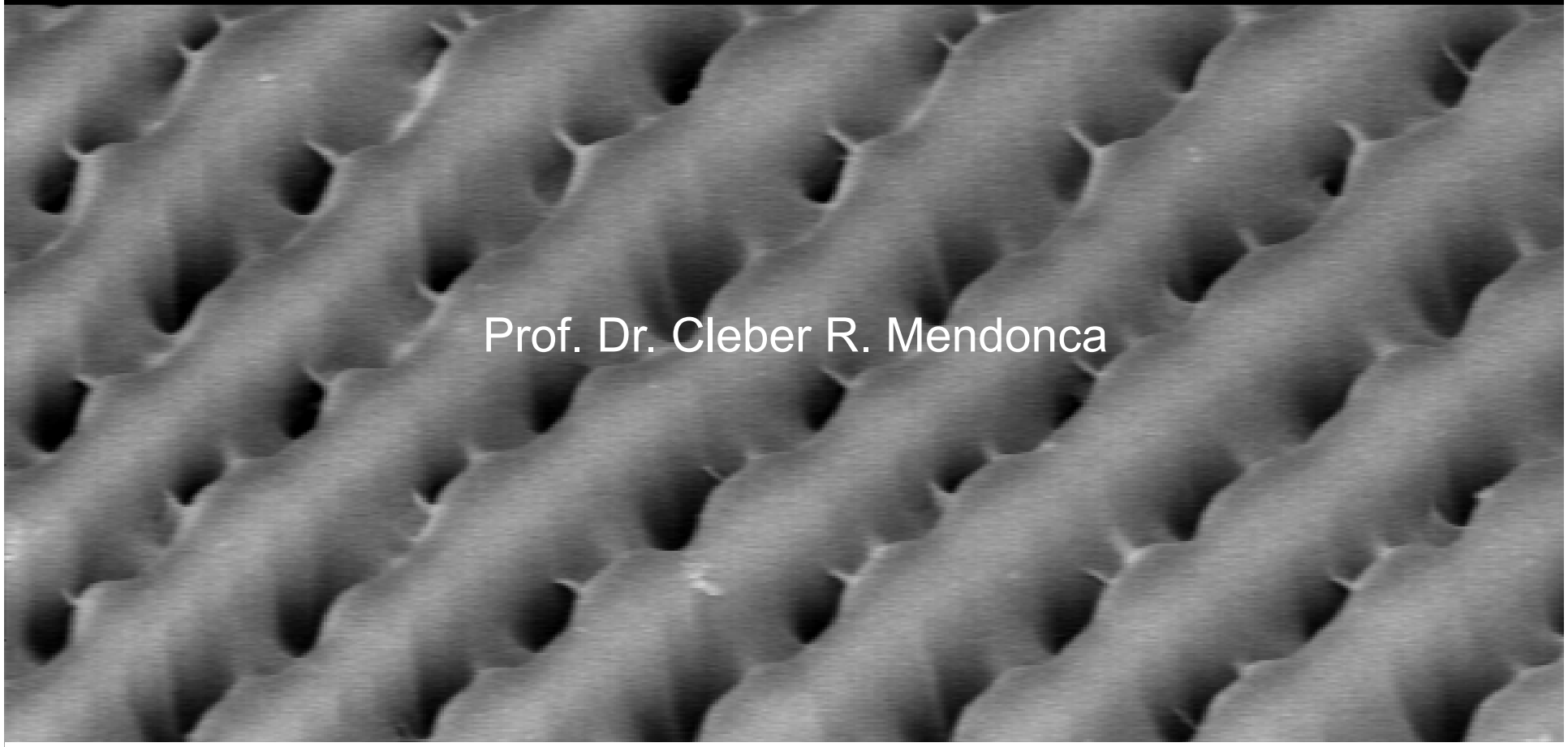
Femtosecond laser microfabrication and micromaching in materials



Prof. Dr. Cleber R. Mendonca

IFSC

USP

Fotônica

University of Sao Paulo - Brazil

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

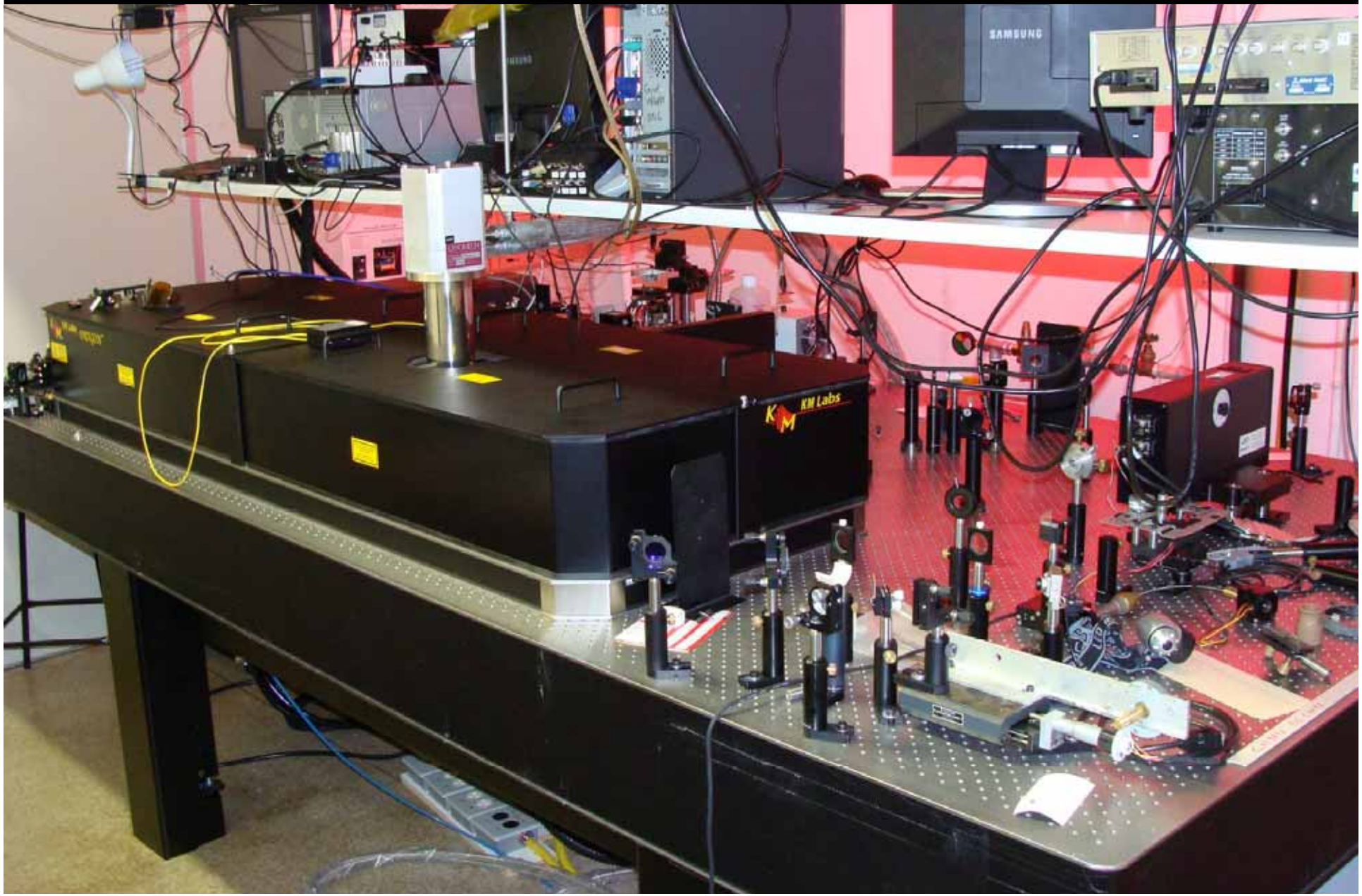
research areas

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

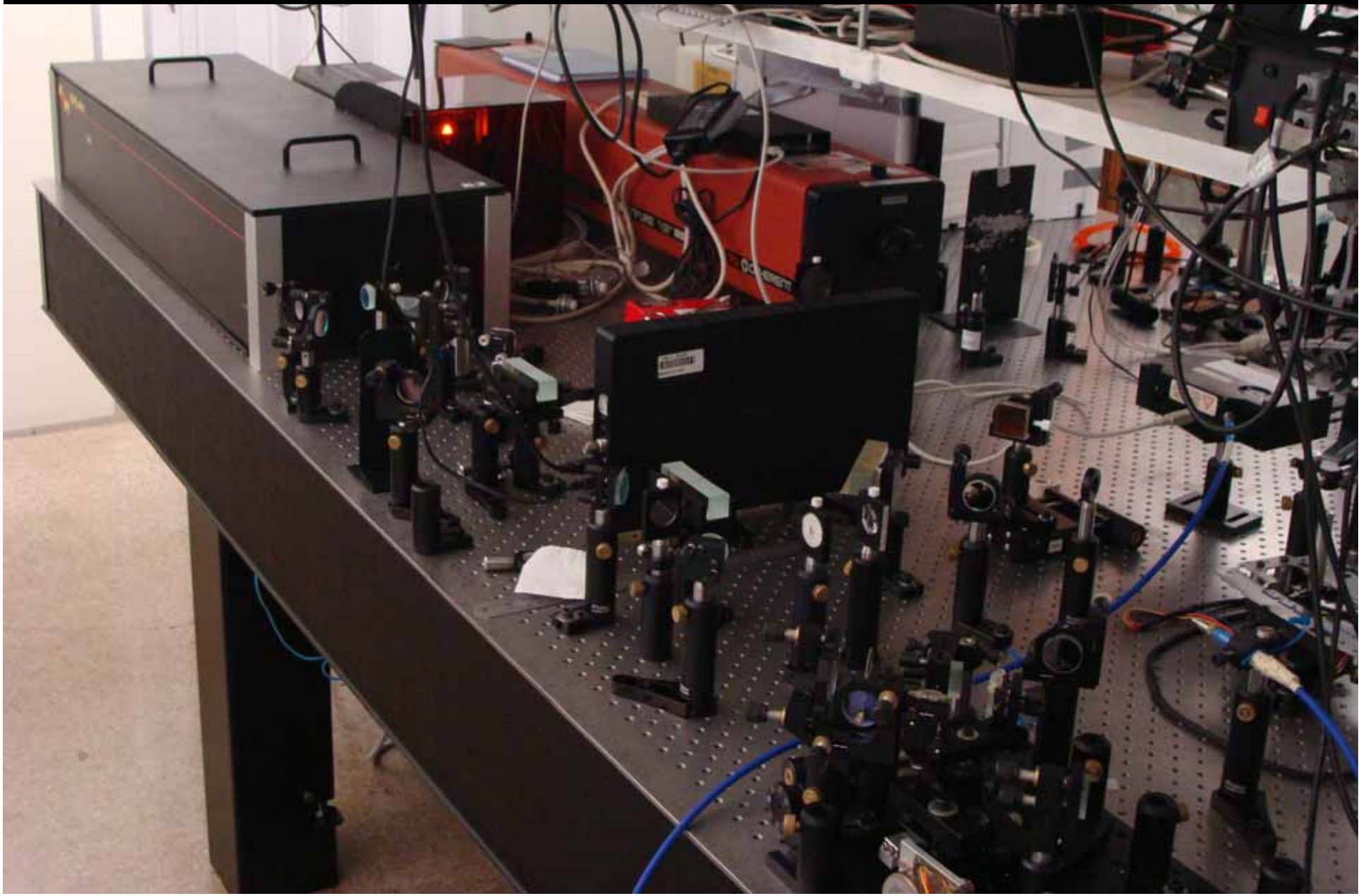
70 ps Q-switch/modelocked laser (532/1064 nm)

150 fs Ti:sapphire amplifier

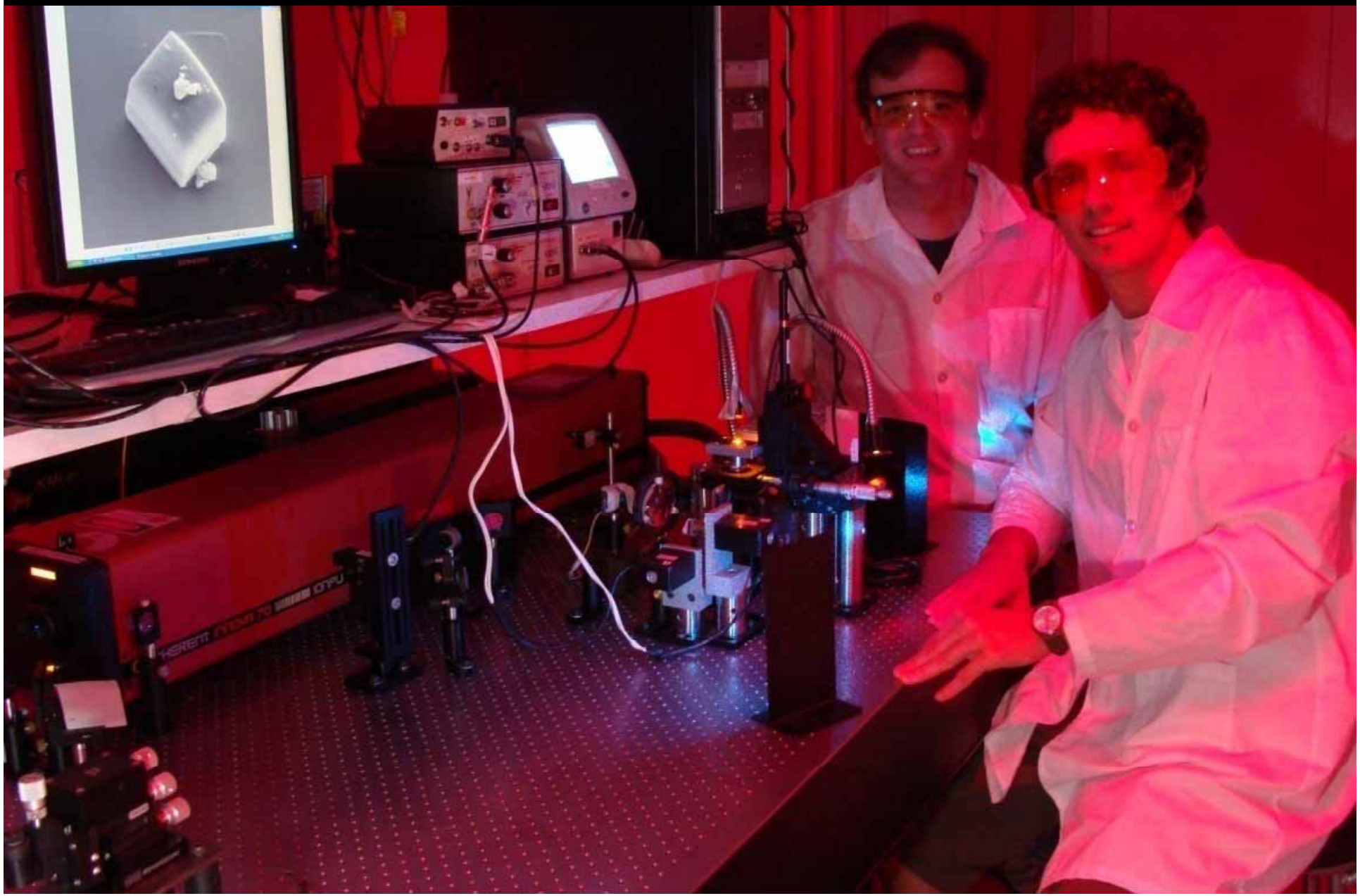
40 fs Ti:sapphire amplifier



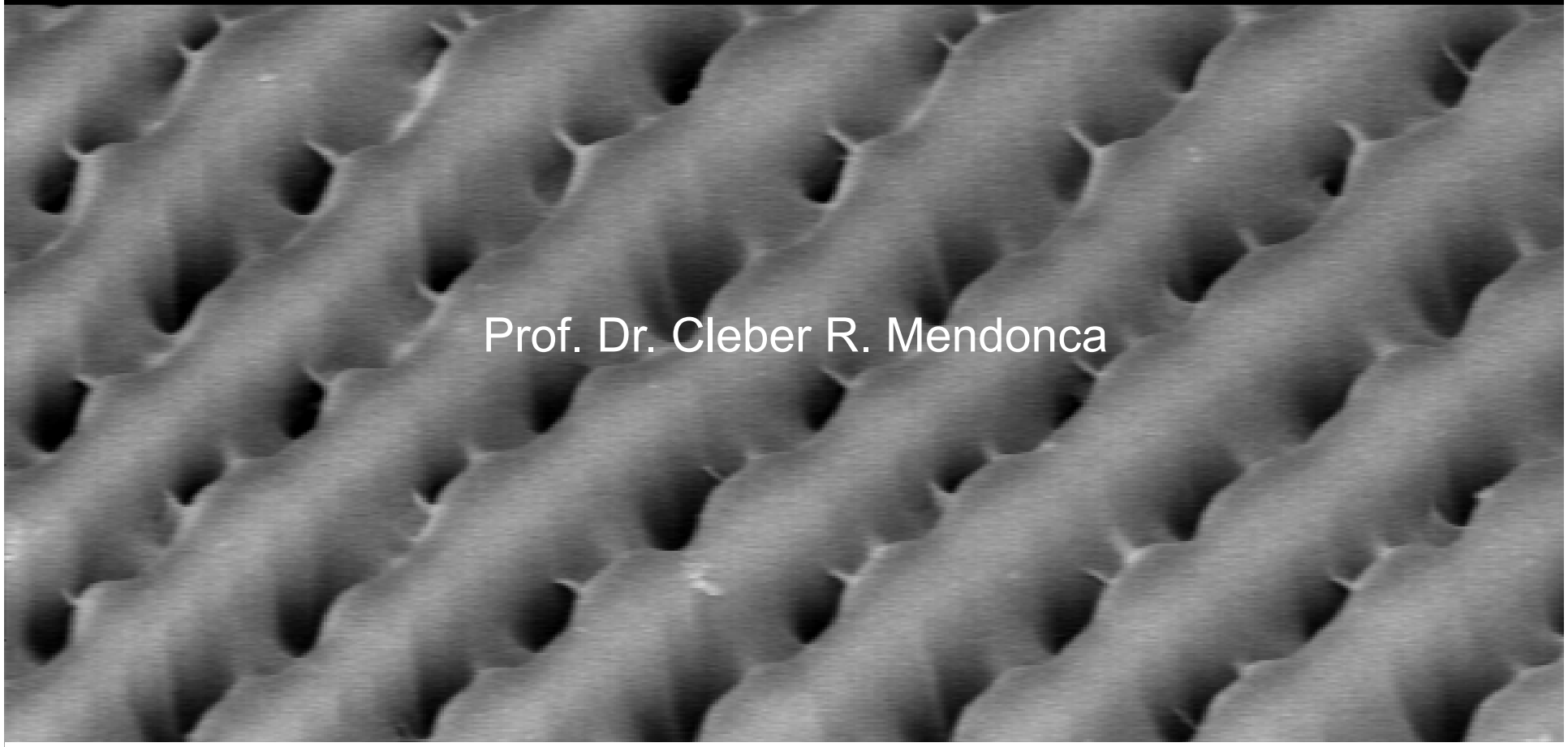
20 fs laser oscillator



microfabrication laboratory



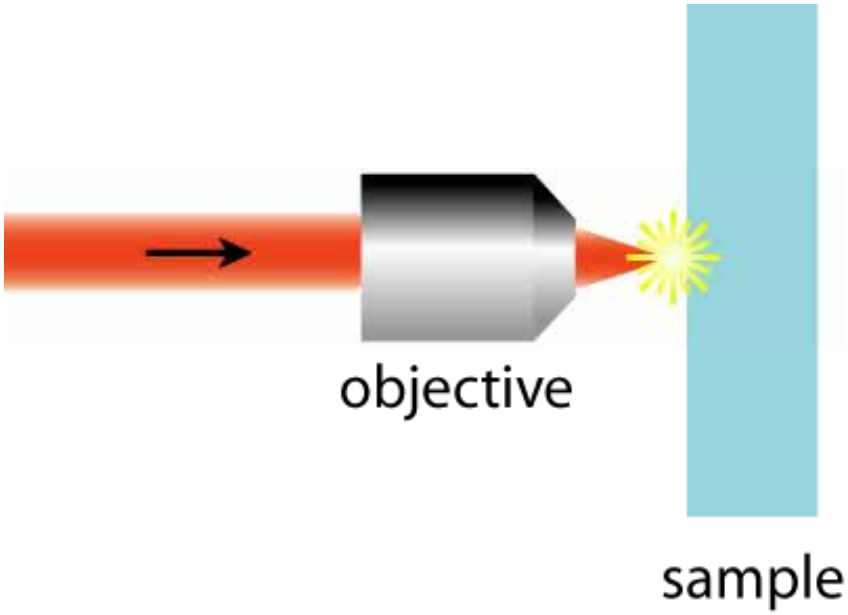
Femtosecond laser microfabrication in polymers



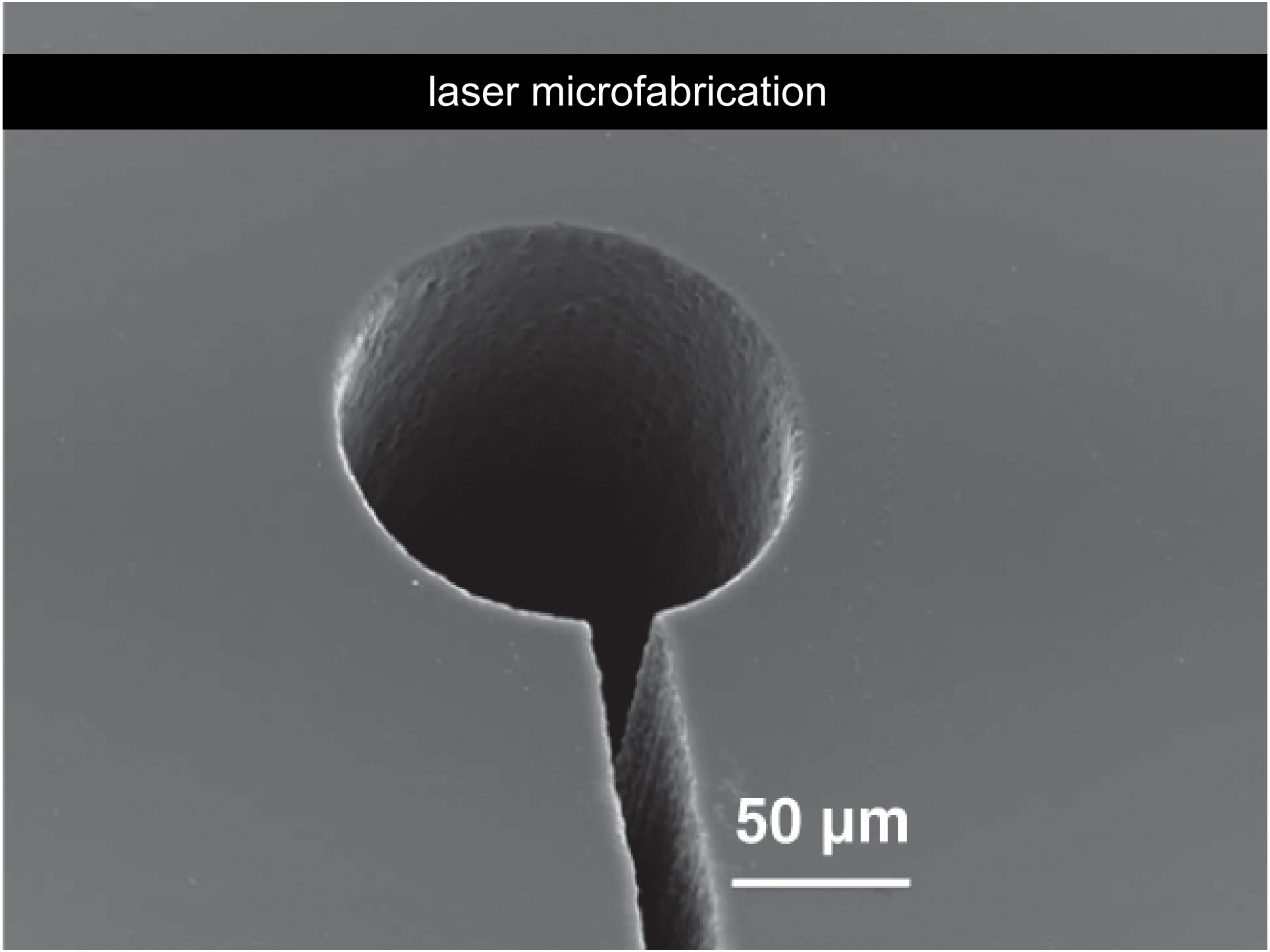
Prof. Dr. Cleber R. Mendonca

laser microfabrication

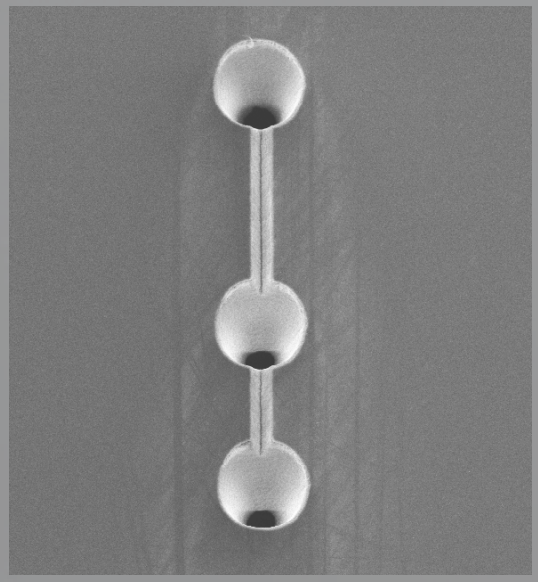
focus laser beam on material's surface



laser microfabrication

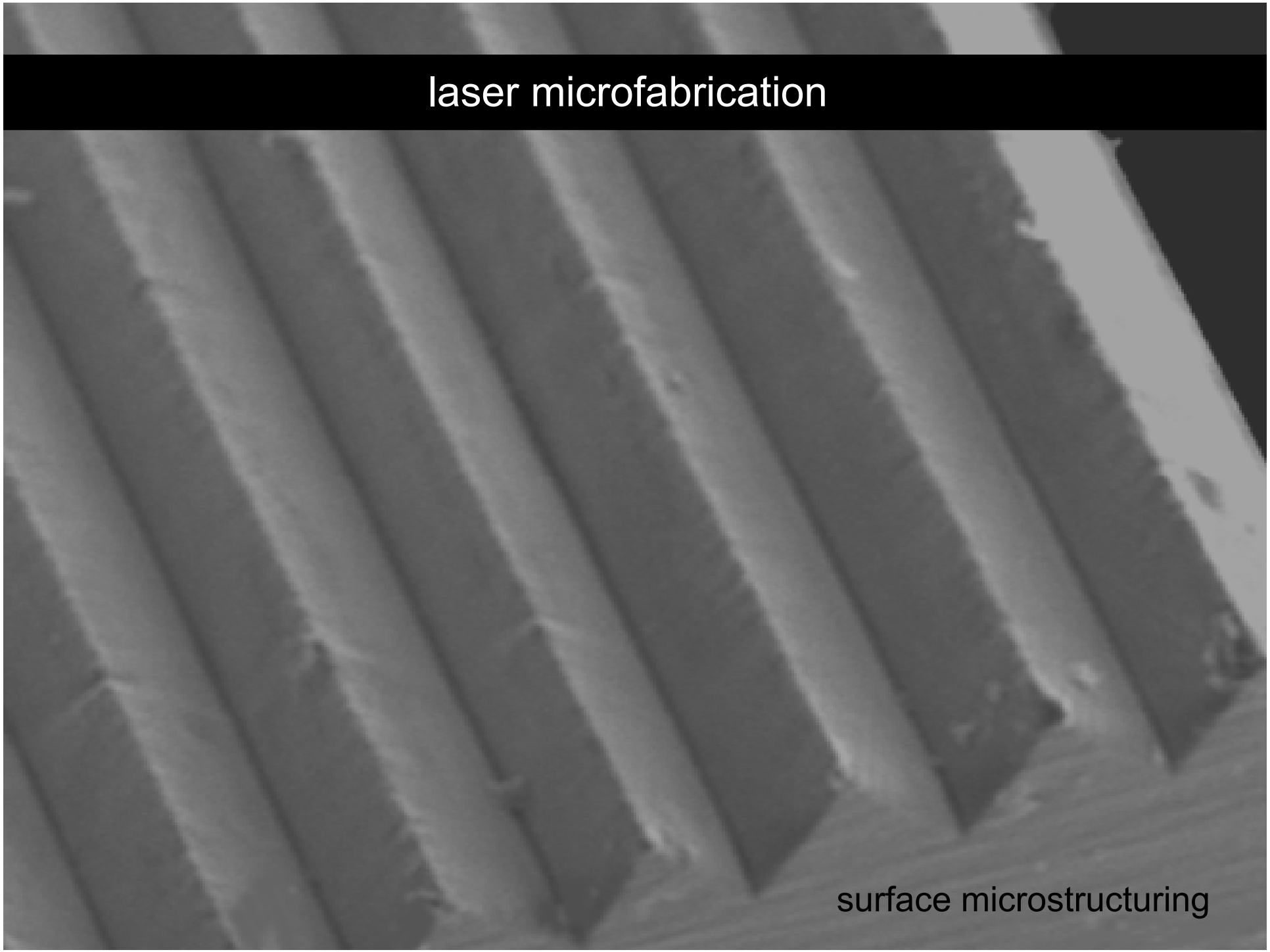


laser microfabrication



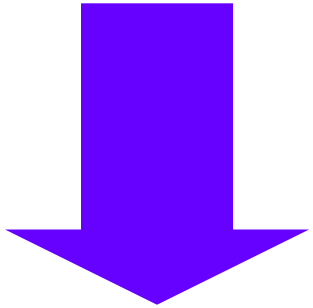
50 µm

laser microfabrication



fs-micromachining

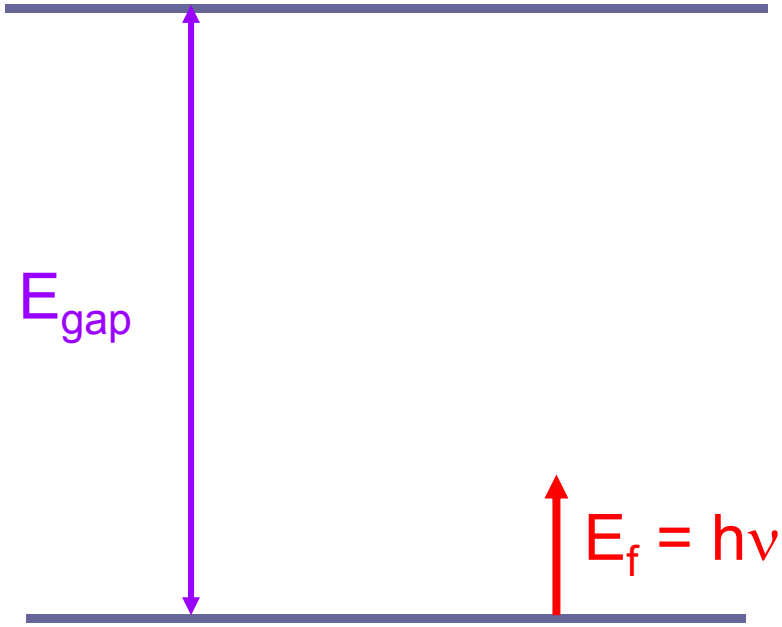
photon energy < bandgap



nonlinear interaction

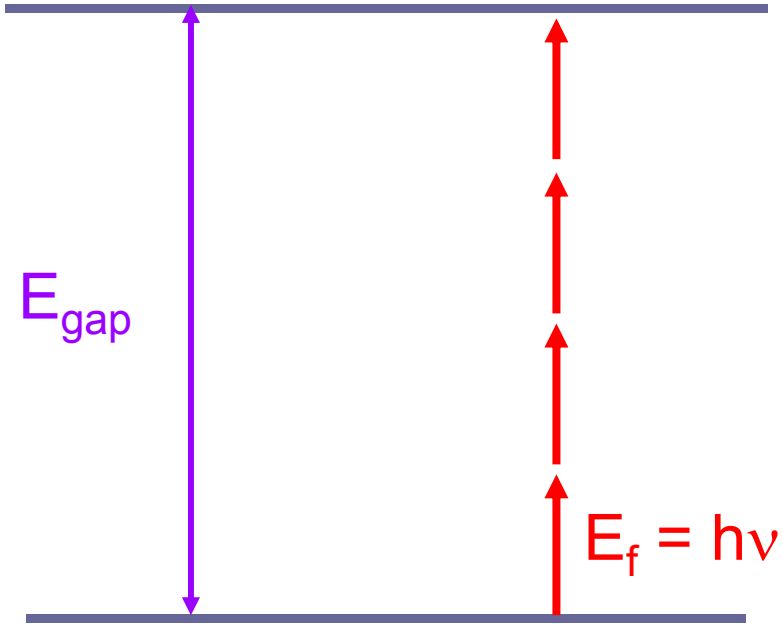
fs-micromachining

nonlinear interaction



fs-micromachining

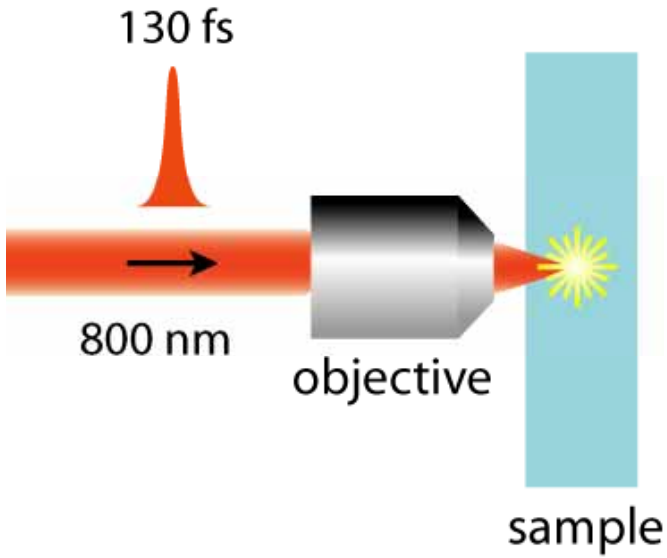
nonlinear interaction



multiphoton absorption

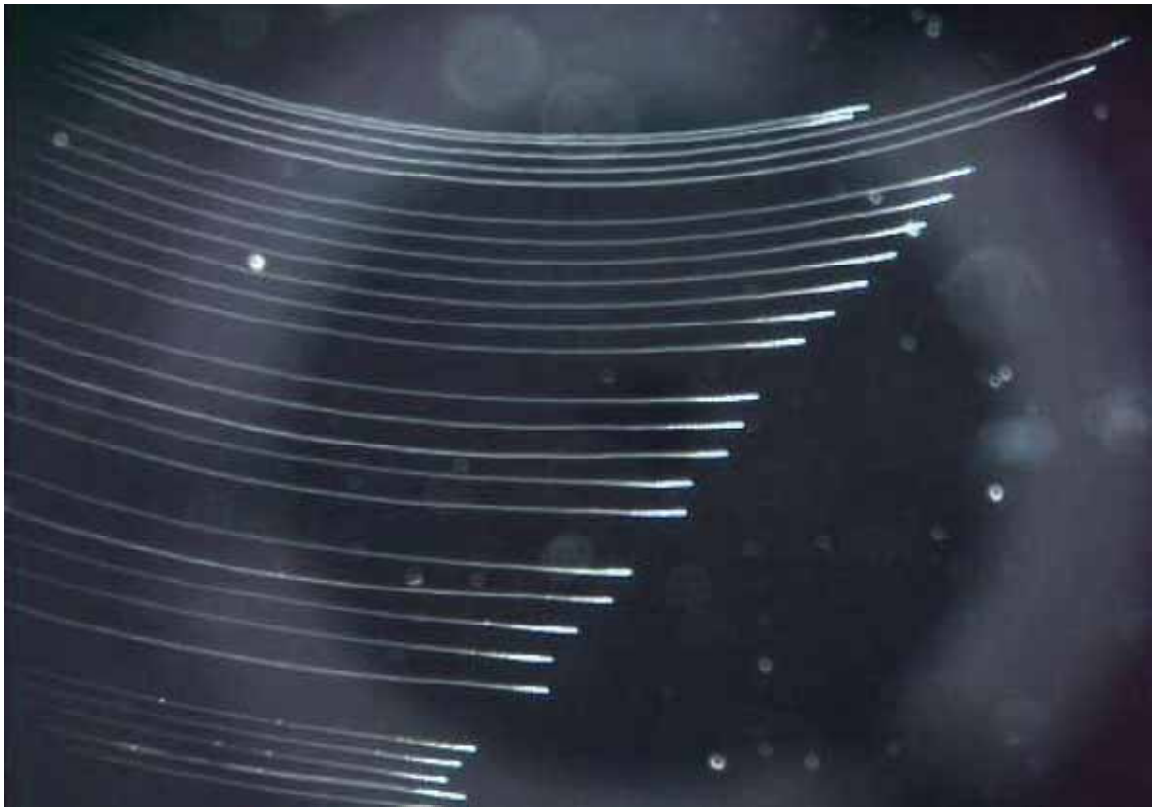
fs-laser microfabrication

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

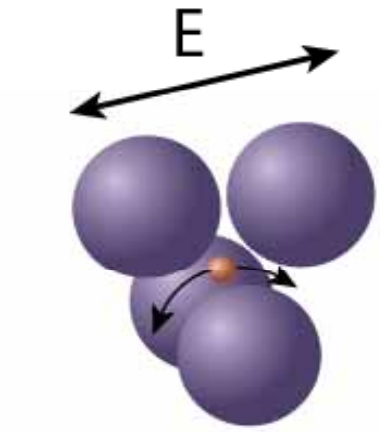
fs-micromachining

- microstructuring MEH-PPV
- waveguides in azopolymers
- micromachining living cells
- superhydrophobic surfaces

two-photon polymerization

- birefringent microstructures
- fluorescent microstructures
- optical circuiting

Nonlinear Optics



anharmonic oscillator

high light intensity

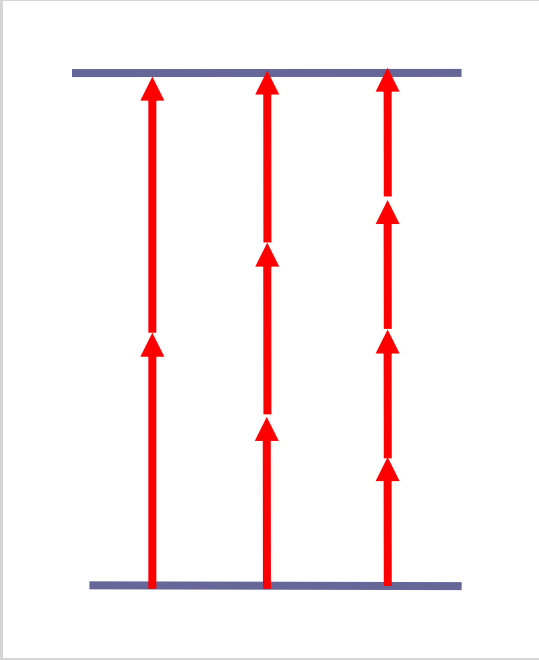
$$E_{rad.} \sim E_{inter.}$$

nonlinear polarization response

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

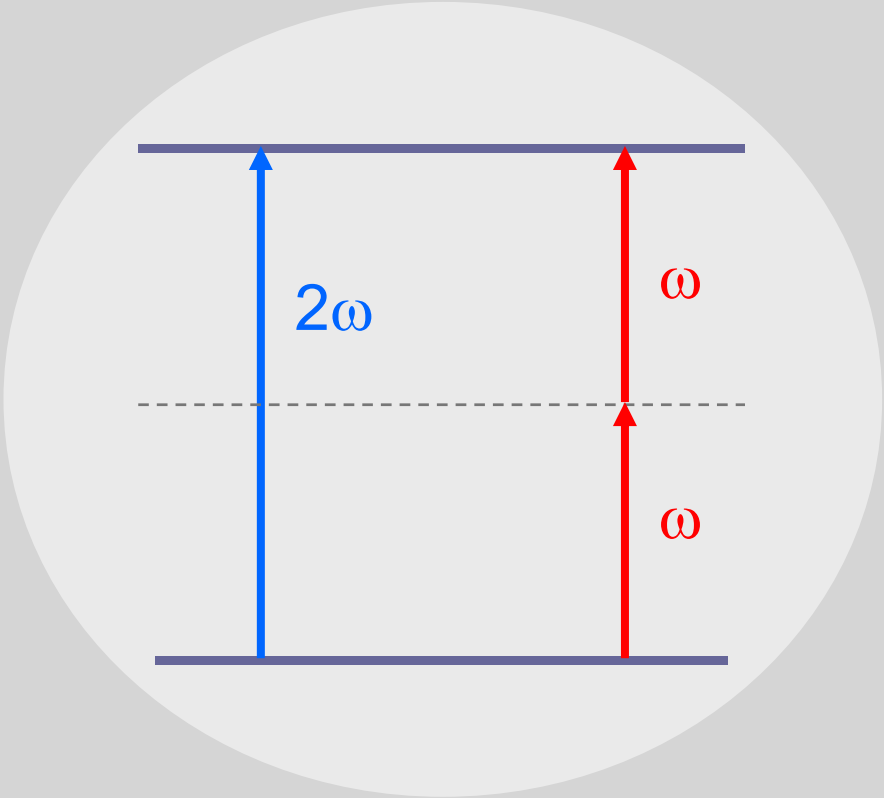
Multi-photon absorption

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



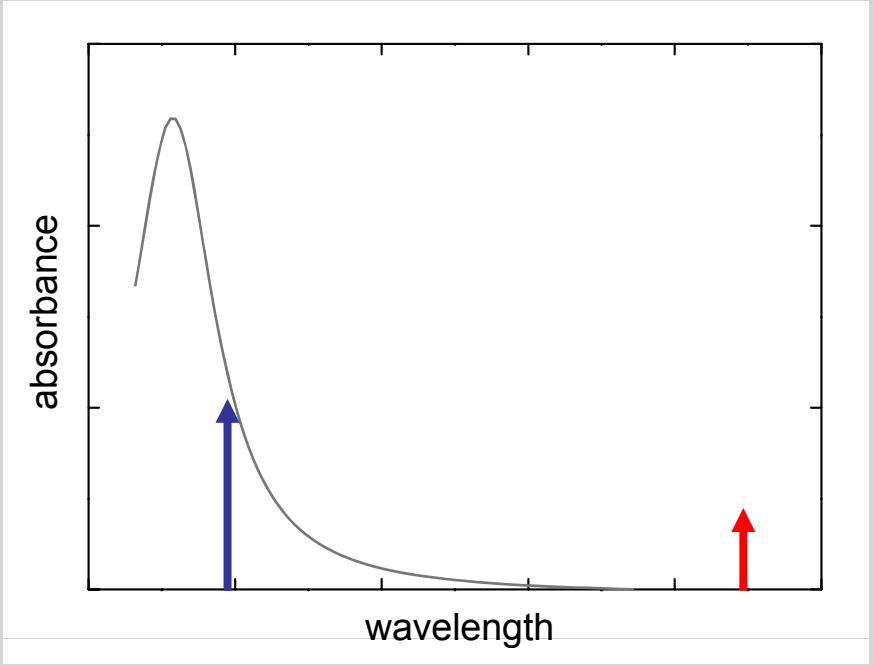
$$\alpha = \alpha_0 + \beta I + \alpha_3 I^2 + \alpha_4 I^3 + \alpha_5 I^4 + \ldots$$

Two-photon absorption



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

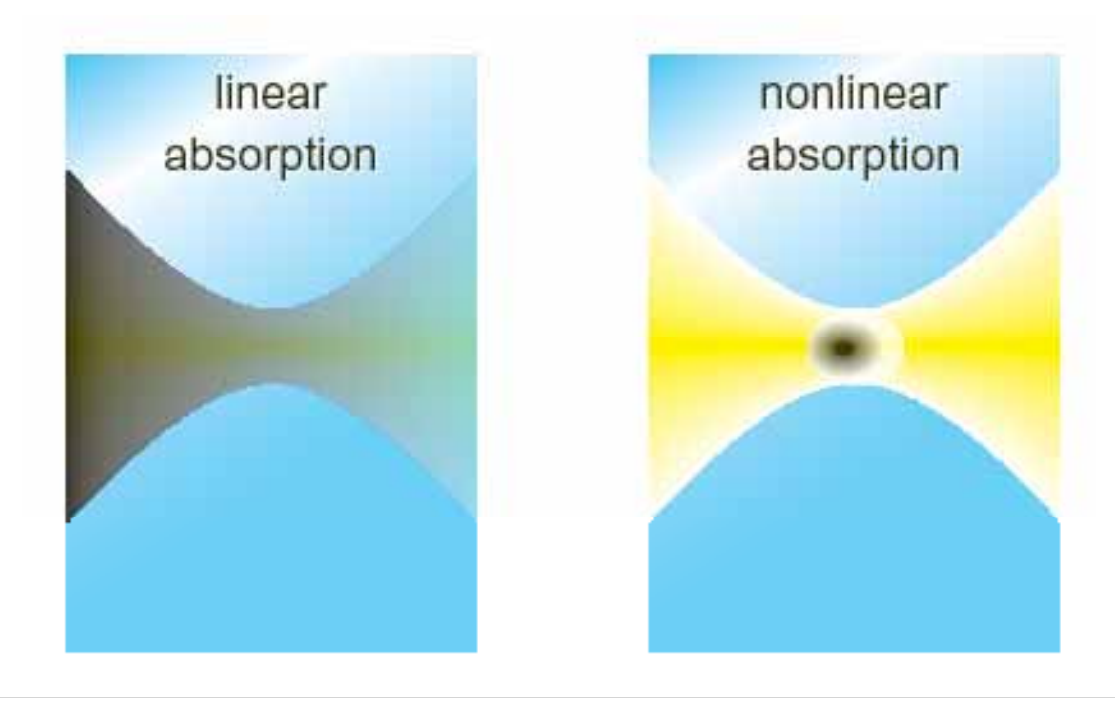
$$\alpha = \alpha_0 + \beta I$$



Two-photon absorption

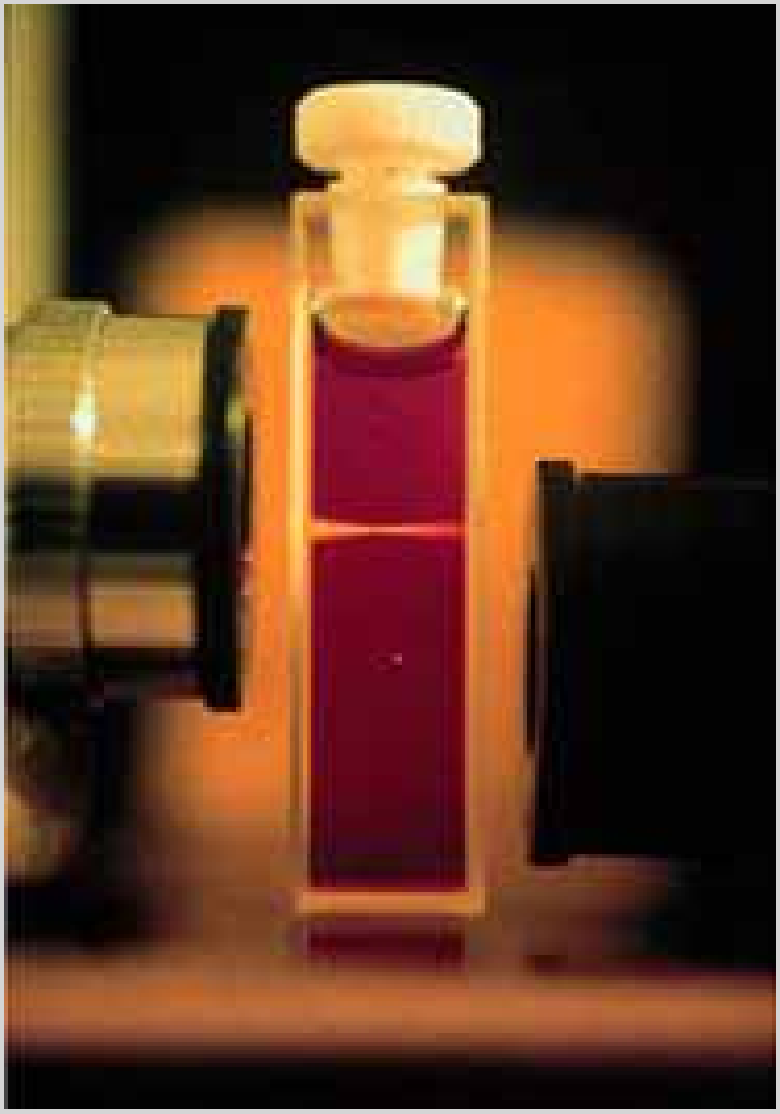
Nonlinear interaction provides spatial confinement of the excitation

fs-microfabrication



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

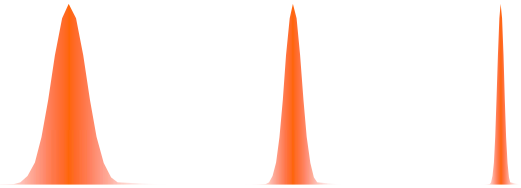
Two-photon absorption



spatial confinement of excitation

femtosecond pulses

Ti:Sapphire lasers

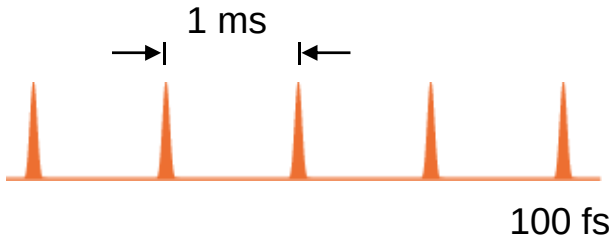


1 fs = 10^{-15} s

Repetition rate

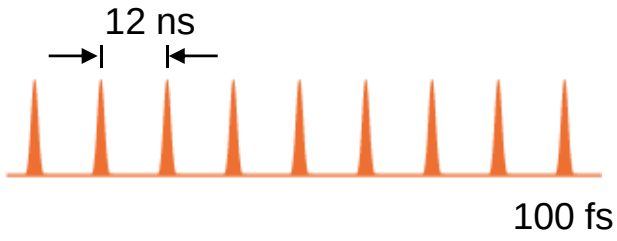
Energy

1 KHz



mJ

86 MHz

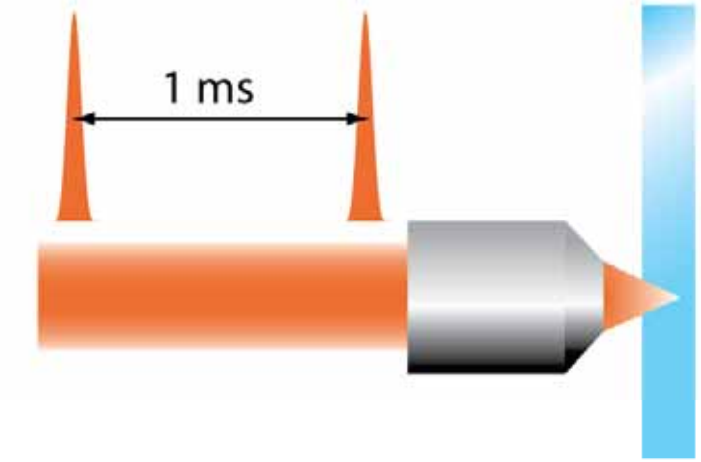


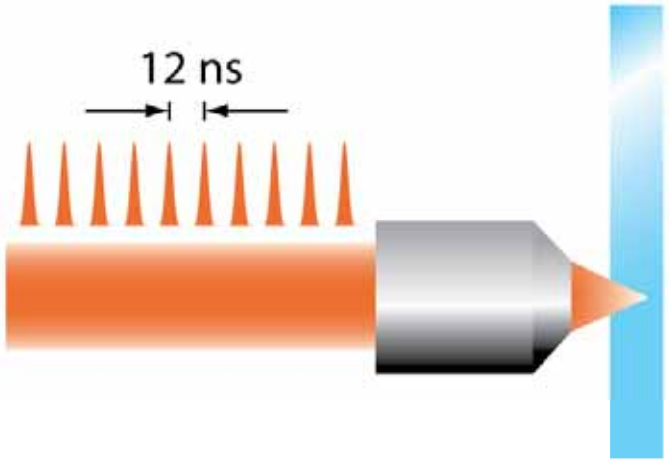
nJ

femtosecond pulses

amplified laser

oscillator



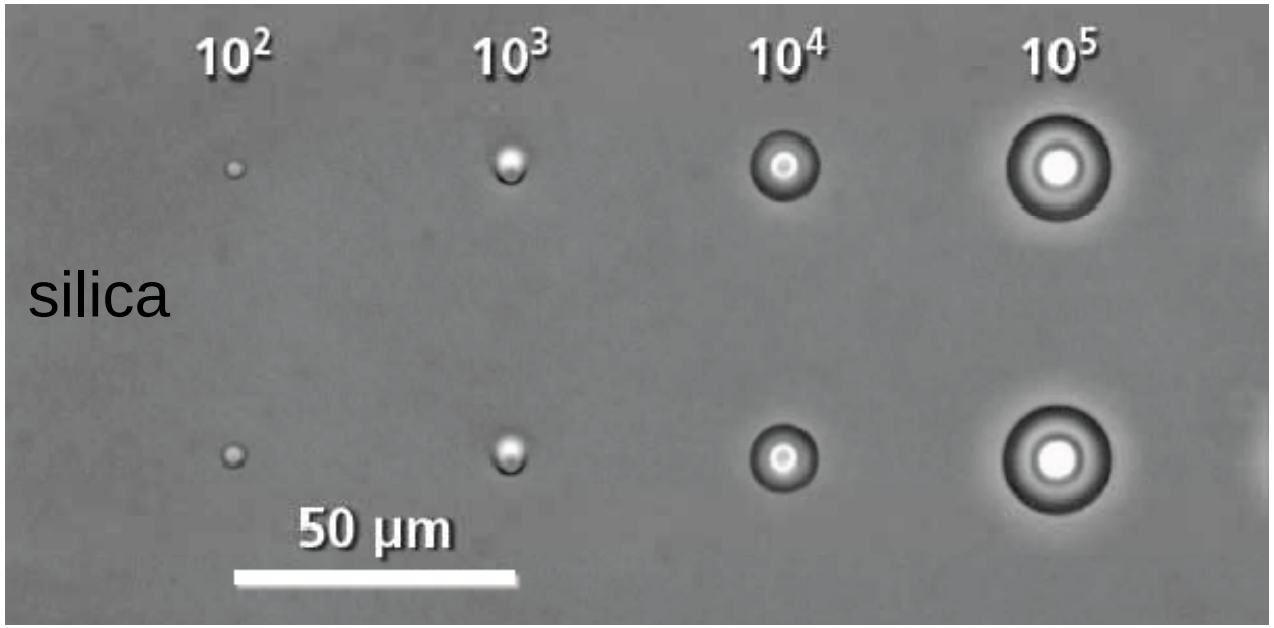


repetitive

cumulative

fs-micromachining

the longer the irradiation the longer the radius



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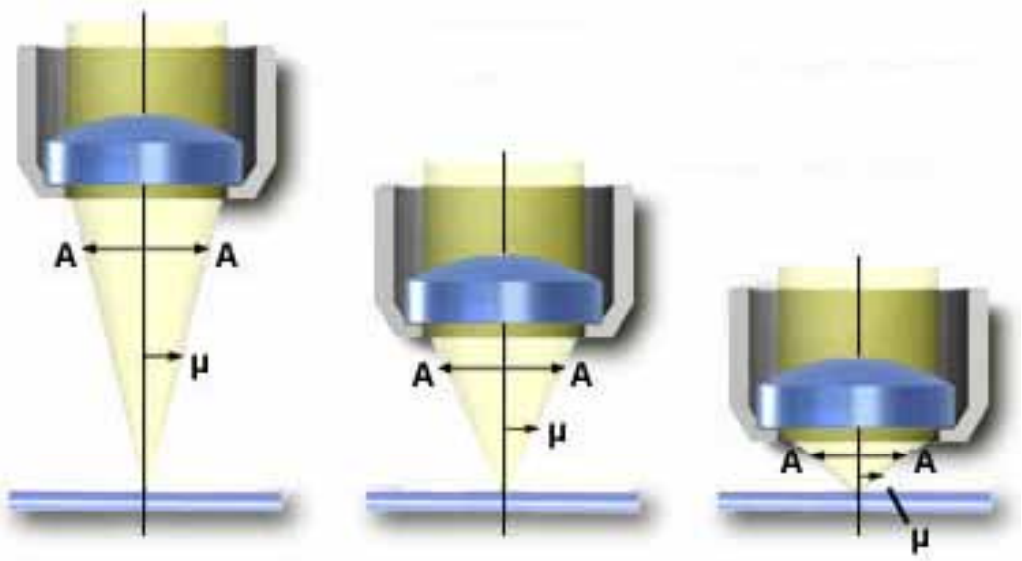
fs-micromachining: focusing



NA = 0.12

μ = 7°

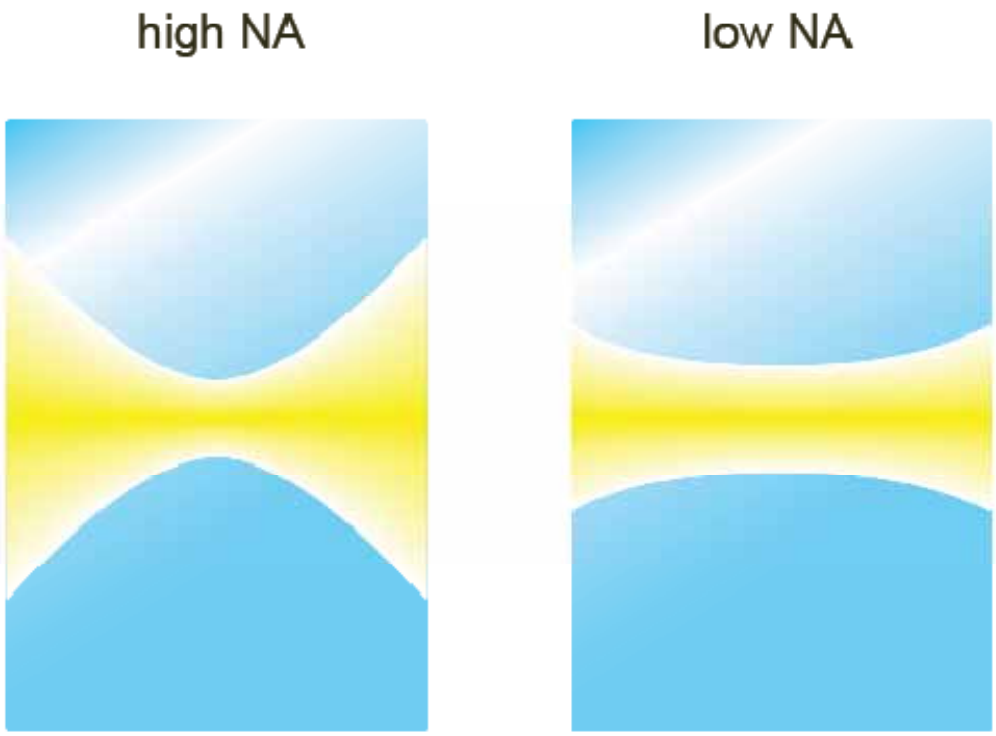
NA = 0.34

μ = 20°

NA = 0.87

μ = 60°

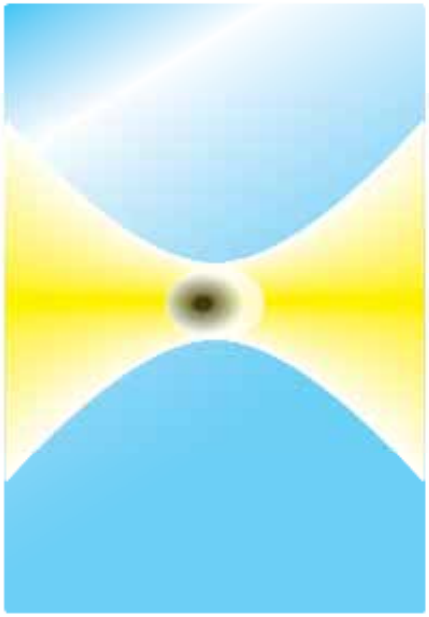
what is the difference ?



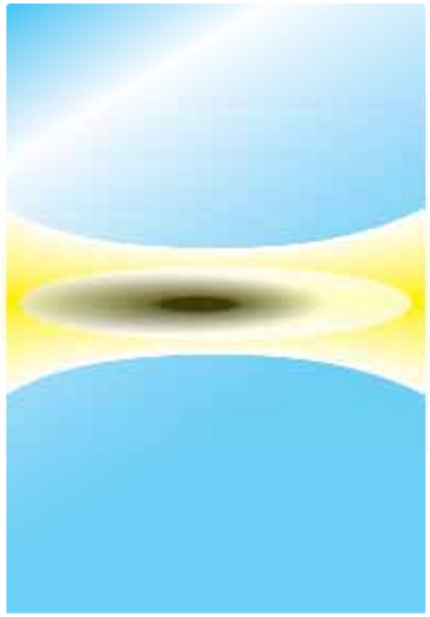
$$w_0 = \frac{\lambda}{\pi NA}\sqrt{1 - NA^2}$$

very different confocal lenght/interaction length

high NA



low NA



fs-micromachining

microfabrication can be controlled by

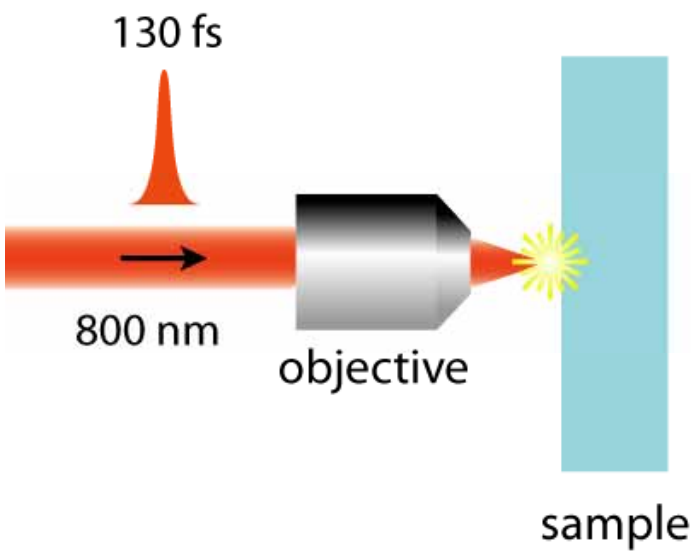
- objective NA
- number of pulses – scanning speed
- pulse energy

two main techniques

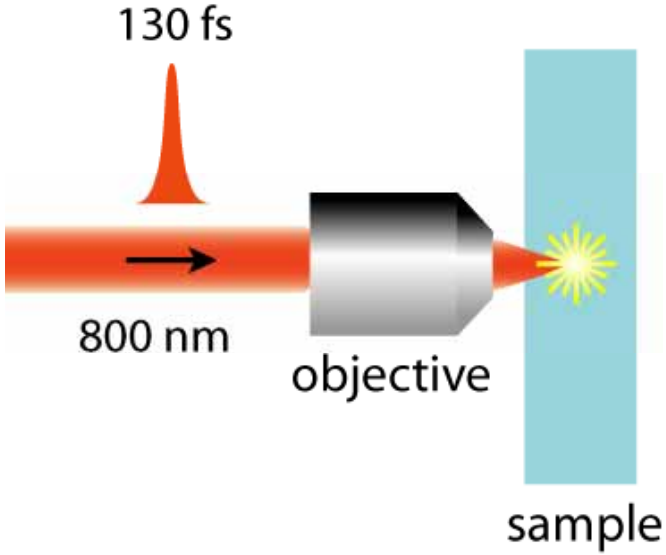
- fs-laser micromachining
- microfabrication via two-photon polymerization

fs-laser micromaching

Surface

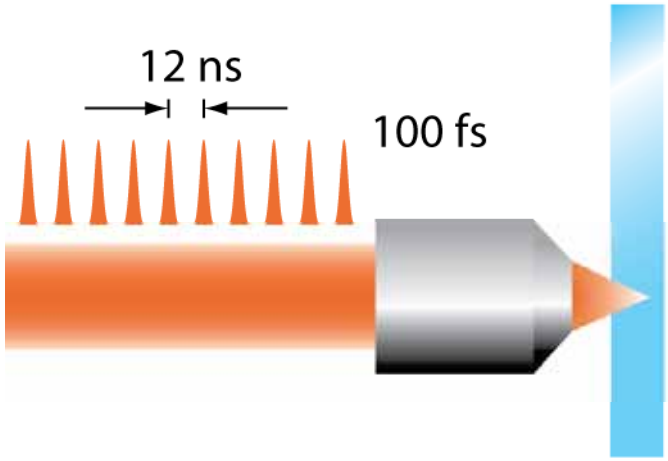


Volume



fs-pulses for micromachining polymers

Oscillator: 80 MHz, 5 nJ

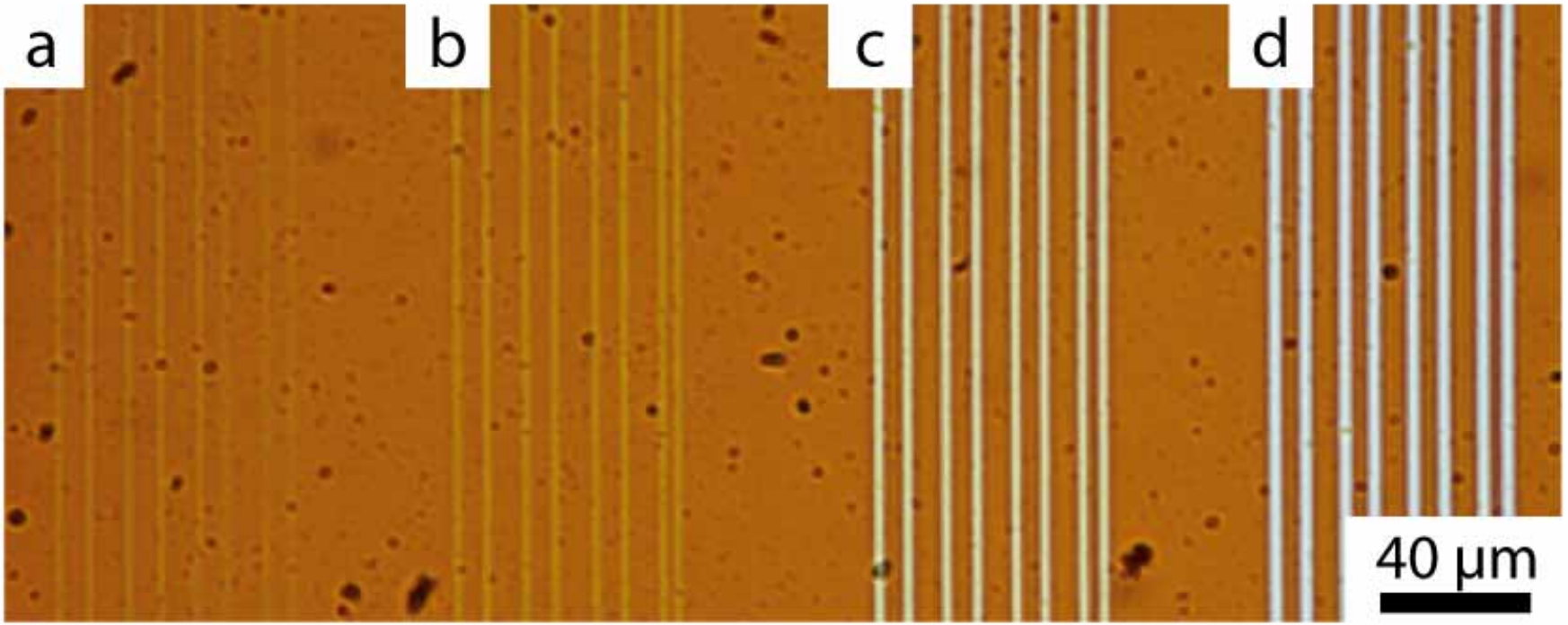


heat diffusion time: t_{diff} ~ 1 μs

cumulative

Micromachining the conductive polymer MEH-PPV

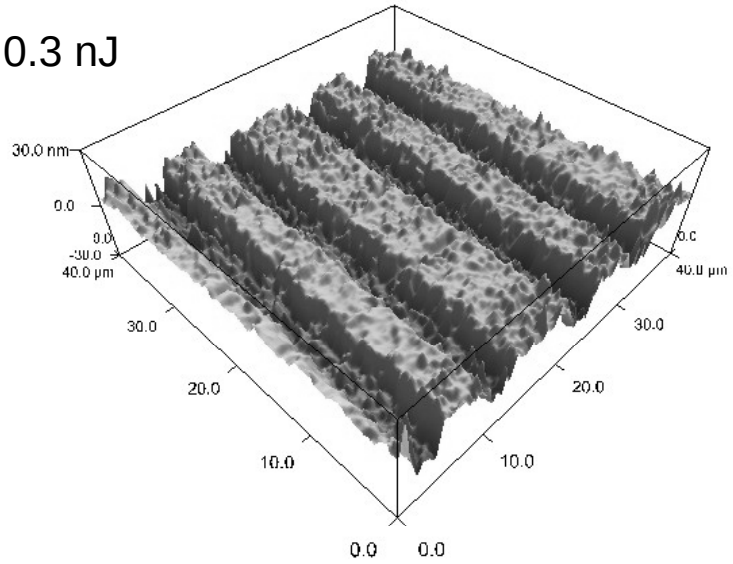
optical microscopy



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

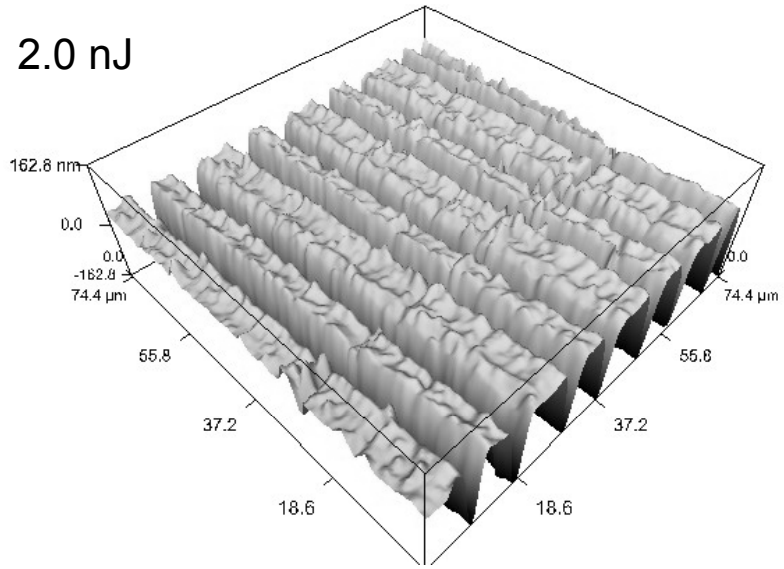
Micromachining the conductive polymer MEH-PPV

a 0.3 nJ

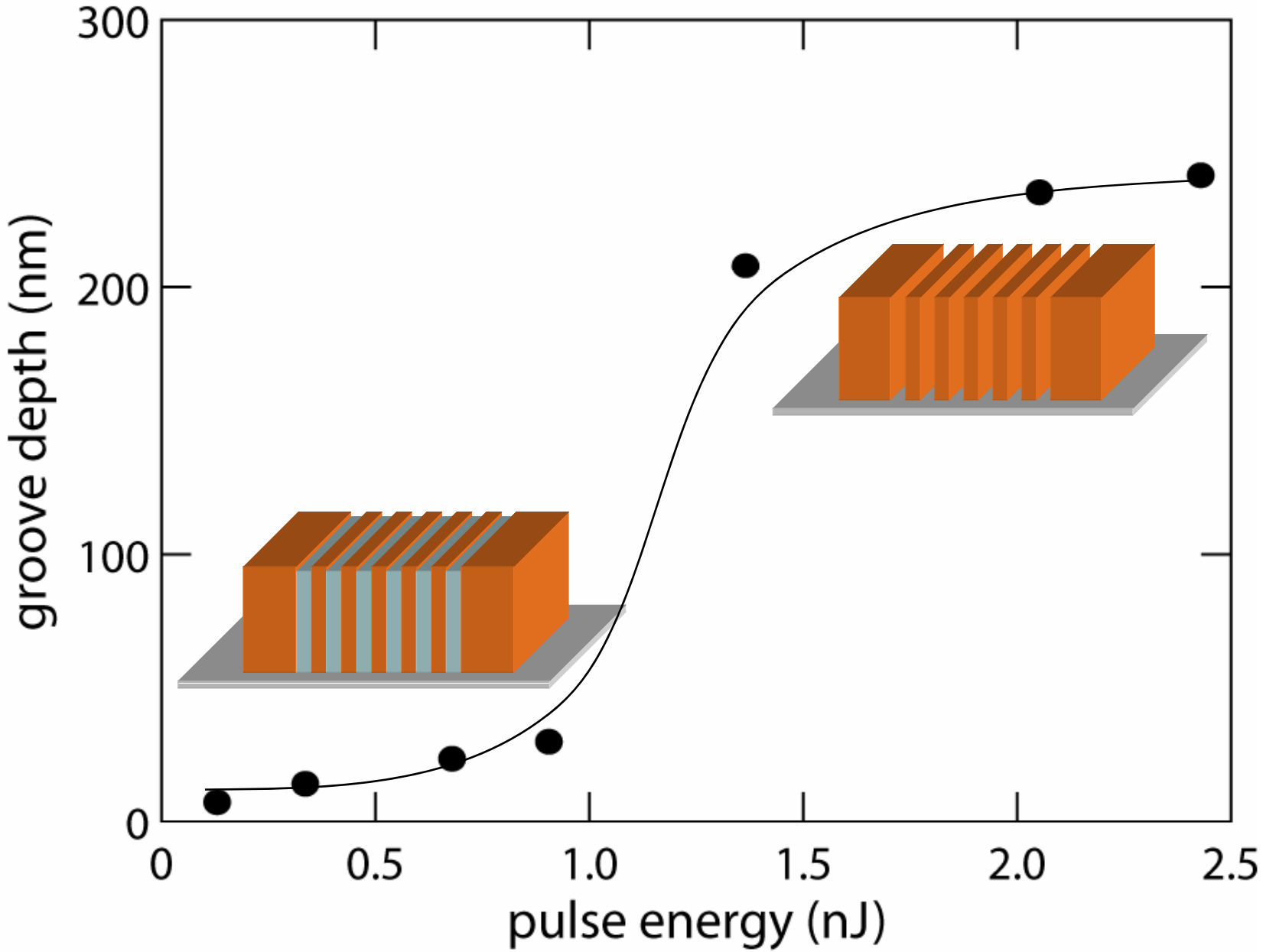


atomic force microscopy

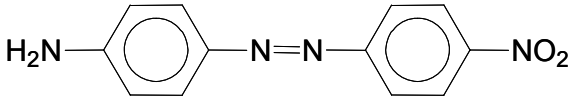
b 2.0 nJ



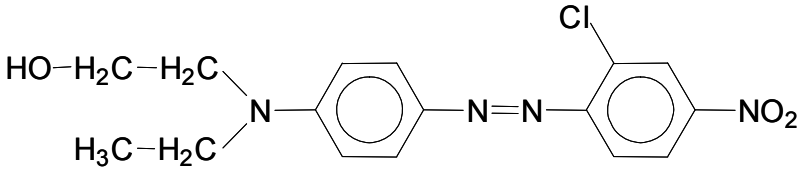
Micromachining the conductive polymer MEH-PPV



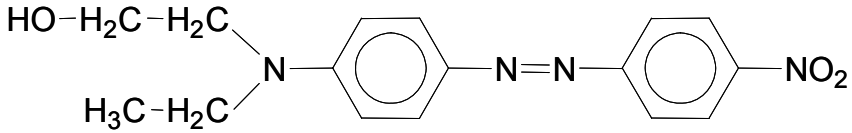
Waveguides in azo-polymers



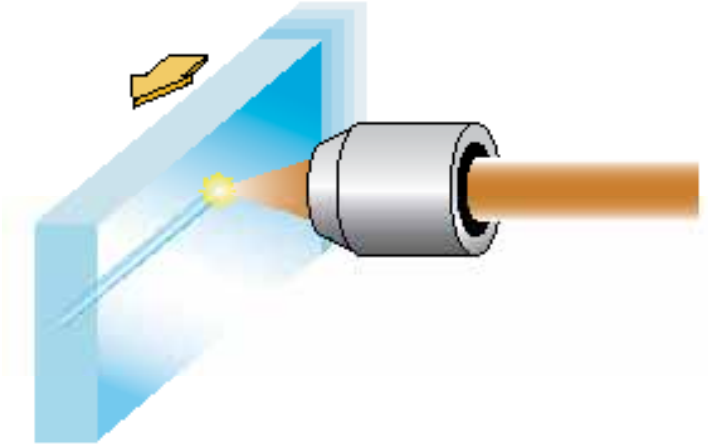
DO3



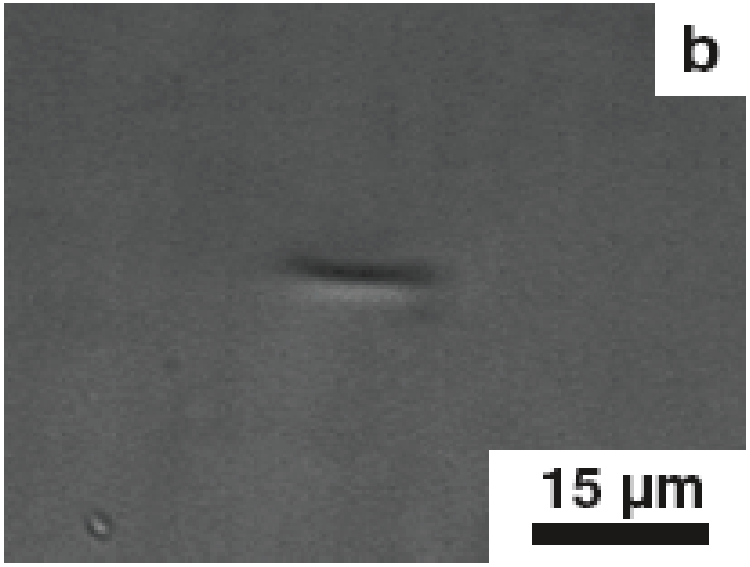
DR13



DR1



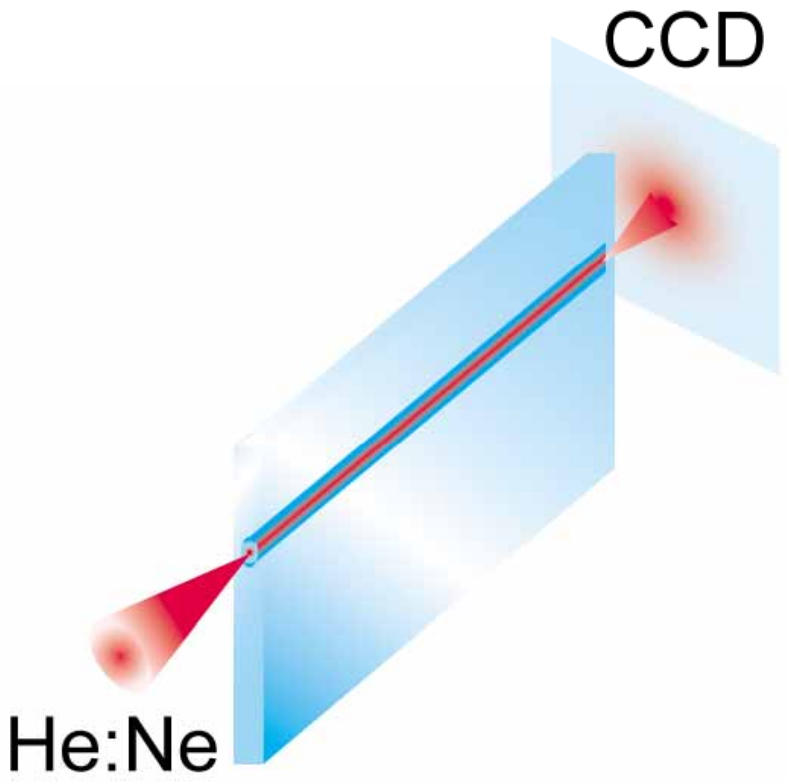
Waveguides in azo-polymers

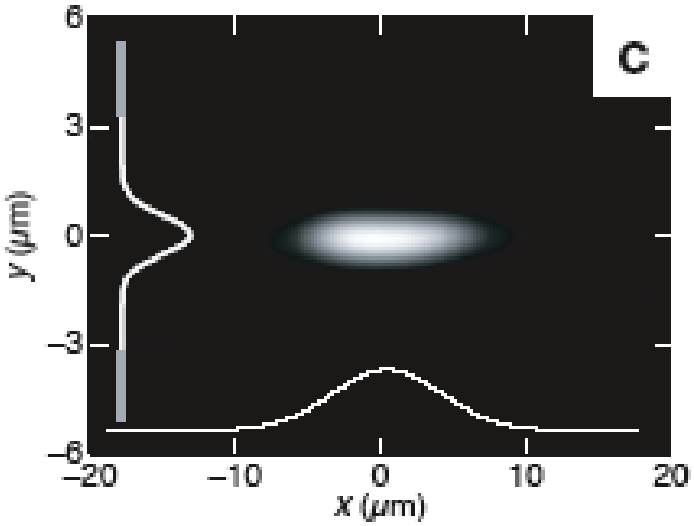


(a) Optical microscope image of the waveguides micromachined (PMMA/DR1)

(b) Cross-sectional view of the waveguides

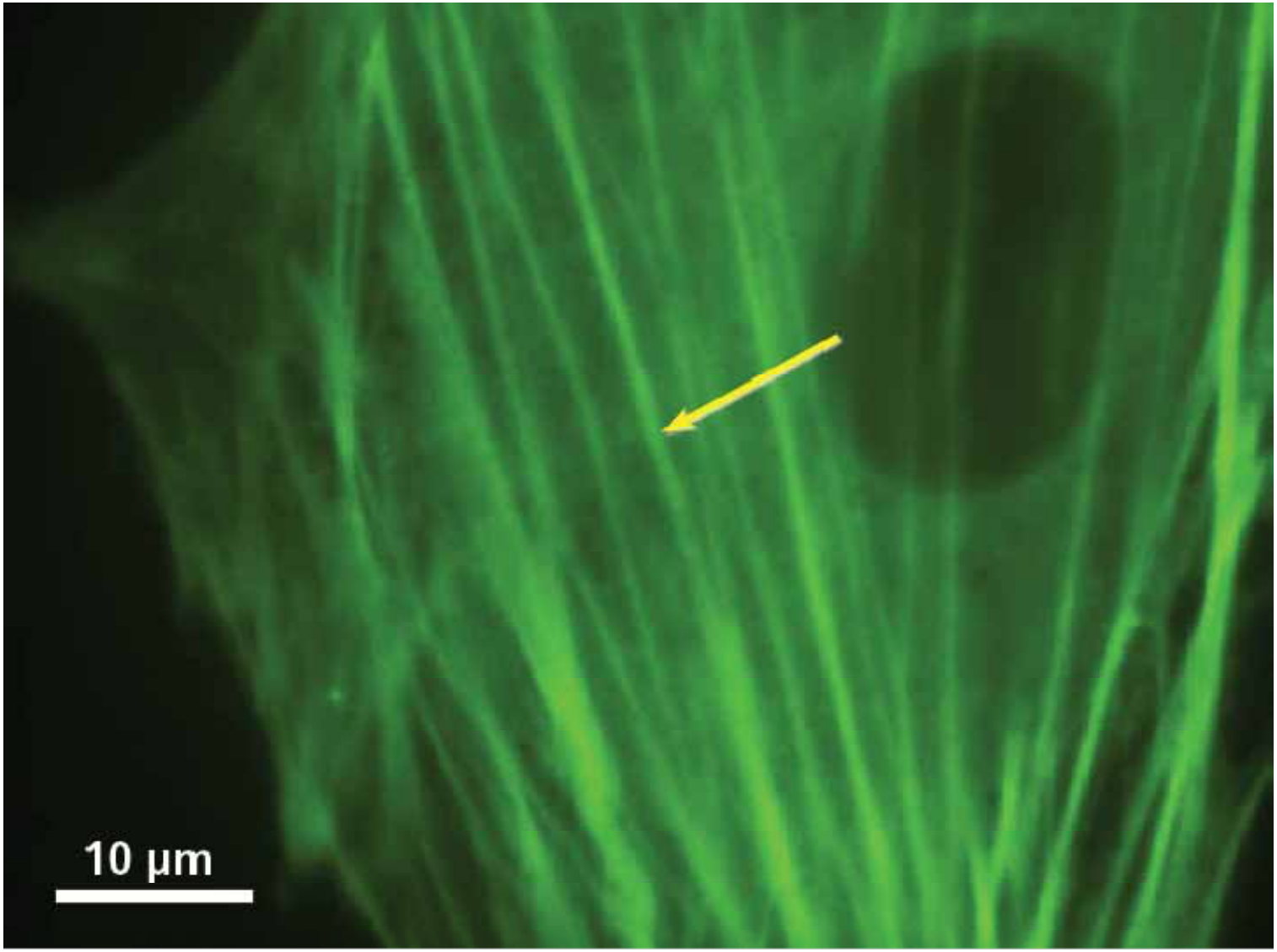
waveguides in azo-polymers





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

Subcellular surgery



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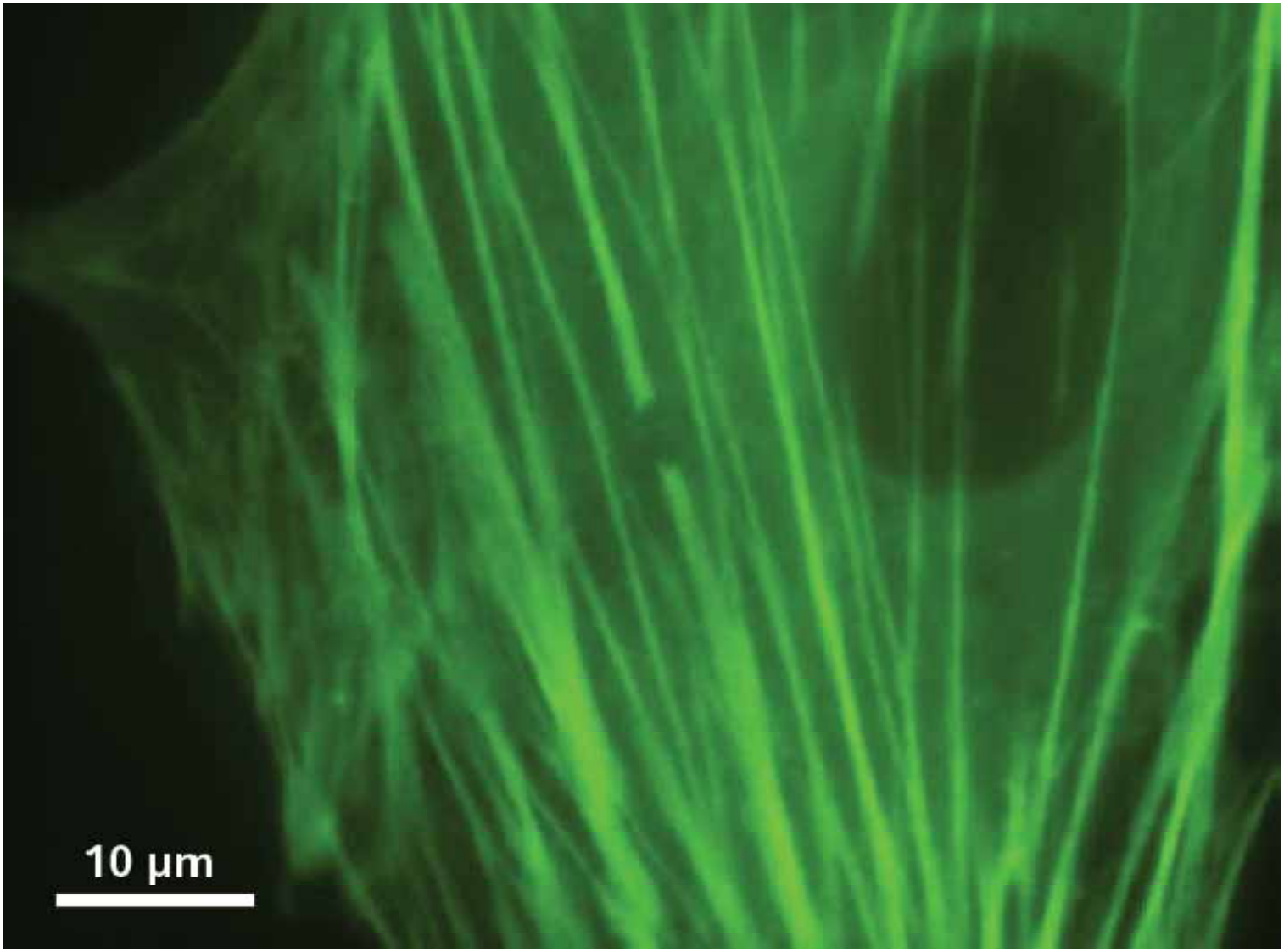
Subcellular surgery



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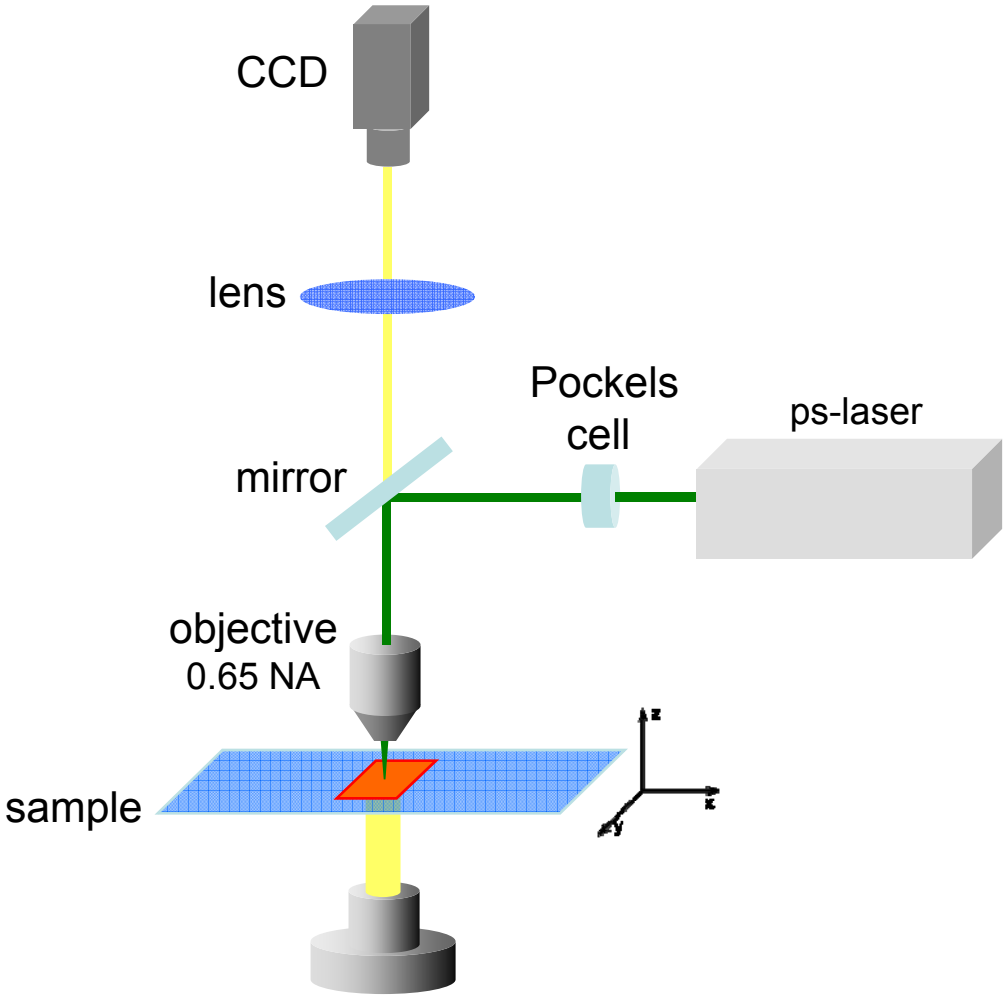
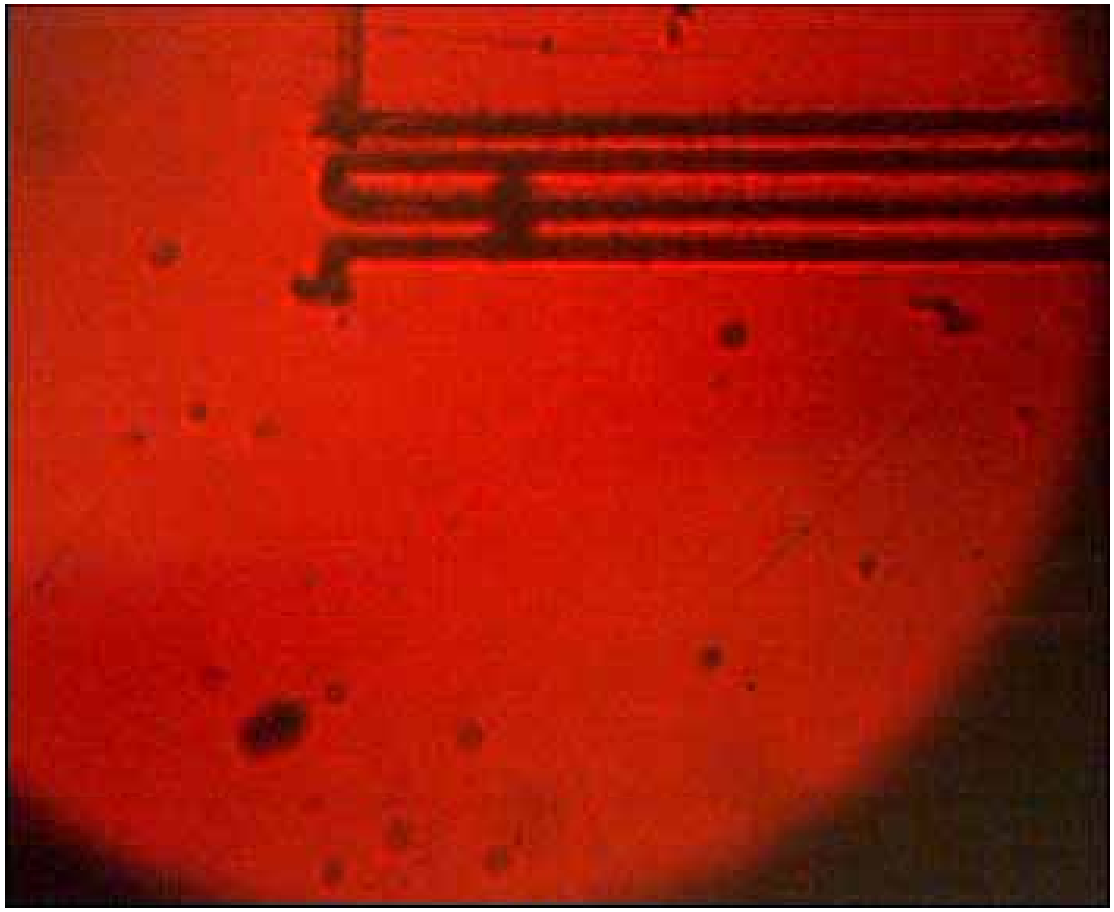
microstructuring polymer: super hydrophobic surface

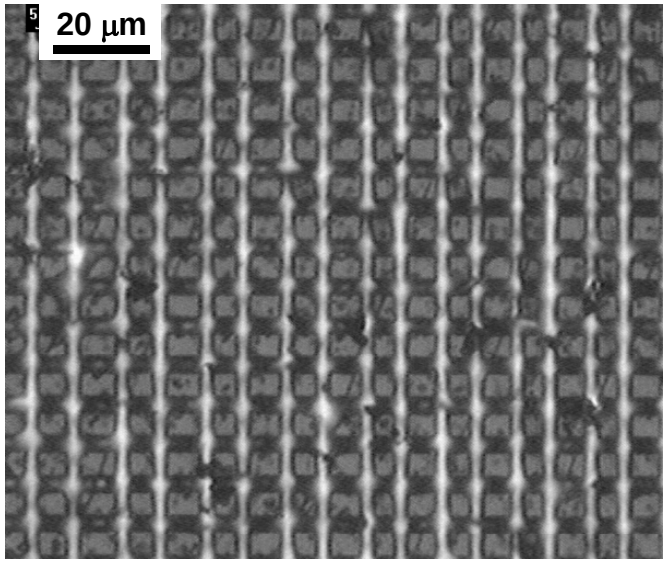


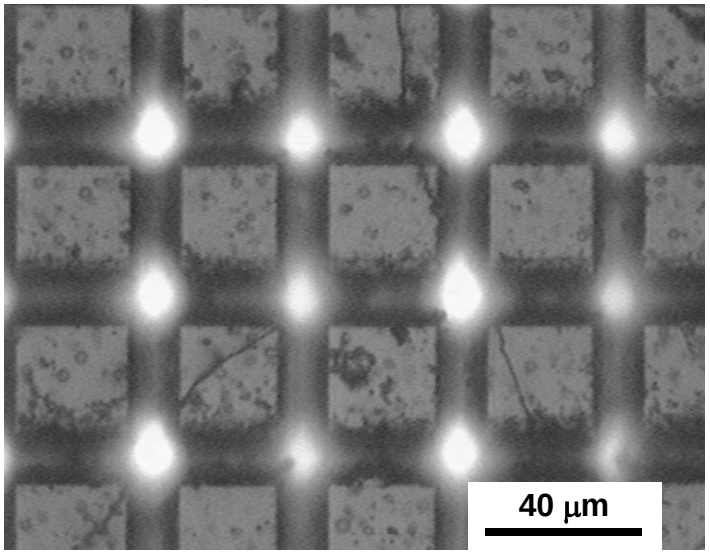
microstructuring polymer: super hydrophobic surface



laser microfabrication: super hydrophobic surface

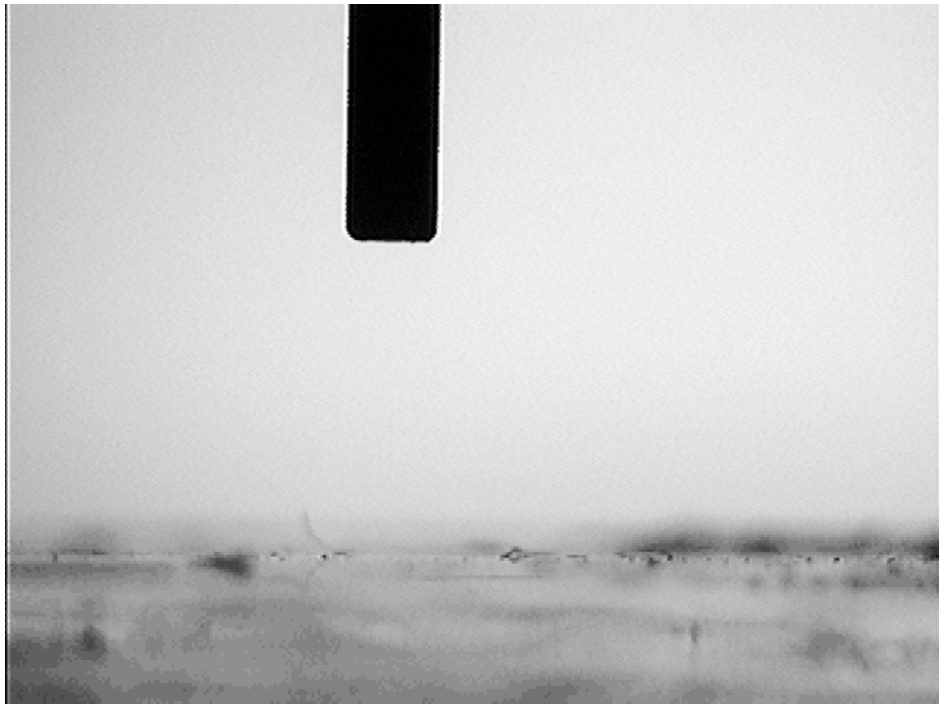
examples of fabricated surfaces



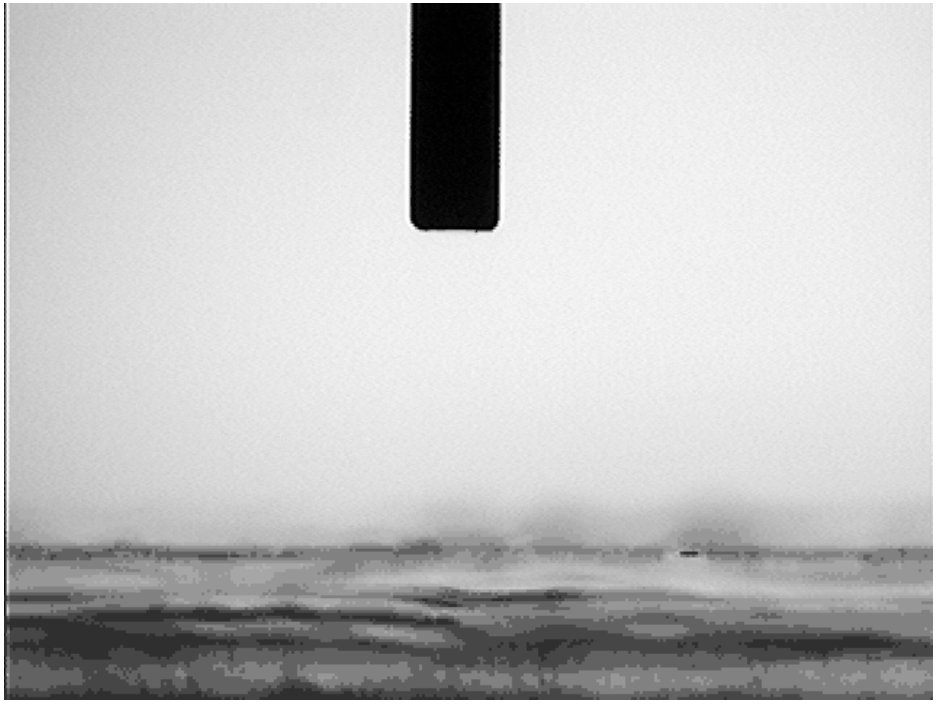


laser microfabrication: super hydrophobic surface

Superhydrophobic surfaces

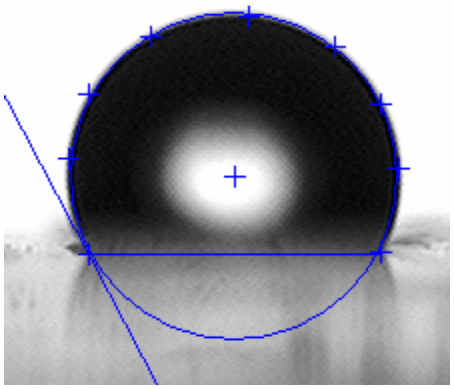


flat surface



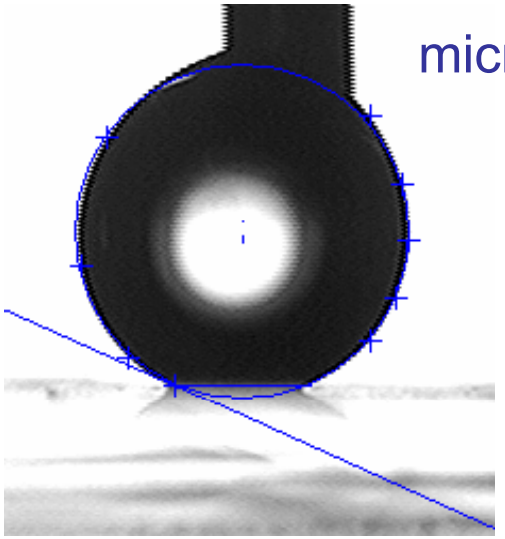
microstructured surface

microstructuring polymer



flat surface

θ = 118º



microstructured surface

θ = 160º

fs-laser microfabrication

Novel concept:

build a microstructure using fs-laser and nonlinear optical processes

two-photon polymerization

applications

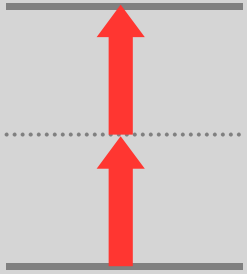
- micromechanics
- waveguides
- microfluidics
- biology
- optical devices

Two-photon polymerization

Monomer + Photoinitiator $\rightarrow$ *Polymer*

light

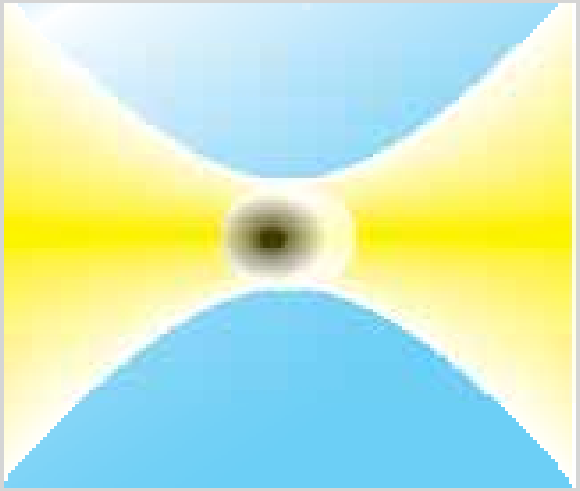
Photoinitiator is excited by ***two-photon absorption***



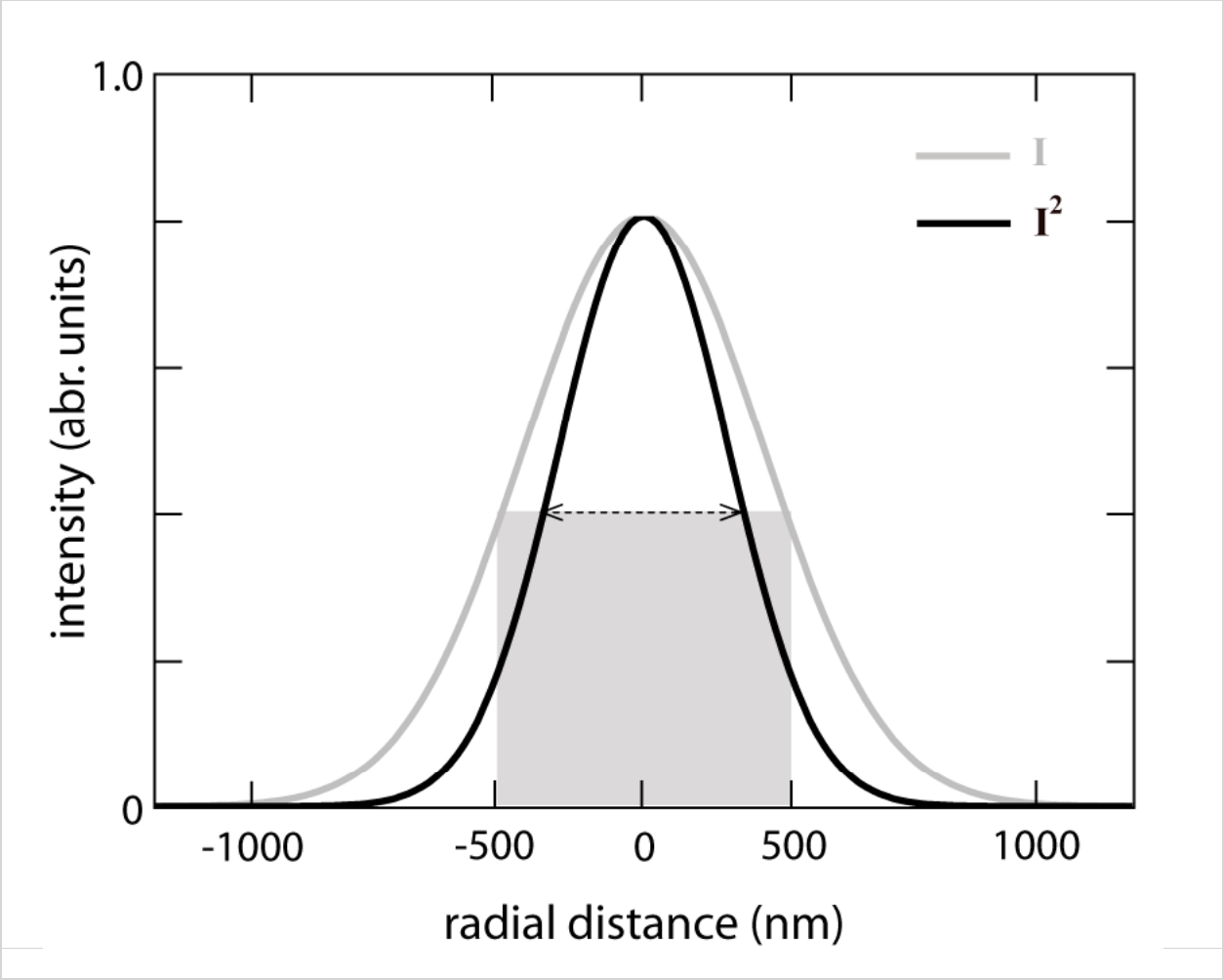
$$R_{2PA} \propto I^2$$

The polymerization is confined to the focal volume.

High spatial resolution

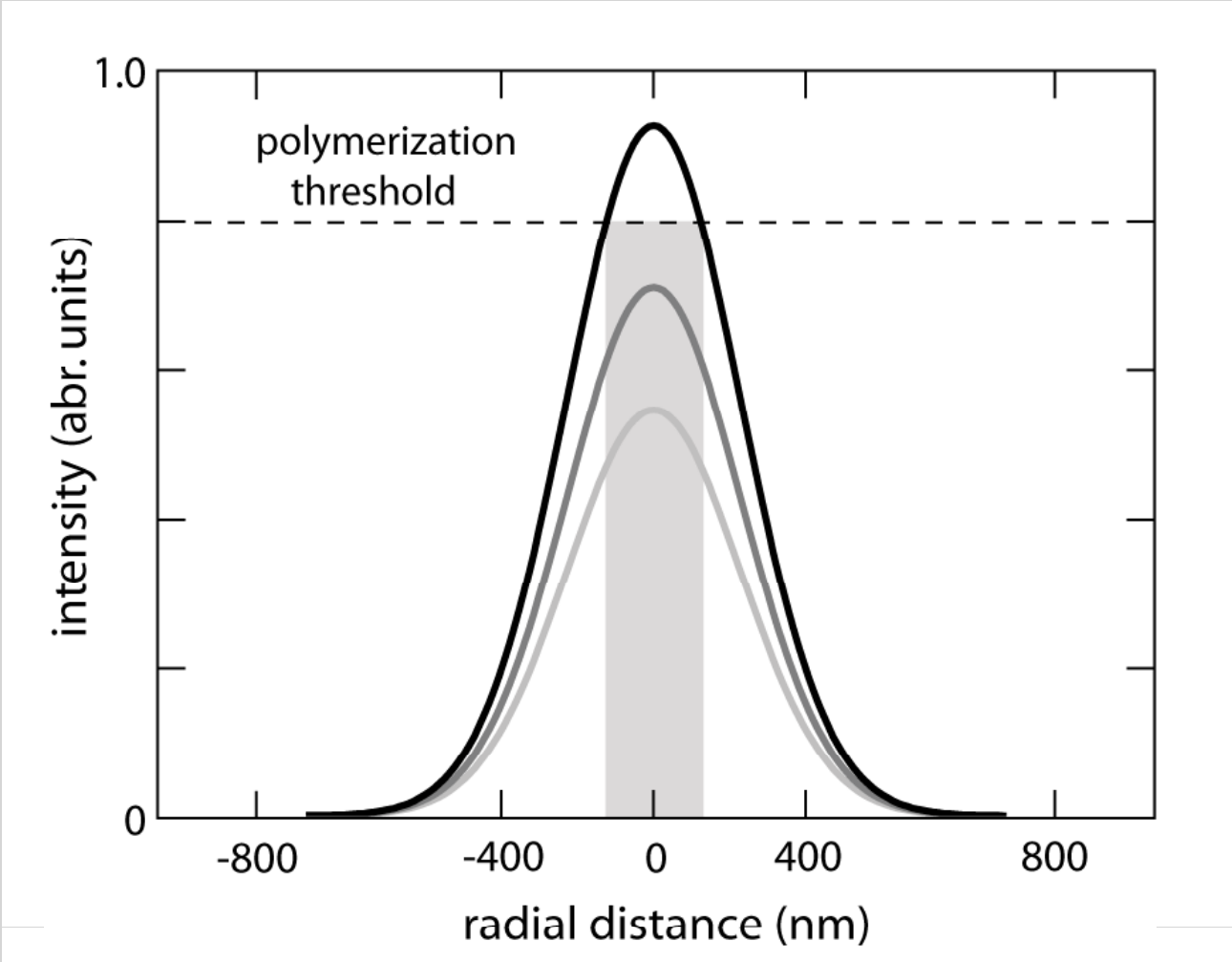


Two-photon polymerization



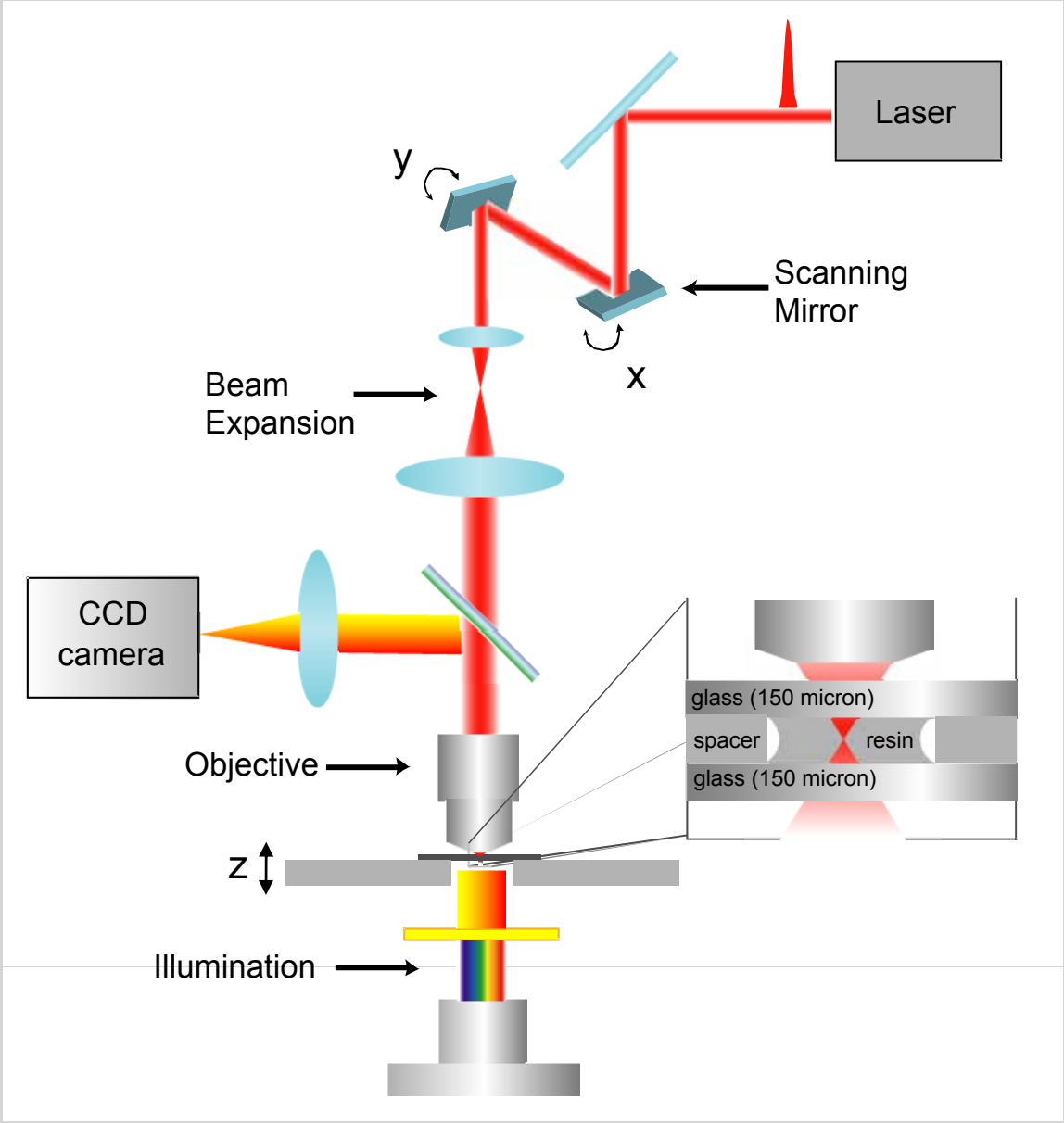
bellow the diffraction limit

Two-photon polymerization



even higher spatial resolution

Two-photon polymerization setup



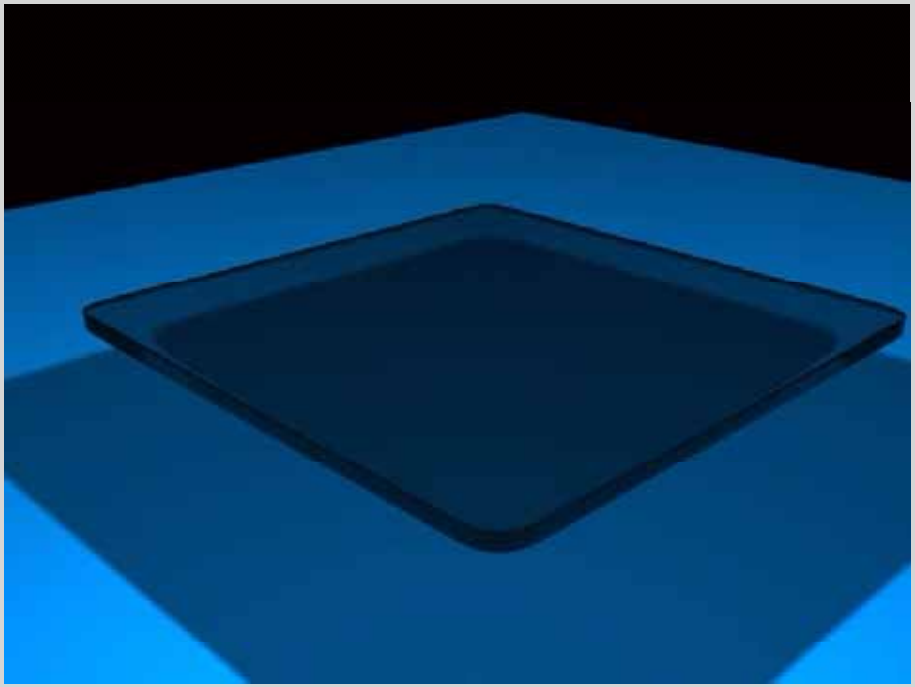
Ti:sapphire laser oscillator

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

Objective

40 x
0.65 NA

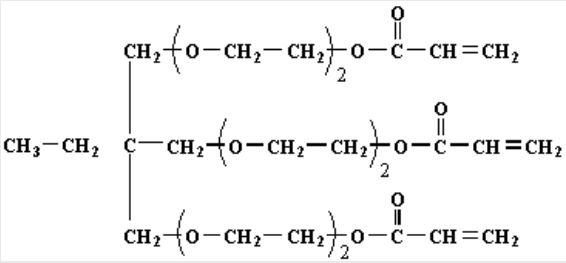
Two-photon polymerization



Resin preparation

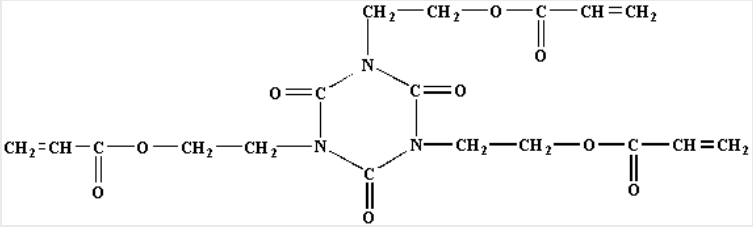
Monomers

Monomer A



reduces the shrinkage upon polymerization

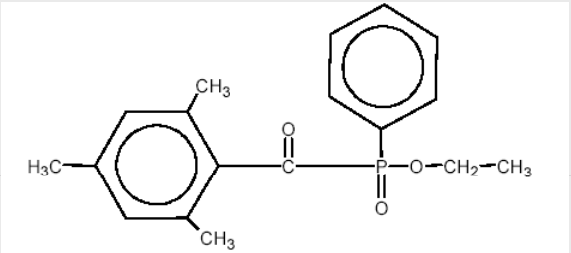
Monomer B



gives hardness to the polymeric structure

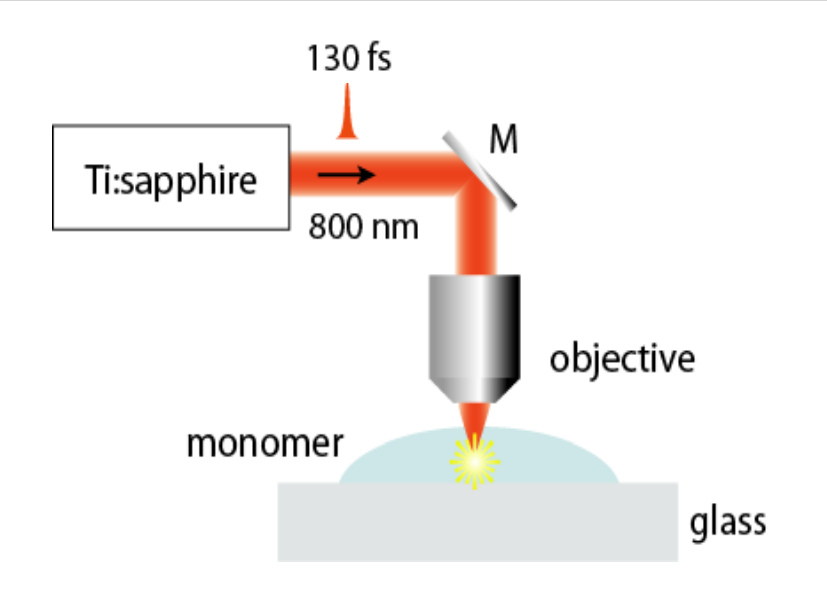
Photoinitiator

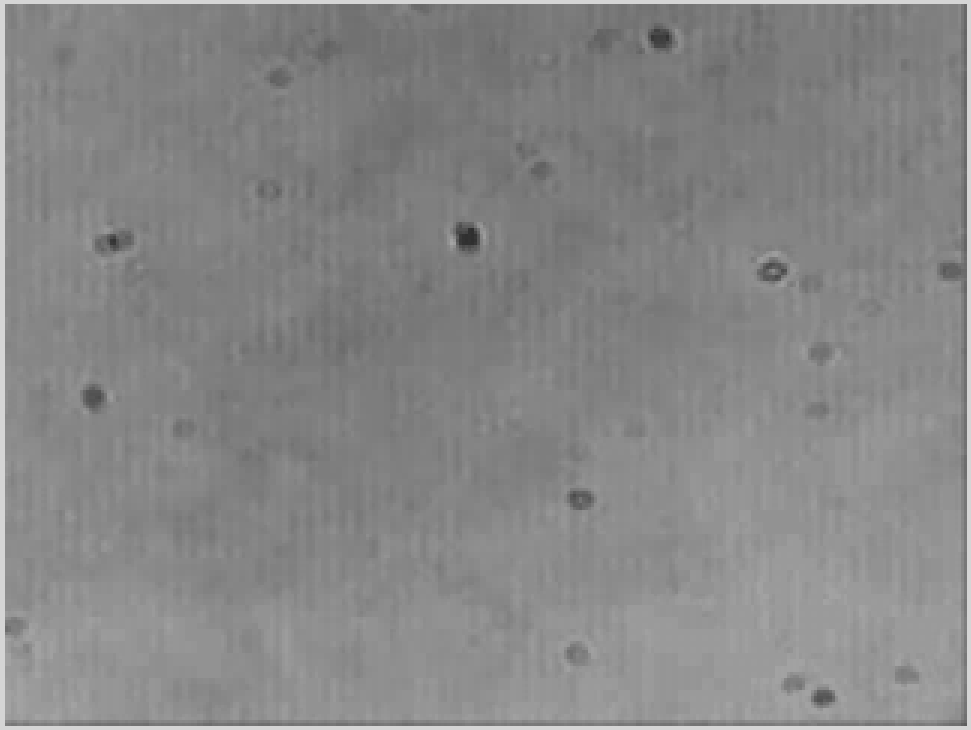
Lucirin TPO-L



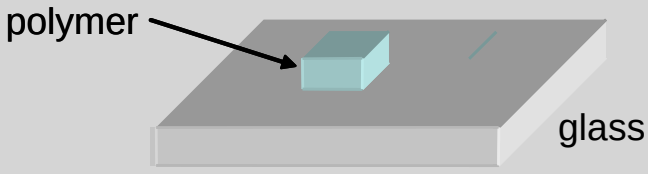
Appl. Phys. A, 90, 633–636 (2008)

Two-photon polymerization

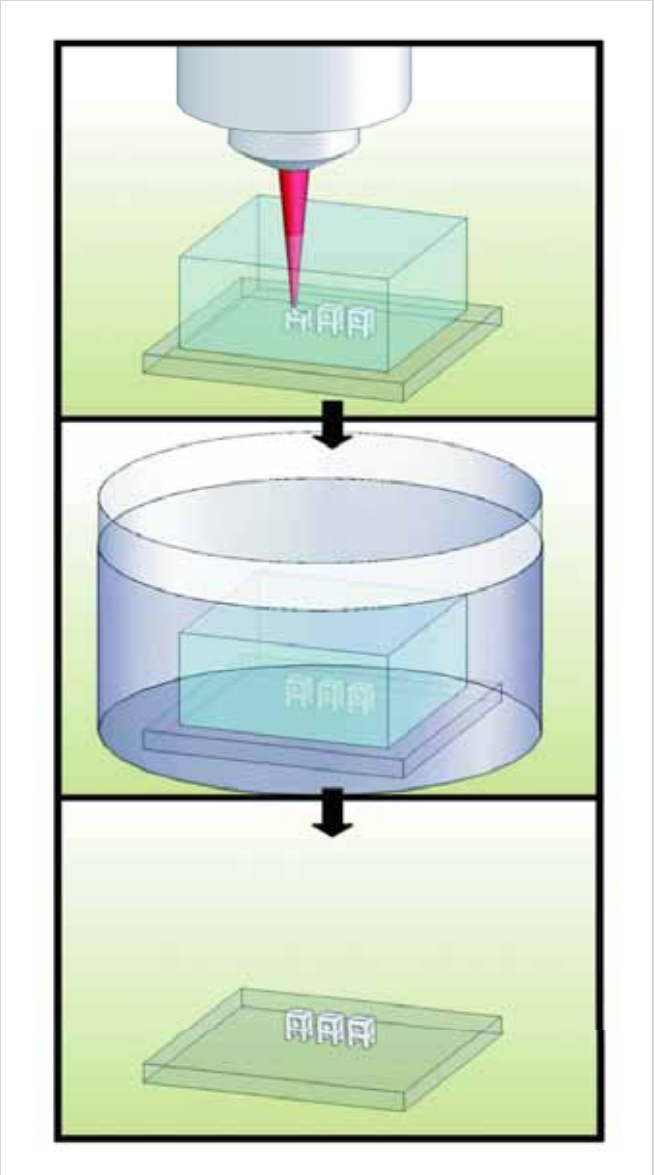




30 μm x 30 μm x 12 μm cube



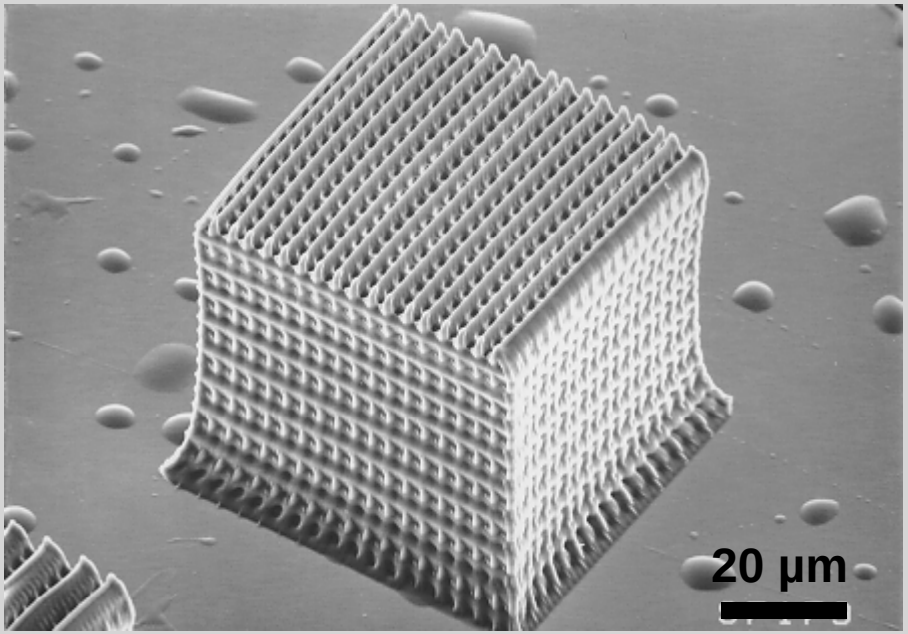
Two-photon polymerization

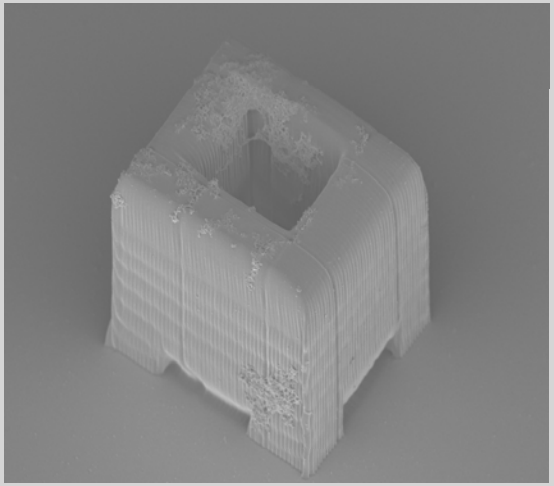


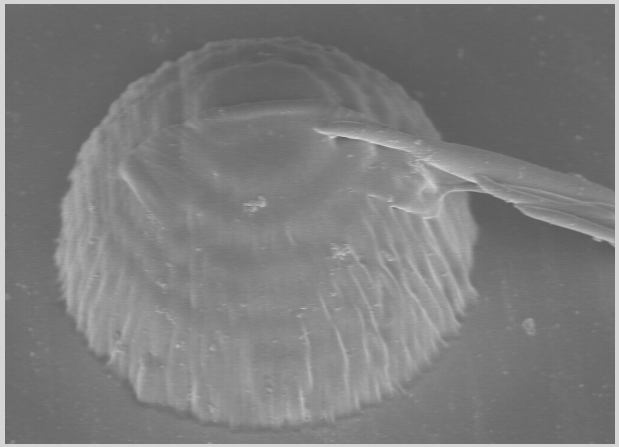
After the fabrication, the sample is immersed in ethanol to wash away any unsolidified resin and then dried

two-photon polymerization

photonic crystal – J. W. Perry

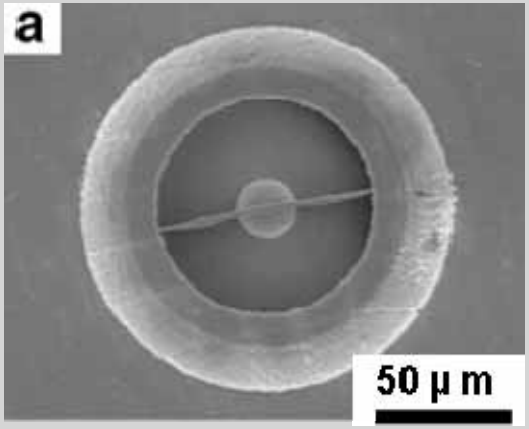


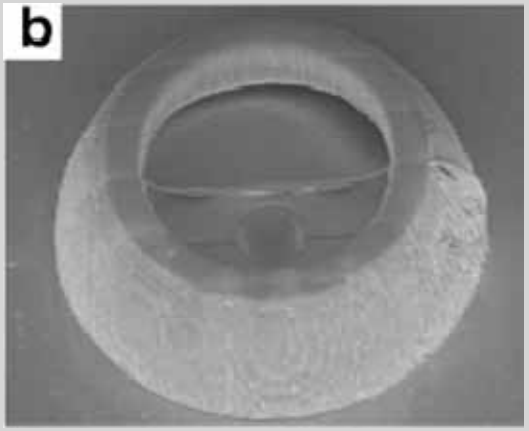


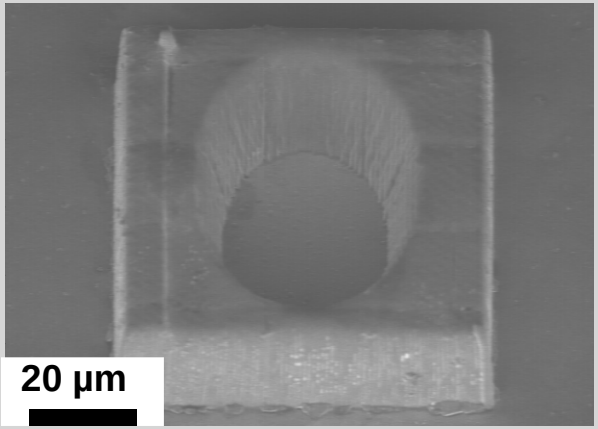


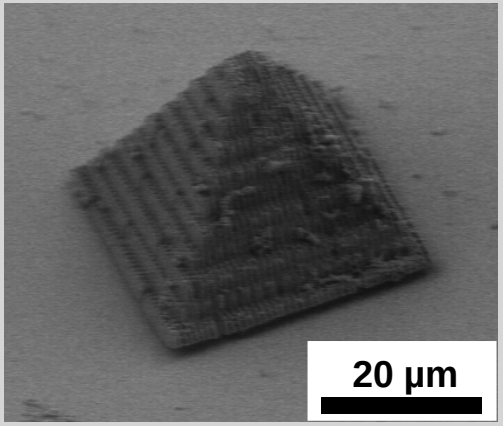
Two-photon polymerization

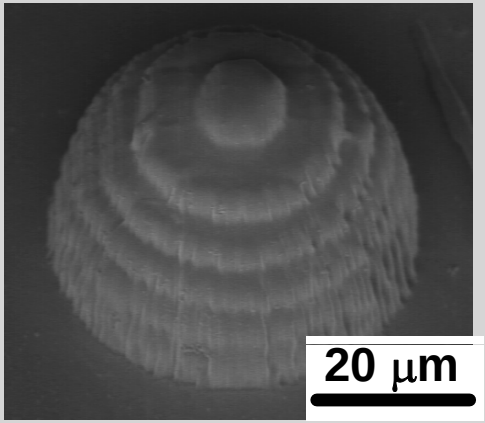
Microstructures fabricated by two-photon polymerization



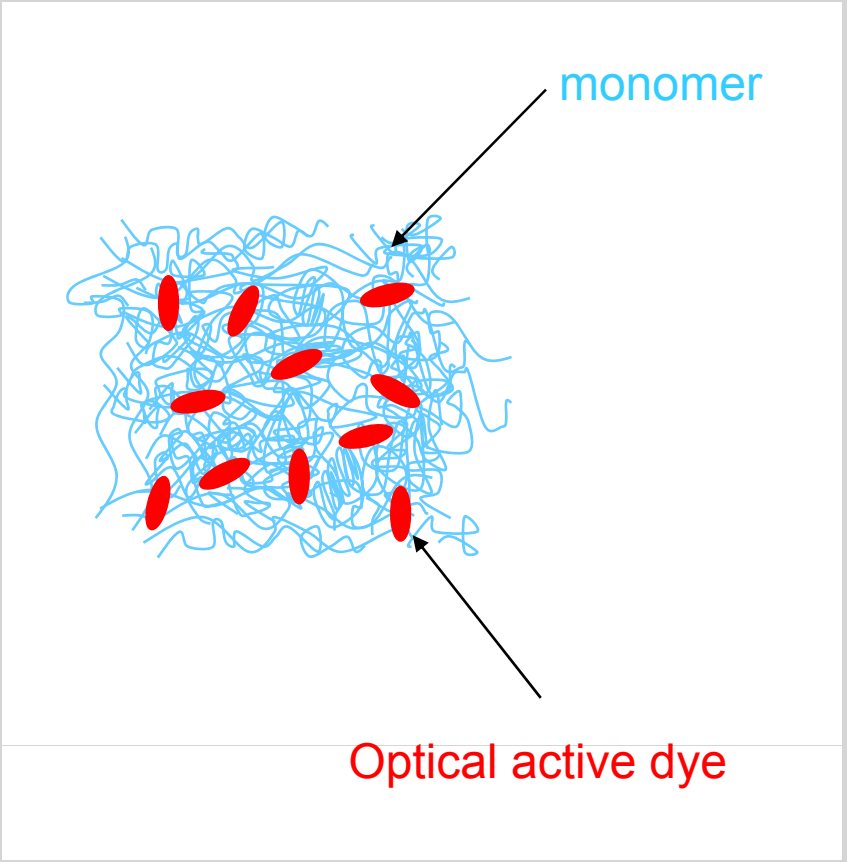


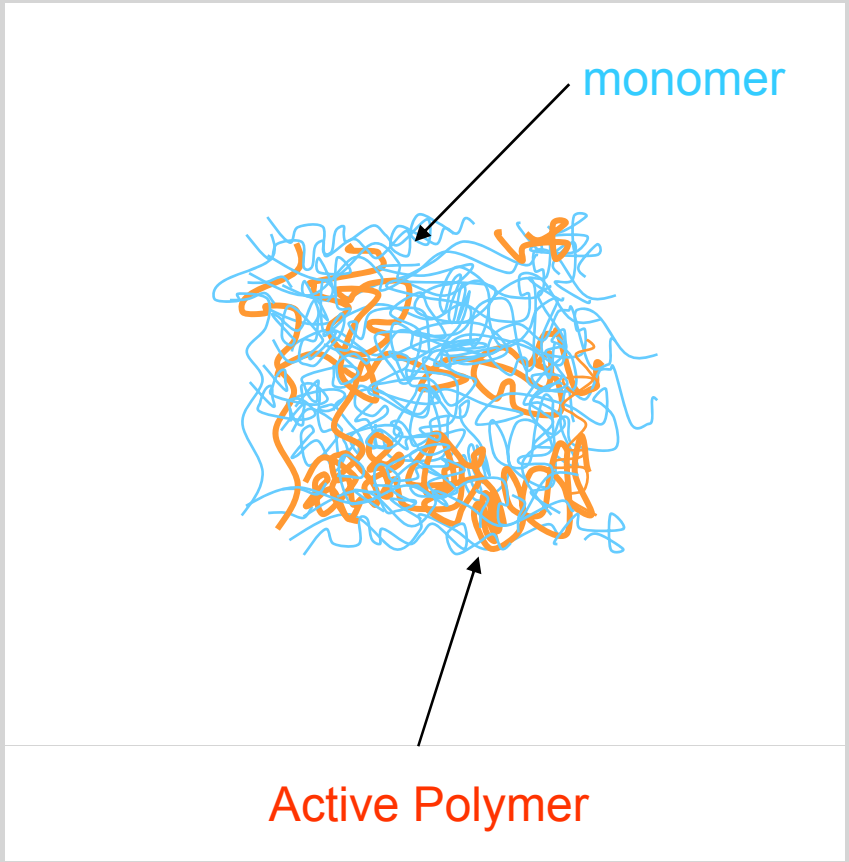






Microstructures containing active compounds





Applications of two-photon polymerization

Optics and Photonics

Doping microstructures with organic molecules and metals

- fluorescence
- birefringence
- conductivity

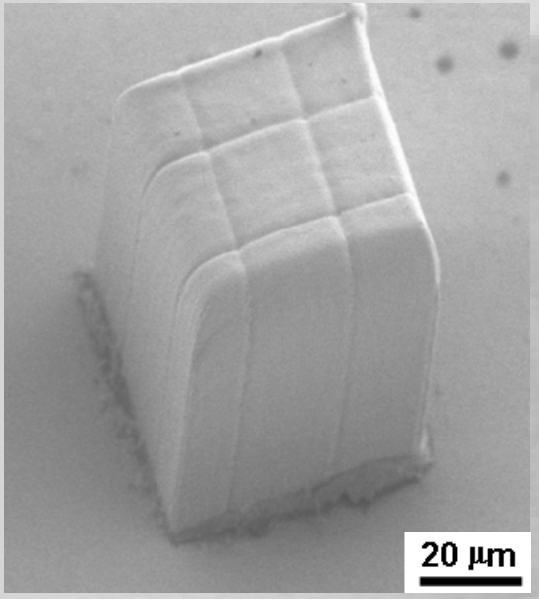
Bio-applications

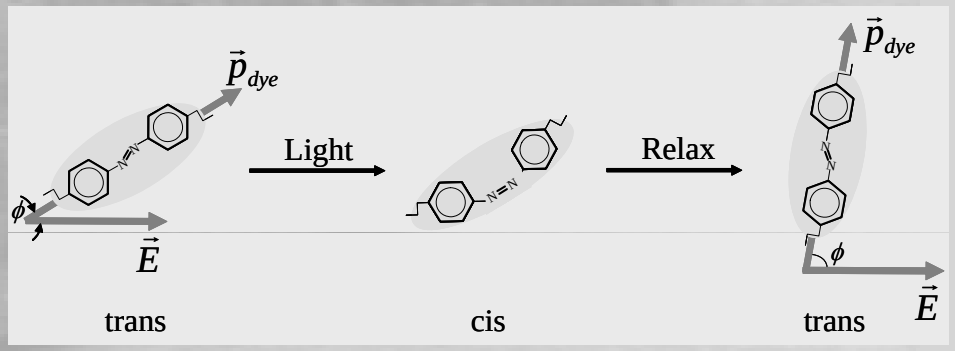
Fabrication using bio-compatible resins to biological applications

- tissue engineering scaffolds
- fabrication of microneedle
- cell study

Other studies

- microstructures for optical storage – birefringence

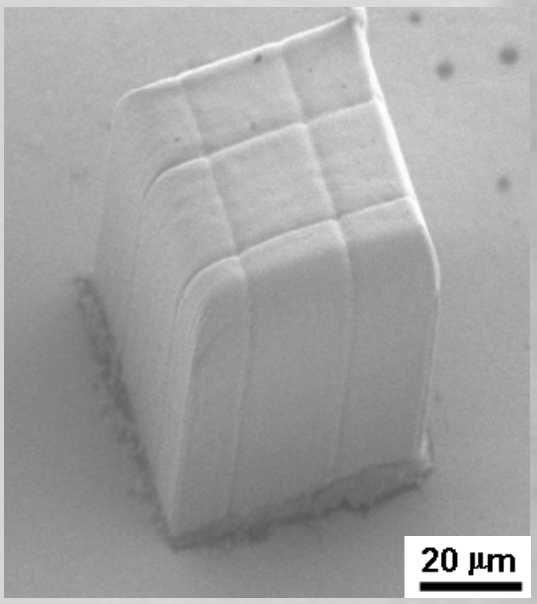




J. Appl. Phys., 102, 13109-1-13109-4 (2007)

Other studies

- microstructures for optical storage – birefringence



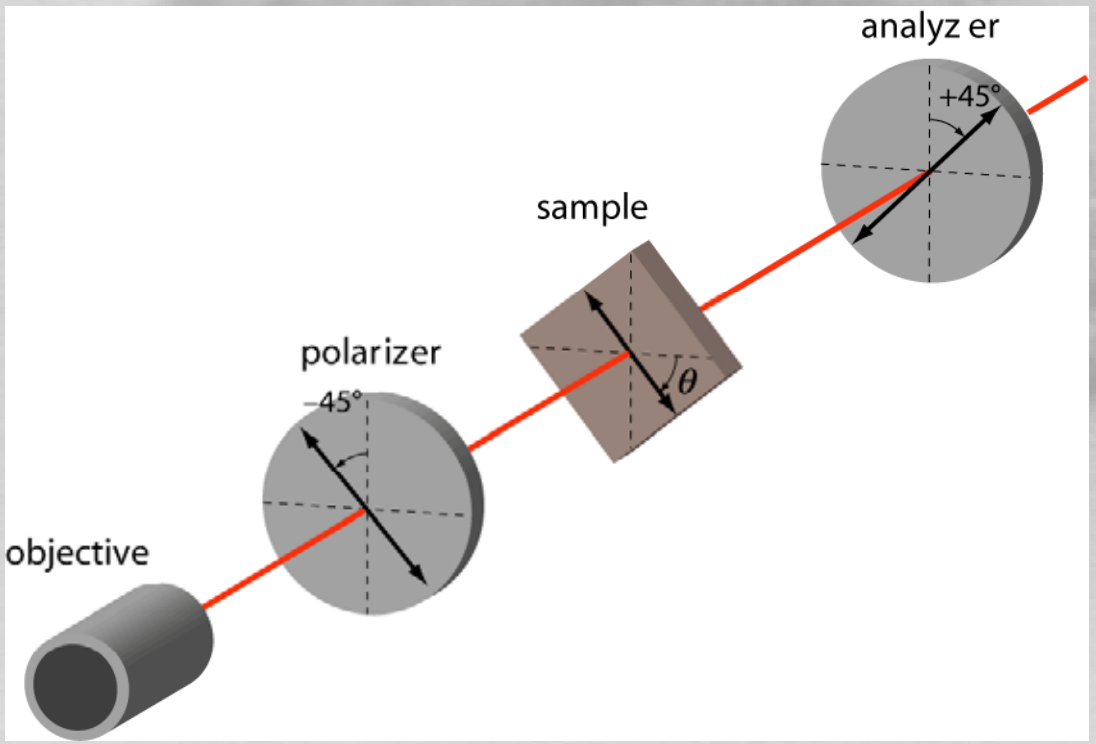
Ar^+ ion laser irradiation

- 514.5 nm
- one minute
- intensity of 600 mW/cm^2

Other studies

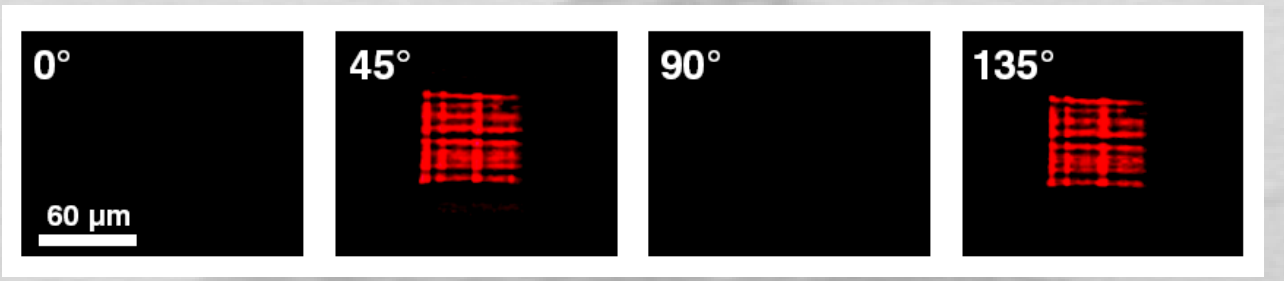
- microstructures for optical storage – birefringence

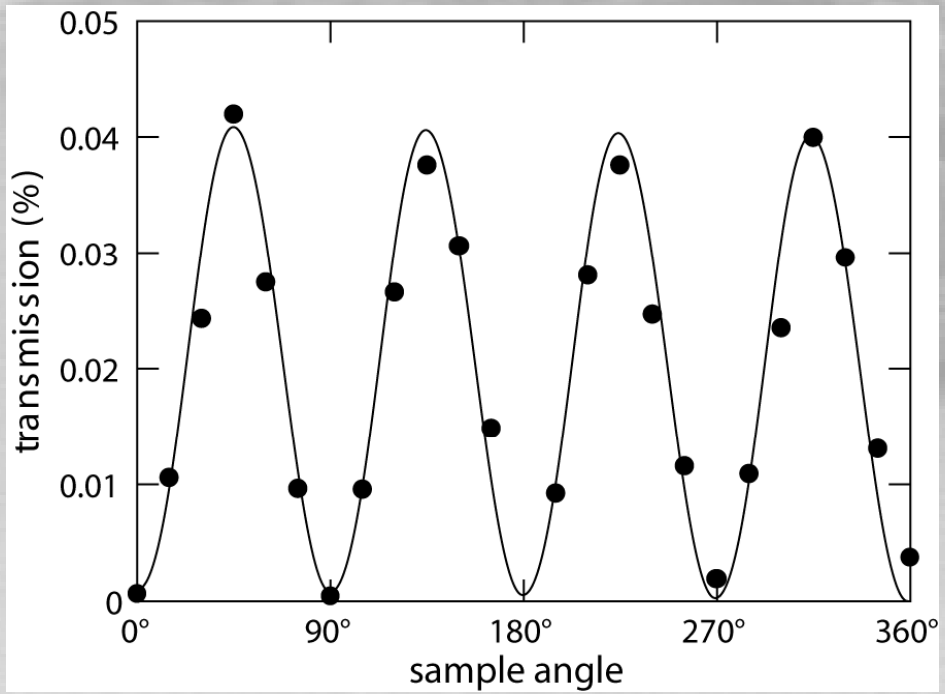
The sample was placed under an optical microscope between crossed polarizers and its angle was varied with respect to the polarizer angle



Other studies

- microstructures for optical storage – birefringence

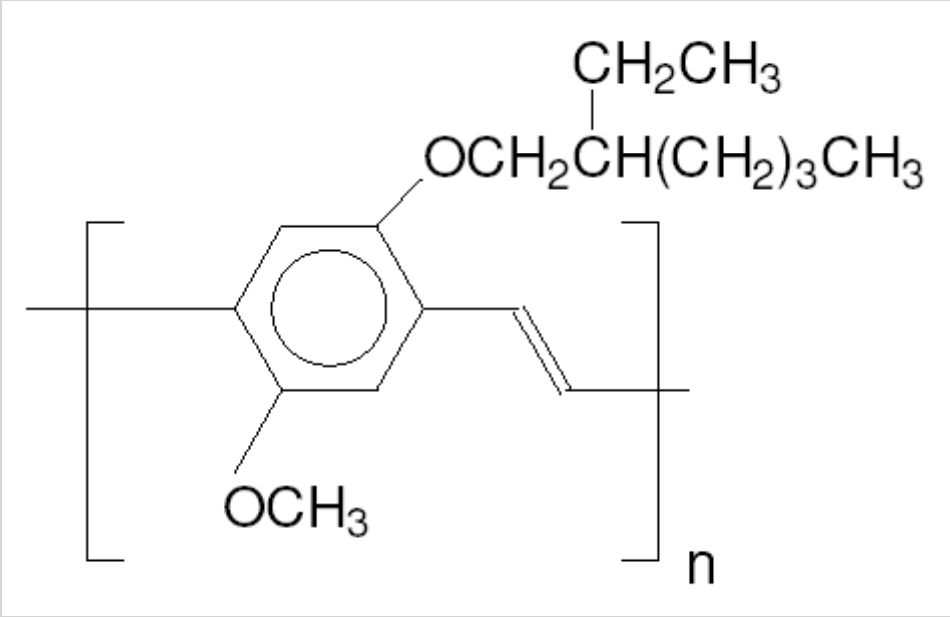




J. Appl. Phys., 102, 13109-1-13109-4 (2007)

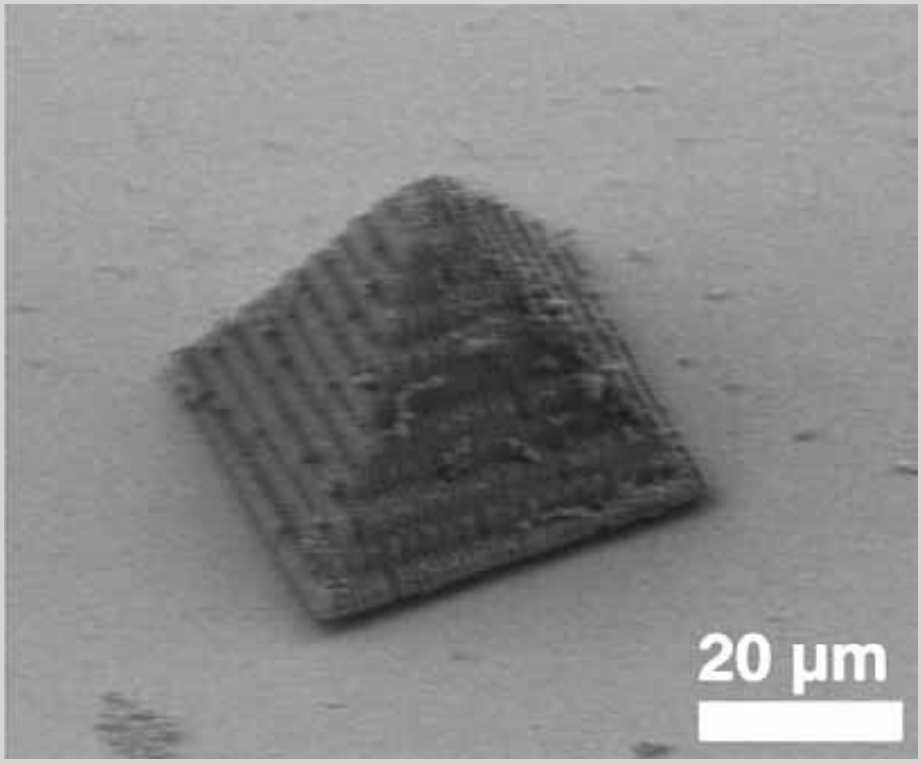
Microstructures containing MEH-PPV

MEH-PPV



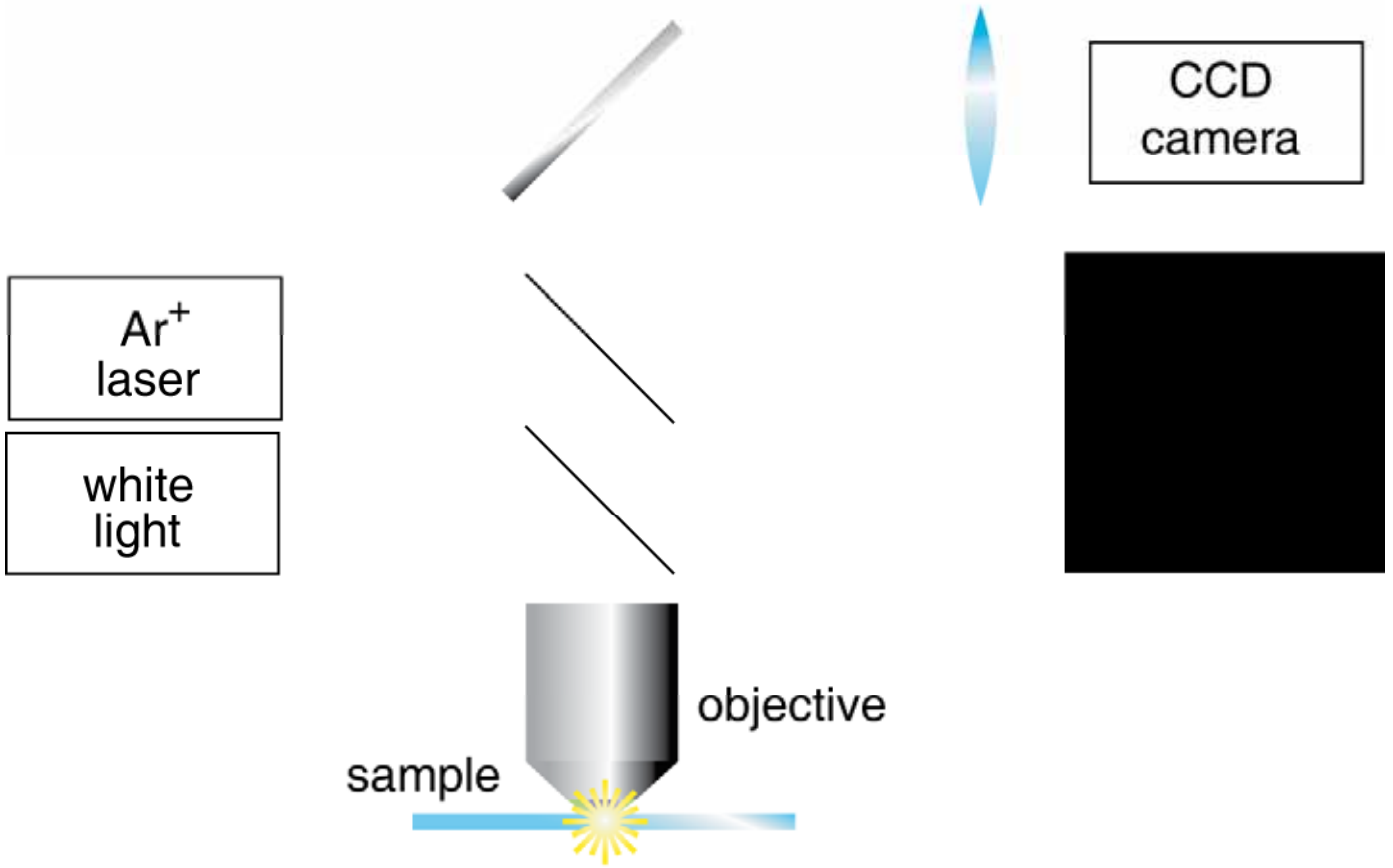
Fluorescence
Electro Luminescent
Conductive

Microstructure containing MEH-PPV

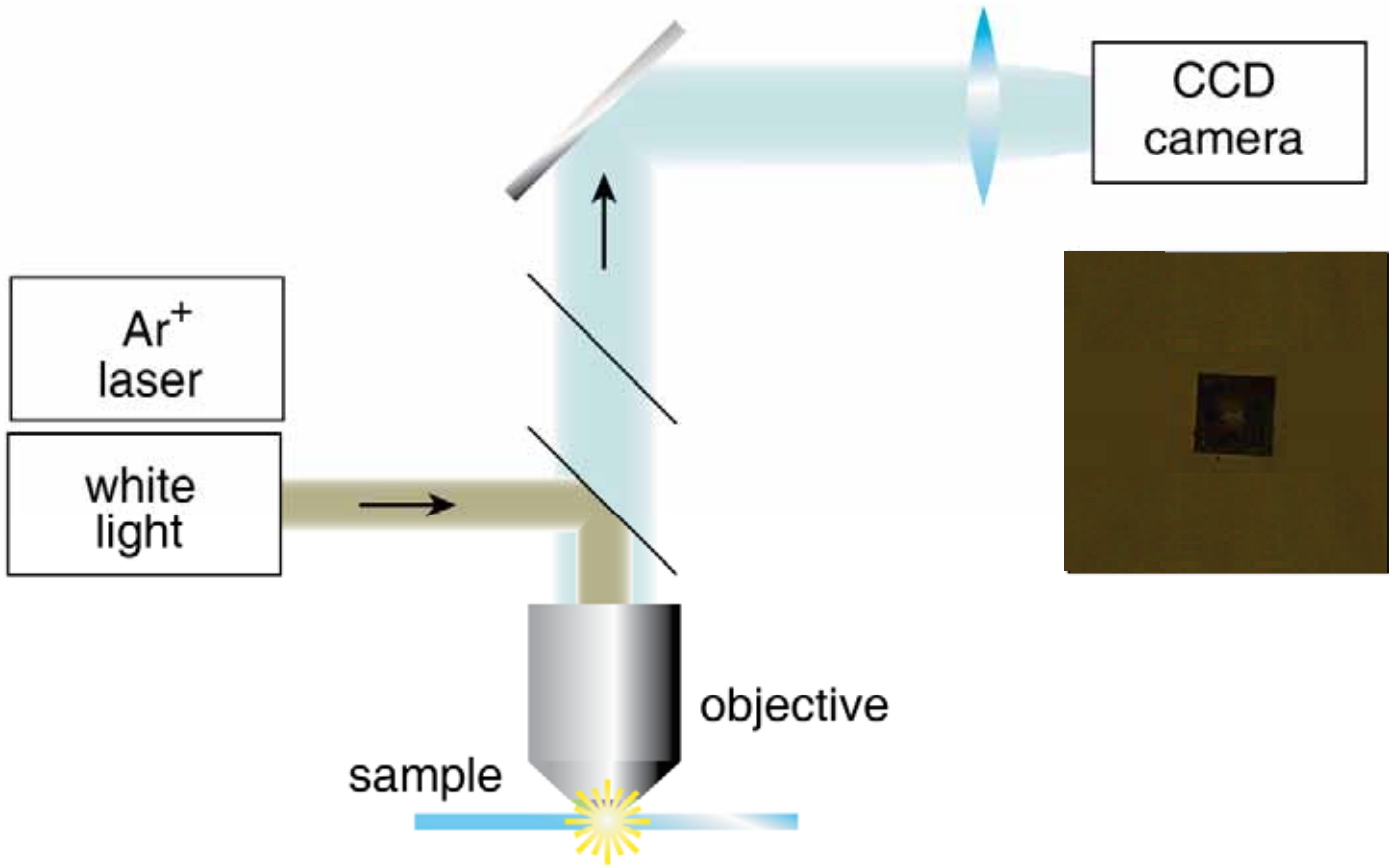


Appl. Phys. Lett., 95 1133091-3 (2009)

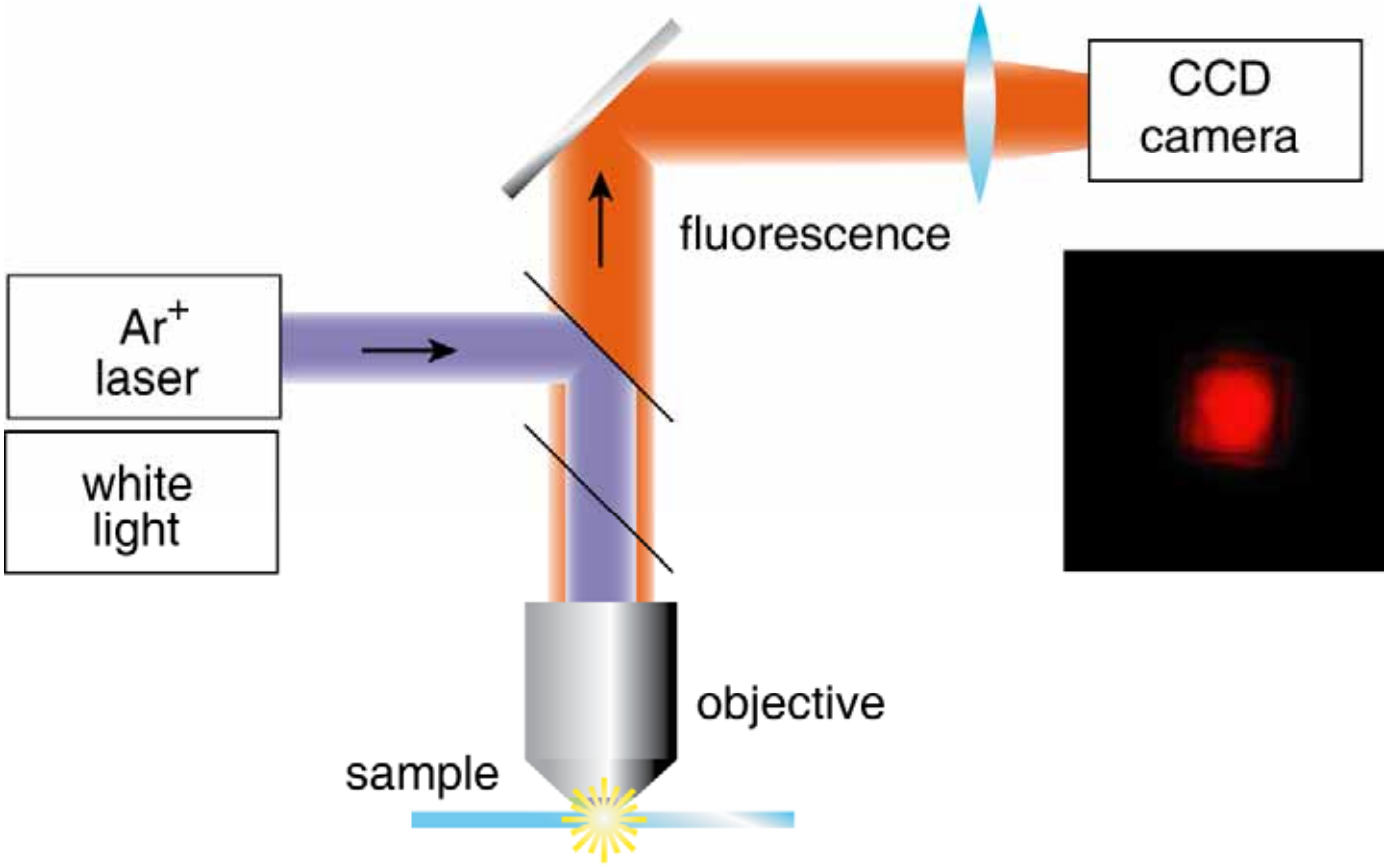
Microstructure containing MEH-PPV



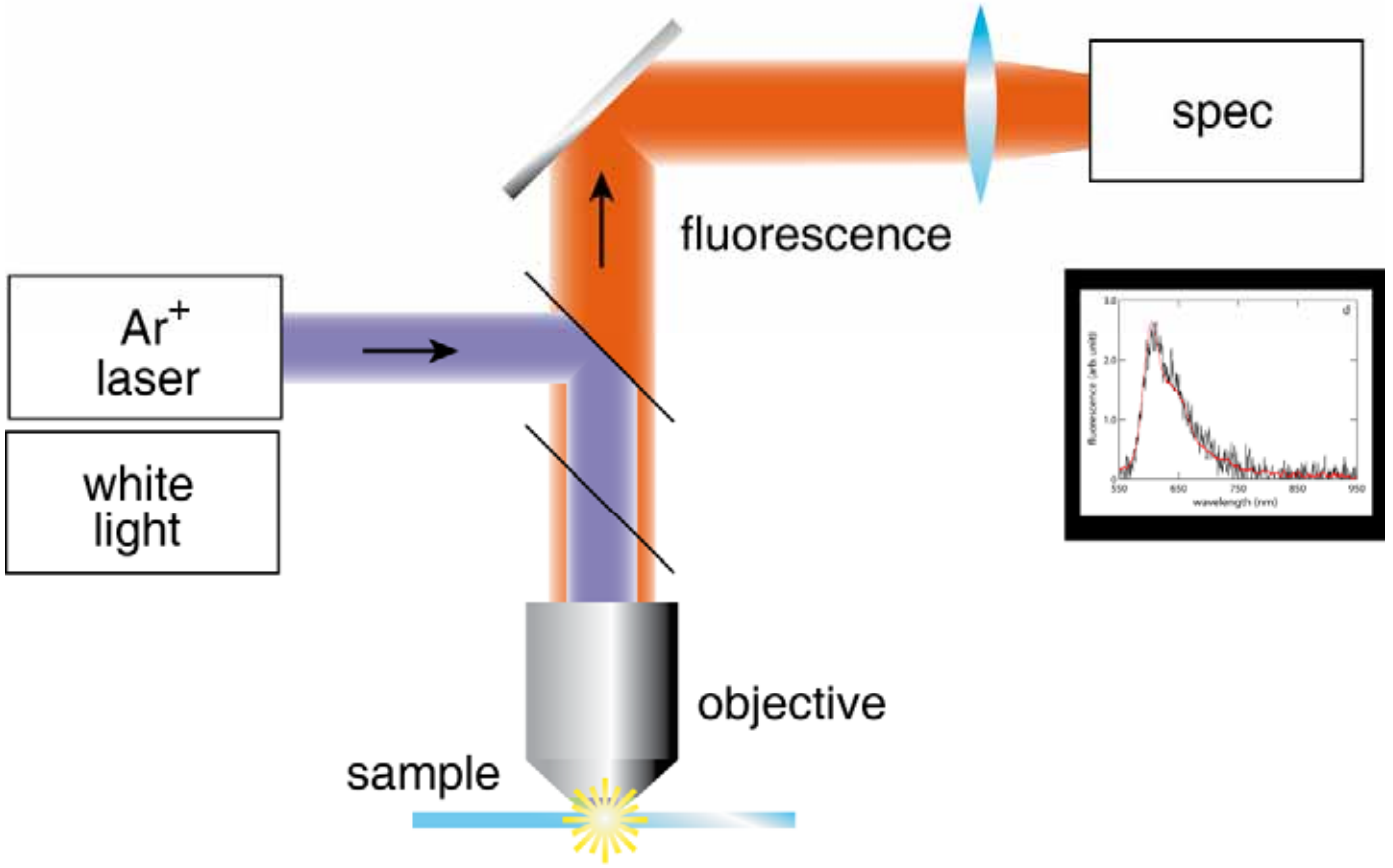
Microstructure containing MEH-PPV



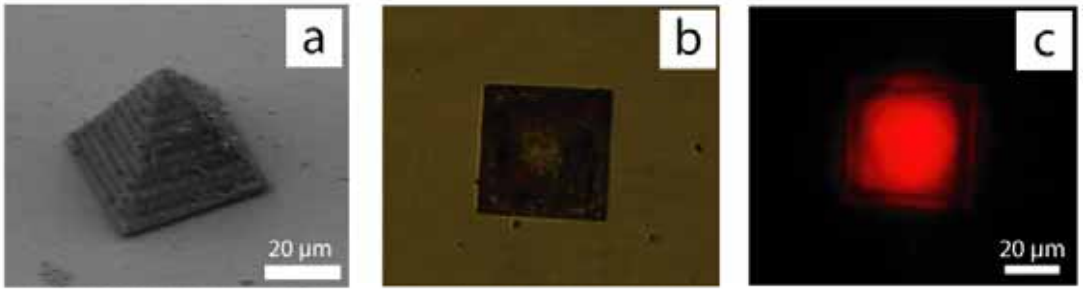
Microstructure containing MEH-PPV

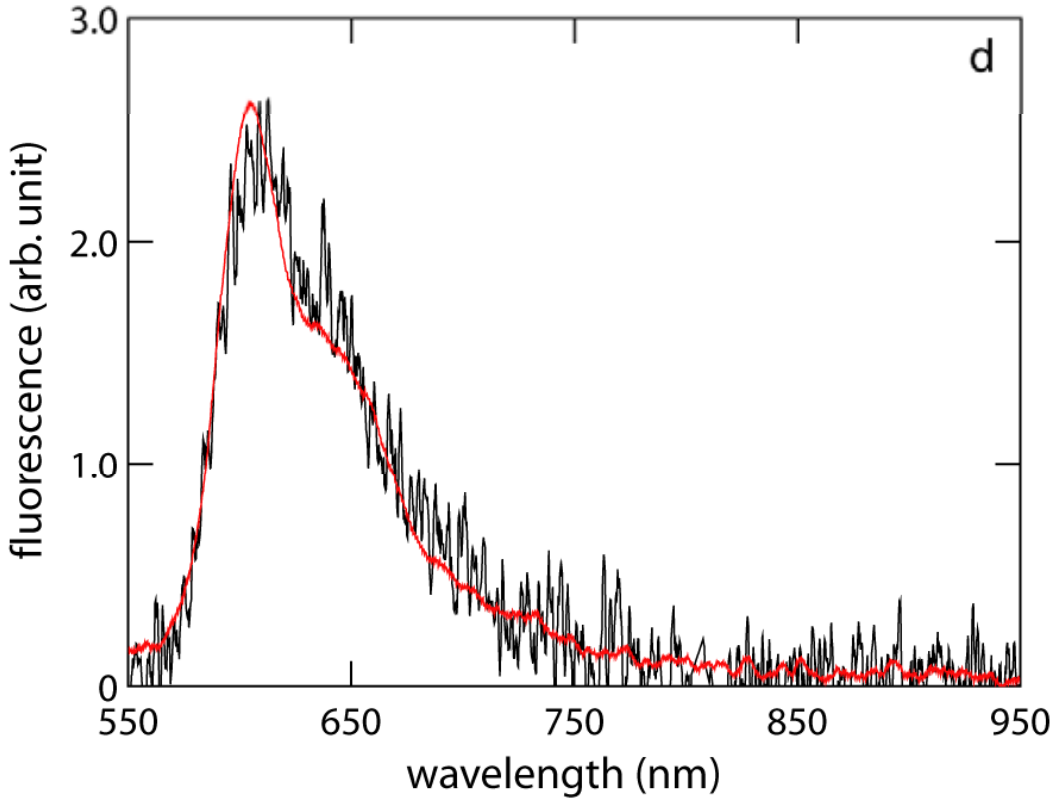


Microstructure containing MEH-PPV



Microstructure containing MEH-PPV





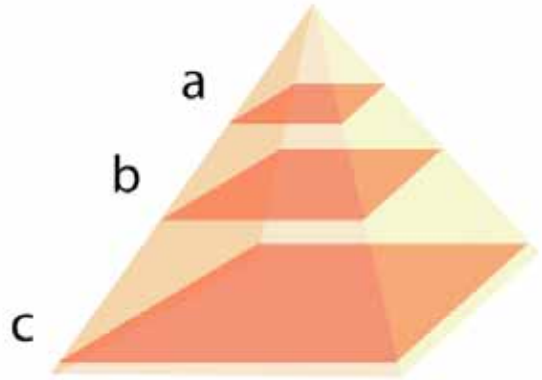
(a) Scanning electron microscopy

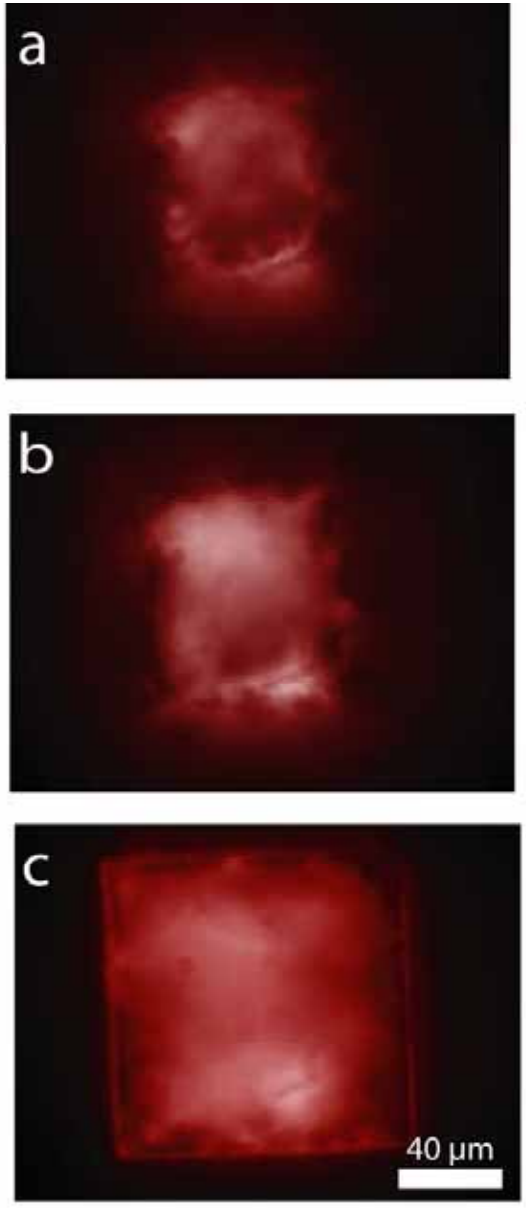
(b,c) Fluorescence microscopy of the microstructure with the excitation OFF (b) and ON (c)

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

Appl. Phys. Lett., 95 1133091-3 (2009)

Microstructure containing MEH-PPV

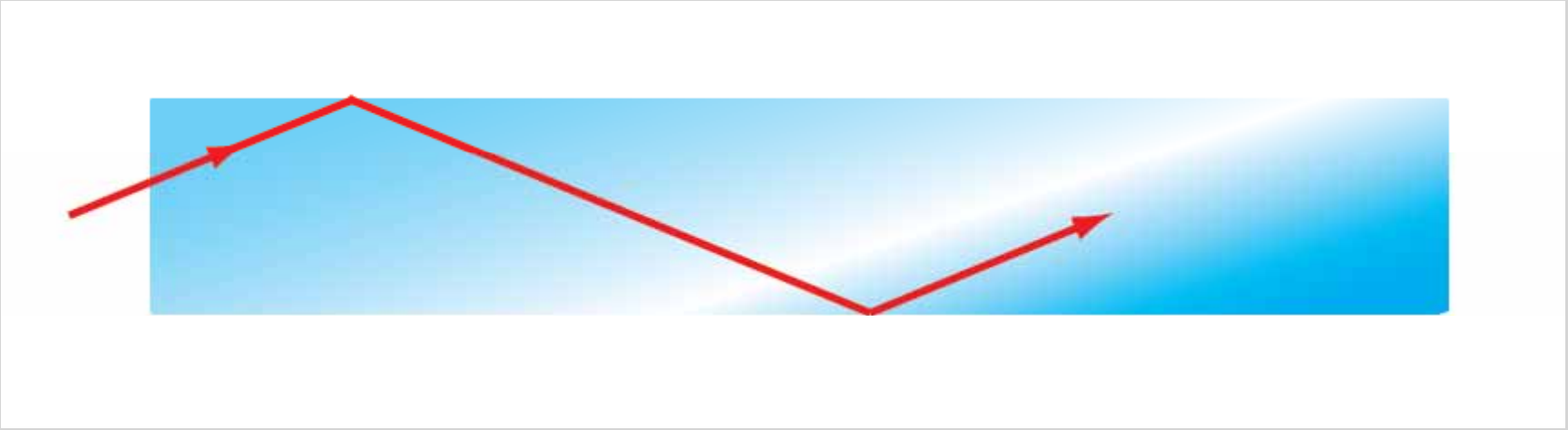




Fluorescent confocal microscopy images in planes separated by 16 μm in the pyramidal microstructure.

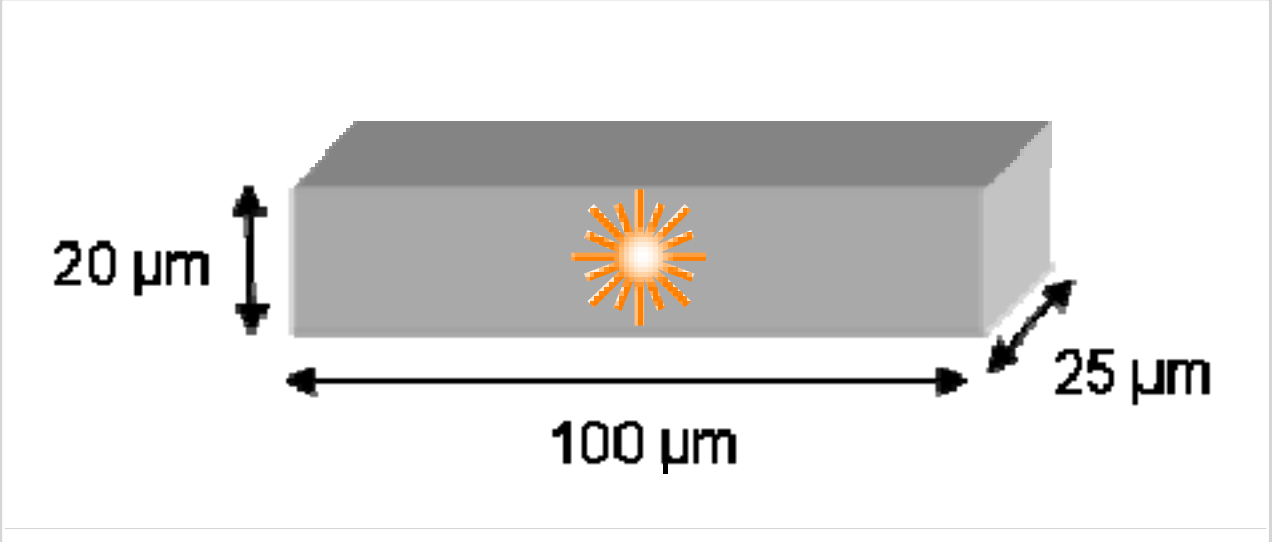
Microstructure containing MEH-PPV

Do we have waveguiding in the microstructure ?

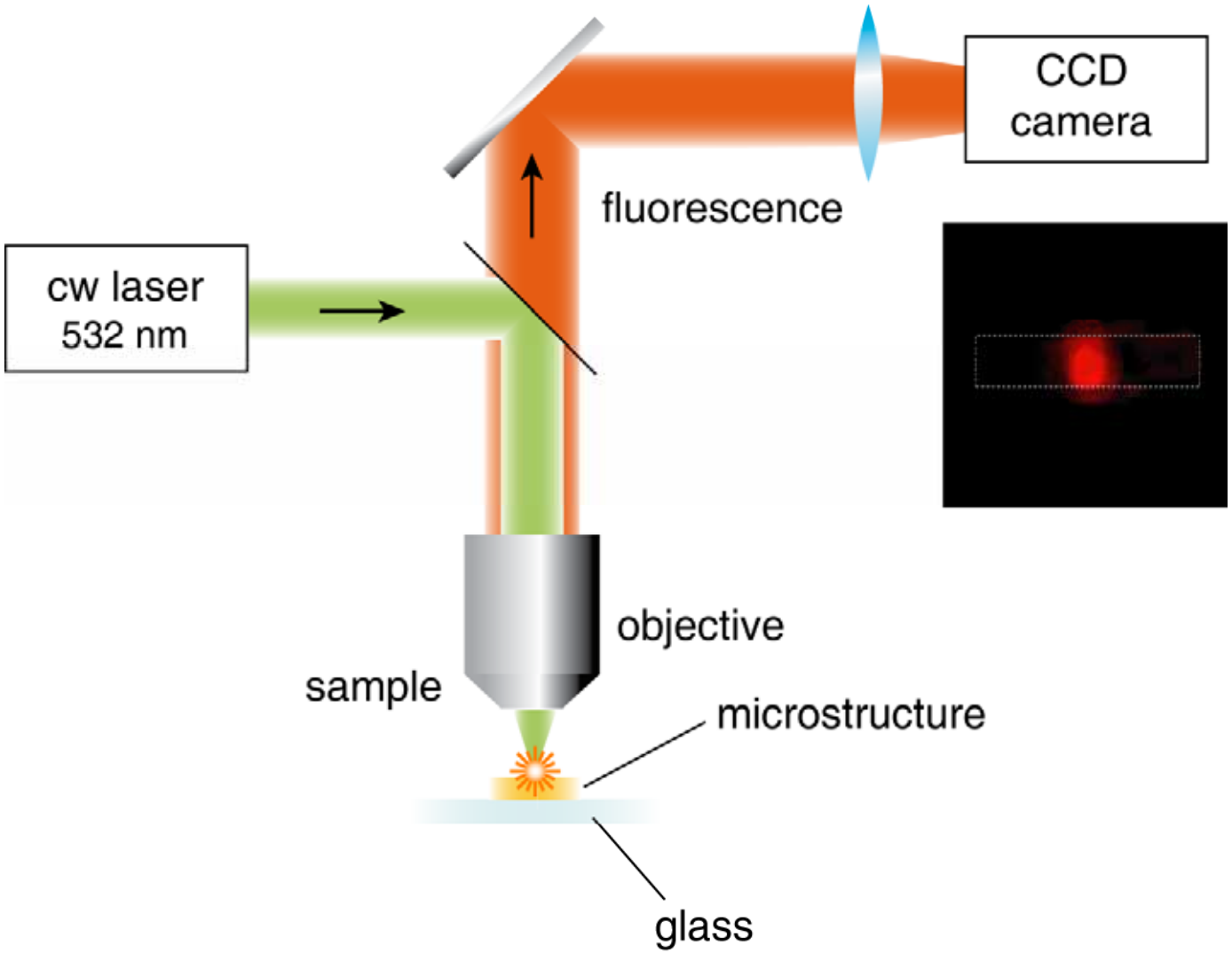


Microstructure containing MEH-PPV

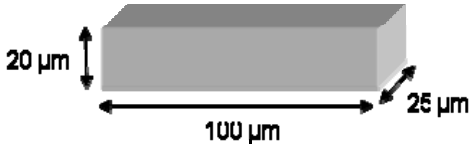
Do we have waveguiding in the microstructure ?

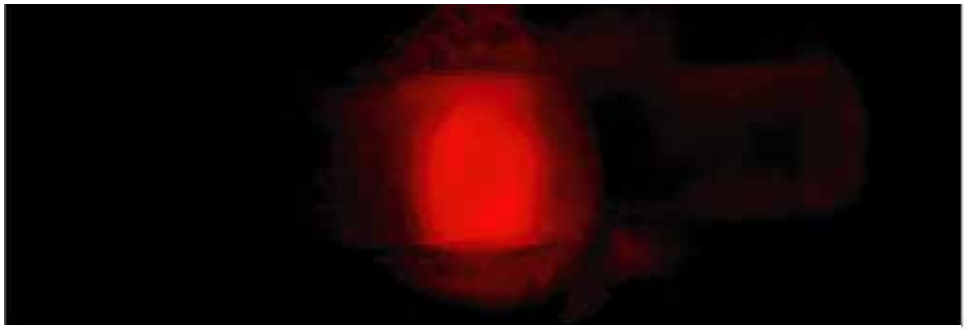


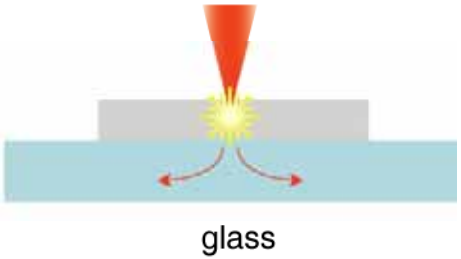
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV

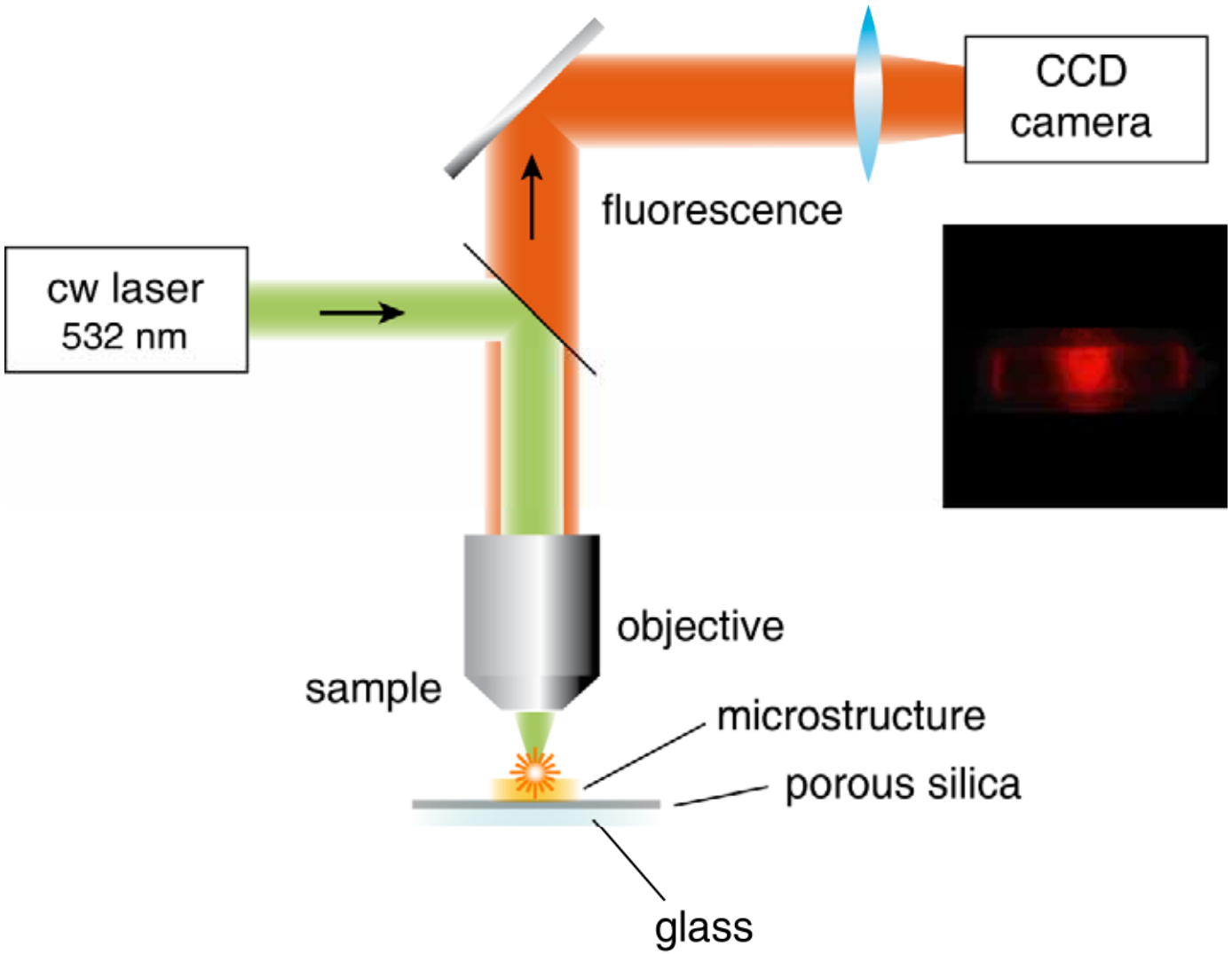




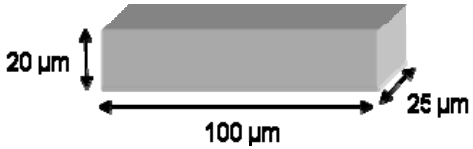


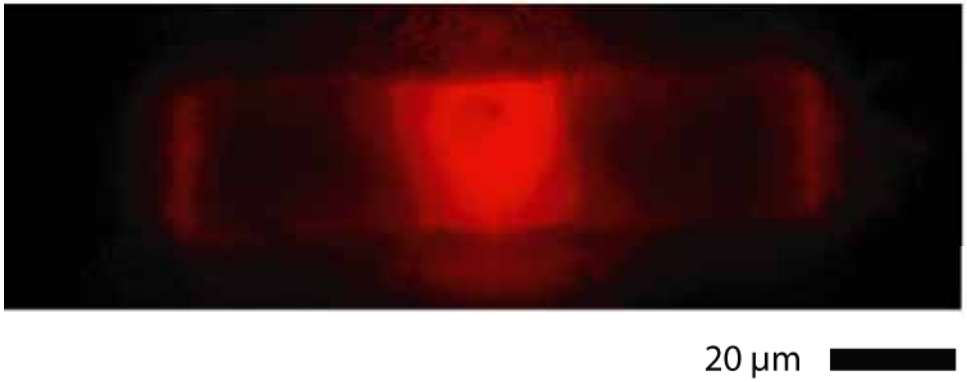
Appl. Phys. Lett., 95 1133091-3 (2009)

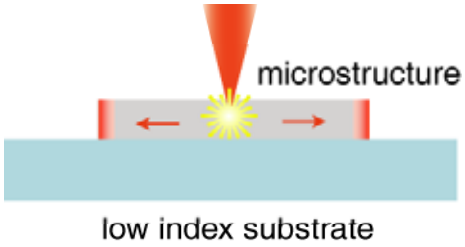
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV





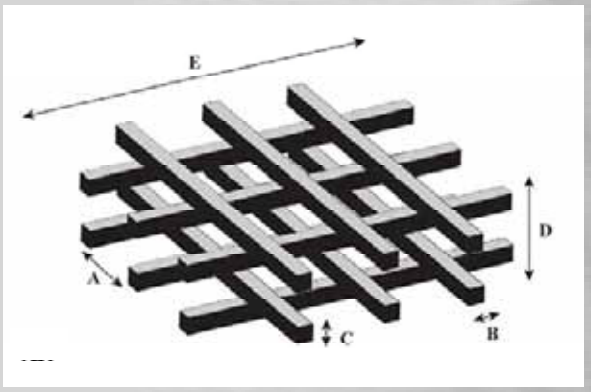


waveguiding of the microstructure fabricated on porous silica substrate (*n*= 1.185)

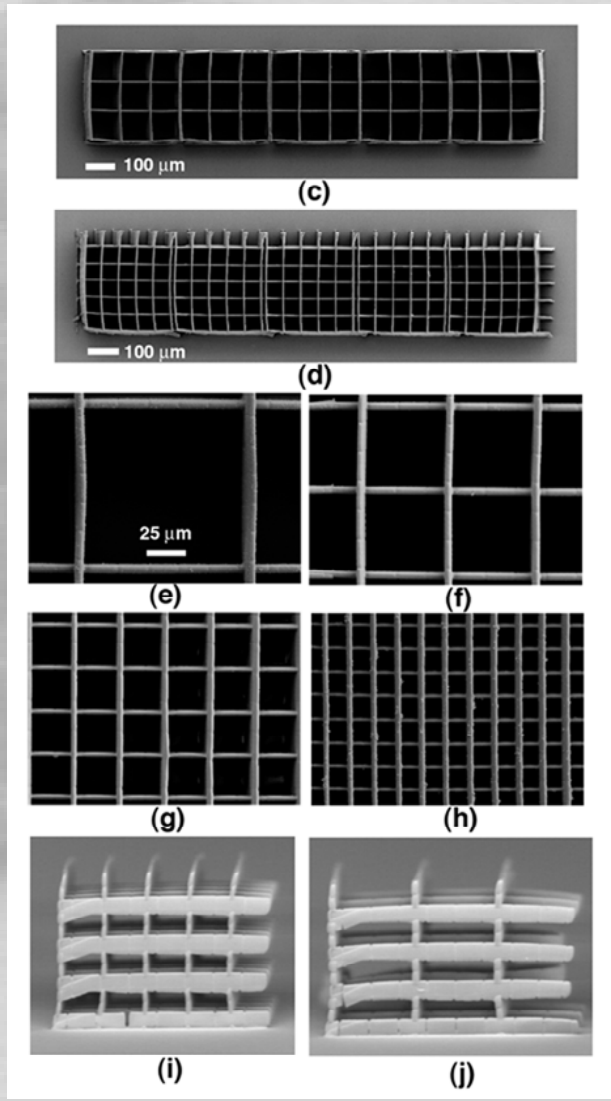
Applications: micro-laser; fluorescent microstructures; conductive microstructures

3D cell migration

- 3D cell migration studies in micro-scaffolds



SEM of the scaffolds



110 µm pore size

52 µm pore size

Top view

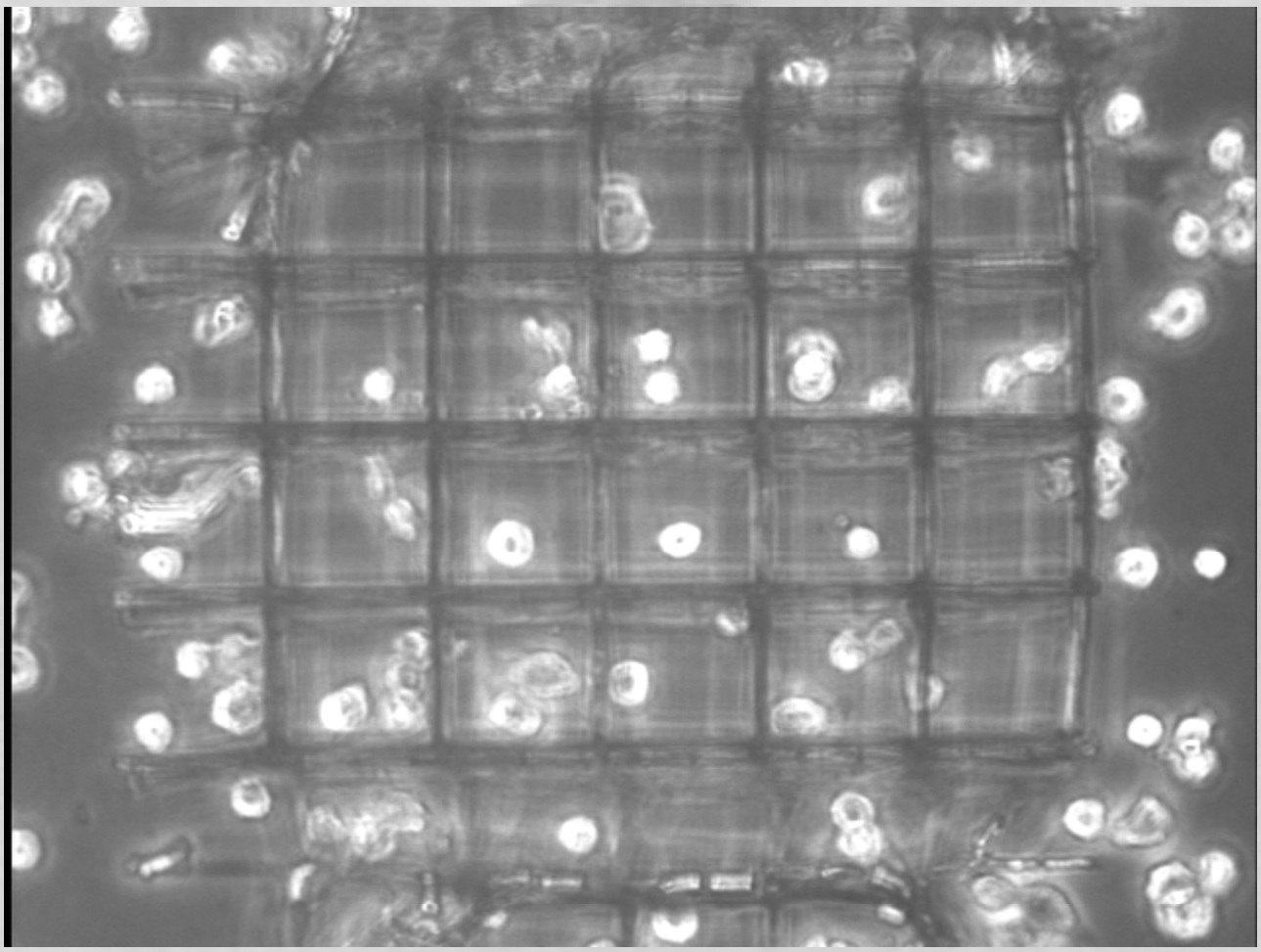
110, 52, 25, 12 µm pore size

Side view

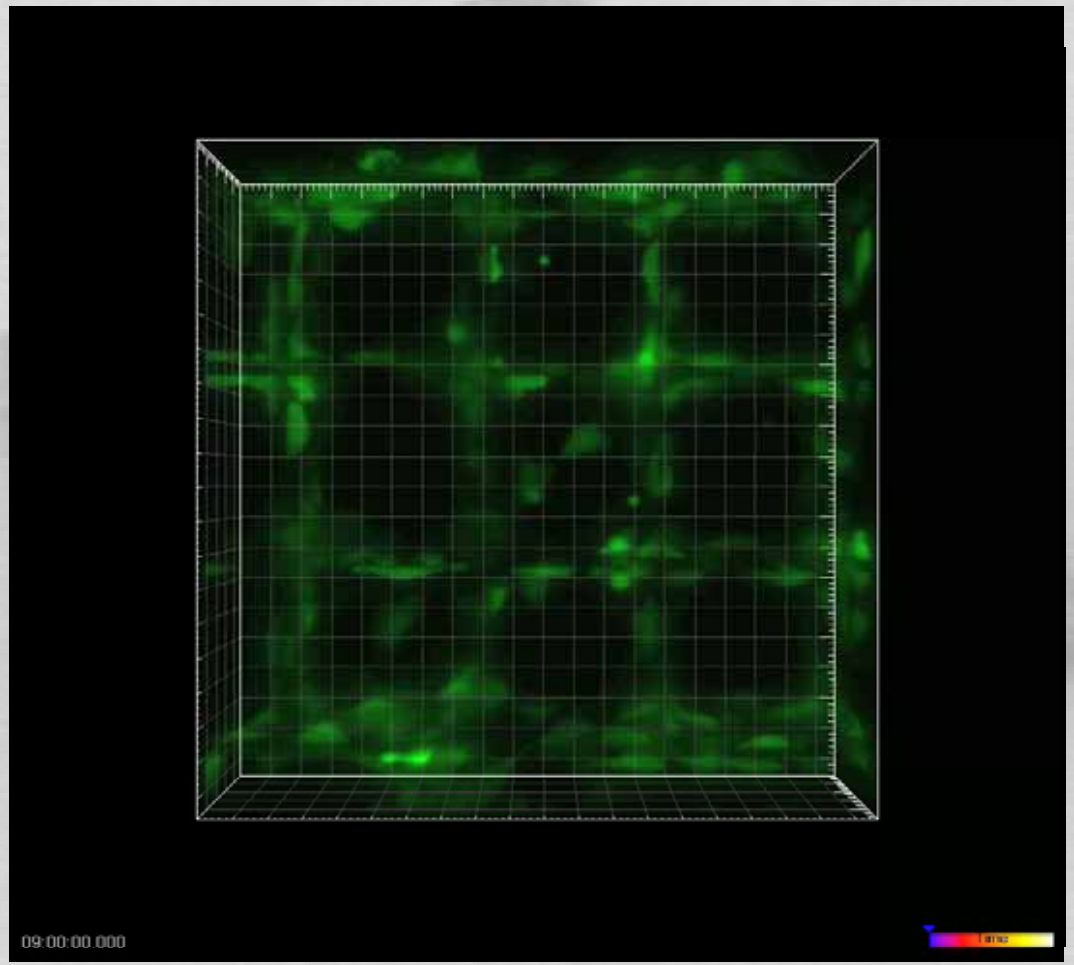
25, 52 µm pore size

3D cell migration

50 μm pore size

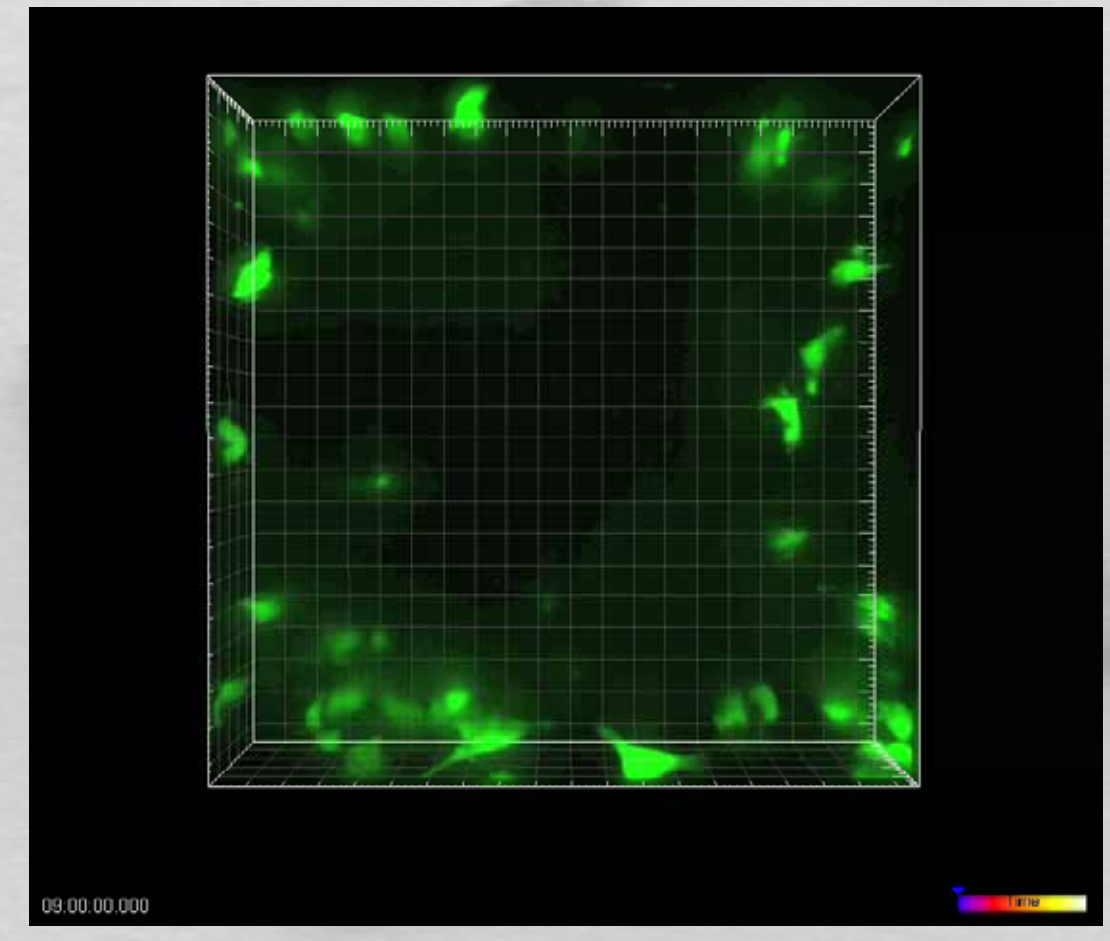


3D cell migration



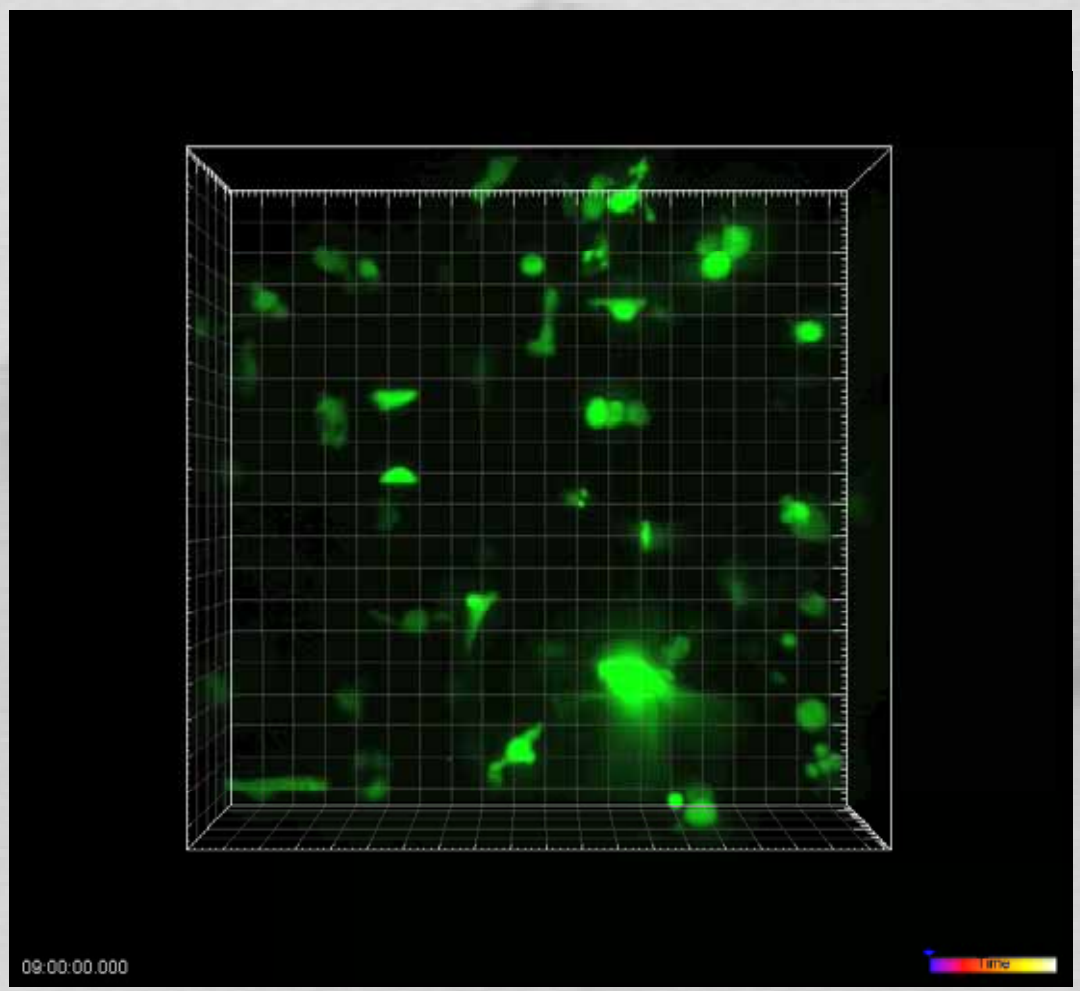
110 μm pore size

3D cell migration



12 μm pore size

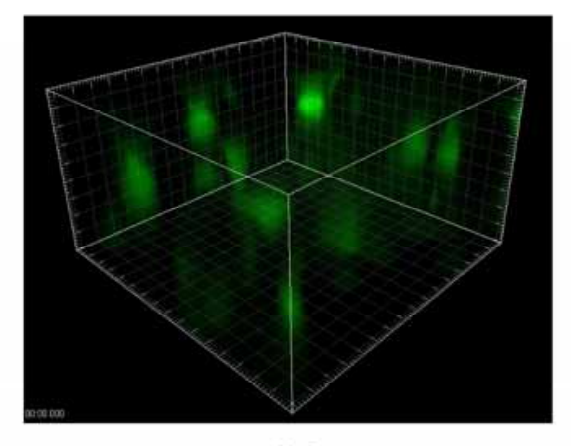
3D cell migration

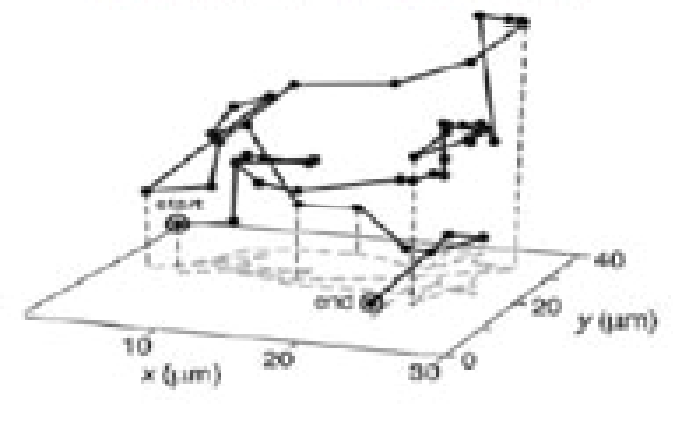


52 μm pore size

3D cell migration

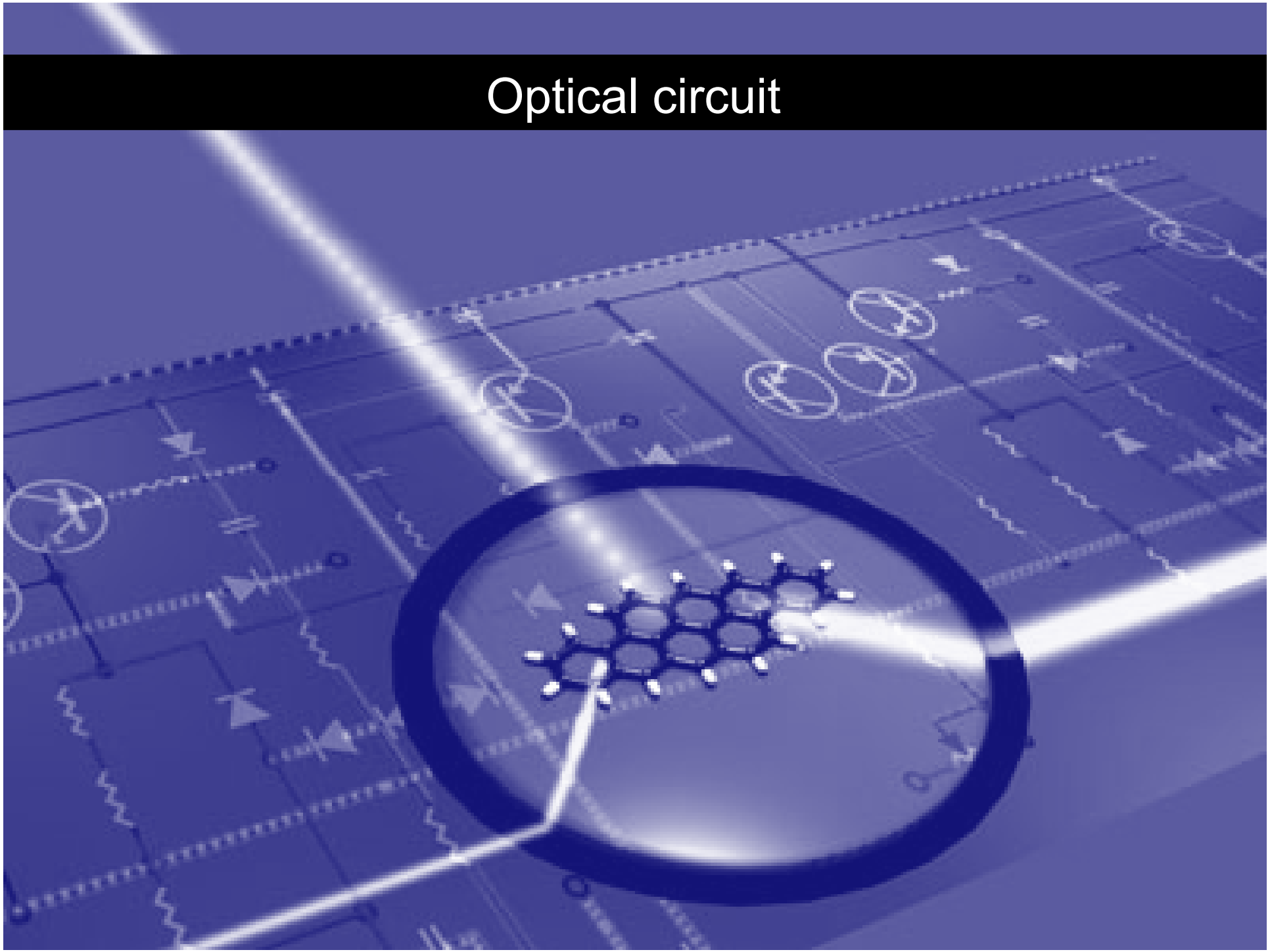
- 3D cell migration studies in micro-scaffolds



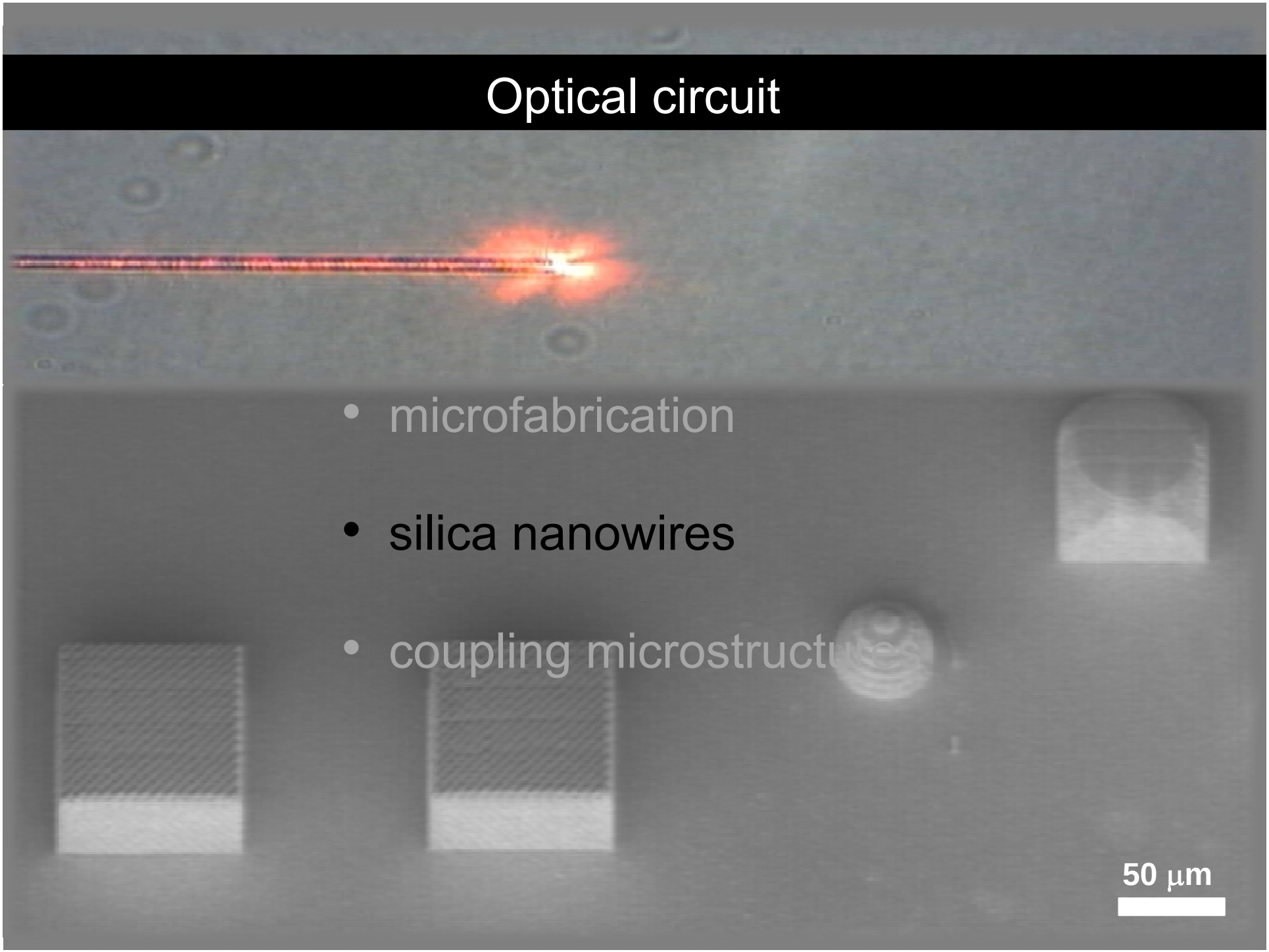


Advanced Materials, 20, 4494-4498 (2008)

Optical circuit



Optical circuit

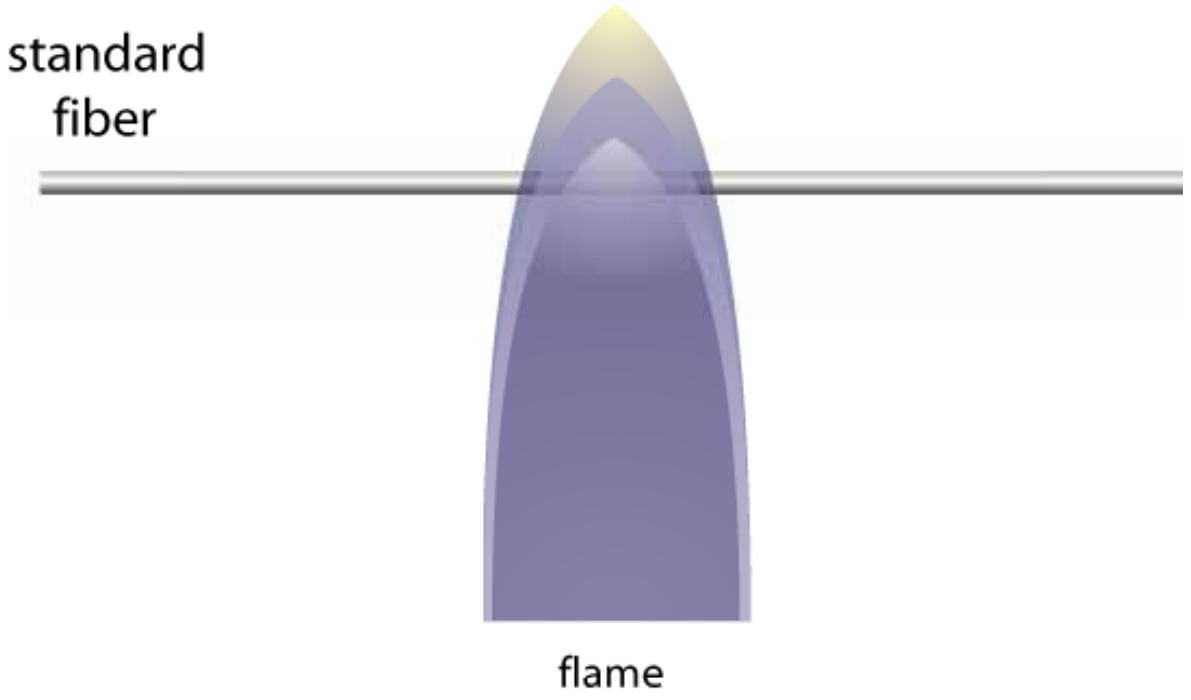


Silica nanowires

nanowires fabrication process

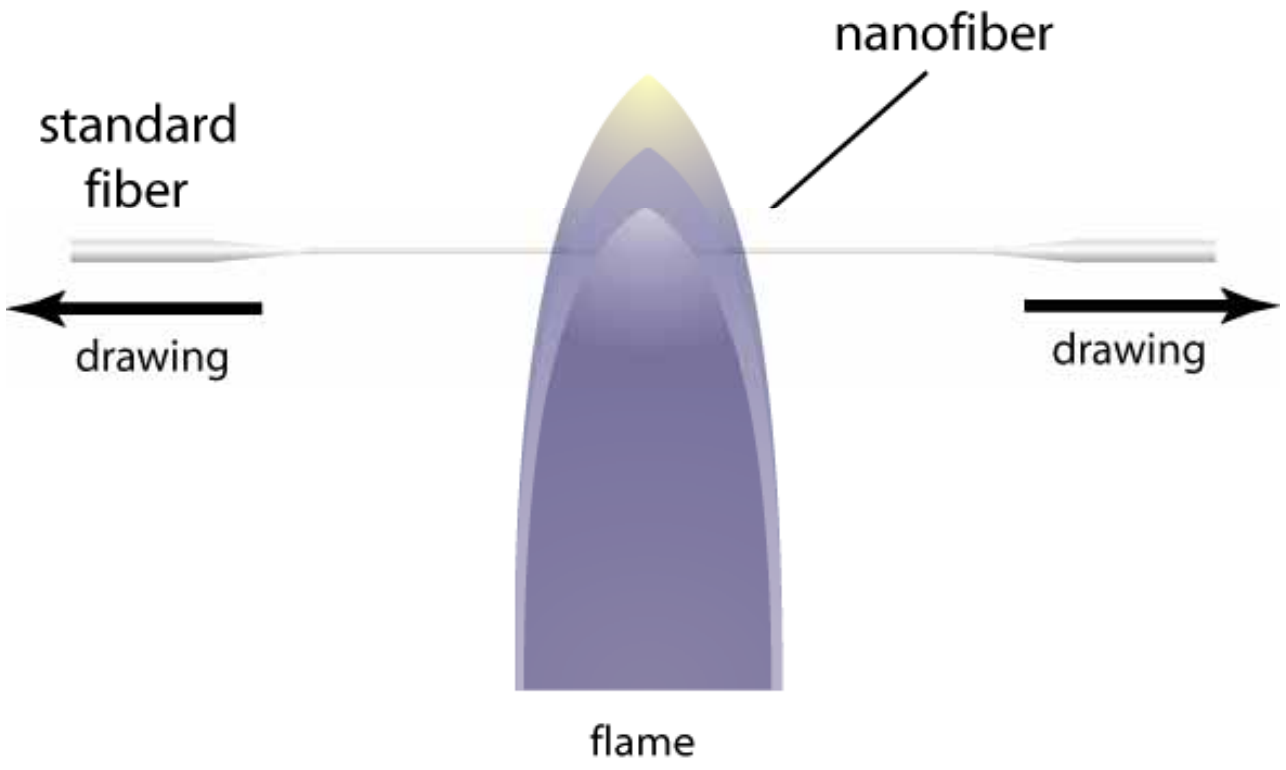
Silica nanowires

nanowires fabrication process



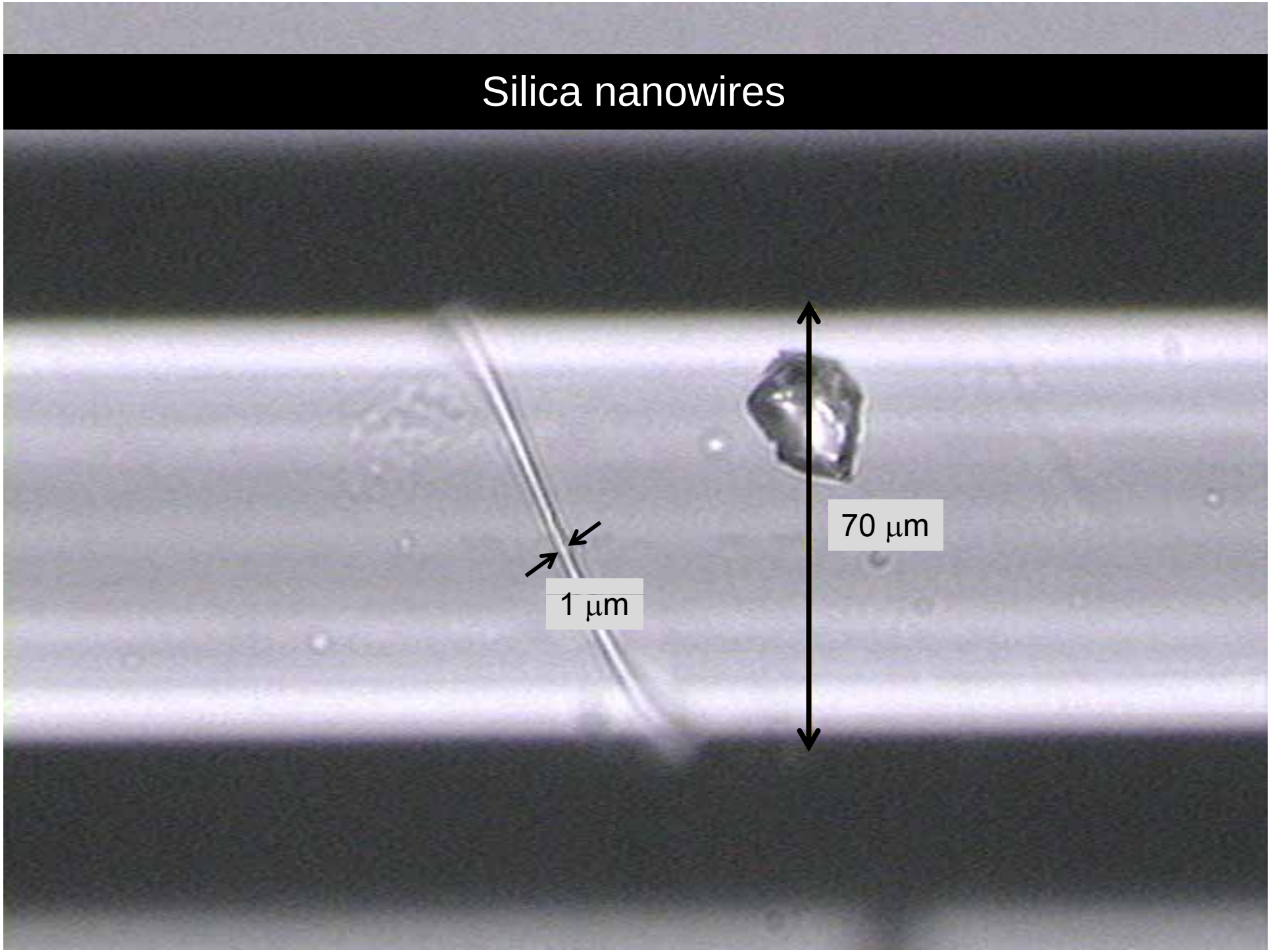
Silica nanowires

nanowires fabrication process

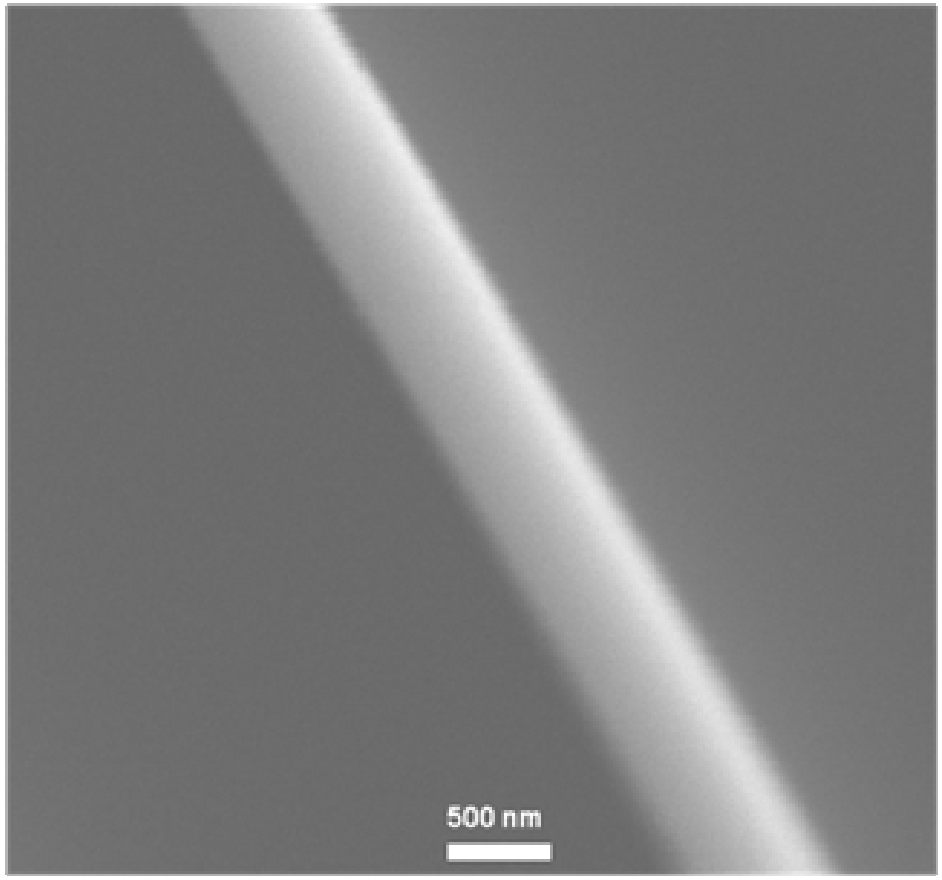


Silica nanowires

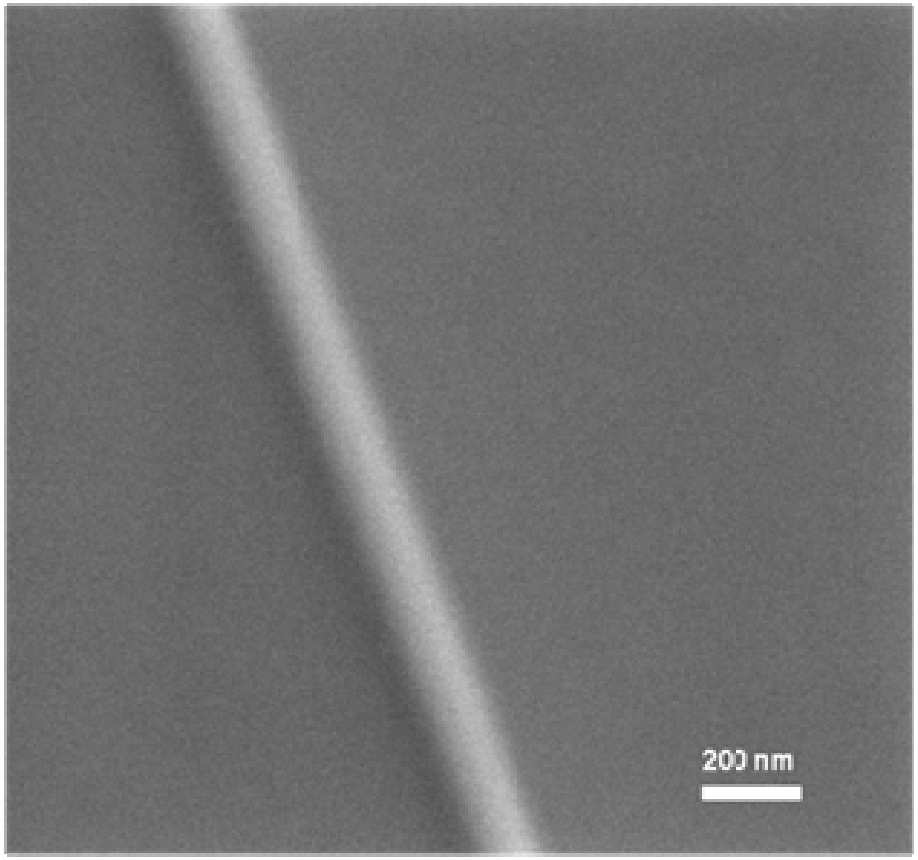
Silica nanowires



Silica nanowires

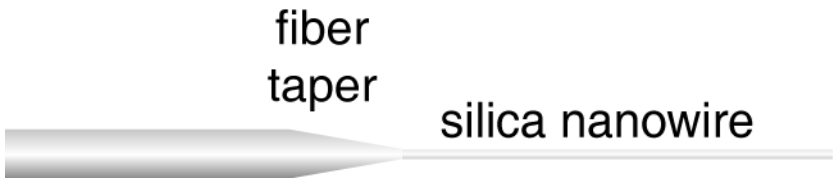


Silica nanowires



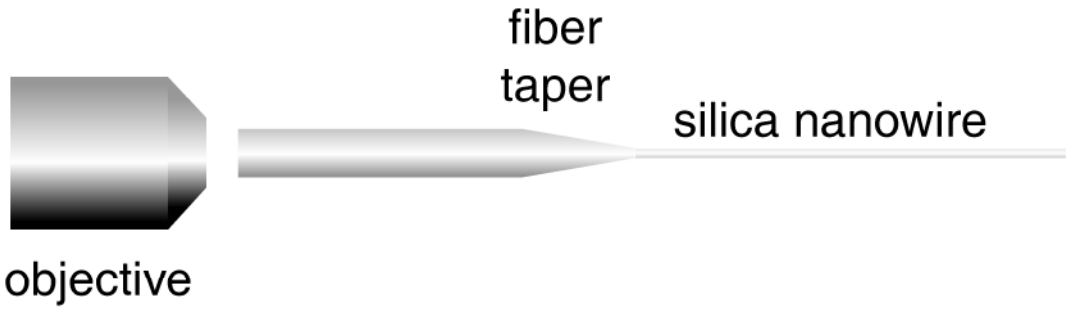
Silica nanowires

coupling light into nanowires



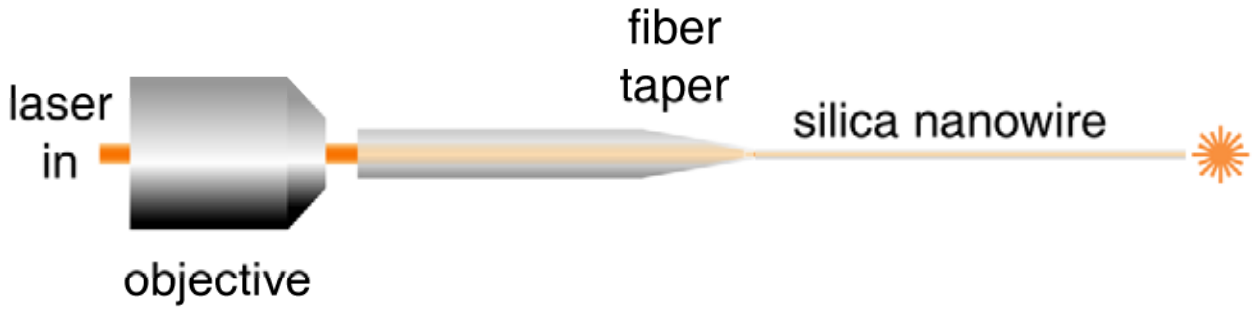
Silica nanowires

coupling light into nanowires



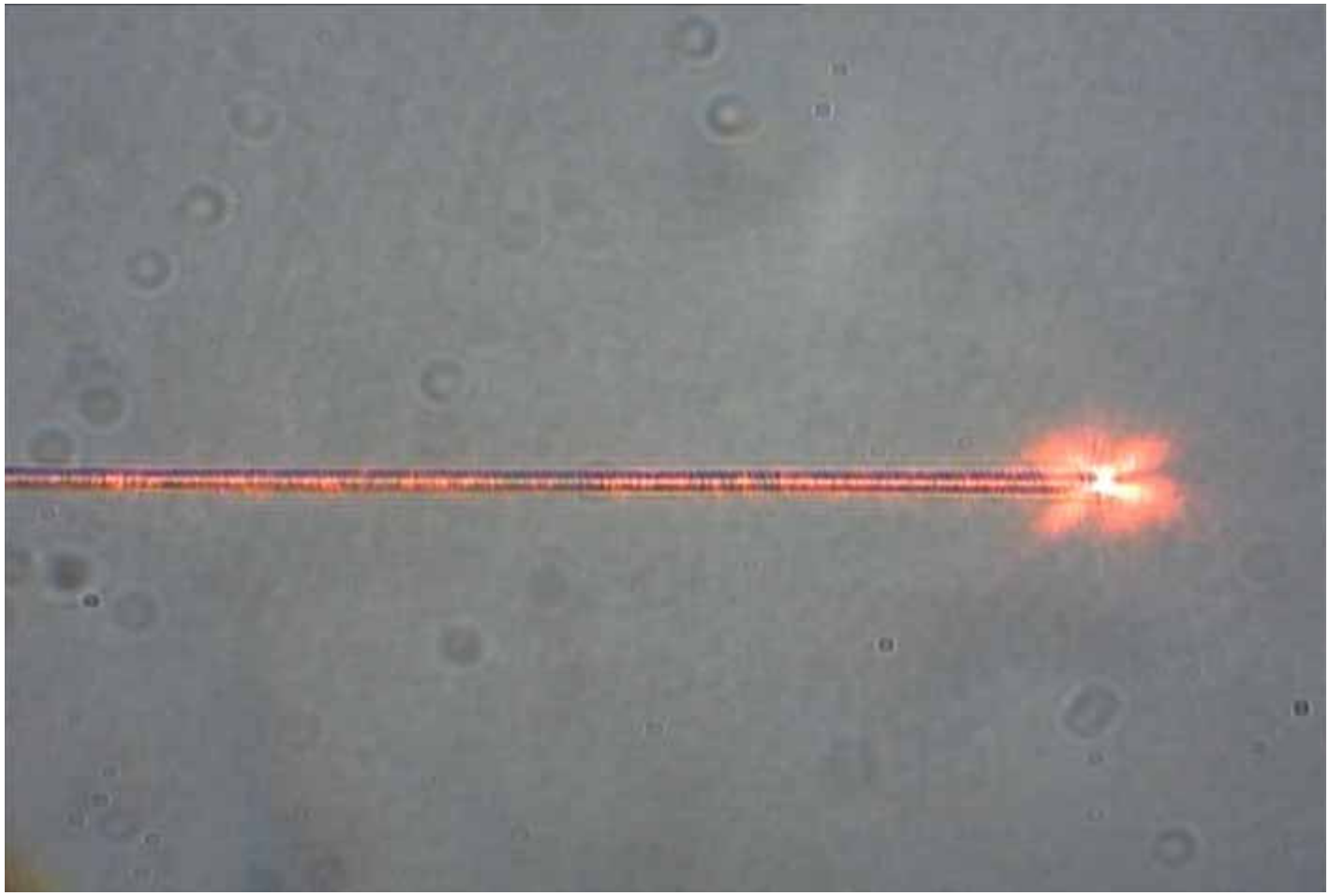
Silica nanowires

coupling light into nanowires

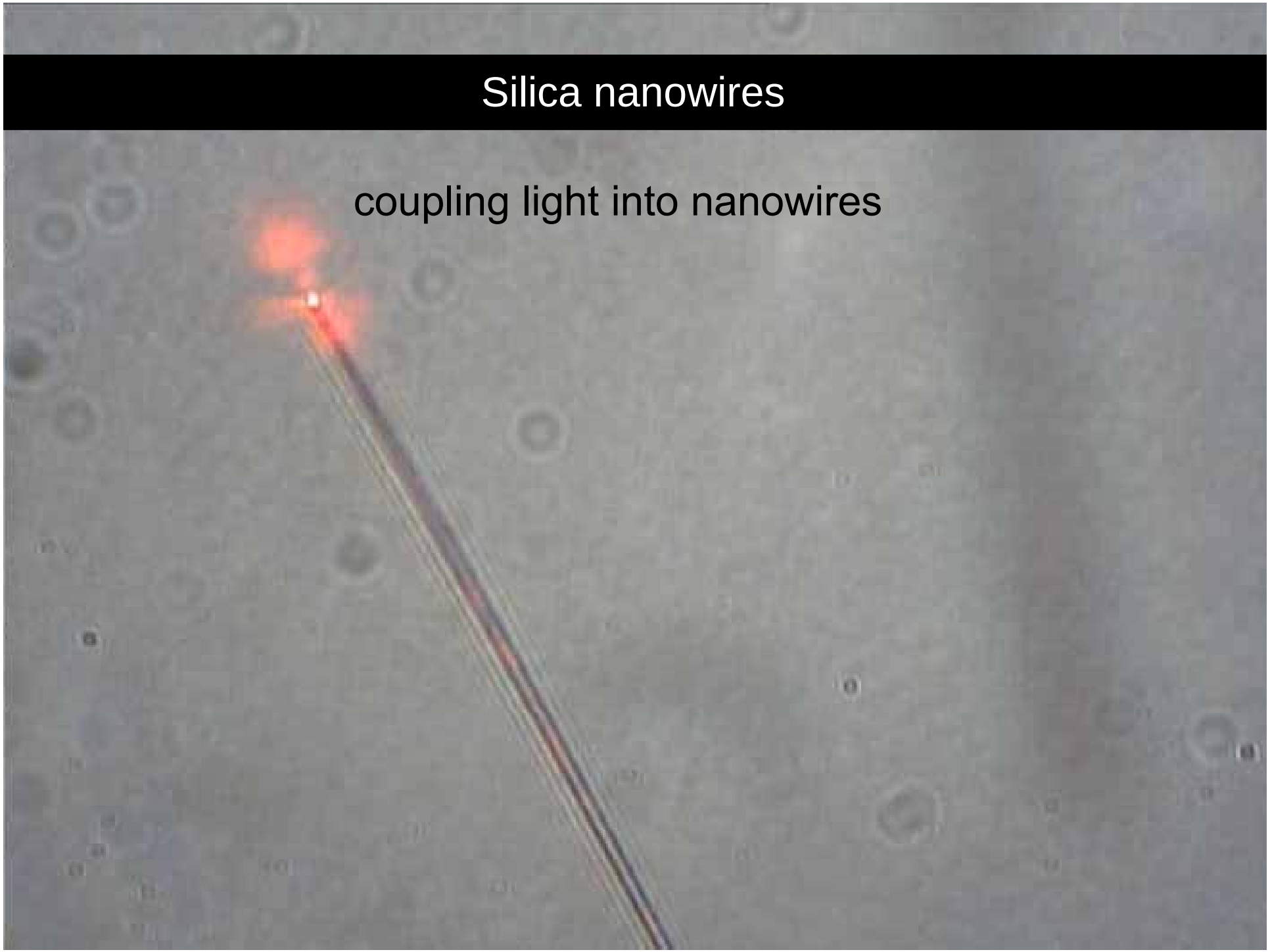


Silica nanowires

coupling light into nanowires

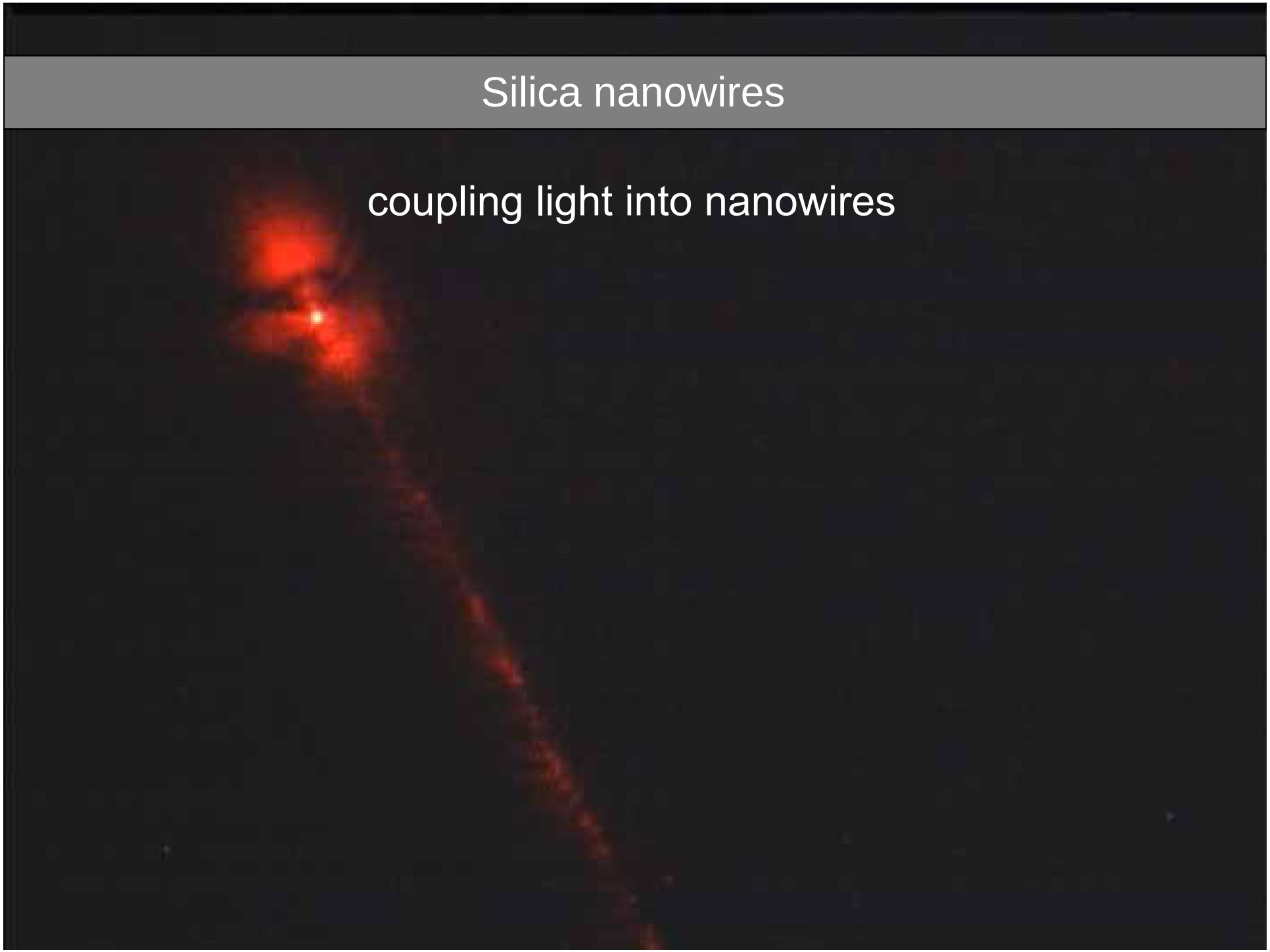


Silica nanowires



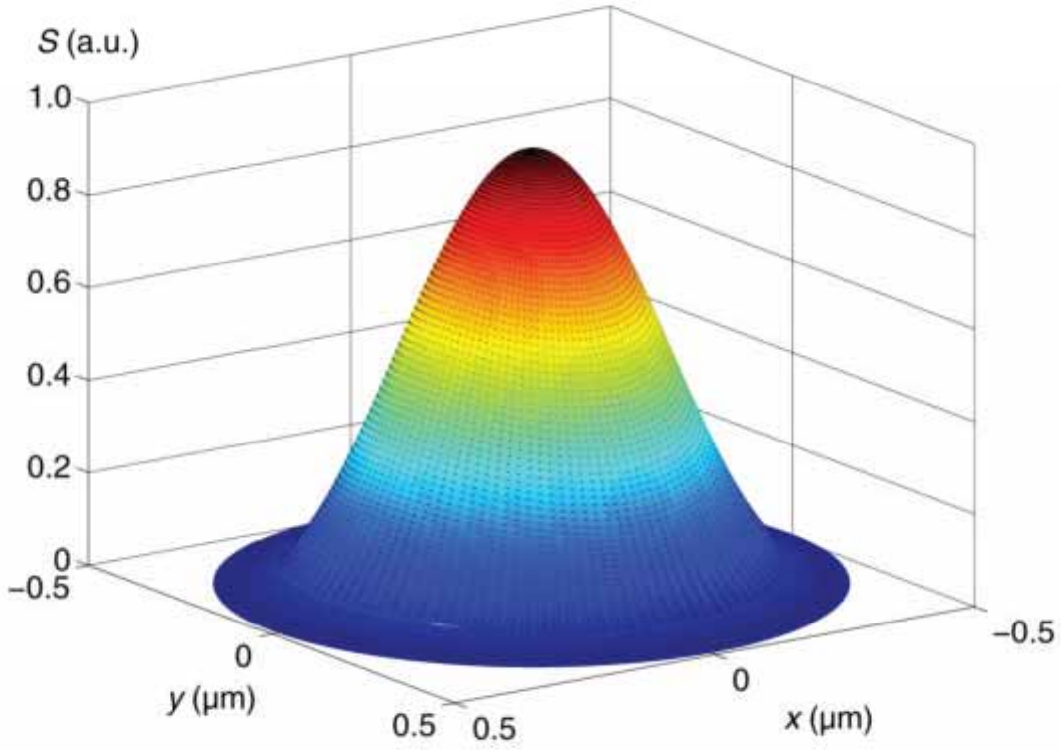
Silica nanowires

coupling light into nanowires



Silica nanowires

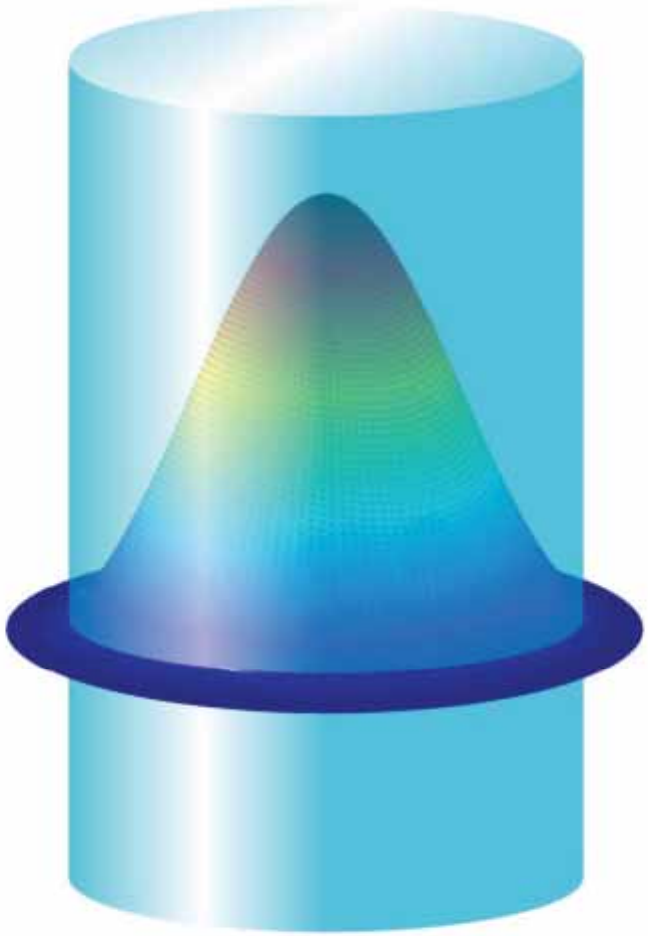
Poynting vector for 800 nm nanowires



Opt. Express 12, 1025-1035 (2004)

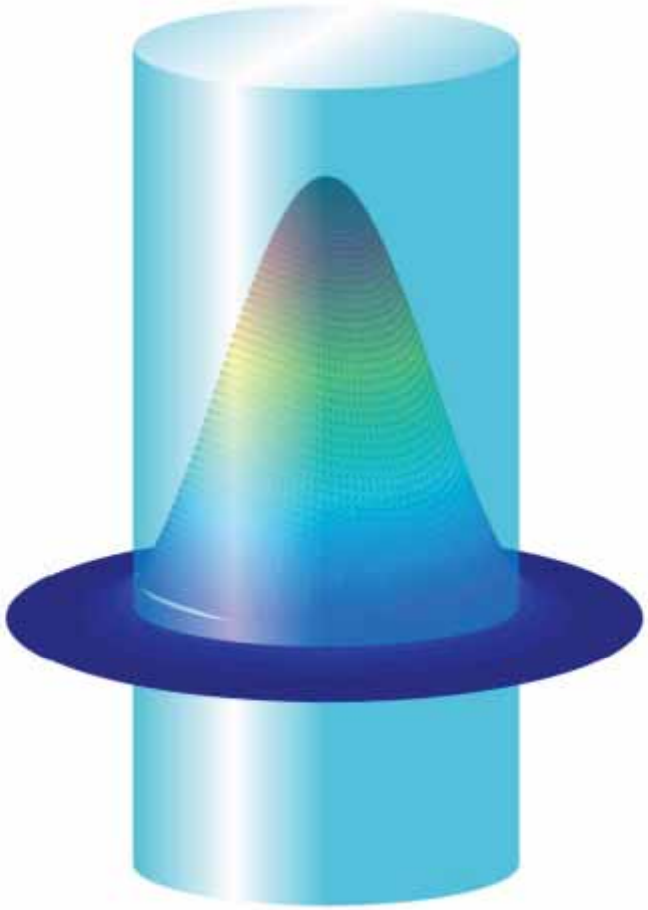
Silica nanowires

Poynting vector for 800 nm nanowires



Silica nanowires

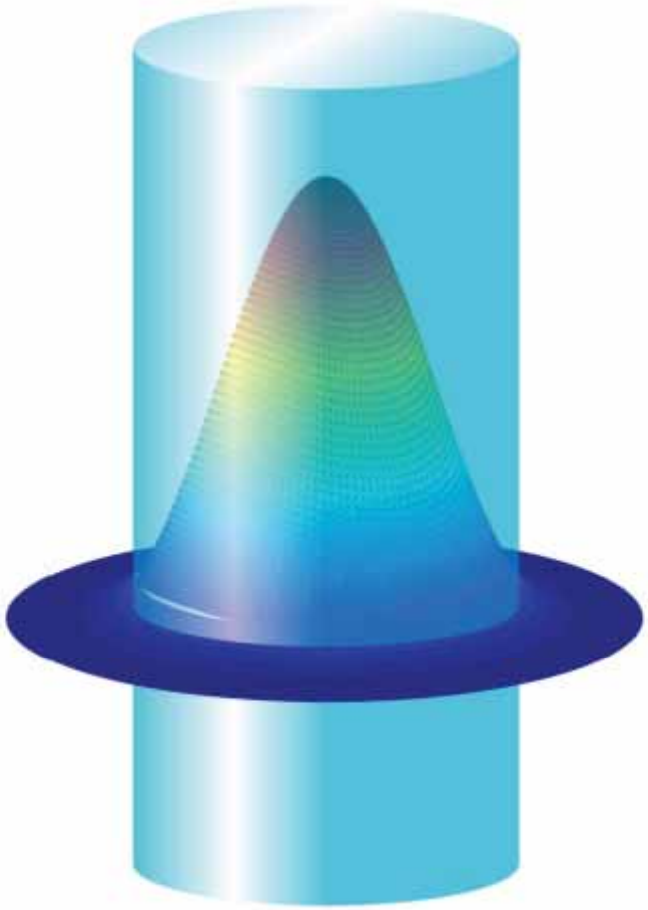
Poynting vector for 600 nm nanowires



Opt. Express 12, 1025-1035 (2004)

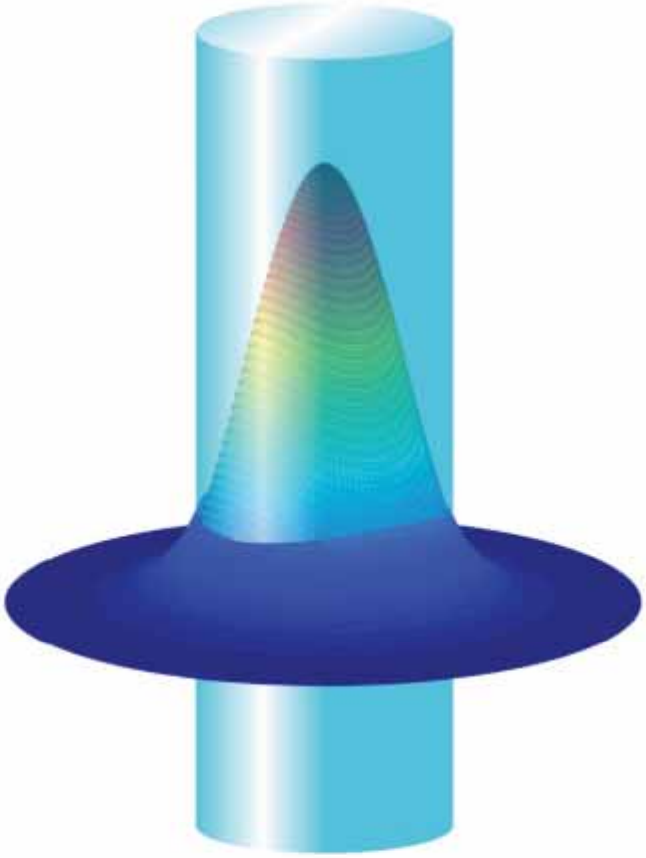
Silica nanowires

Poynting vector for 600 nm nanowires



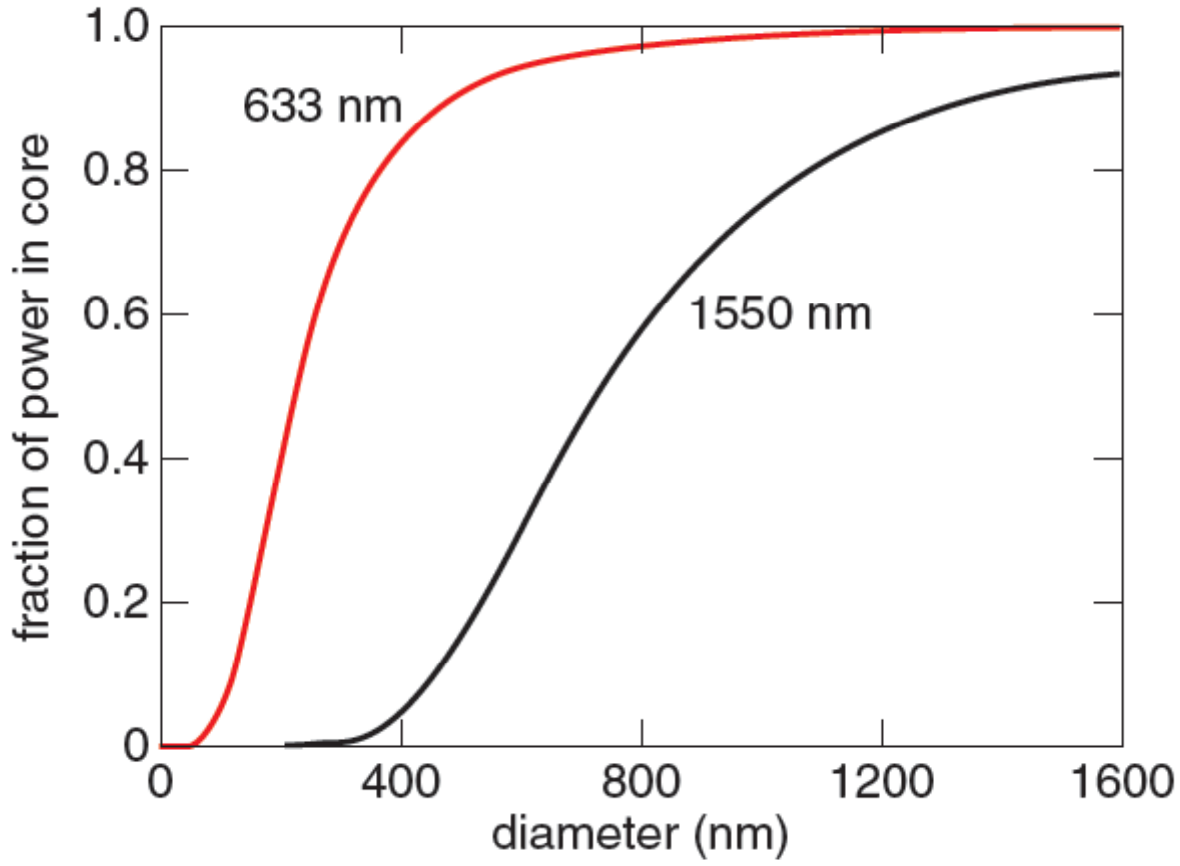
Silica nanowires

Poynting vector for 400 nm nanowires



Silica nanowires

Power fraction in the core of the nanowires



Opt. Express 12, 1025-1035 (2004)

Silica nanowires

Manipulating the nanowires

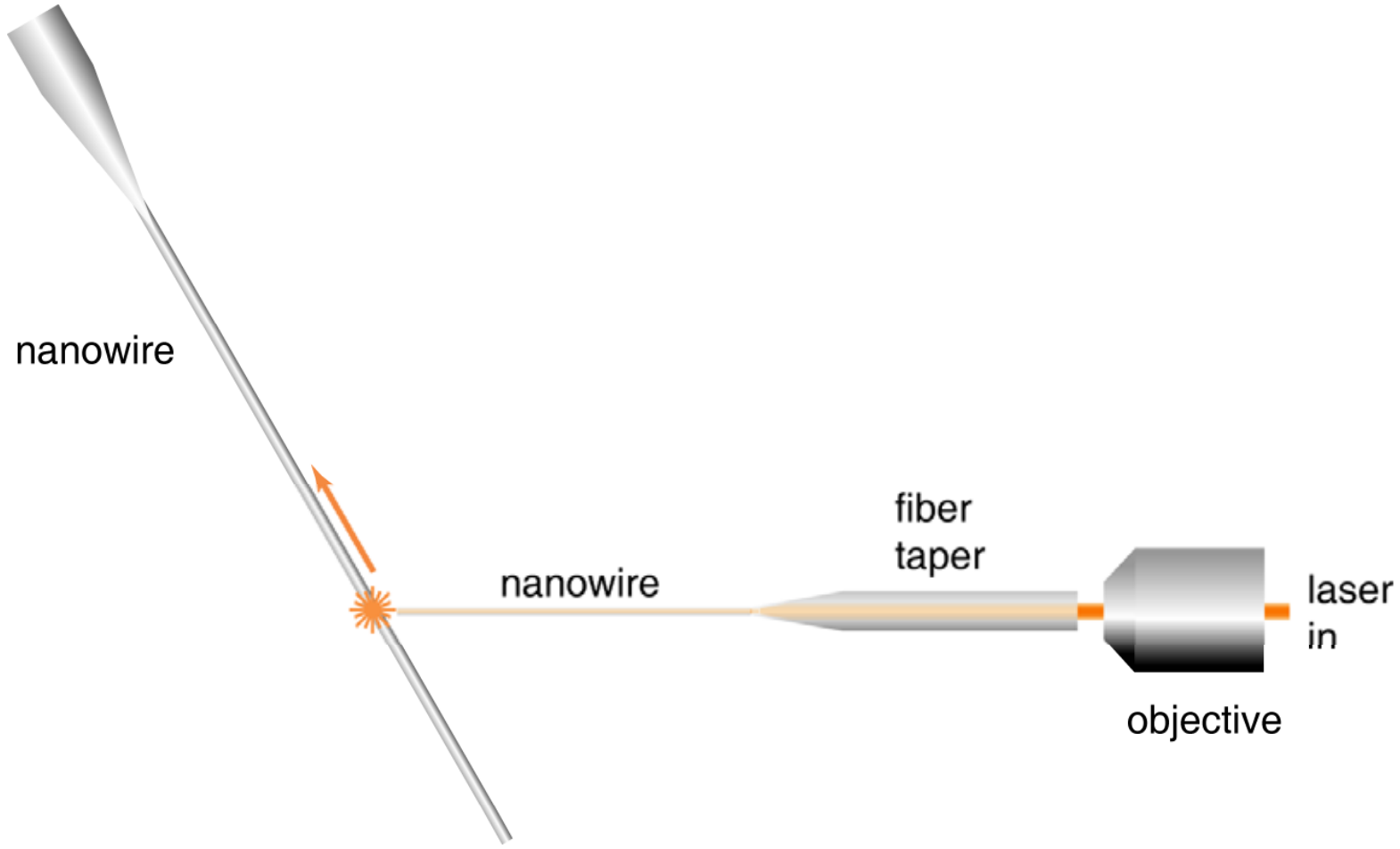
Silica nanowires

Silica nanowires

Silica nanowires

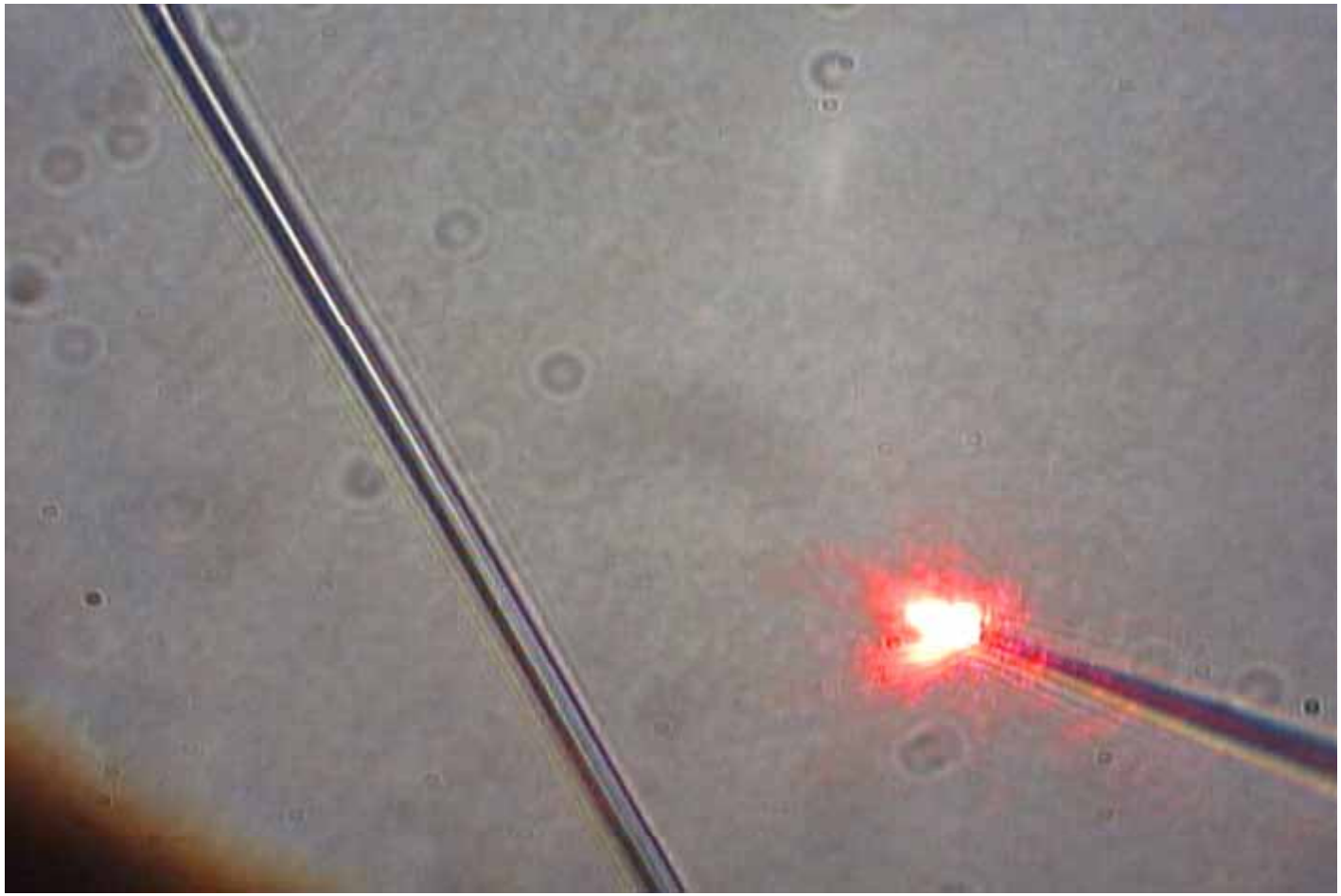
Silica nanowires

coupling light into nanowires



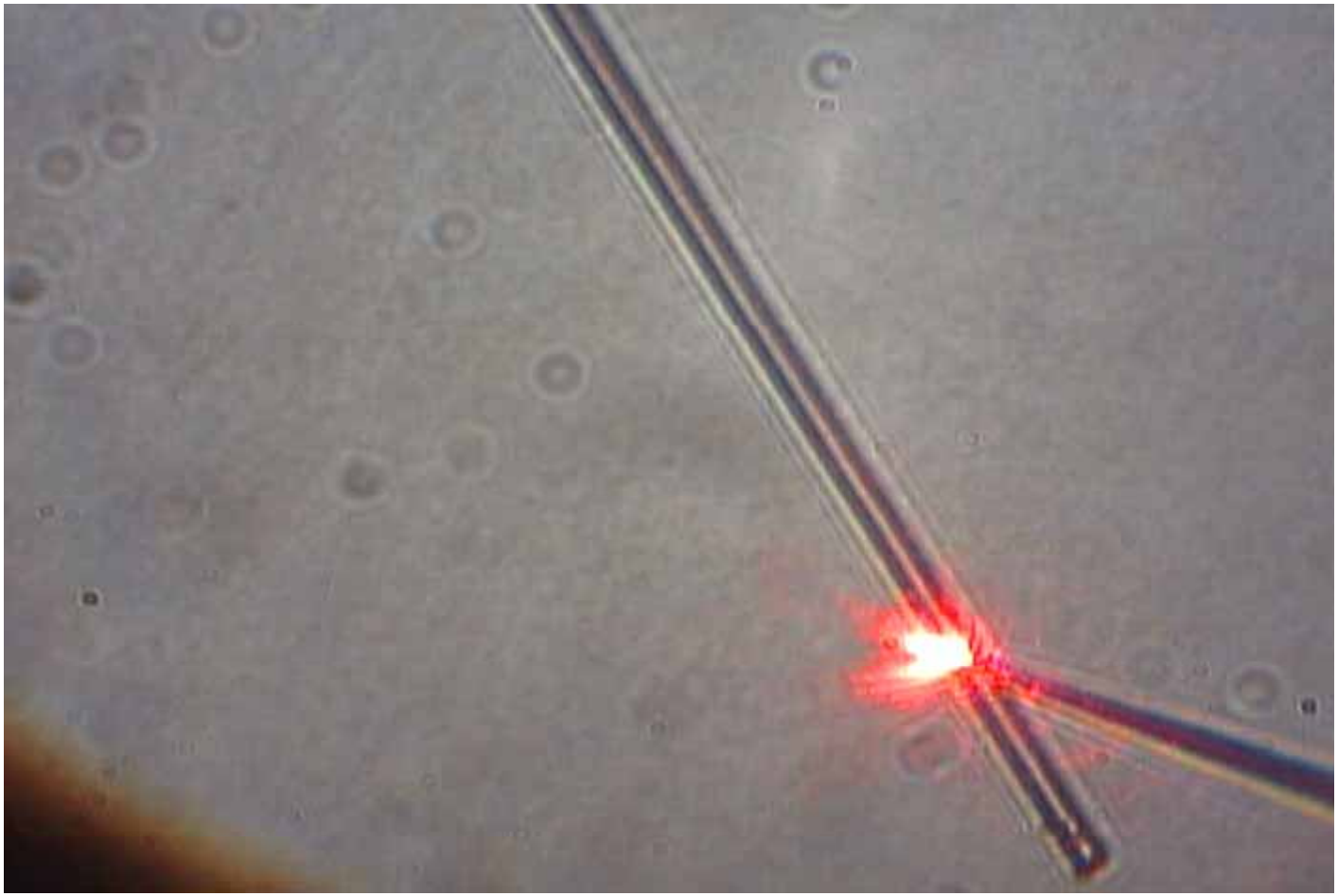
Silica nanowires

coupling light into nanowires

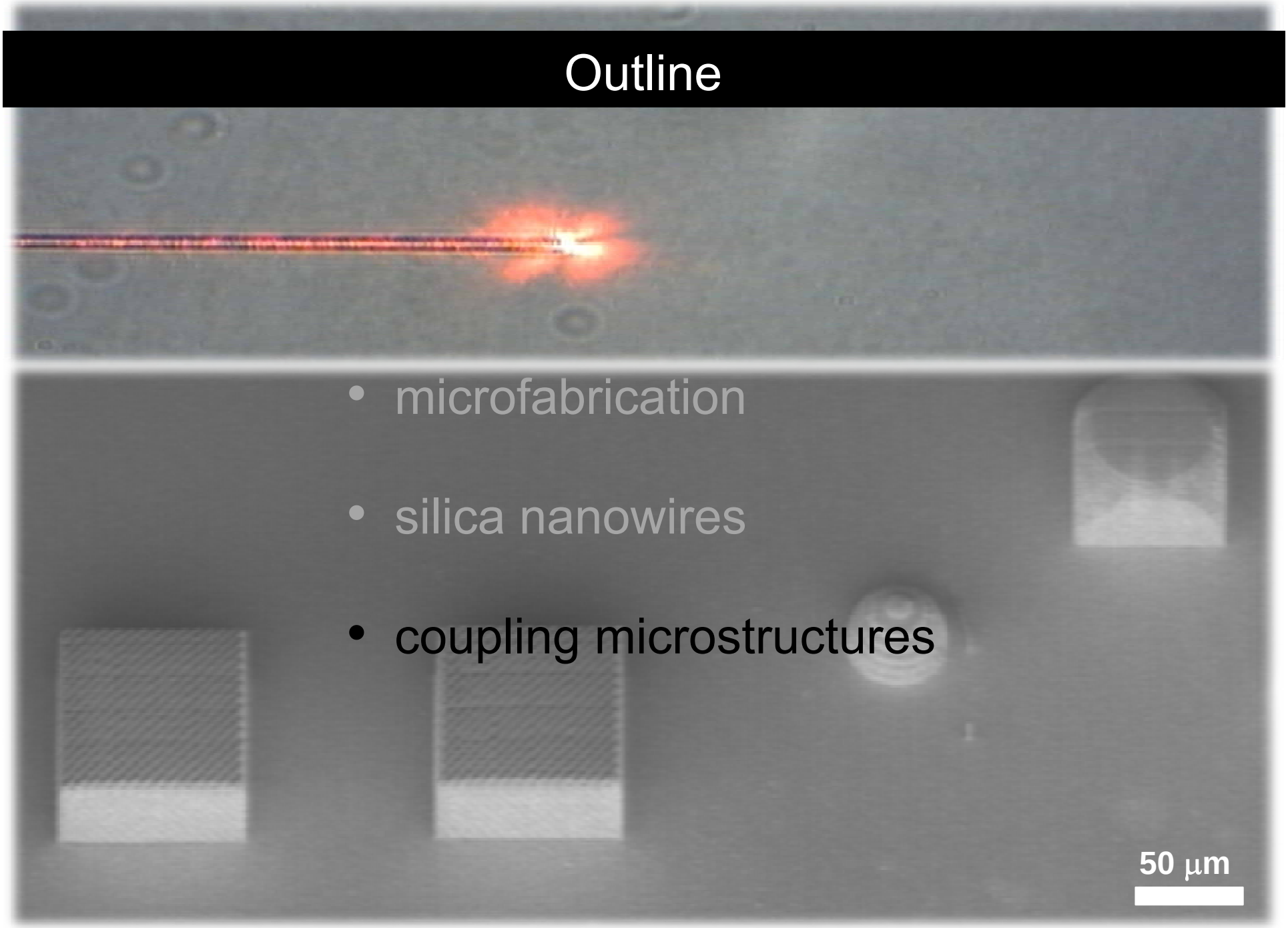


Silica nanowires

coupling light into nanowires

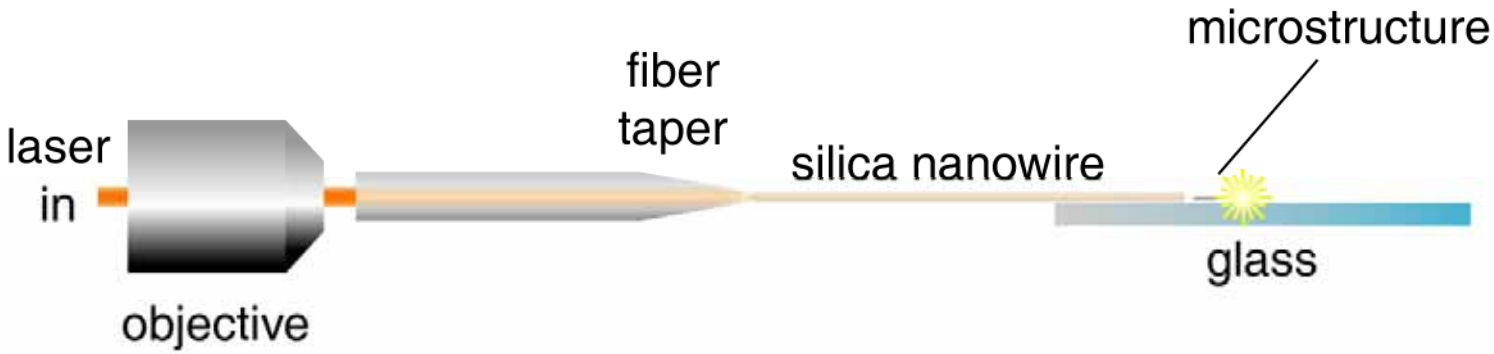


Outline

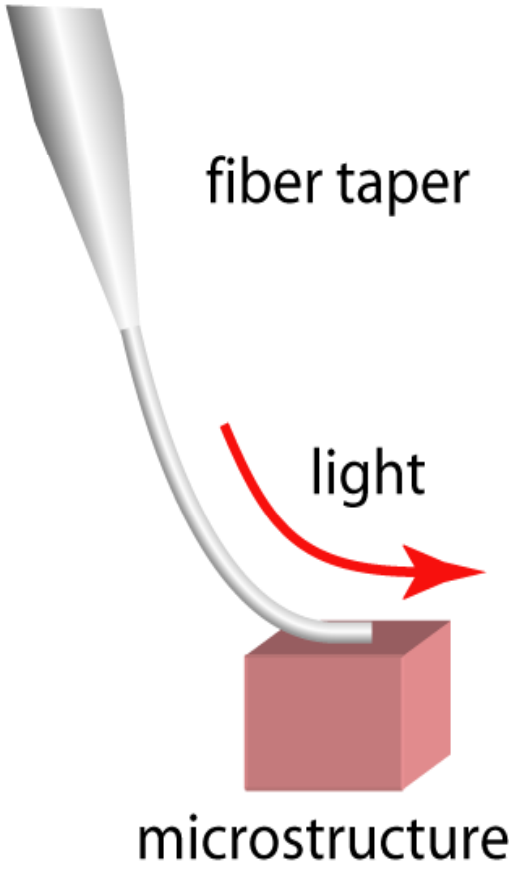


- microfabrication
- silica nanowires
- coupling microstructures

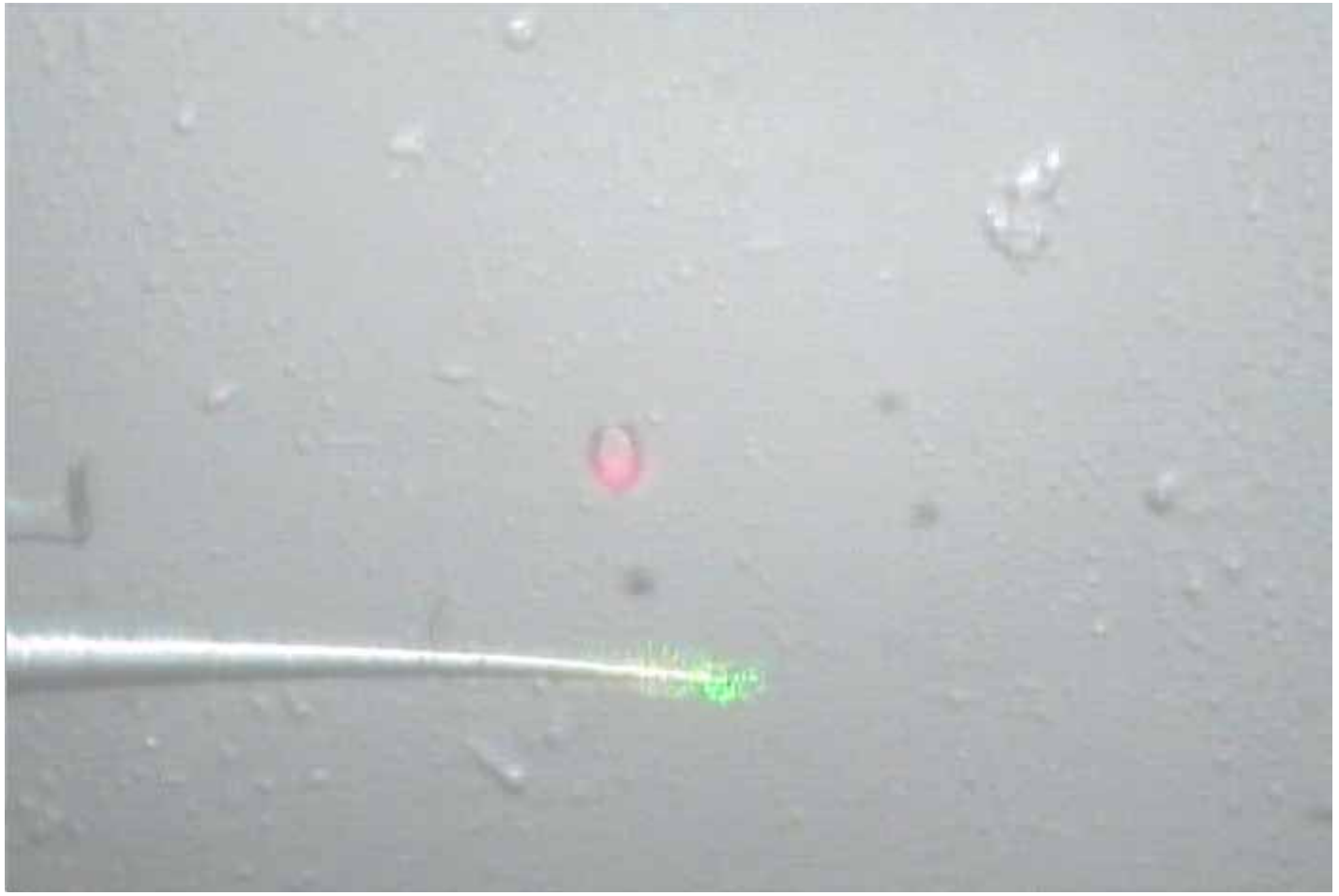
Coupling microstructures



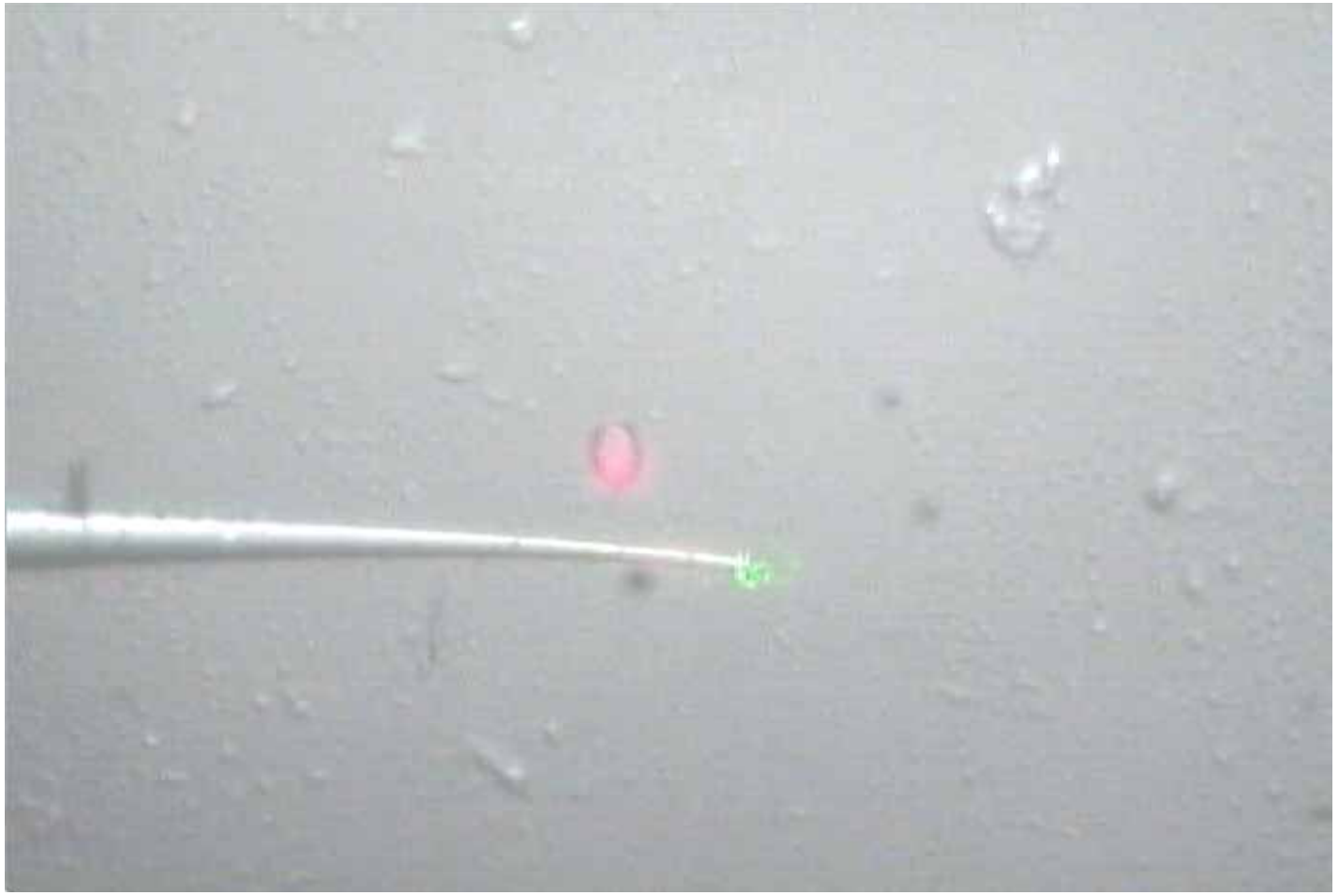
Coupling microstructures



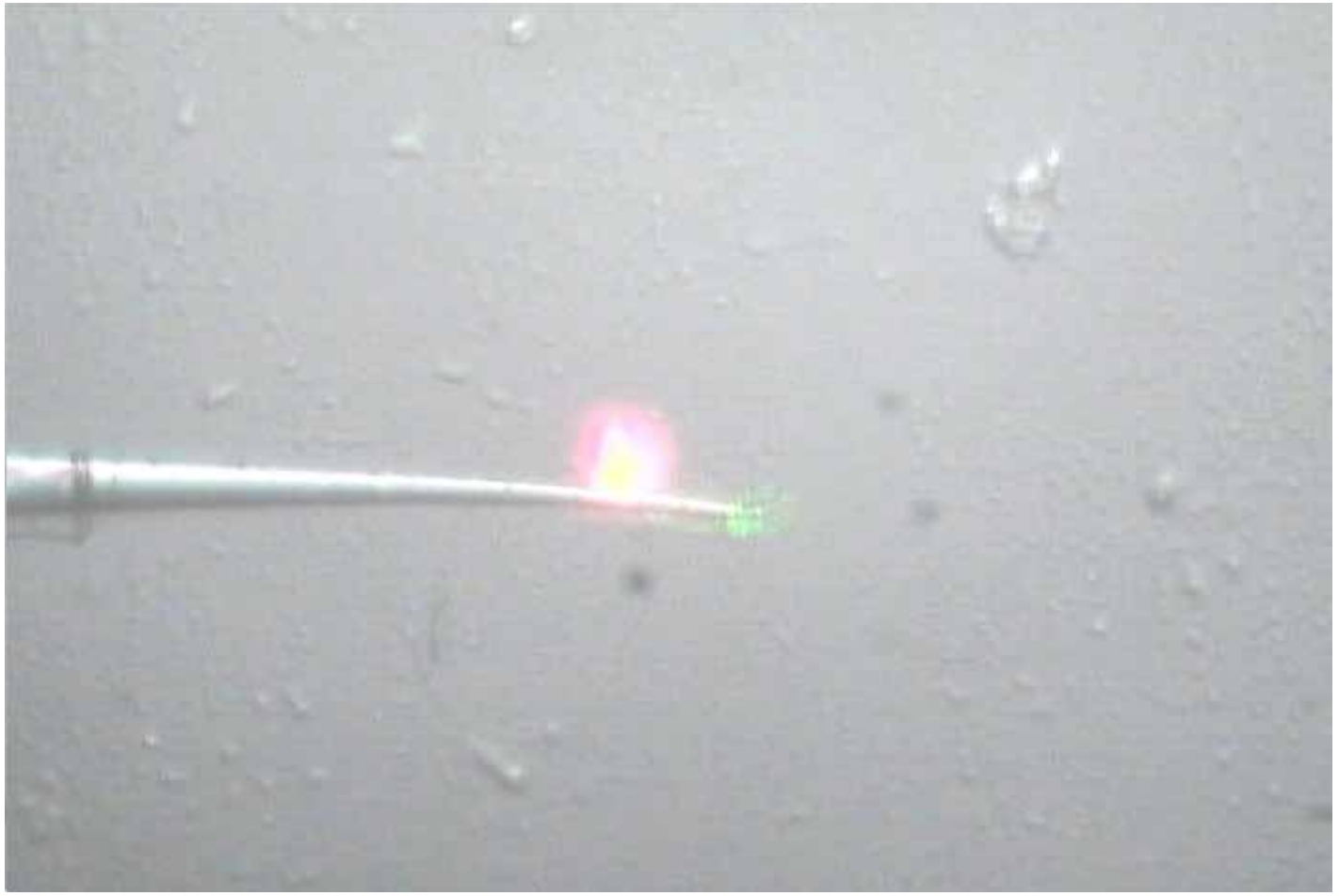
Coupling microstructures



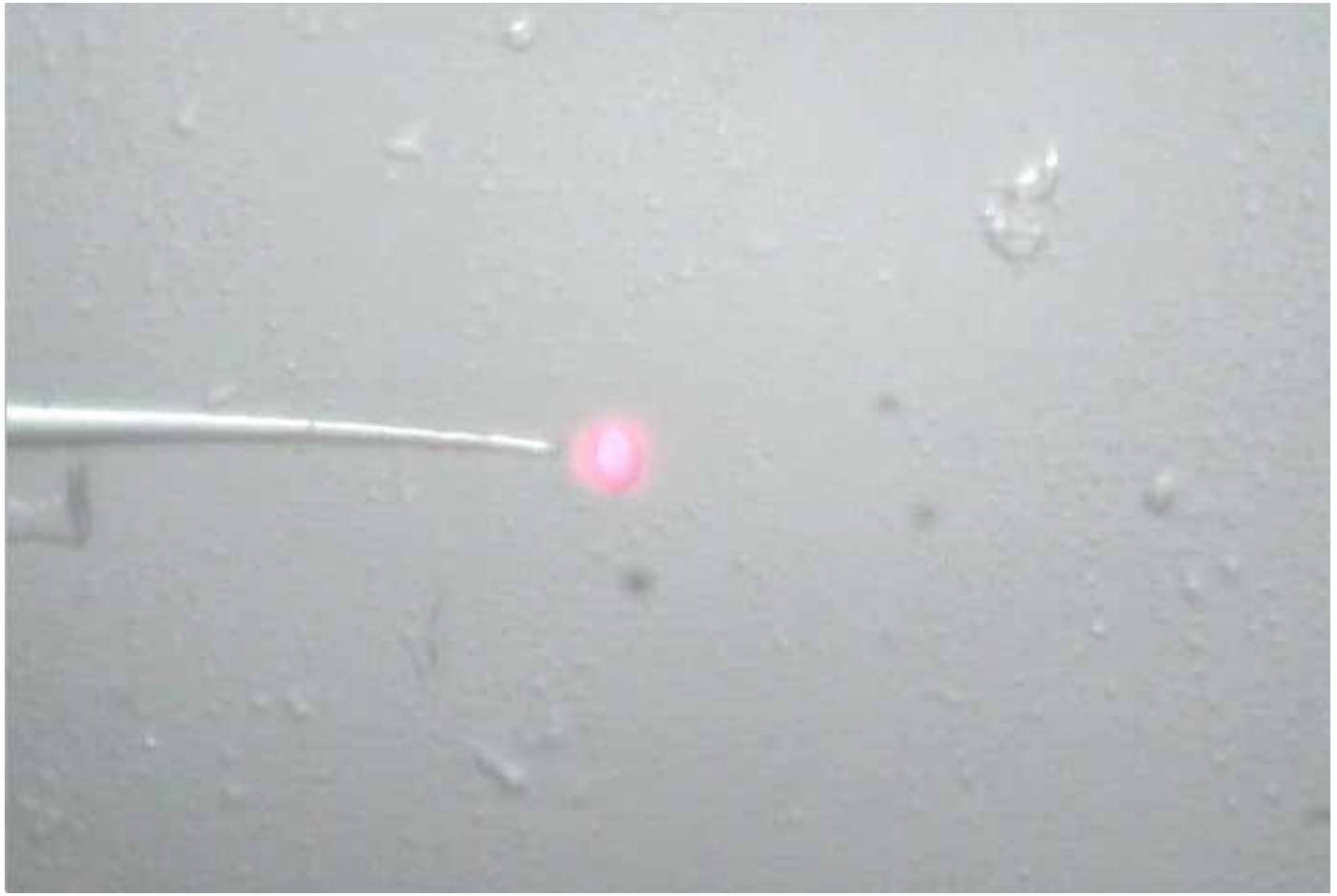
Coupling microstructures



Coupling microstructures



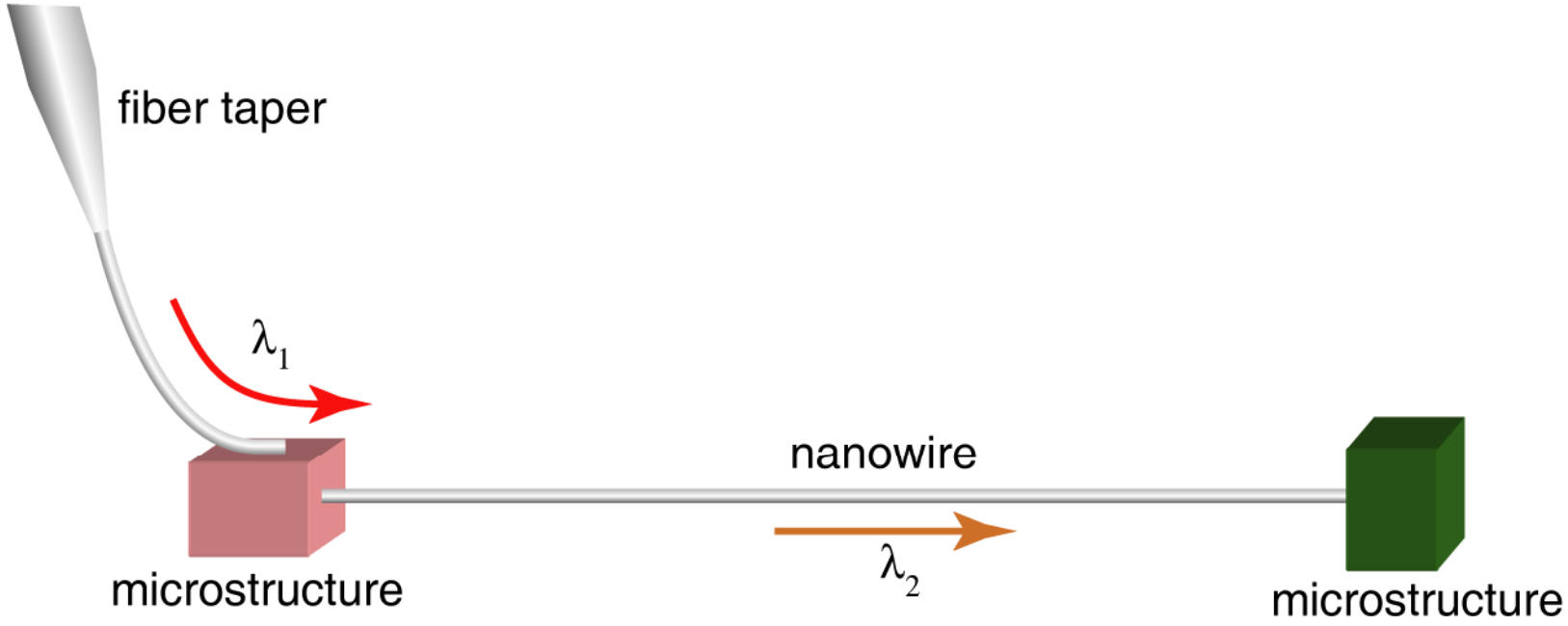
Coupling microstructures



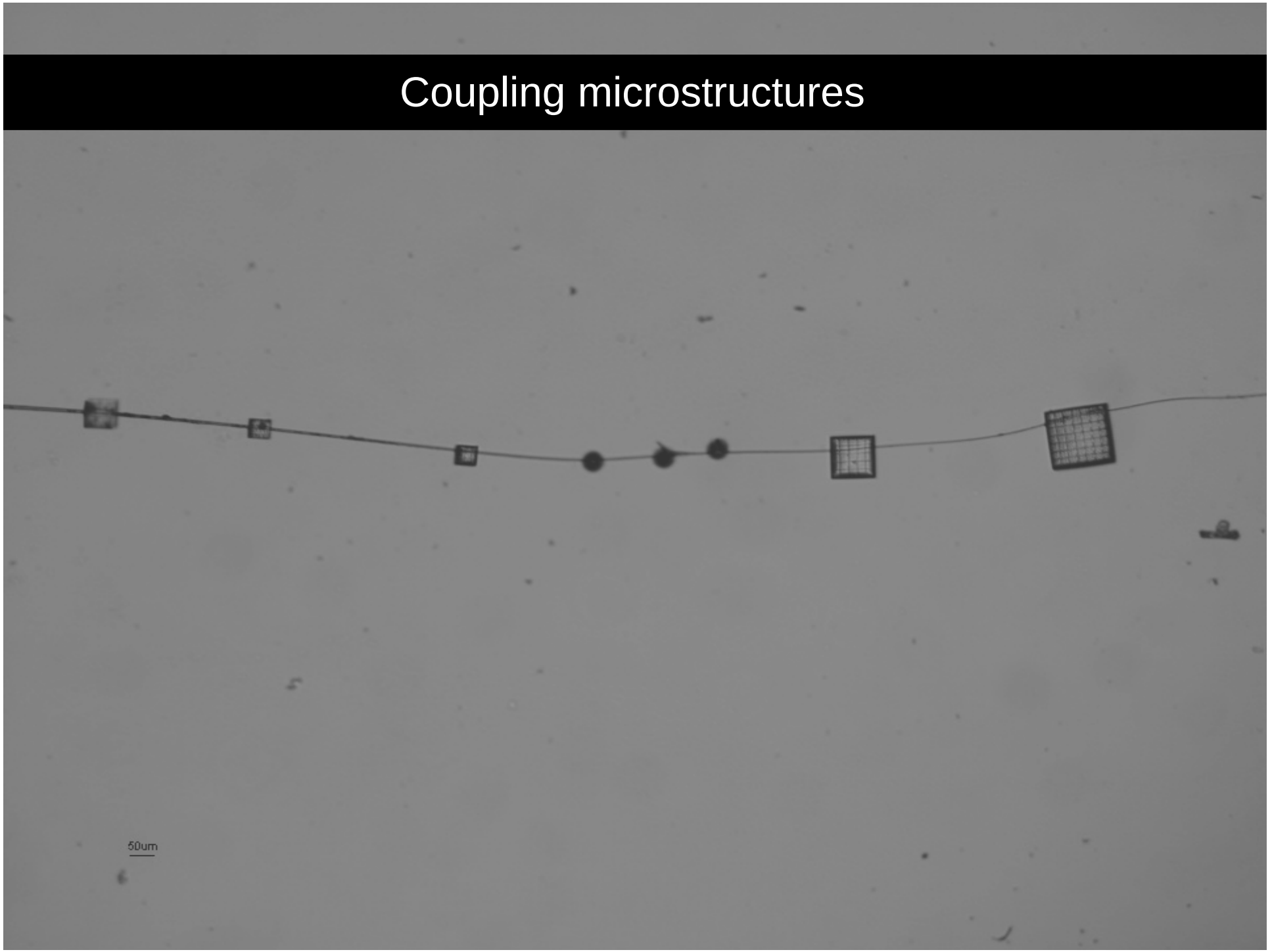
Coupling microstructures

Silica nanowires

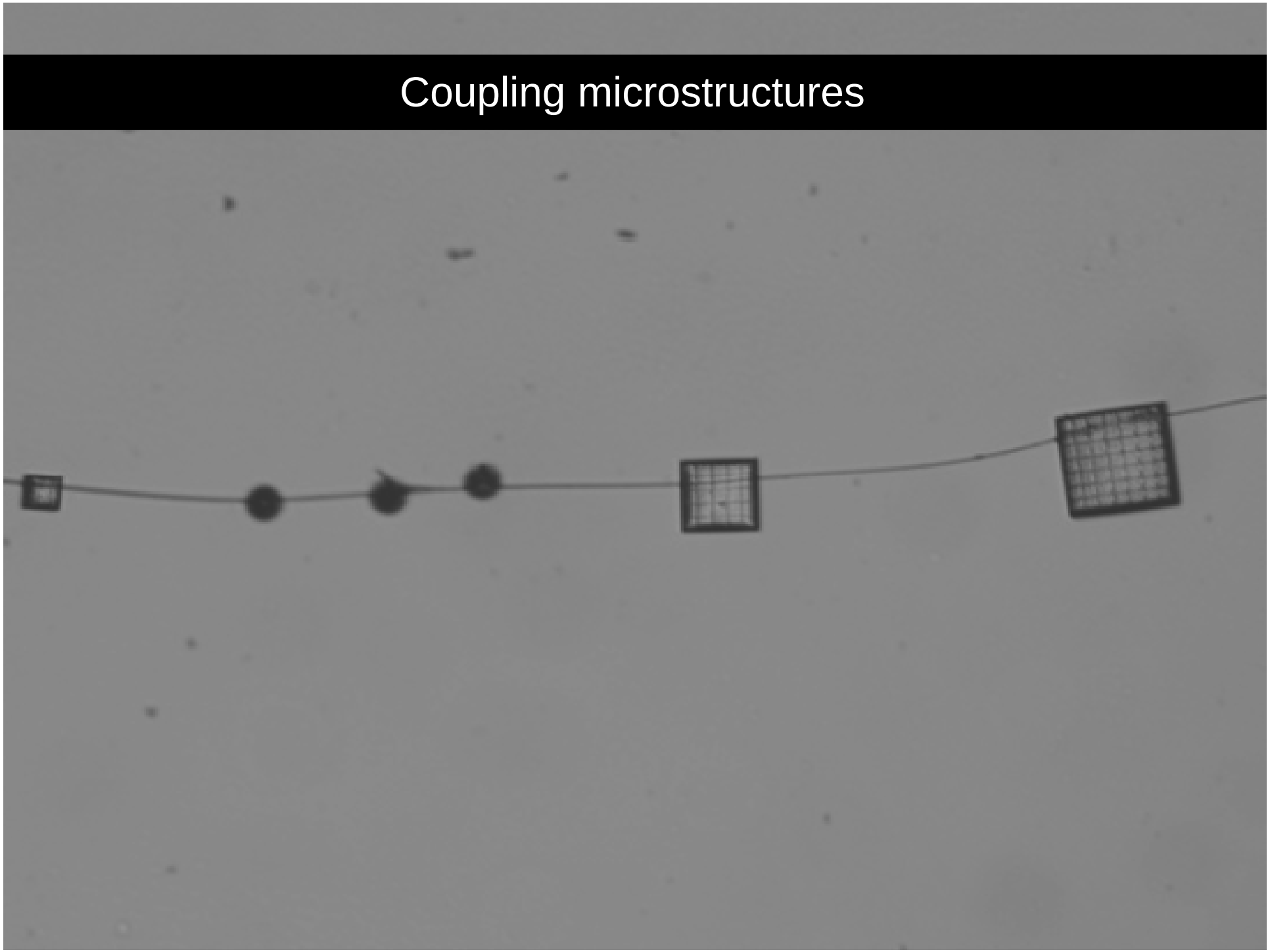
Coupling microstructures



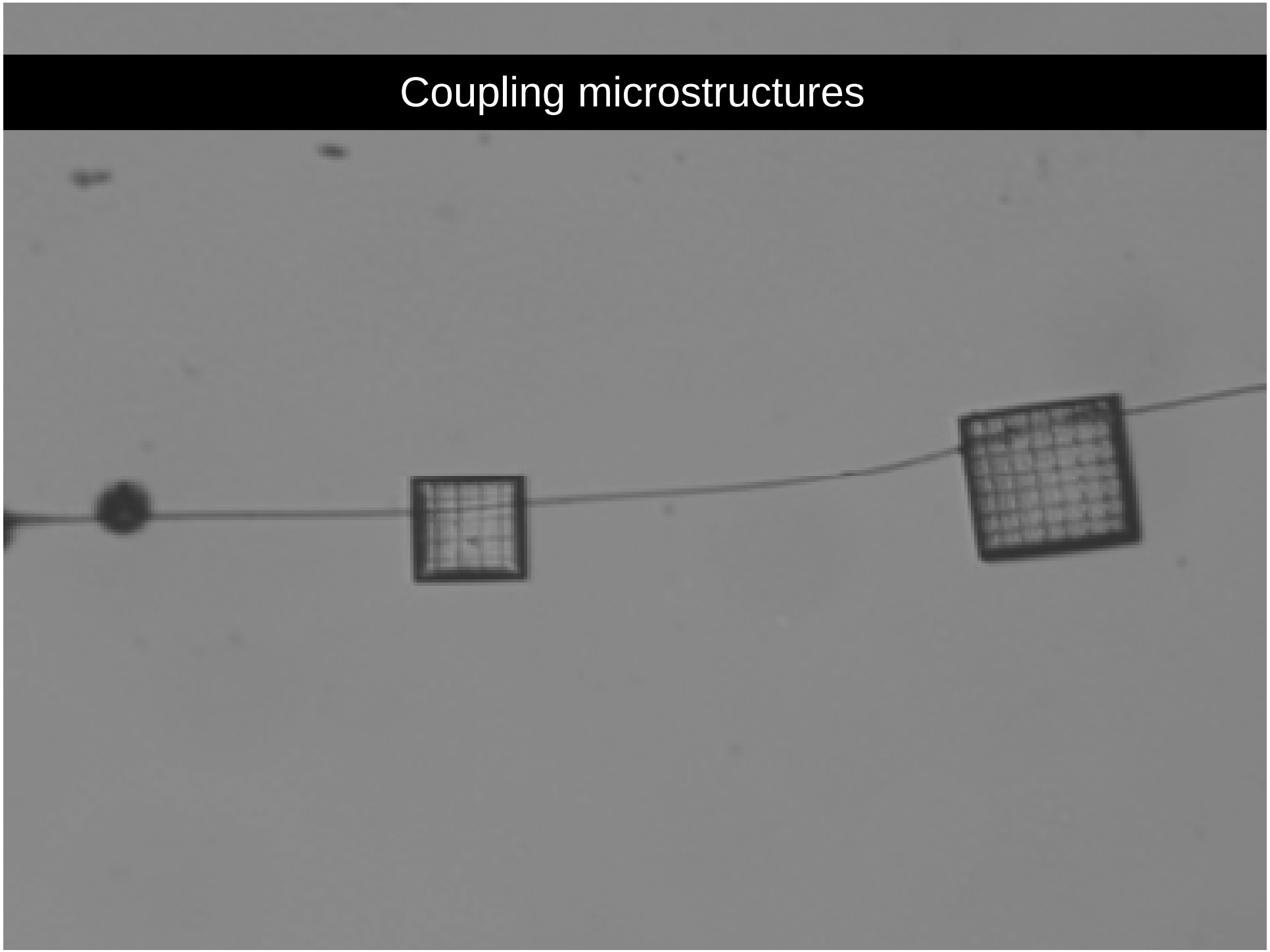
Coupling microstructures



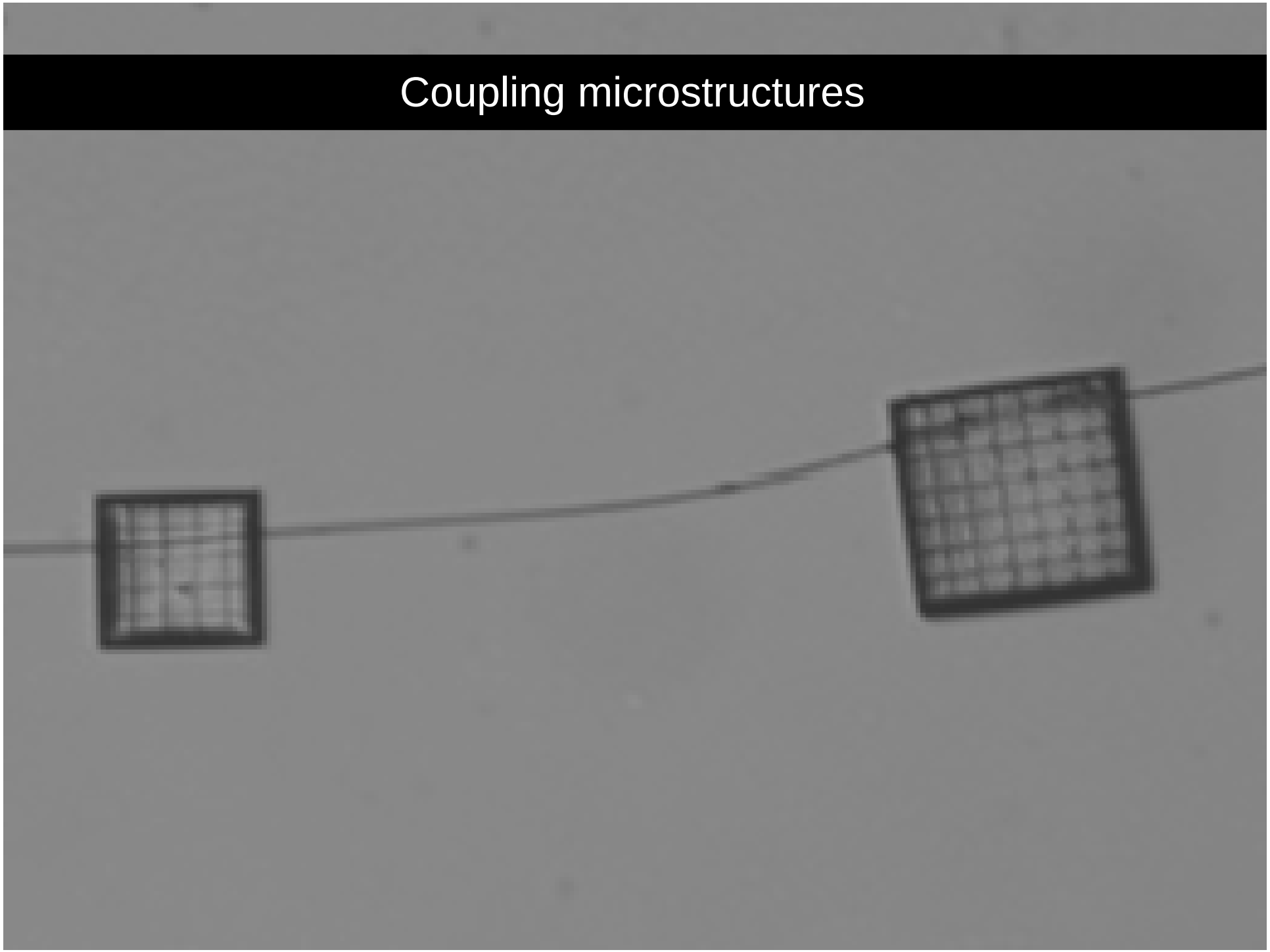
Coupling microstructures



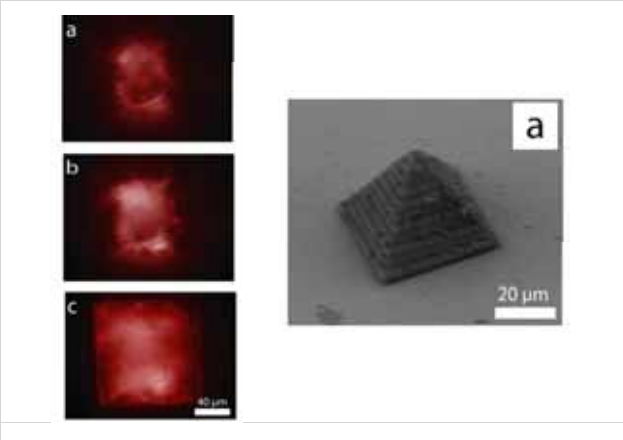
Coupling microstructures

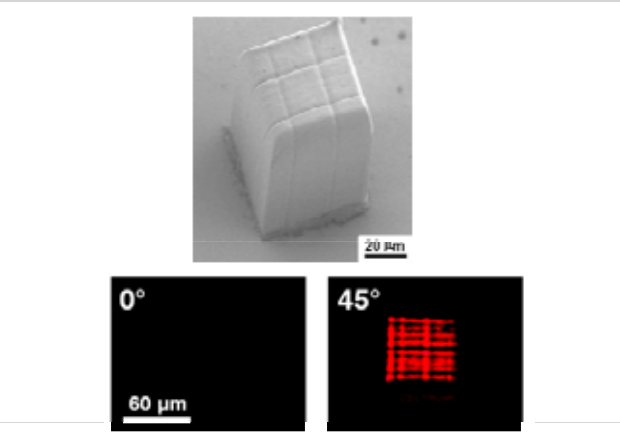


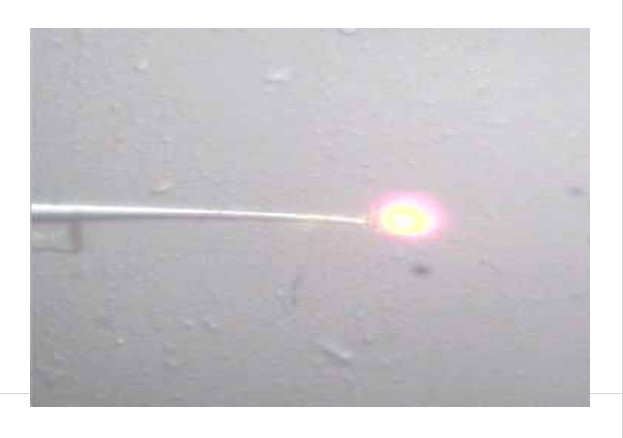
Coupling microstructures

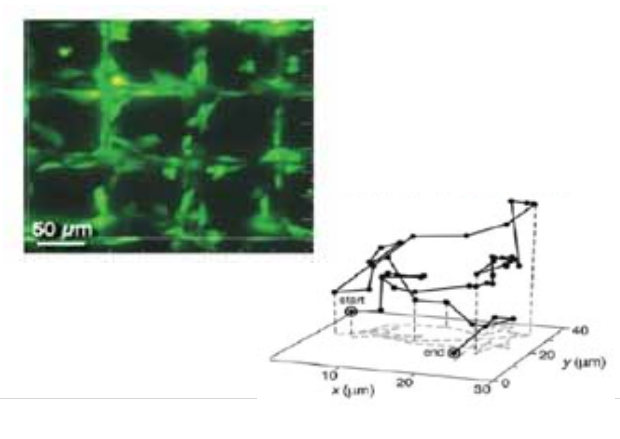


Summary









Acknowledgments

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