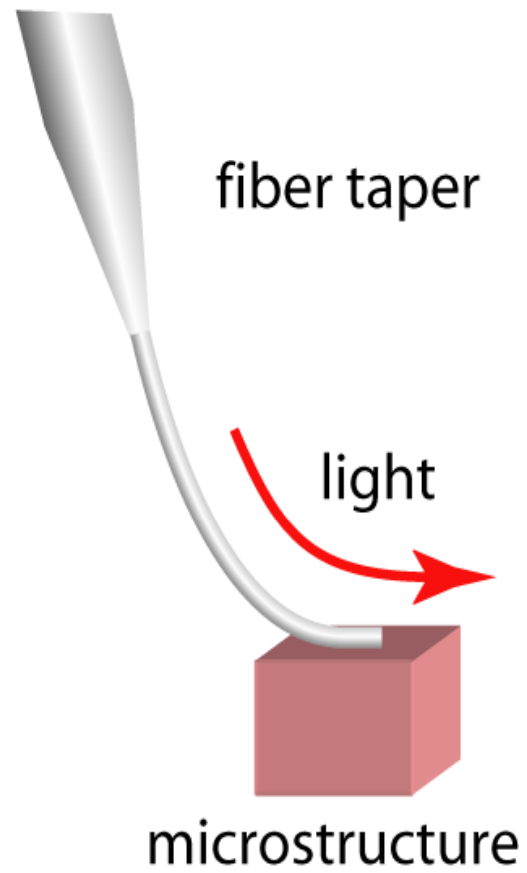
- microfabrication
- silica nanowires
- coupling microstructures

50 μm

Coupling microstructures



Coupling microstructures



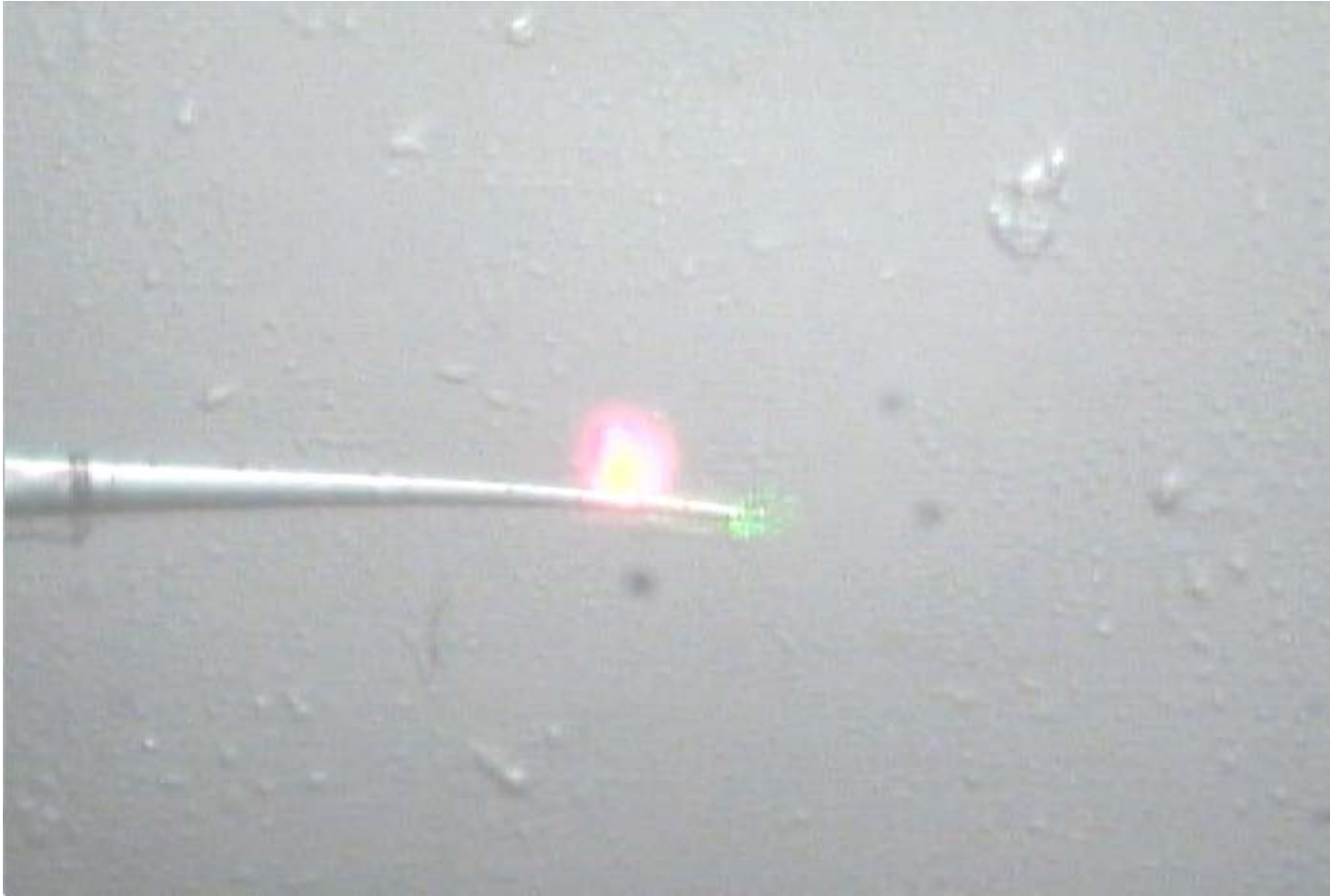
Coupling microstructures



Coupling microstructures



Coupling microstructures



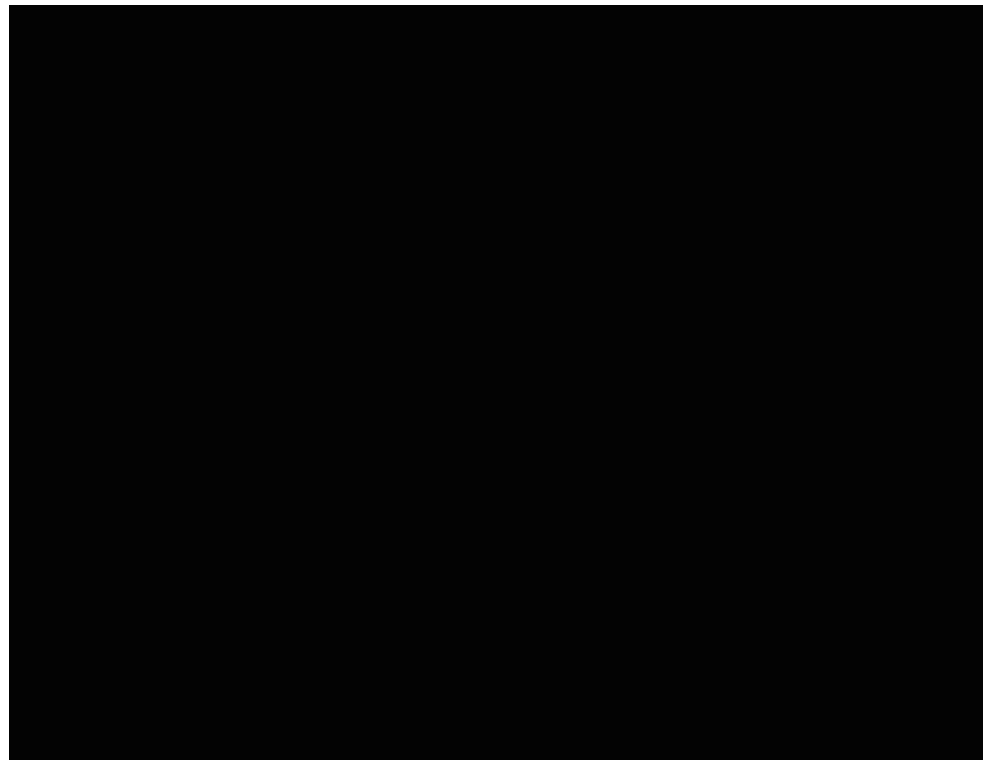
Coupling microstructures



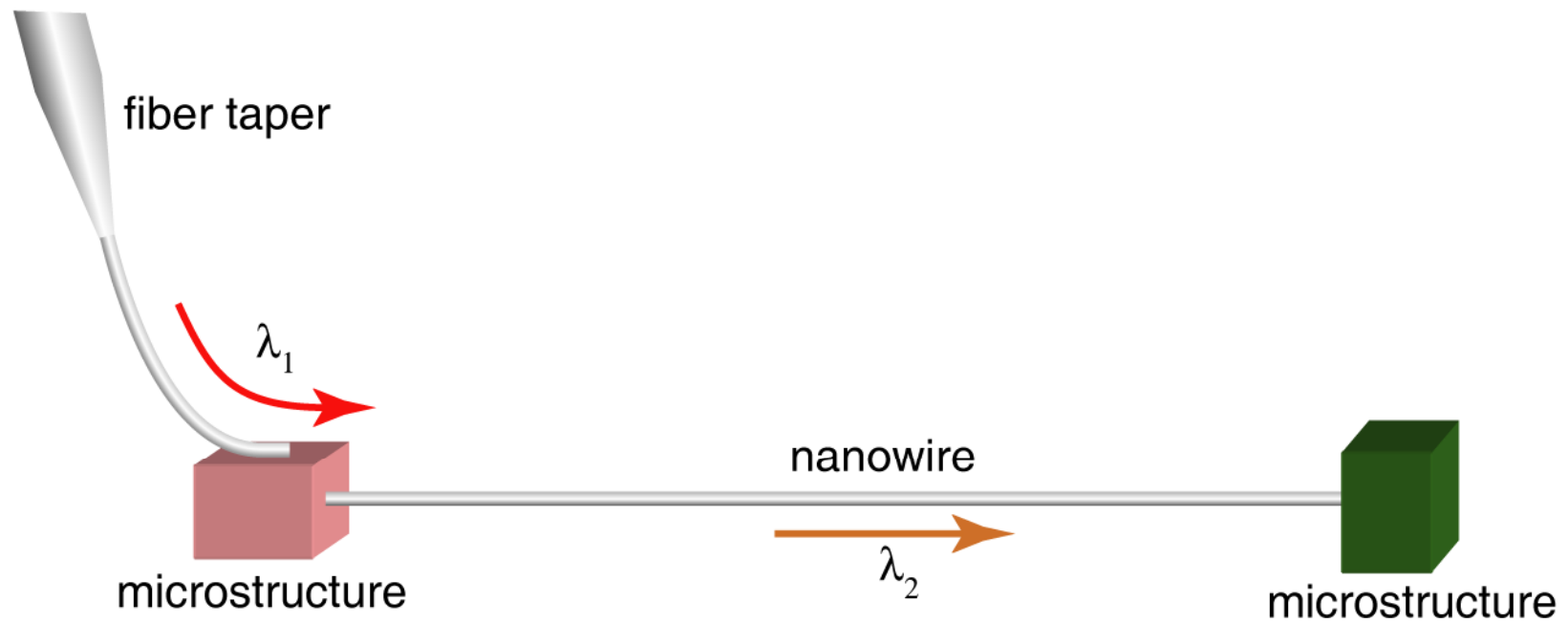
Coupling microstructures



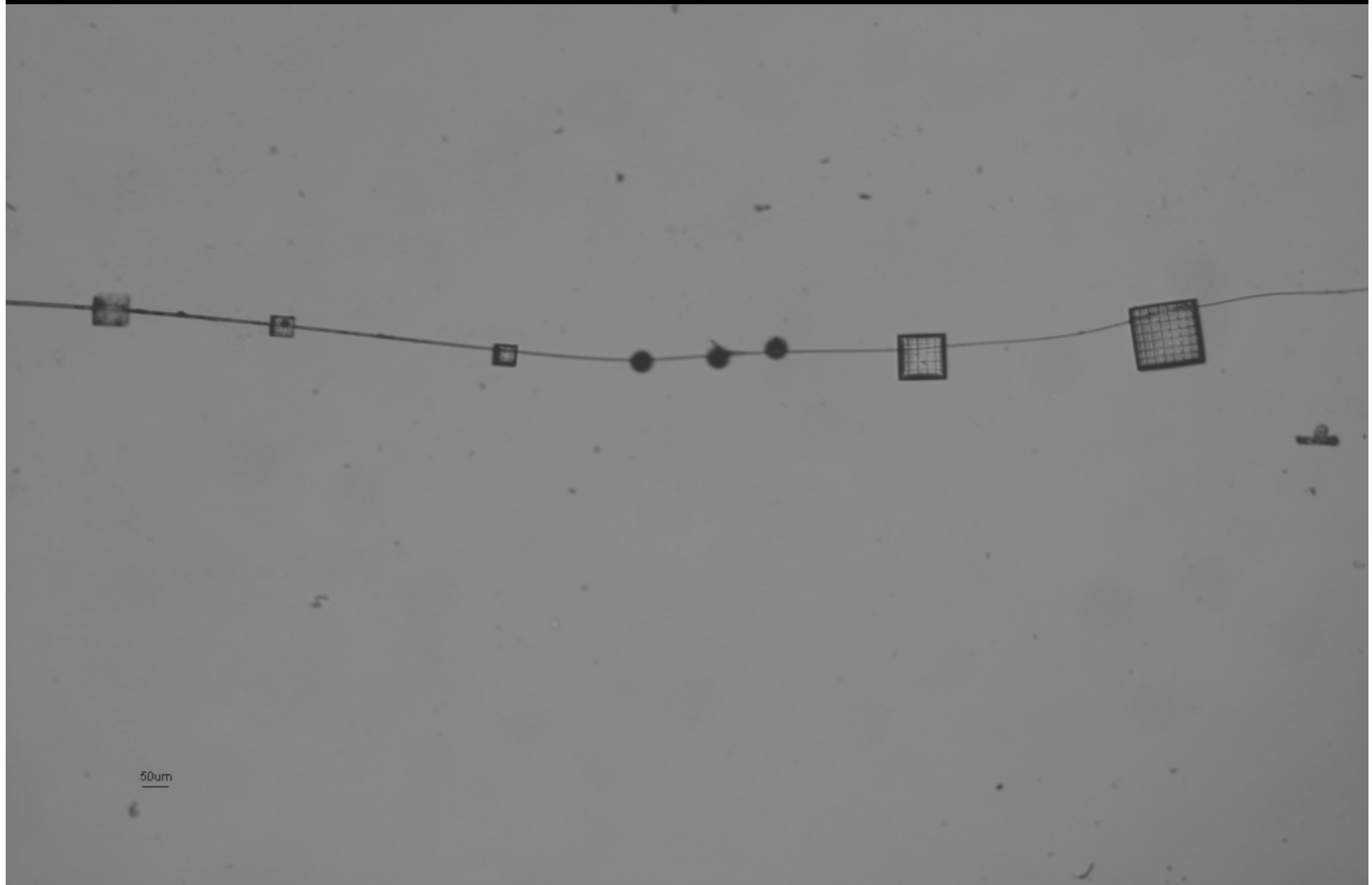
Silica nanowires



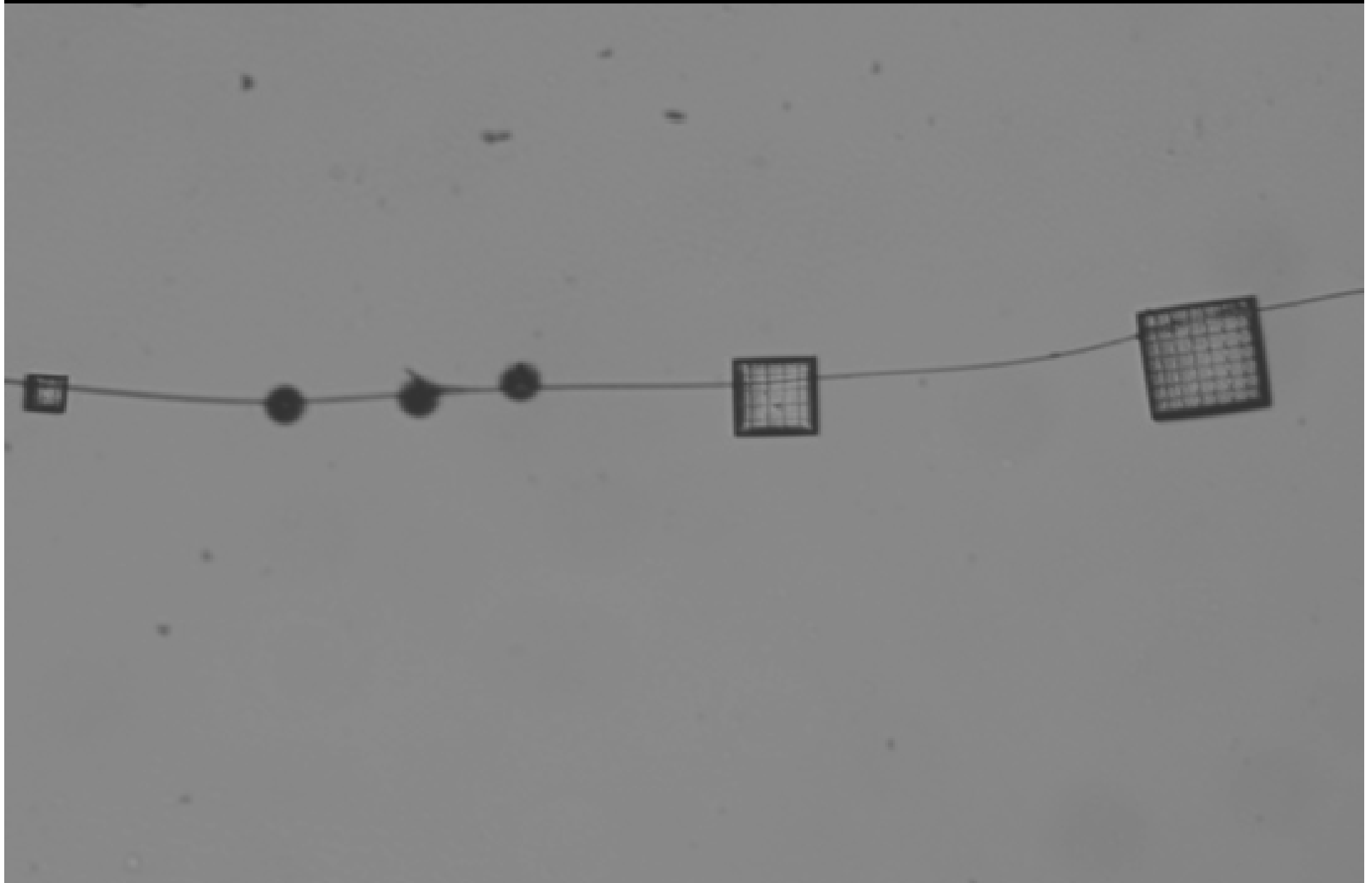
Coupling microstructures



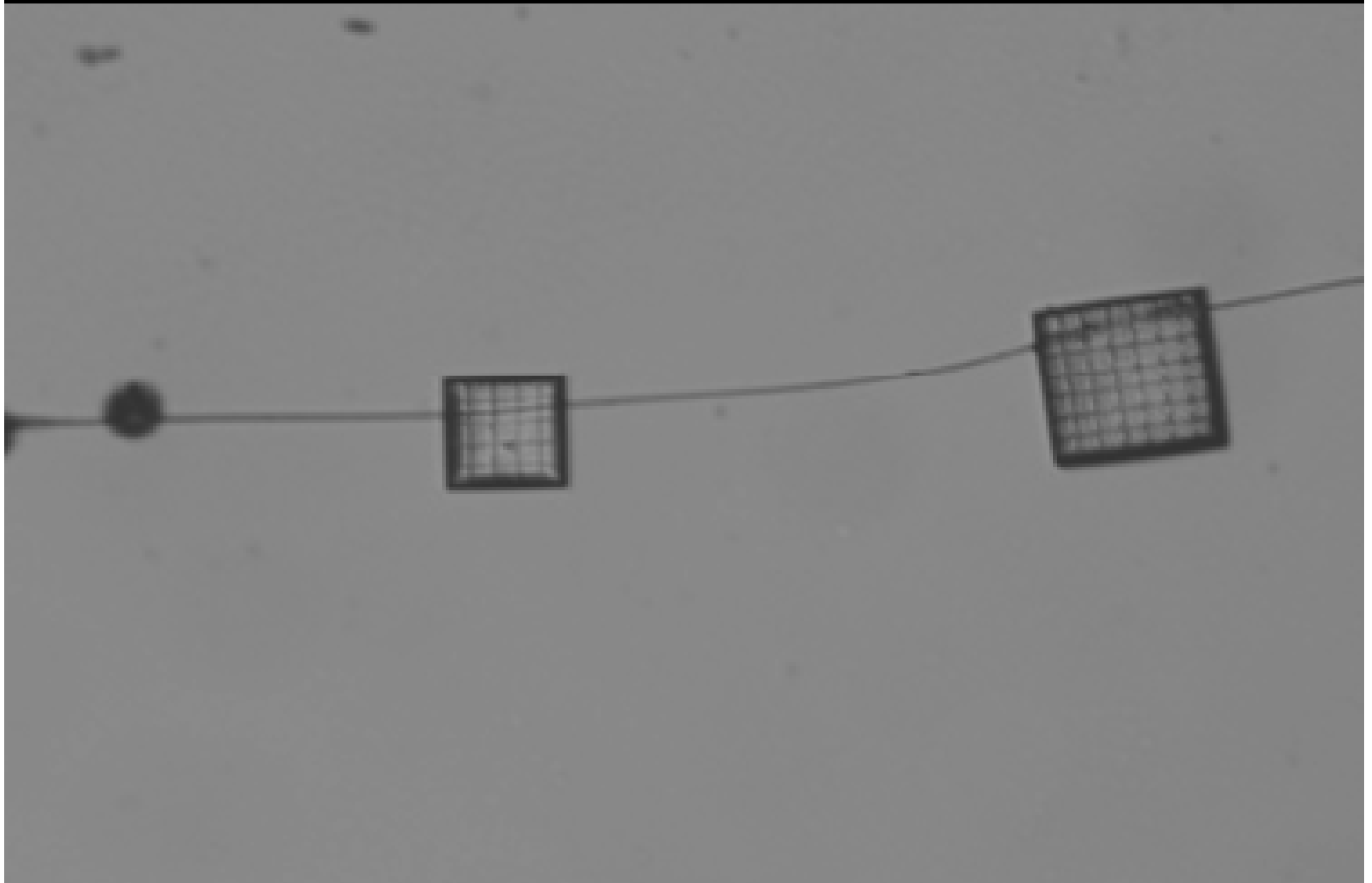
Coupling microstructures



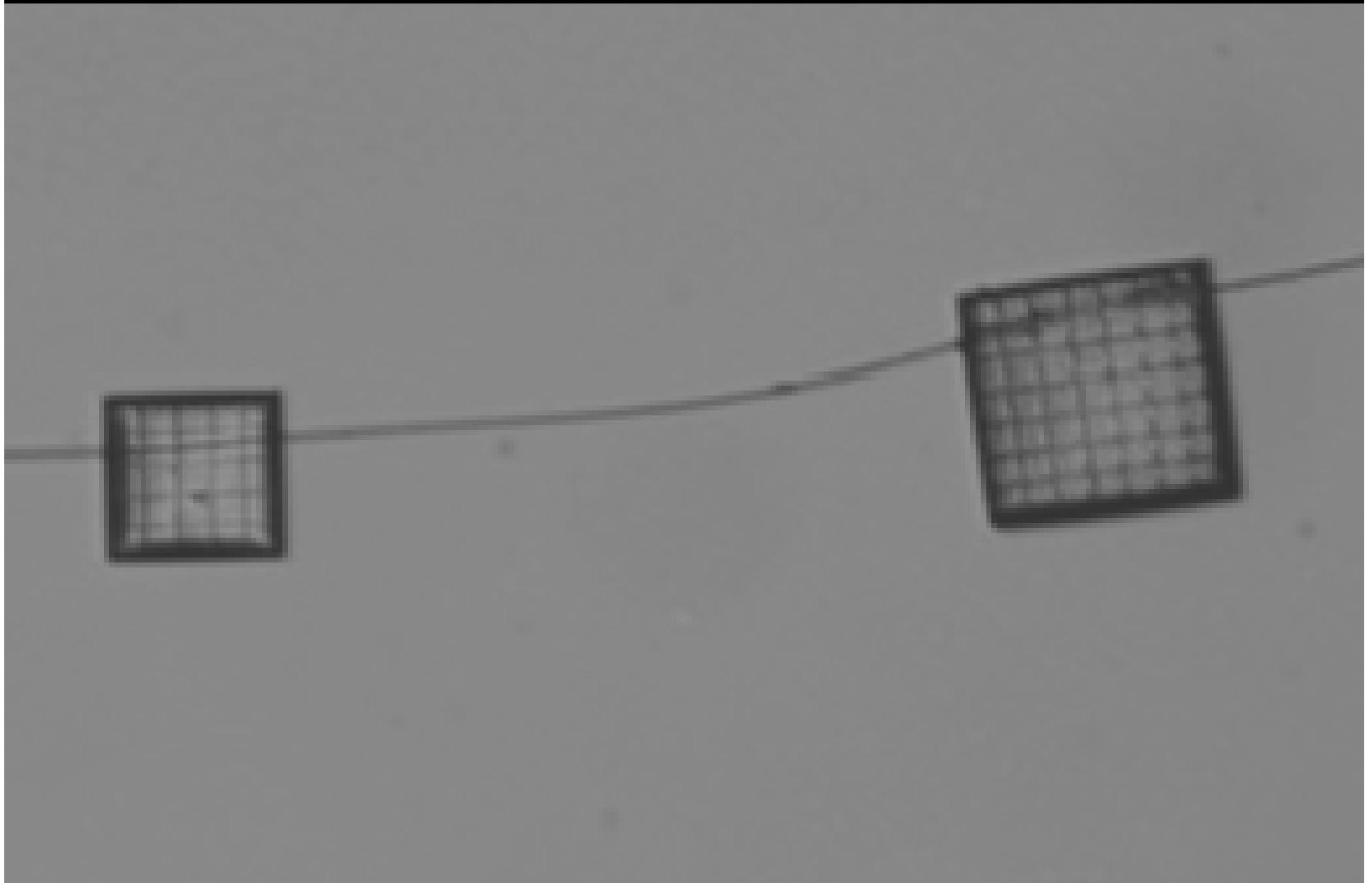
Coupling microstructures



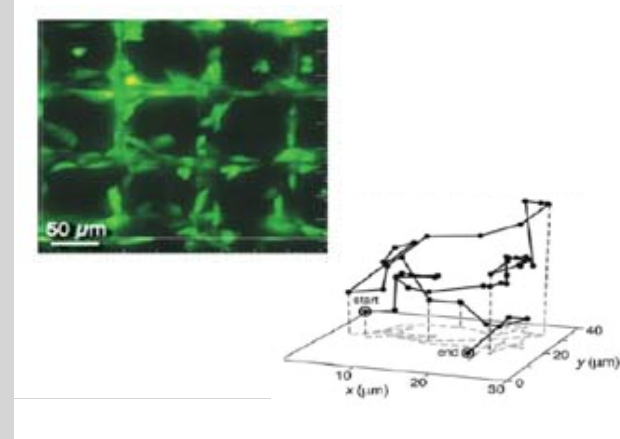
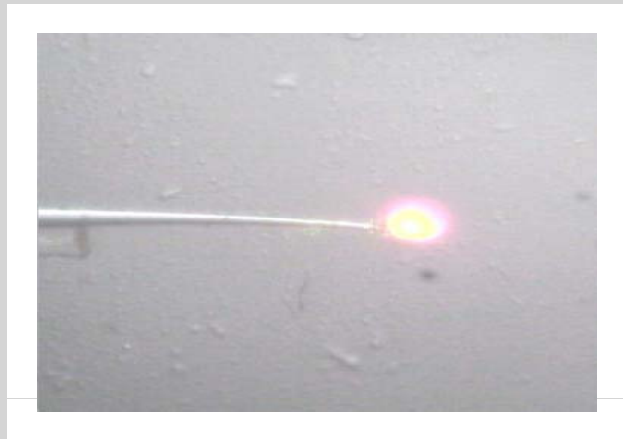
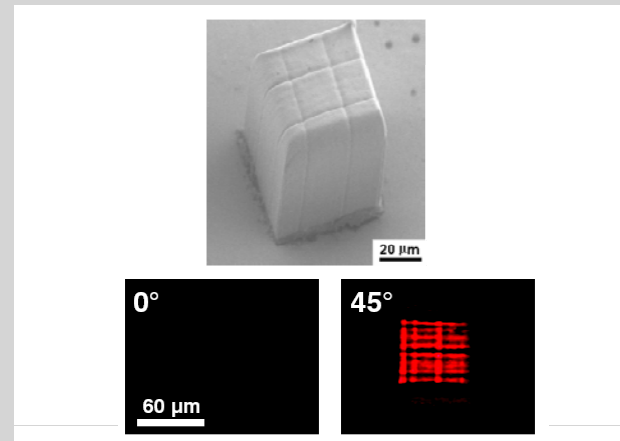
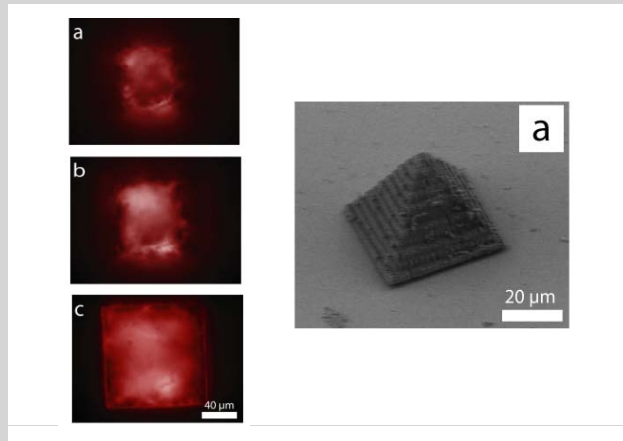
Coupling microstructures



Coupling microstructures



Summary



Acknowledgments

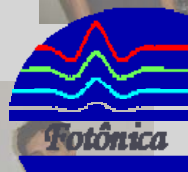
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CAPES
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NSF
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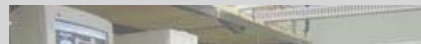
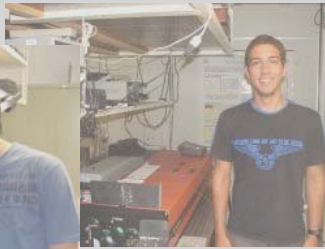
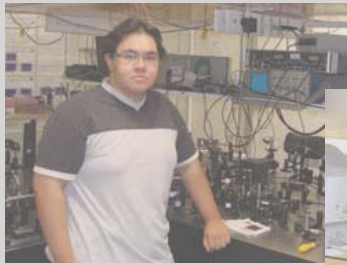
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Thank you !



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