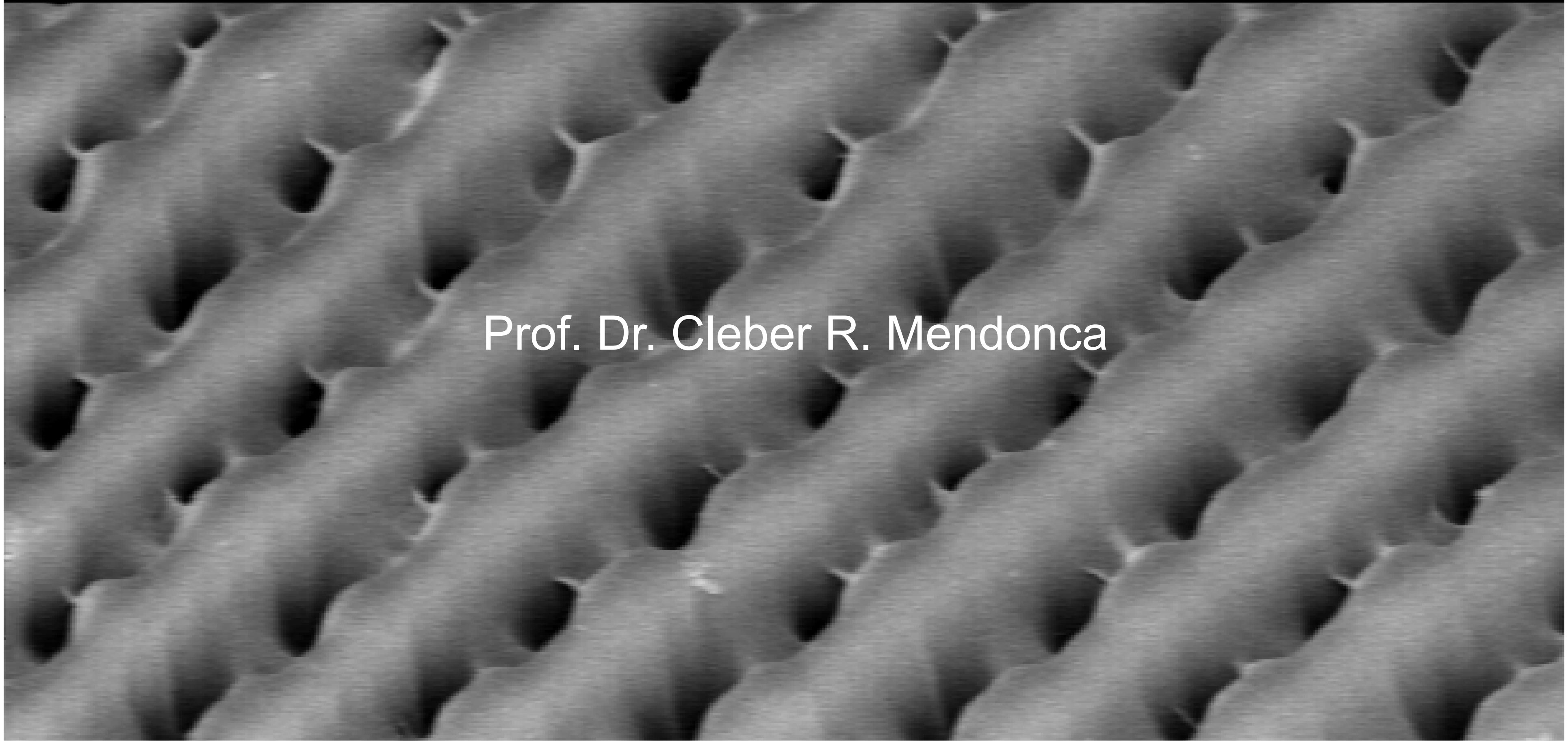
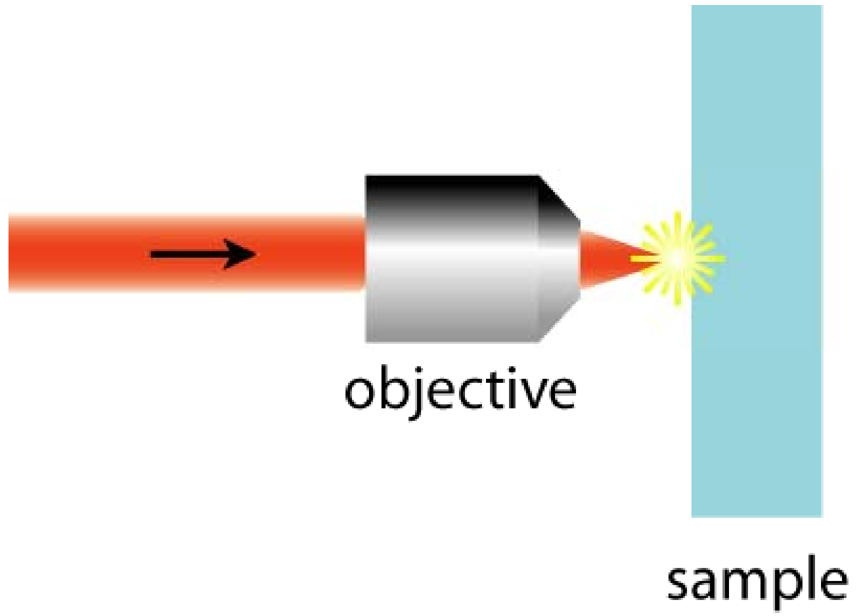
Femtosecond laser microfabrication in polymers



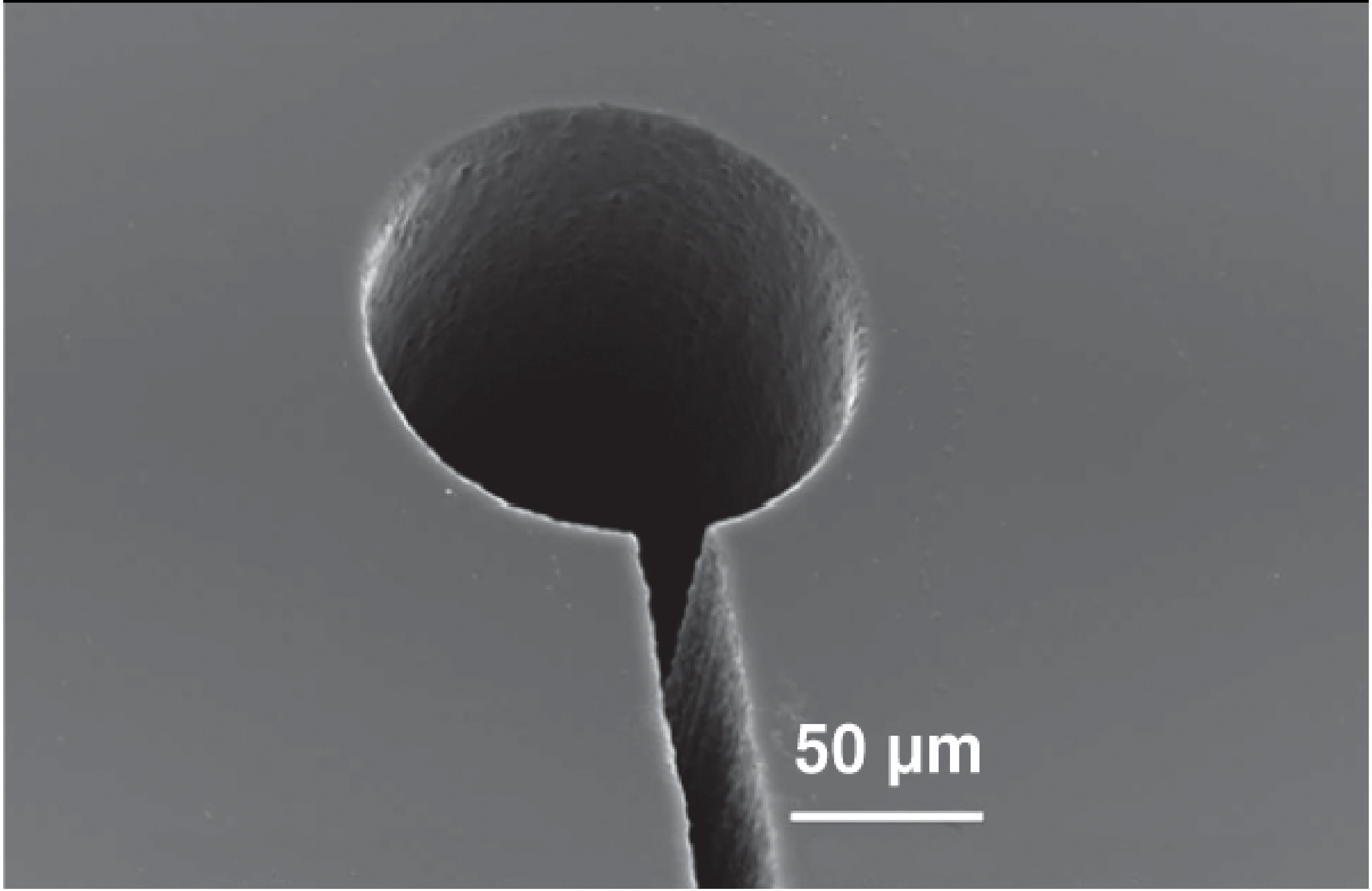
Prof. Dr. Cleber R. Mendonca

laser microfabrication

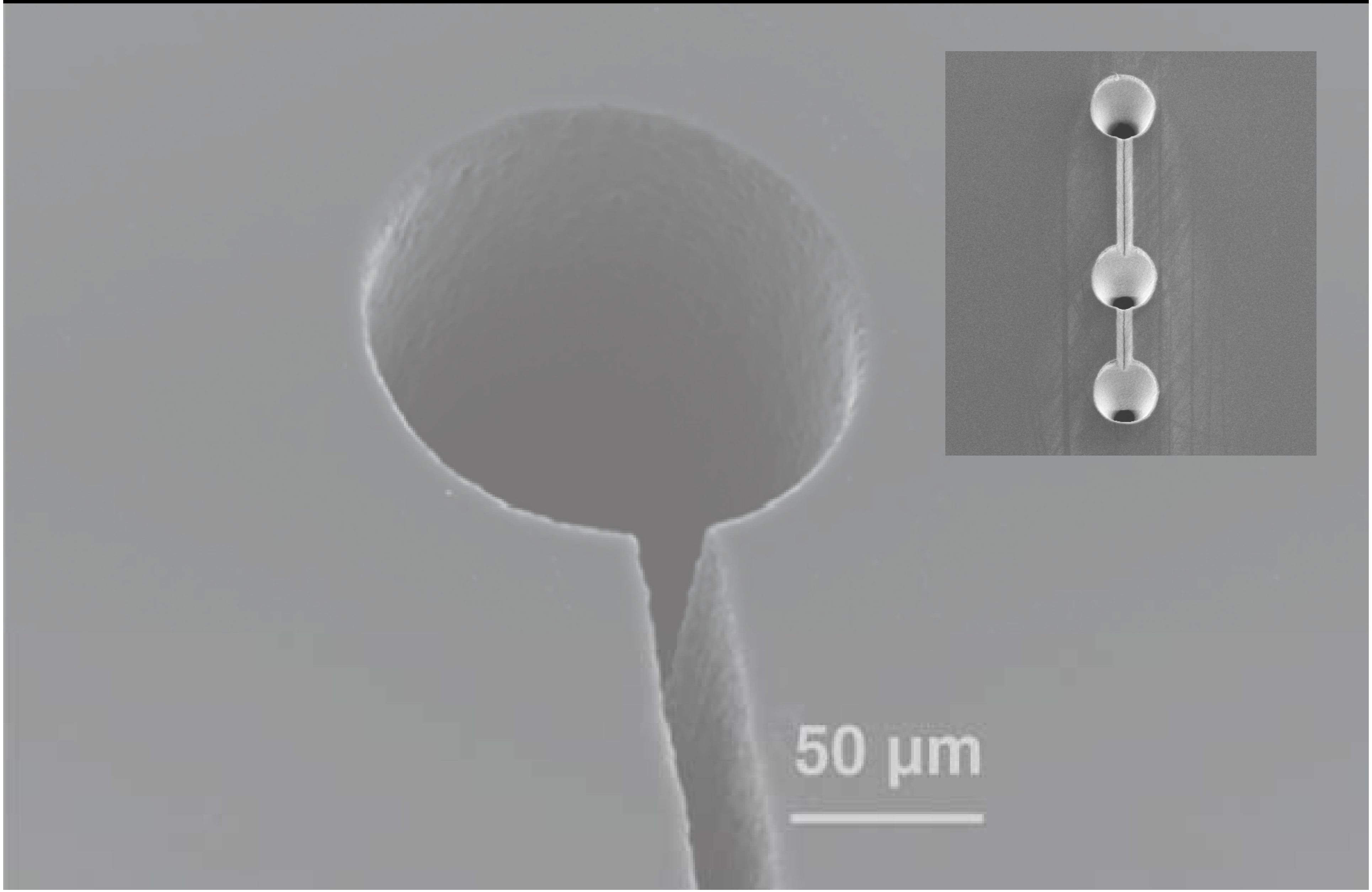
focus laser beam on material's surface



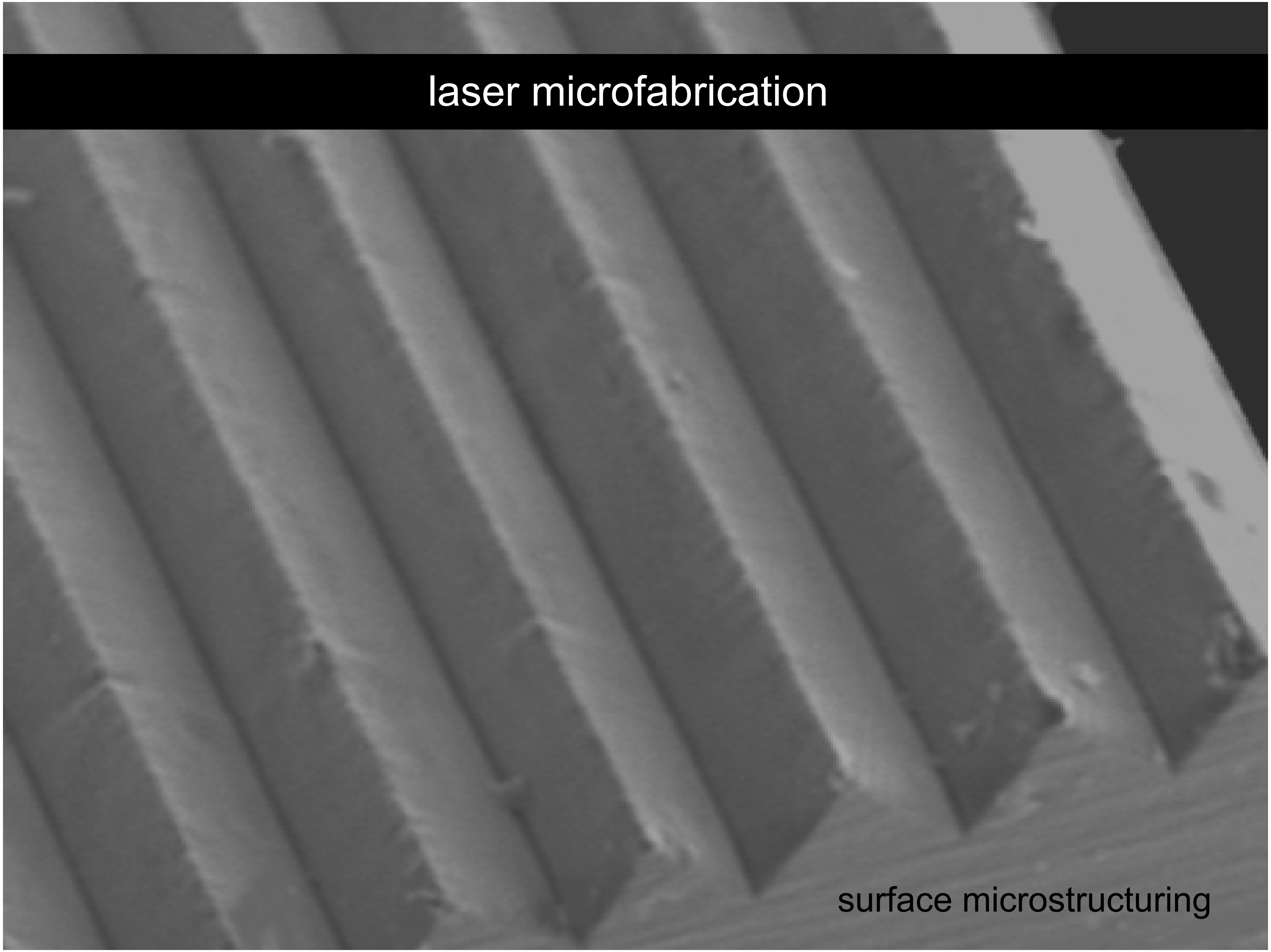
laser microfabrication



laser microfabrication



laser microfabrication



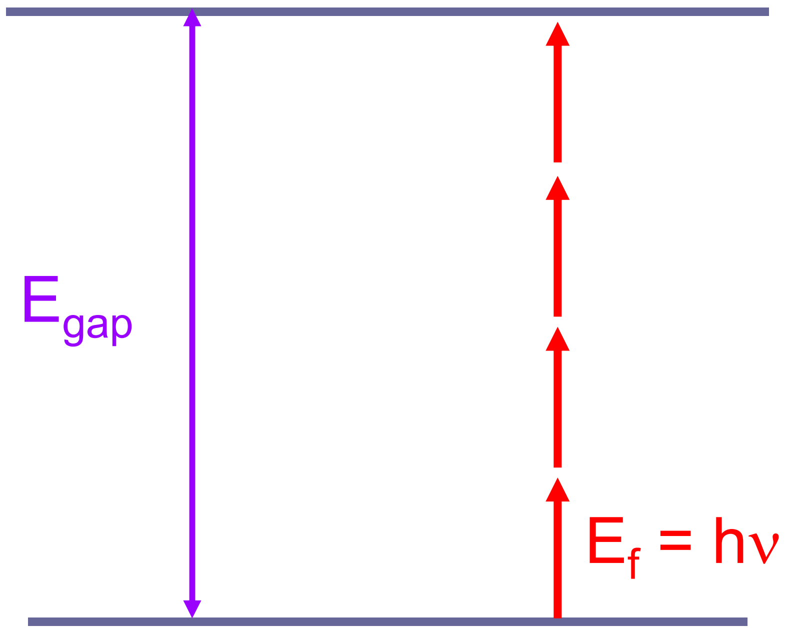
fs-micromachining

photon energy < bandgap

nonlinear interaction

fs-micromachining

nonlinear interaction



multiphoton absorption

introduction

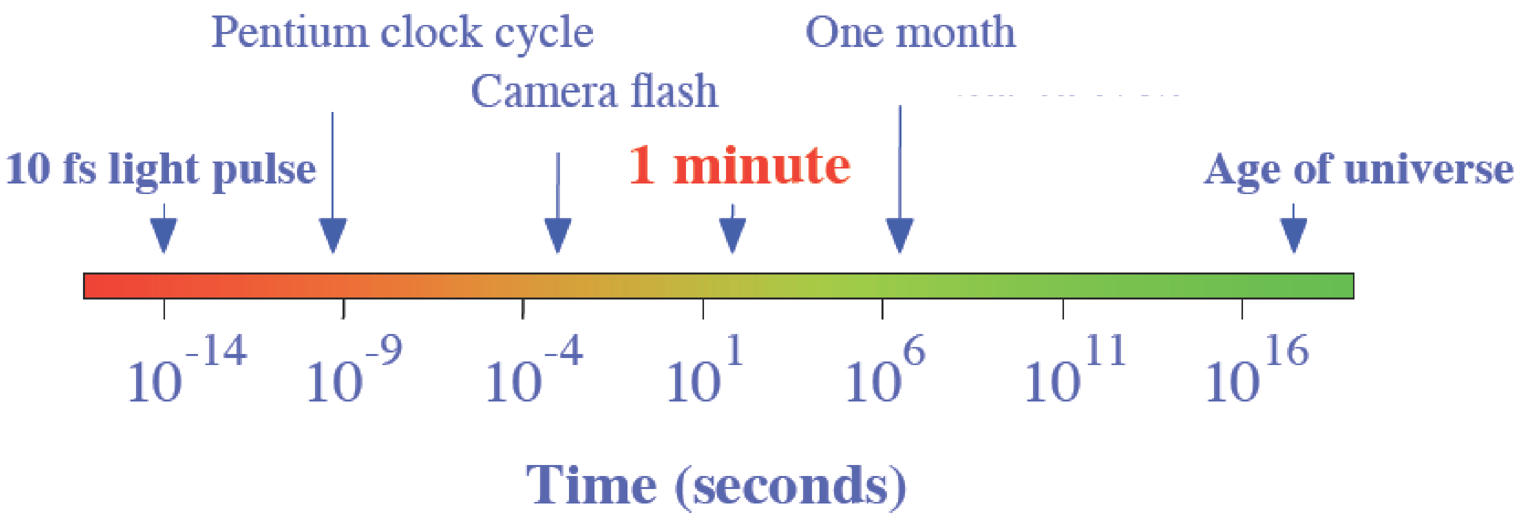
short pulse duration → high intensity

(even at low energy)

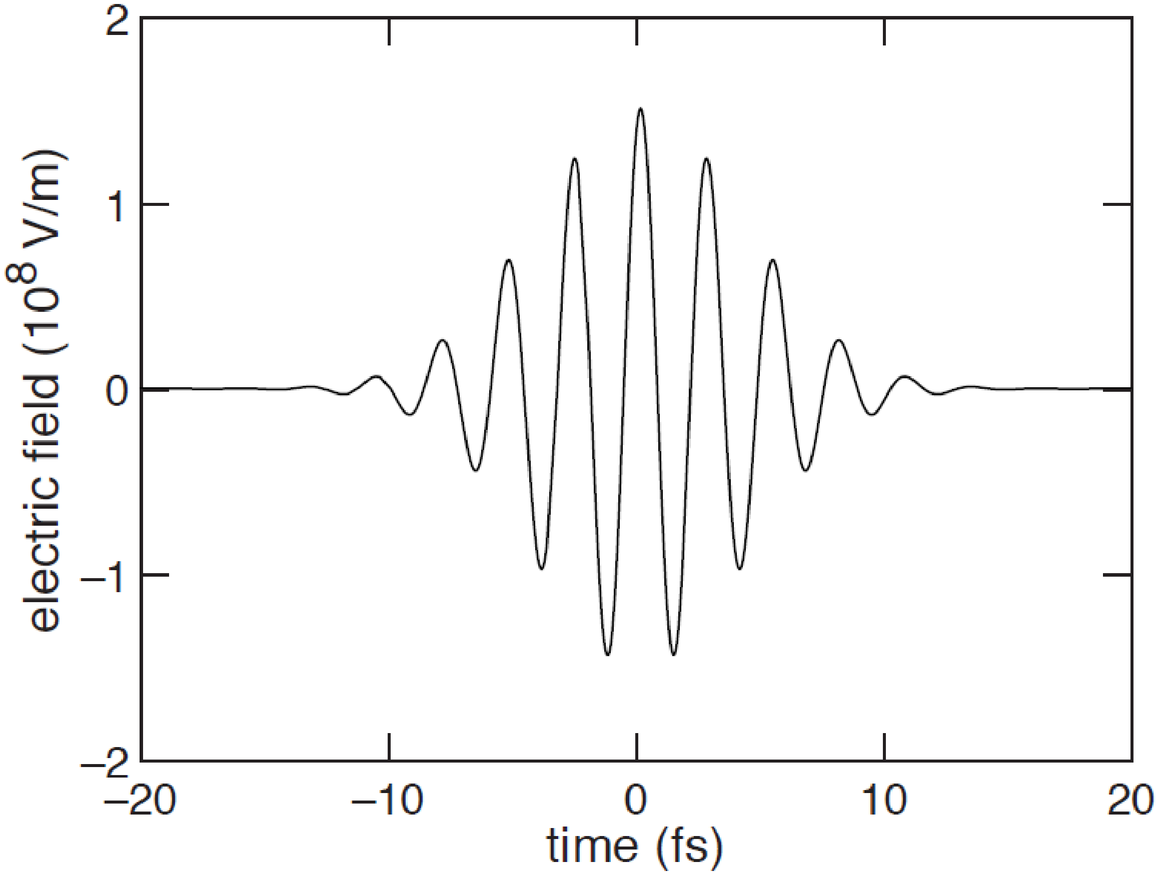
introduction

how short is a femtosecond pulse ?

1 fs = 10^{-15} s

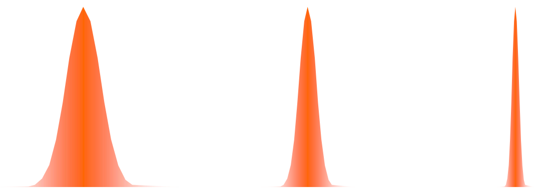


how short is a femtosecond pulse ?



introduction

Ti:Sapphire lasers



100 fs 50 fs 20 fs

Very intense light

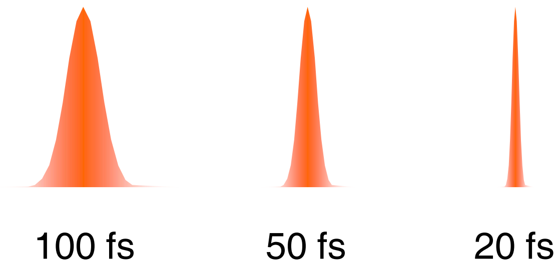
Laser intensities ~ 100 GW/cm^2

1 x 10^{11}W/cm^2

Laser pointer: 1 mW/cm^2 (1 x10^{-3} W/ cm^2)

introduction

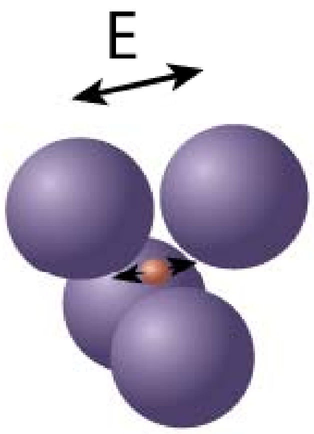
Ti:Sapphire lasers



Very intense light

Nonlinear Optical Phenomena

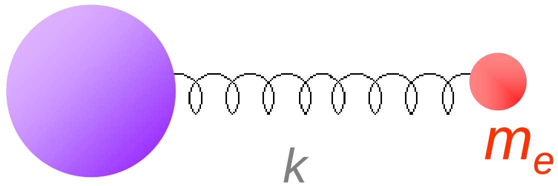
Light matter interaction



harmonic oscillator

Semiclassical treatment

electron on a spring



oscillation frequency

$$\omega_0 = \sqrt{\frac{k}{m_e}}$$

Linear optical processes

$E_{radiation} << E_{interatomic}$

Induced polarization

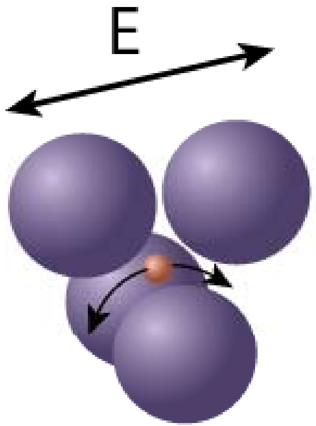
$$P = \chi E$$ linear response

absorption $\alpha = \alpha(\lambda)$

refraction $n = n(\lambda)$

independent of the light intensity

Nonlinear optical processes



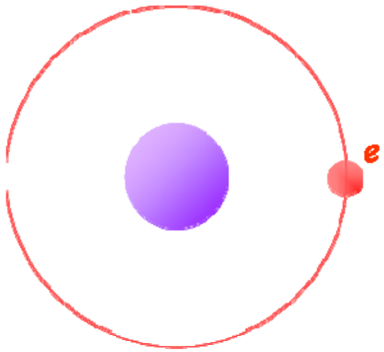
high light intensity

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

How high should be the light intensity ?

Nonlinear Optics

Inter-atomic electric field



$e = 1.6 \times 10^{-19}$ C
$r \sim 4$ Å

$E \sim 1 \times 10^{10}$ V/m

cw laser

P = 20 W
$w_o = 20\ \mu m$

$$I = \frac{2P}{\pi w_0^2}$$

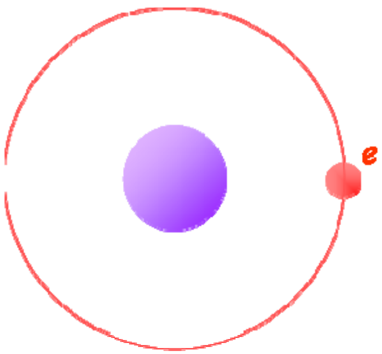
$I = 3 \times 10^{10}$ W/m^2

$$I = \frac{1}{2} c n \varepsilon_0 E_0^2$$

$E_o = 4 \times 10^6$ V/m

Nonlinear Optics

Inter-atomic electric field



e = 1.6×10^{-19} C
r ~ 4 Å

E ~ 1×10^{10} V/m

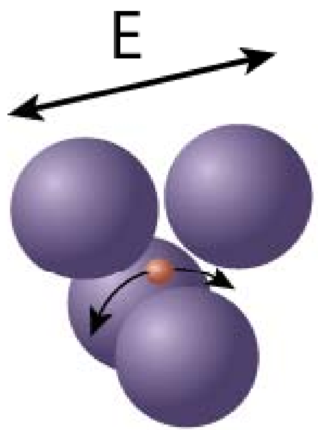
pulsed laser

I = 10 GW/cm^2 =
10×10^{13} W/m^2

$$I = \frac{1}{2} c n \varepsilon_0 E_0^2$$

E_o= 1×10^8 V/m

Nonlinear Optics



anharmonic oscillator

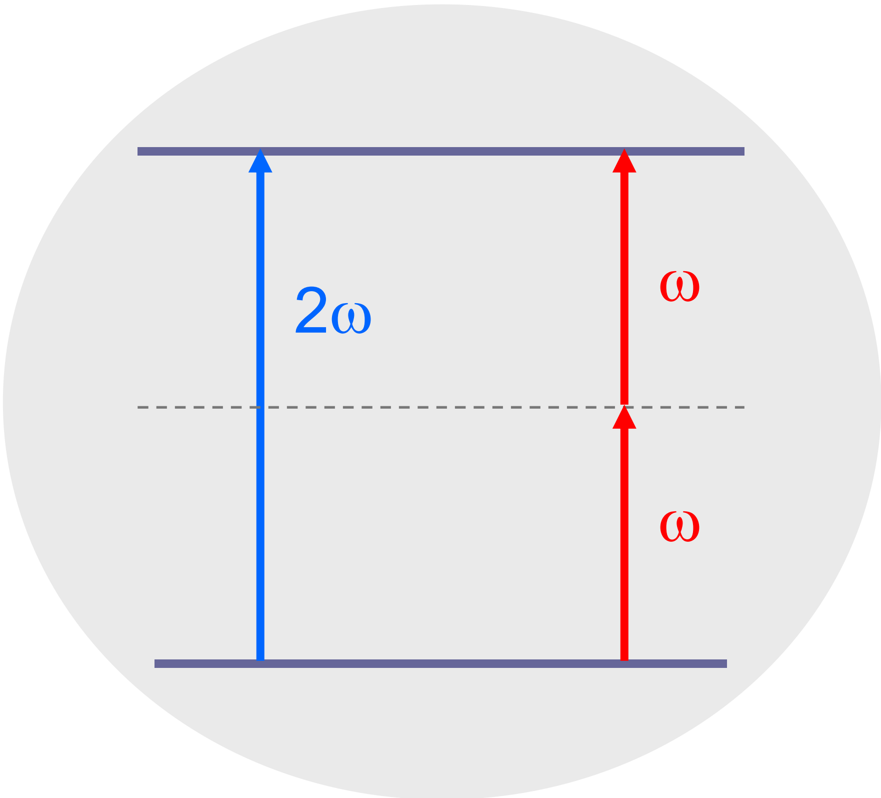
high light intensity

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

nonlinear polarization response

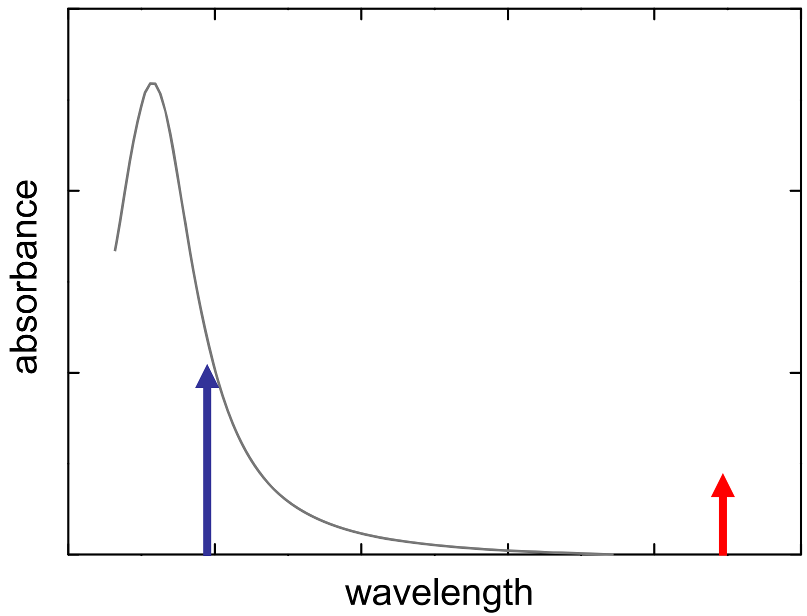
$$P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$$

Two-photon absorption



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

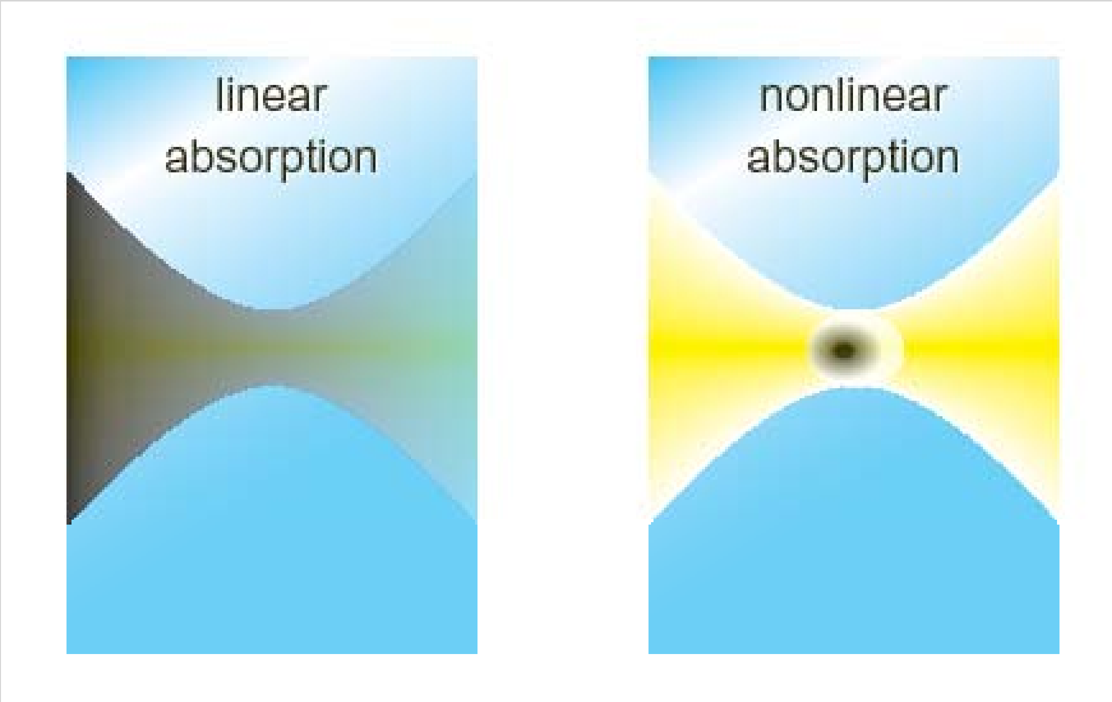
Third order processes $\chi^{(3)}$



Two-photon absorption

Nonlinear interaction provides spatial confinement of the excitation

fs-microfabrication



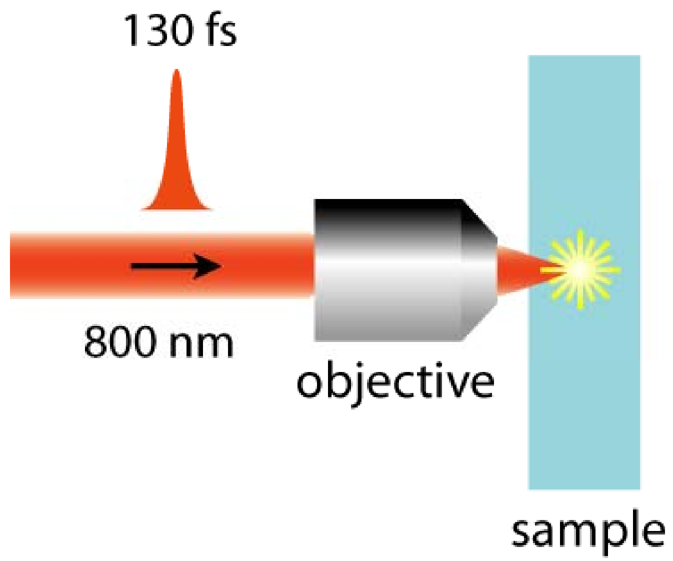
$$\alpha = \alpha_0 \qquad \alpha = \alpha_0 + \beta I$$

Two-photon absorption

spatial confinement of excitation

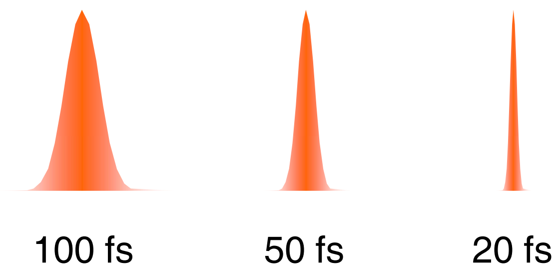
fs-laser microfabrication

focus laser beam inside material



femtosecond pulses

Ti:Sapphire lasers

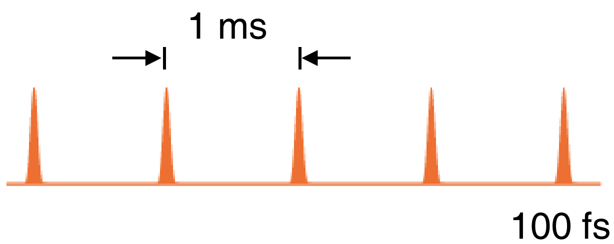


1 fs = 10^{-15} s

Repetition rate

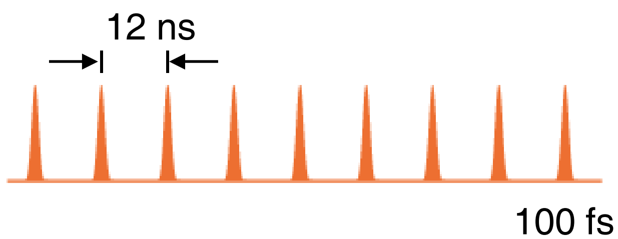
Energy

1 KHz



mJ

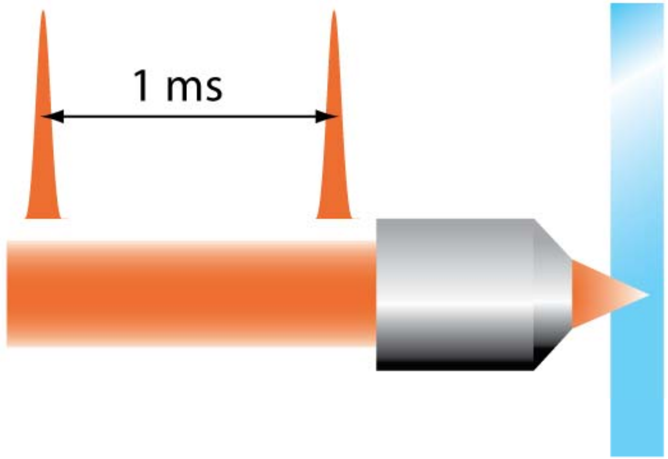
86 MHz



nJ

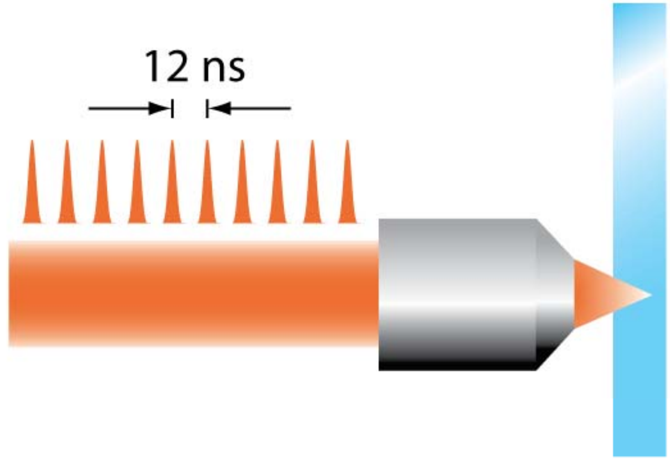
femtosecond pulses

amplified laser



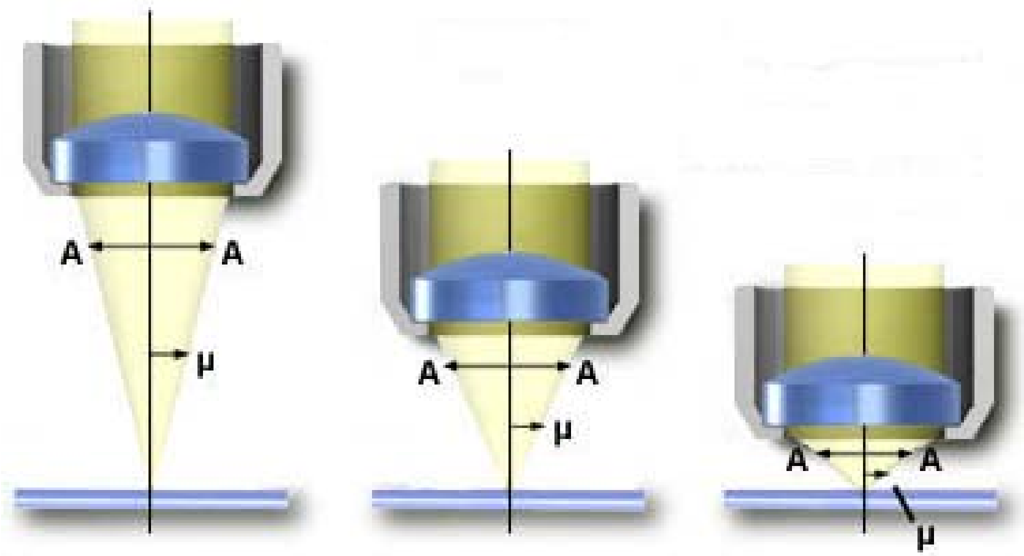
repetitive

oscillator



cumulative

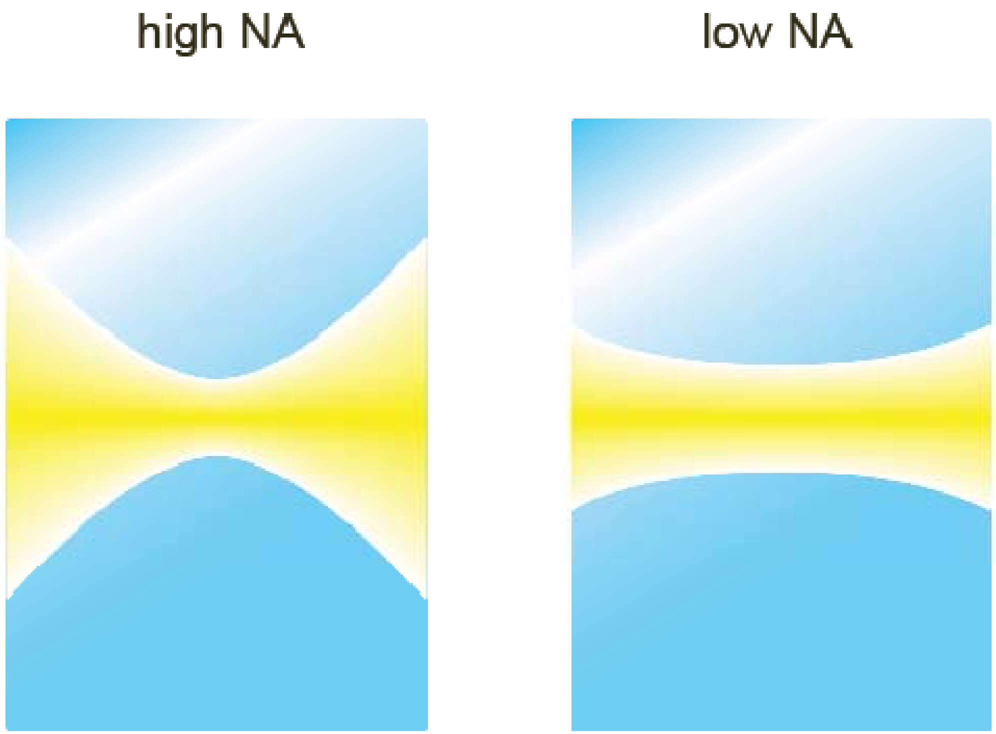
fs-micromachining: focusing



NA = 0.12 NA = 0.34 NA = 0.87

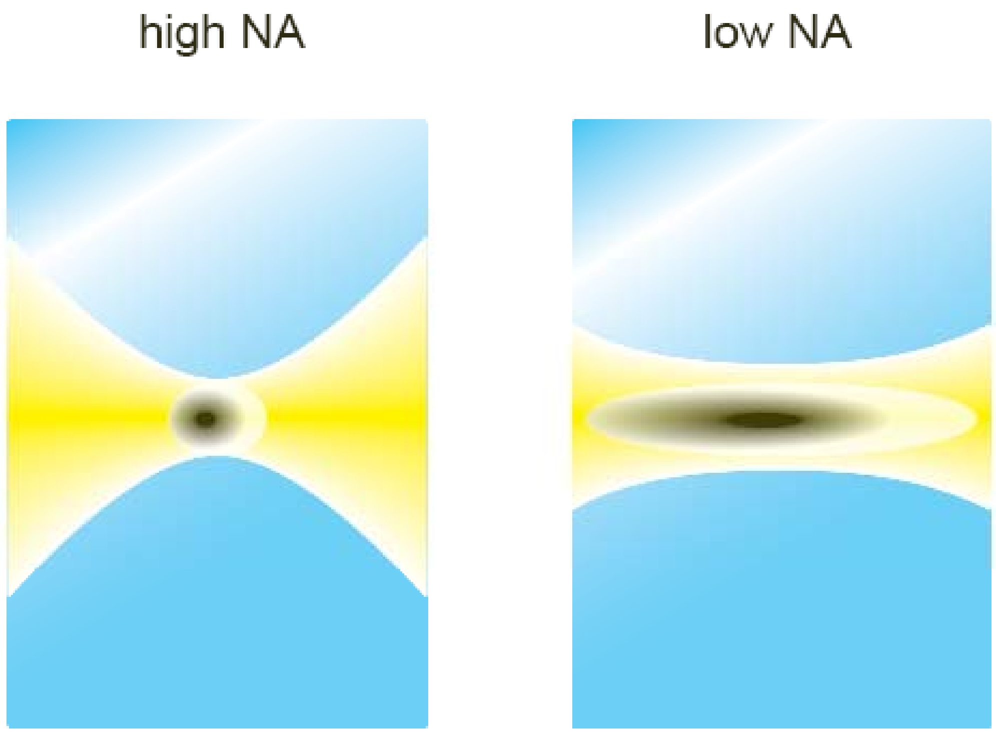
$\mu = 7^o$ $\mu = 20^o$ $\mu = 60^o$

what is the difference ?



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

very different confocal lenght/interaction length

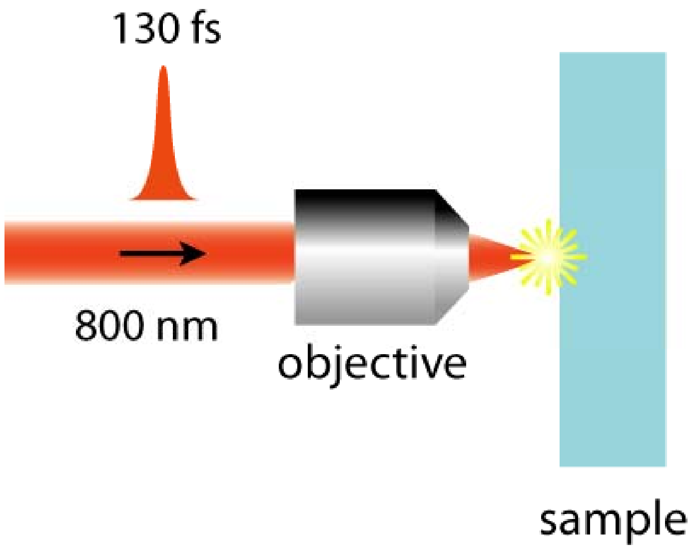


two main techniques

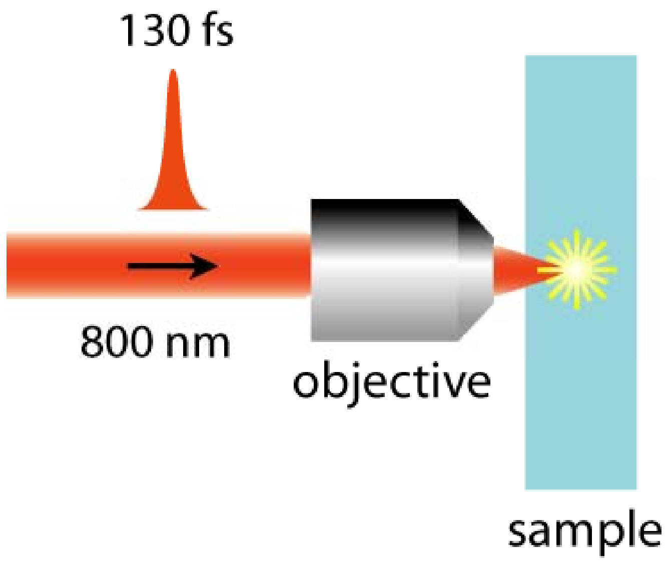
- fs-laser micromachining
- microfabrication via two-photon polymerization

fs-laser micromaching

Surface

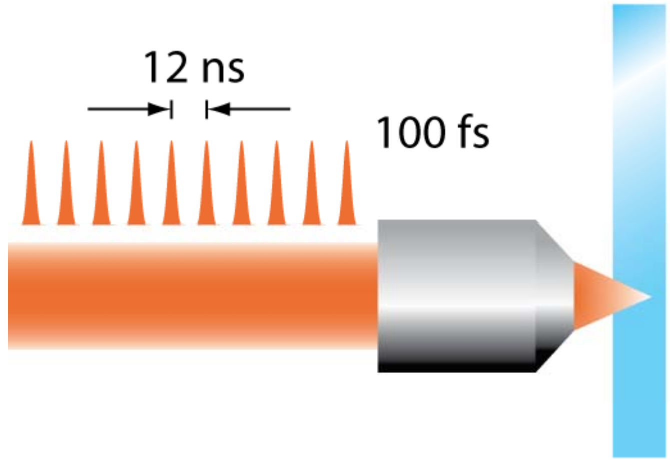


Volume



fs-pulses for micromachining polymers

Oscillator: 80 MHz, 5 nJ

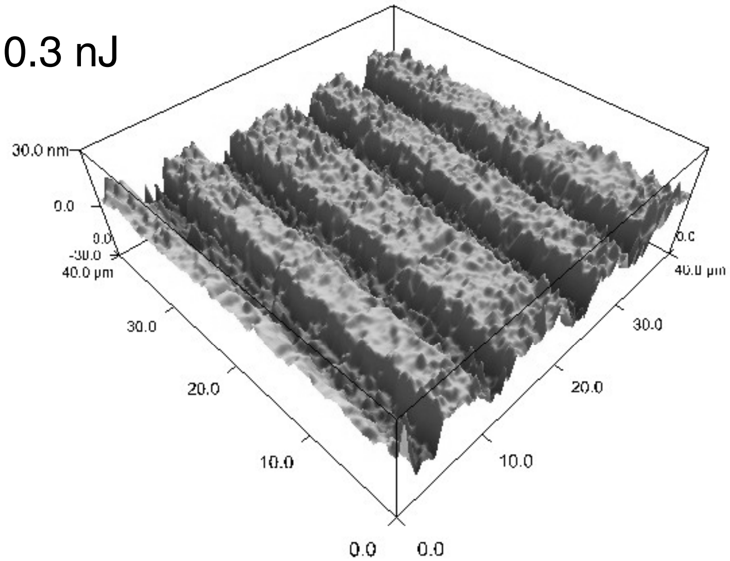


heat diffusion time: $t_{diff} \sim 1\ \mu s$

cumulative

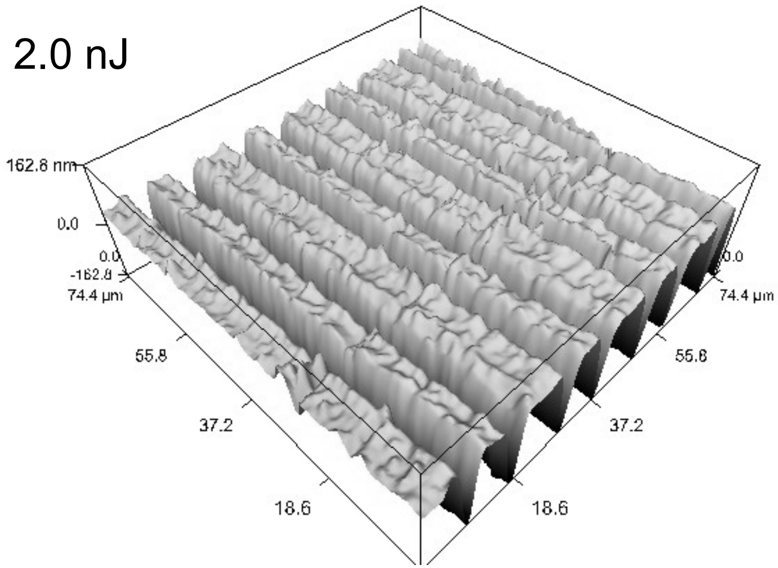
Micromachining the conductive polymer MEH-PPV

a 0.3 nJ

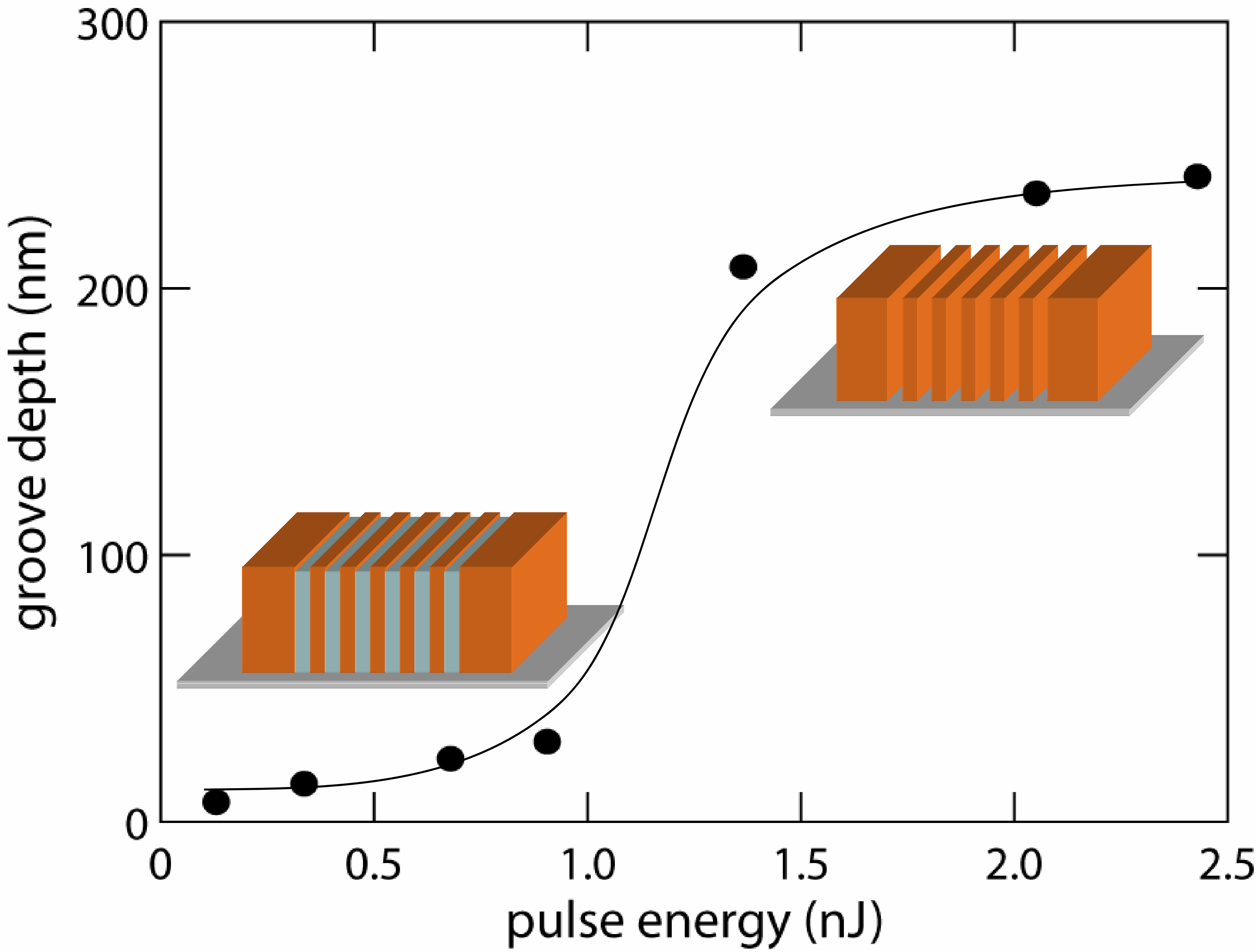


atomic force microscopy

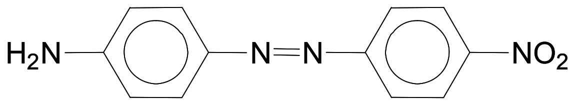
b 2.0 nJ



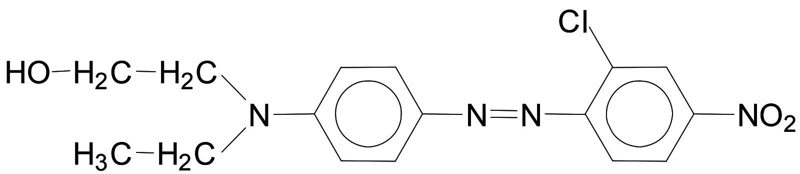
Micromachining the conductive polymer MEH-PPV



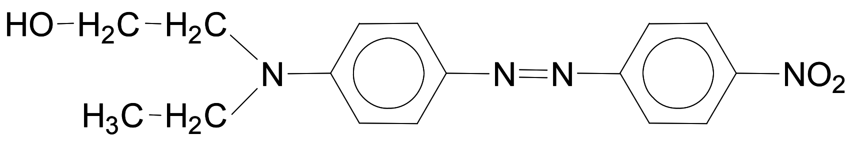
Waveguides in azo-polymers



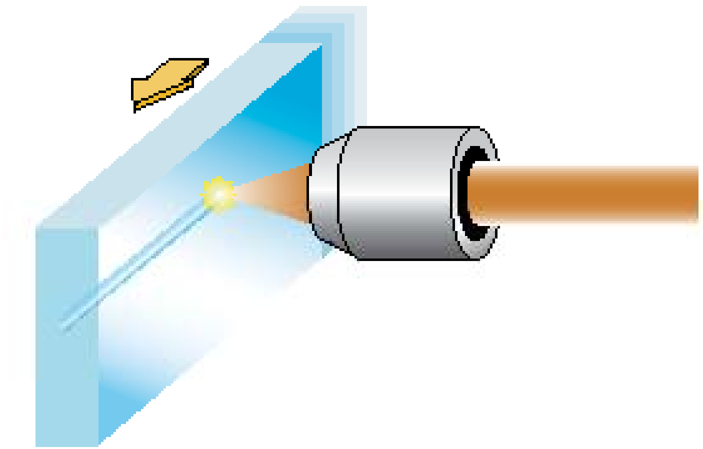
DO3



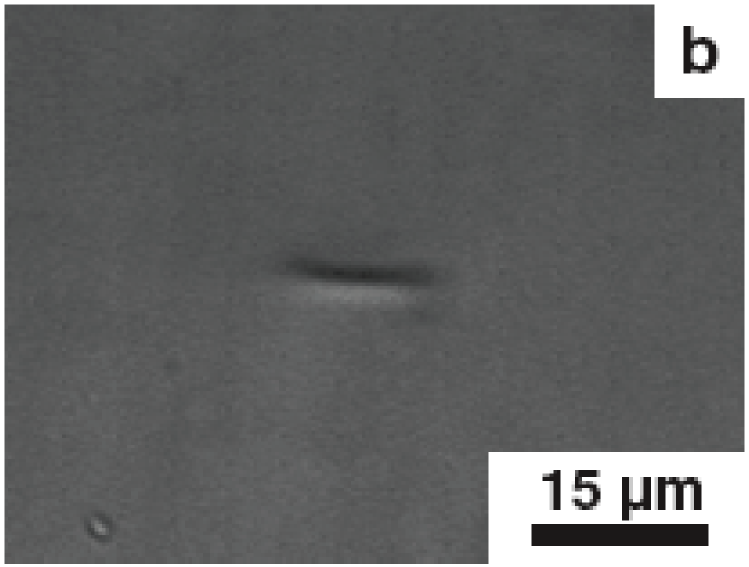
DR13



DR1



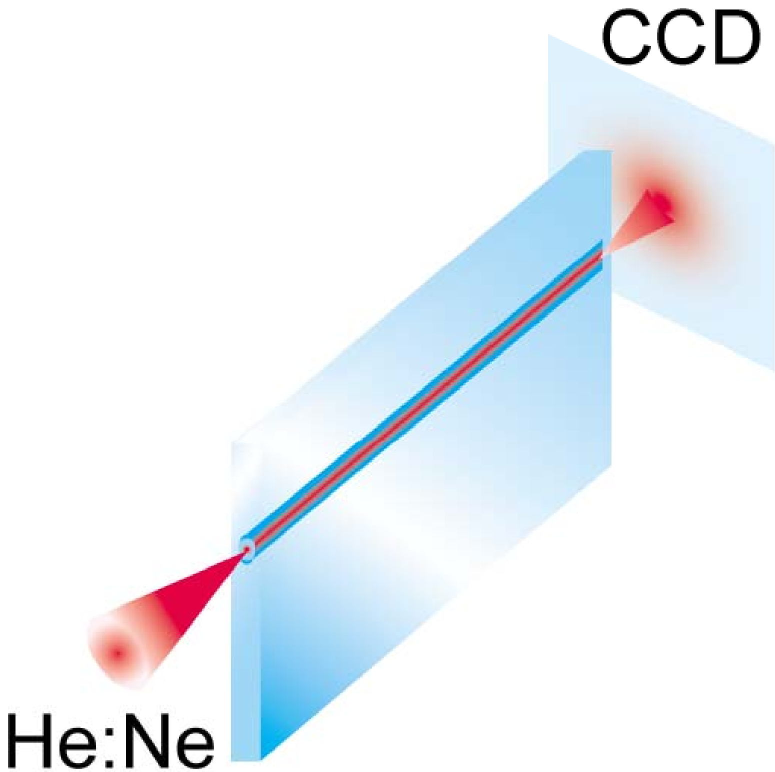
Waveguides in azo-polymers

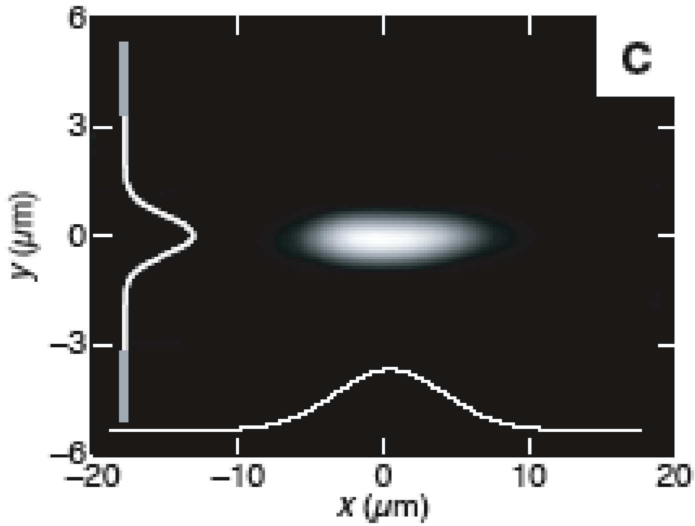


(a) Optical microscope image of the waveguides micromachined (PMMA/DR1)

(b) Cross-sectional view of the waveguides

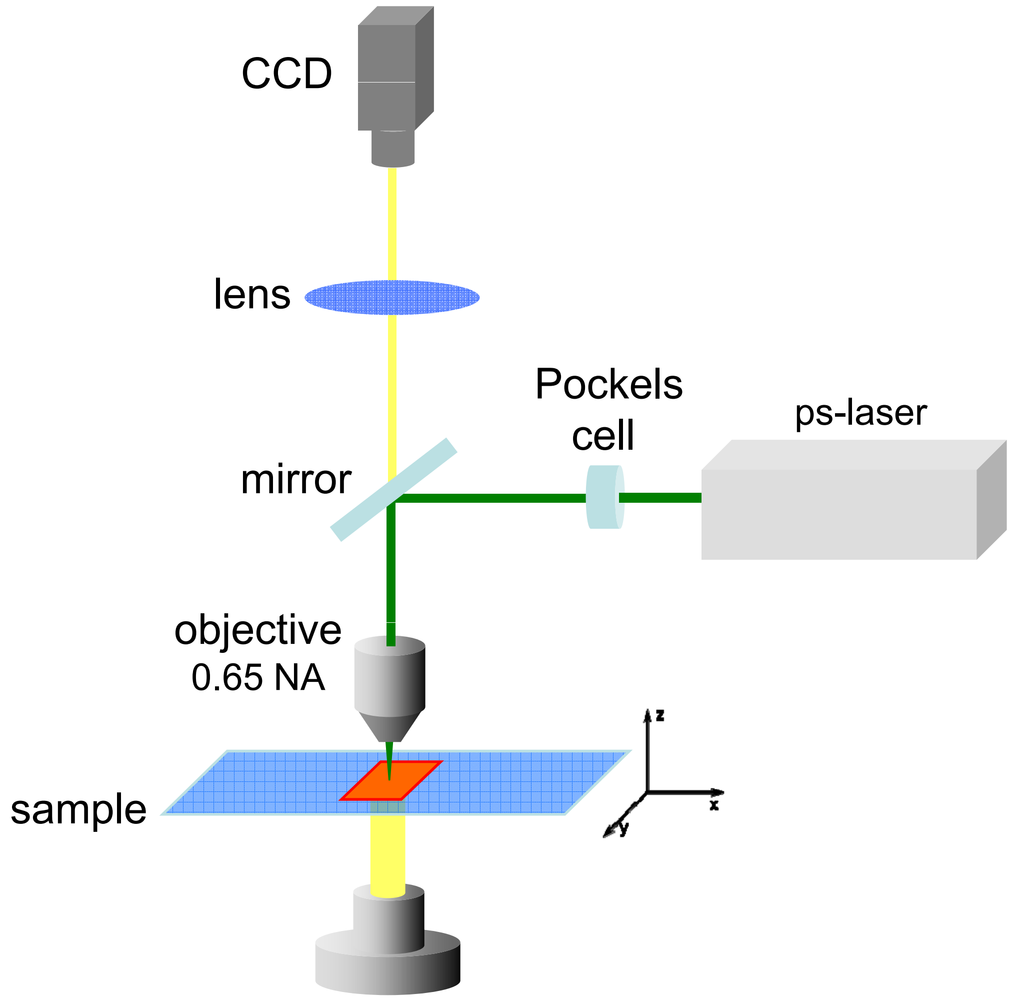
waveguides in azo-polymers





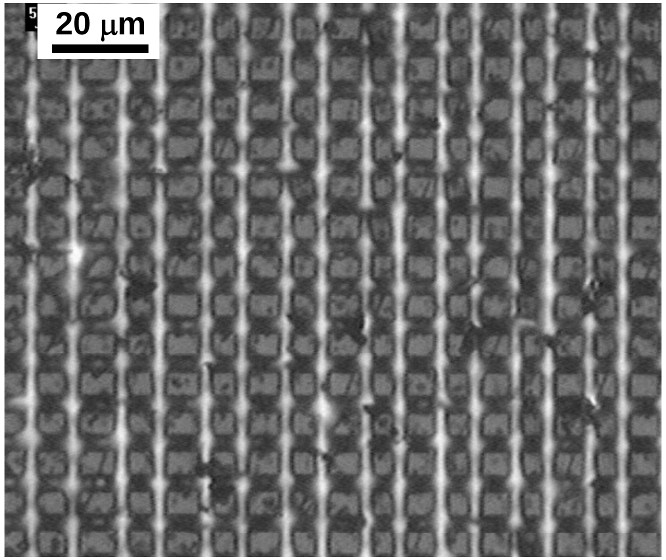
(c) Output image of the mode profile of 632.8-nm light coupled through the waveguide

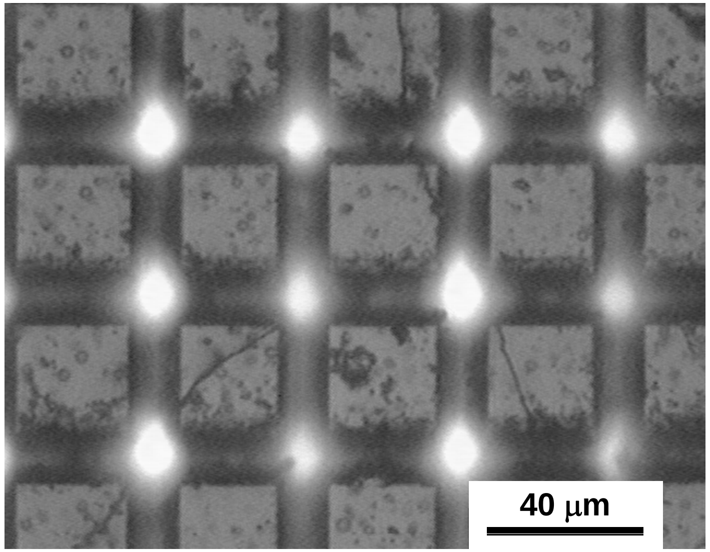
microstructuring polymer: super hydrophobic surface



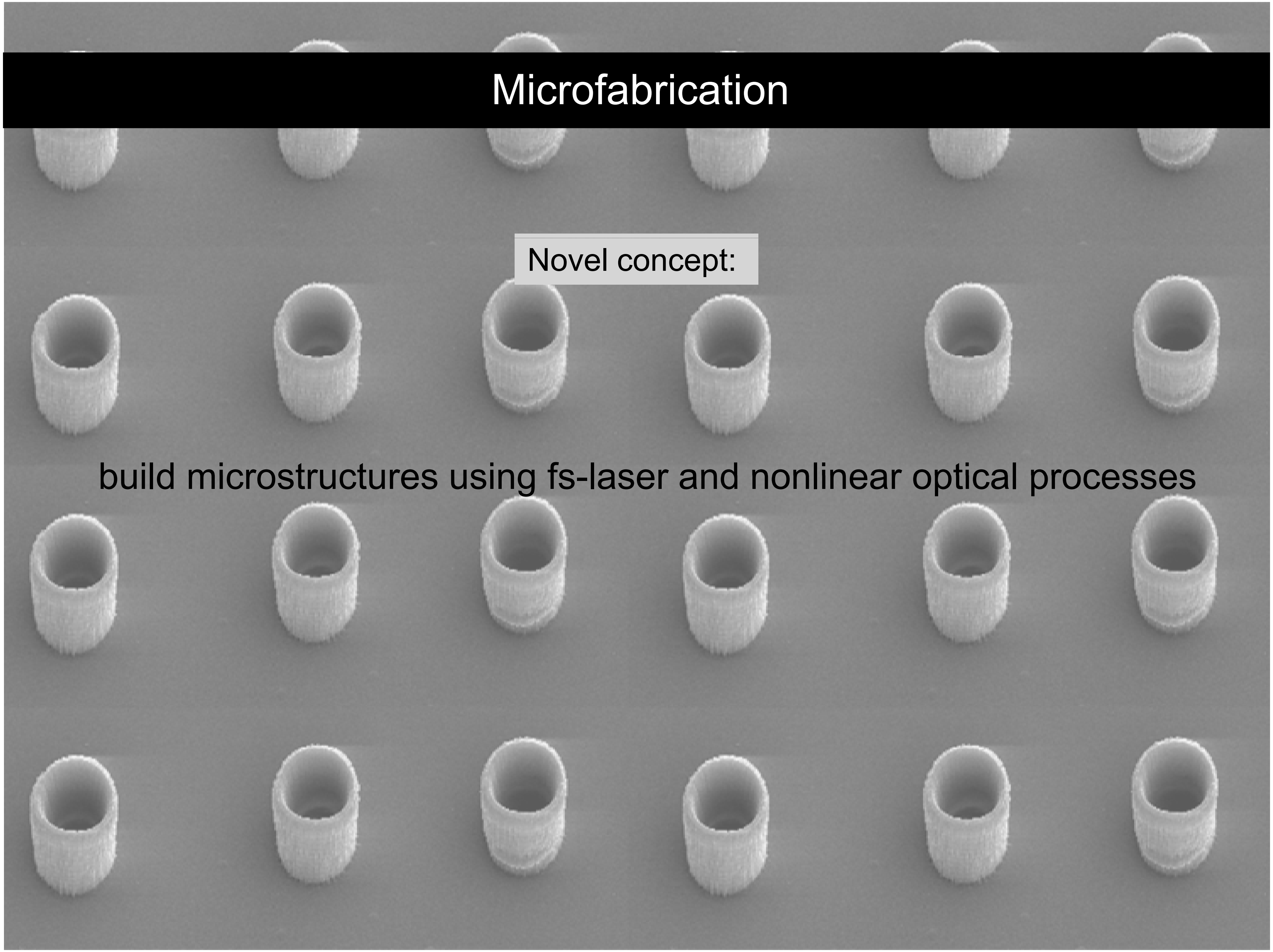
laser microfabrication: super hydrophobic surface

examples of fabricated surfaces





Microfabrication



Novel concept:

build microstructures using fs-laser and nonlinear optical processes

Two-photon polymerization

Photopolymerization

Monomer + Photoinitiator $\rightarrow$ *Polymer*

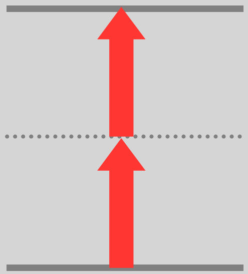
light

Two-photon polymerization

Monomer + Photoinitiator $\rightarrow$ *Polymer*

light

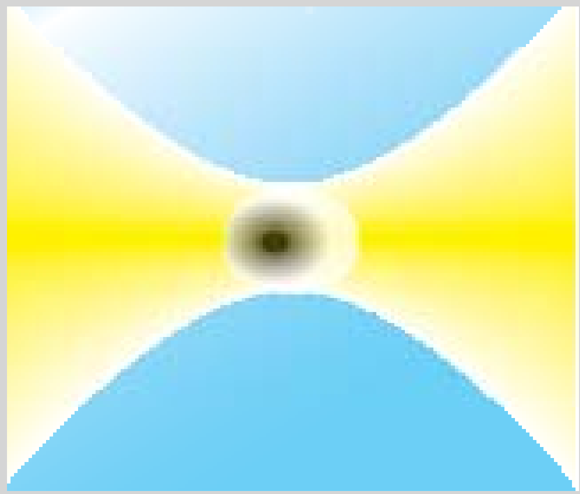
Photoinitiator is excited by ***two-photon absorption***



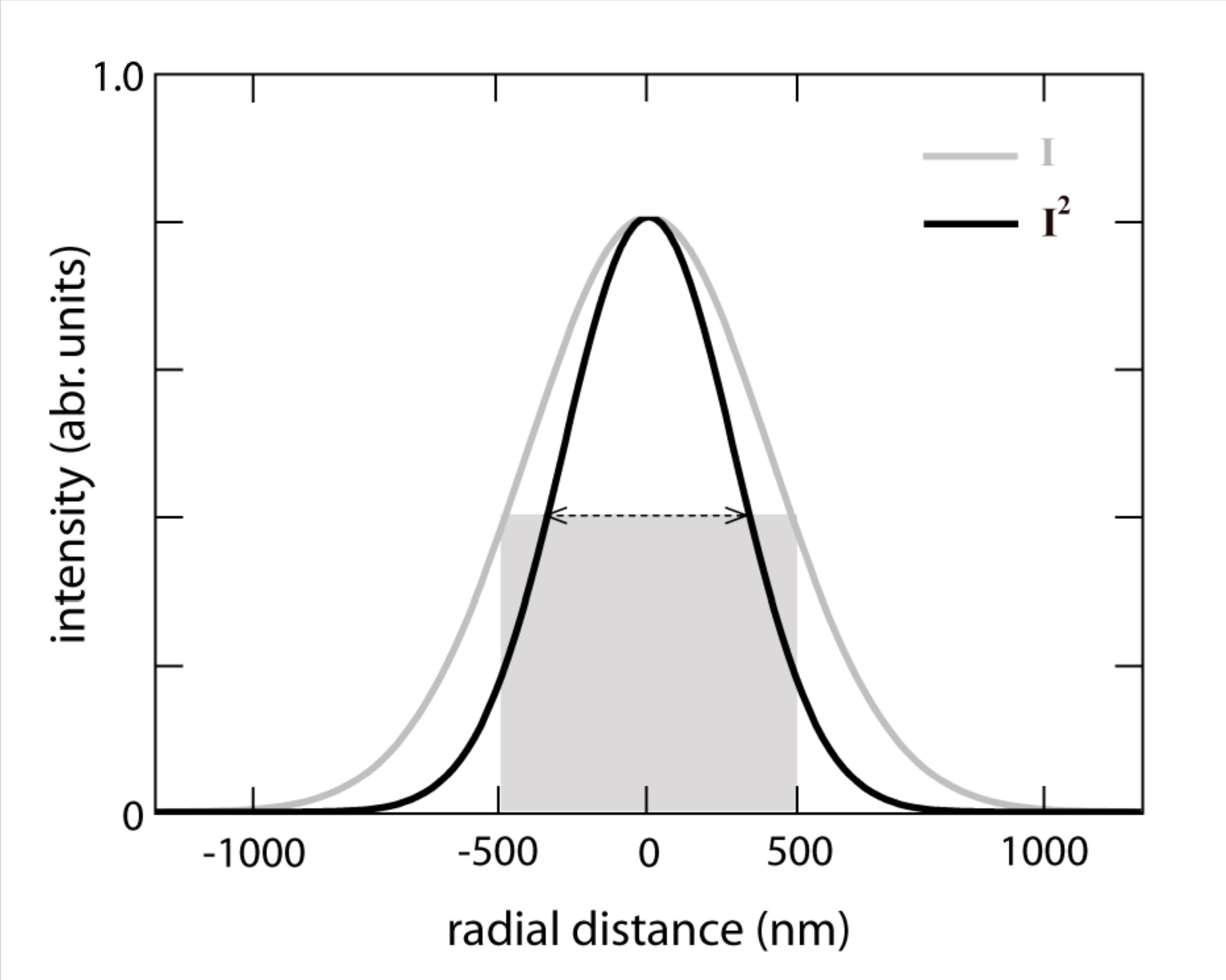
$$R_{2PA} \propto I^2$$

The polymerization is confined to the focal volume.

High spatial resolution

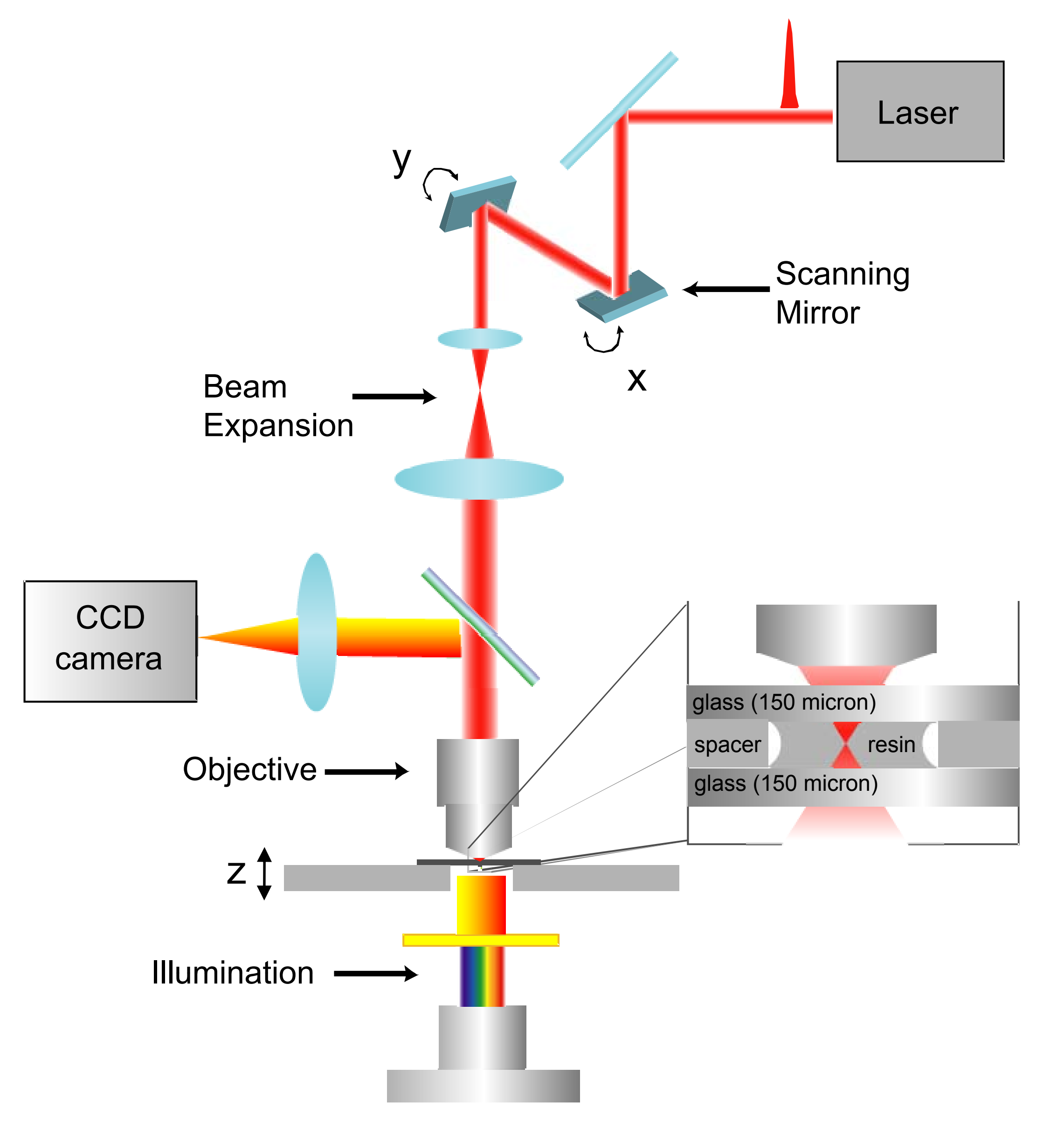


Two-photon polymerization



bellow the diffraction limit

Two-photon polymerization setup



Ti:sapphire laser oscillator

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

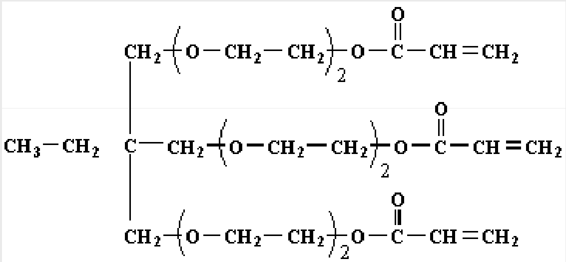
Objective

40 x
0.65 NA

Resin preparation

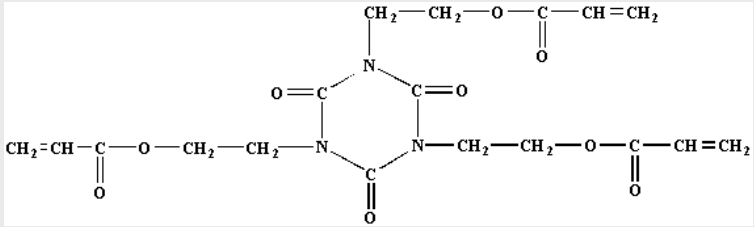
Monomers

Monomer A



reduces the shrinkage upon polymerization

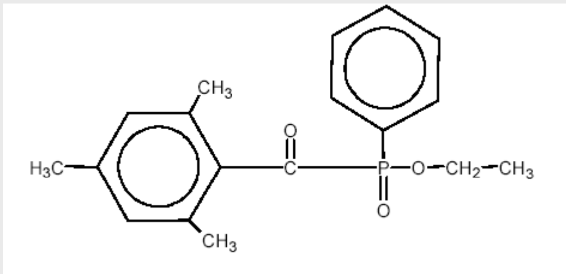
Monomer B



gives hardness to the polymeric structure

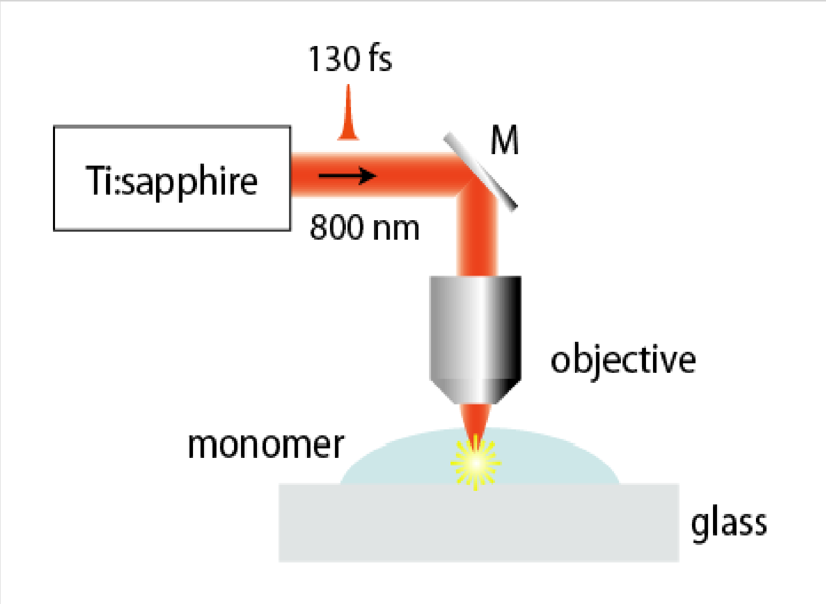
Photoinitiator

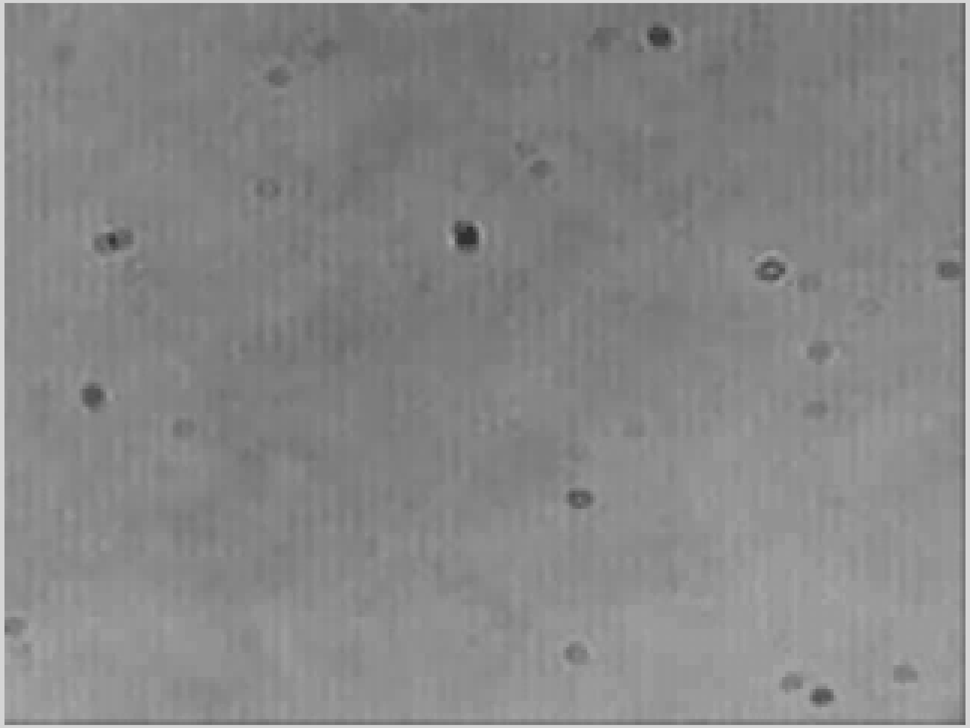
Lucirin TPO-L



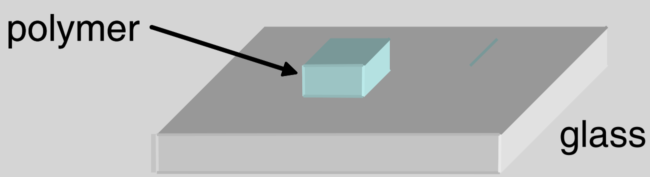
Appl. Phys. A, 90, 633–636 (2008)

Two-photon polymerization

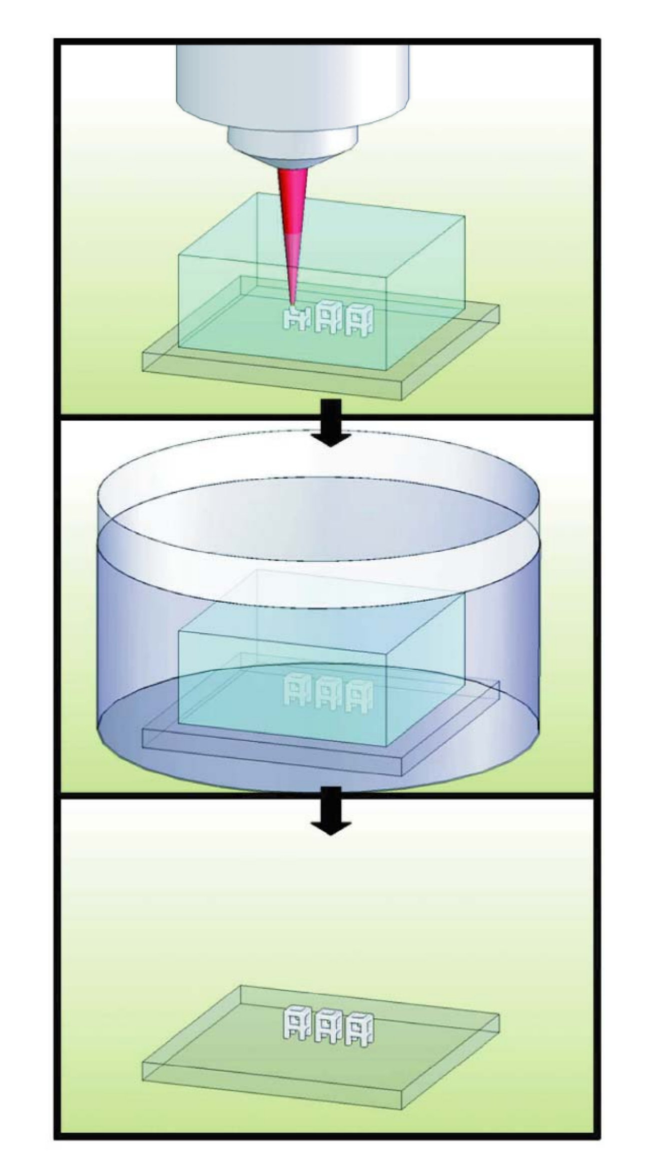




30 µm x 30 µm x 12 µm cube



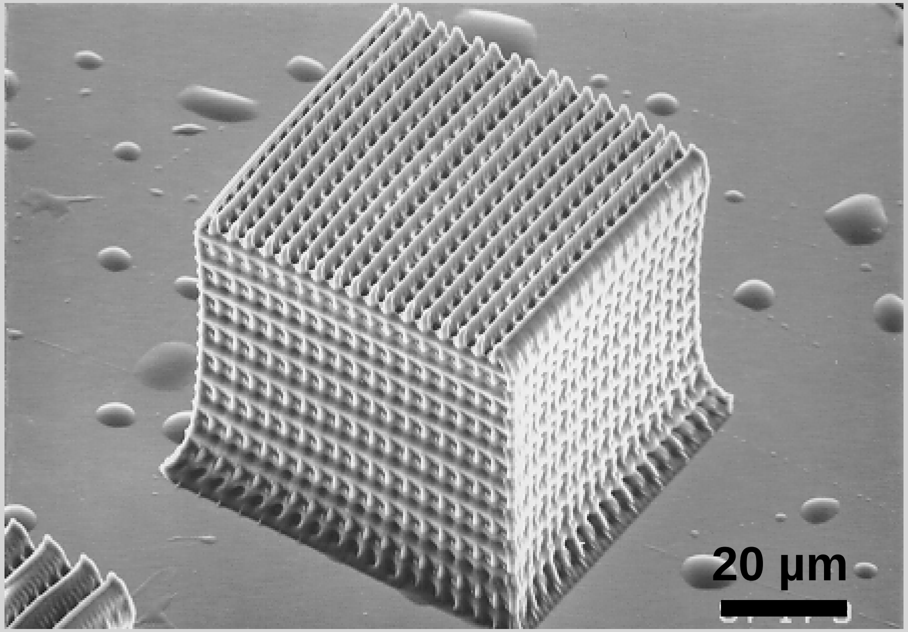
Two-photon polymerization

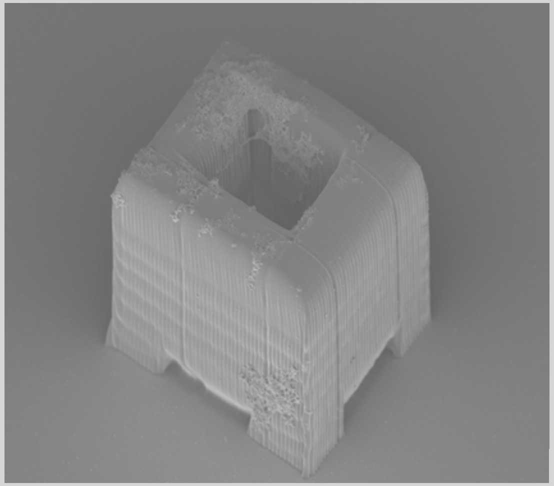


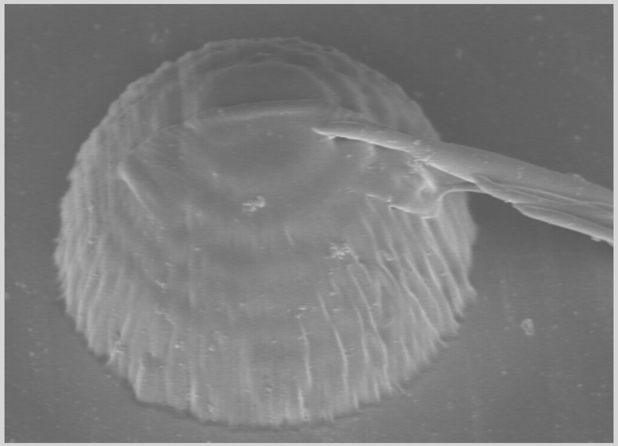
After the fabrication, the sample is immersed in ethanol to wash away any unsolidified resin and then dried

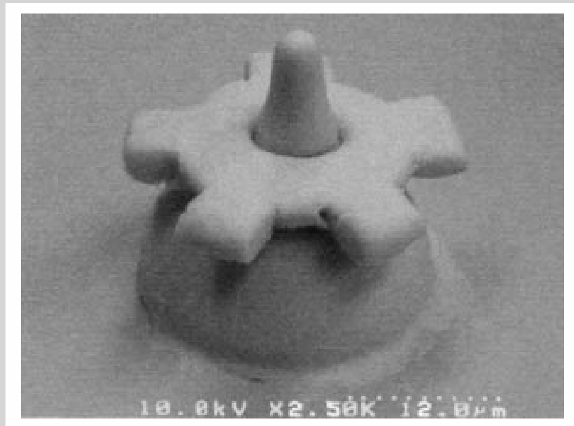
two-photon polymerization

photonic crystal – J. W. Perry



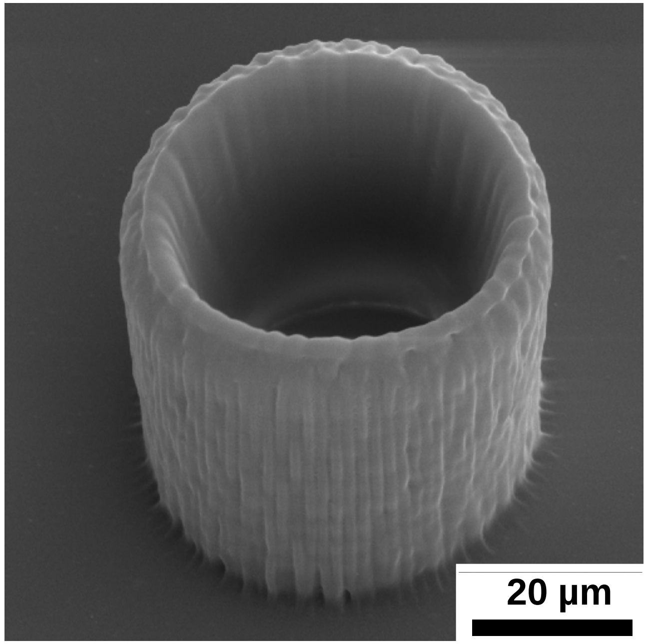


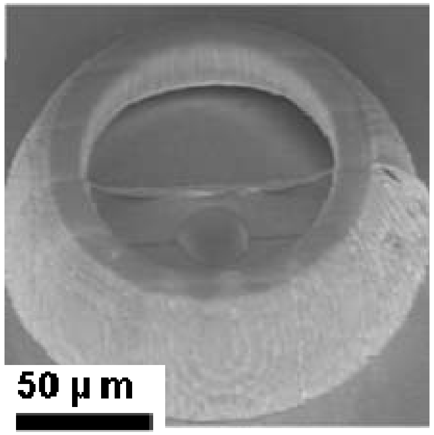


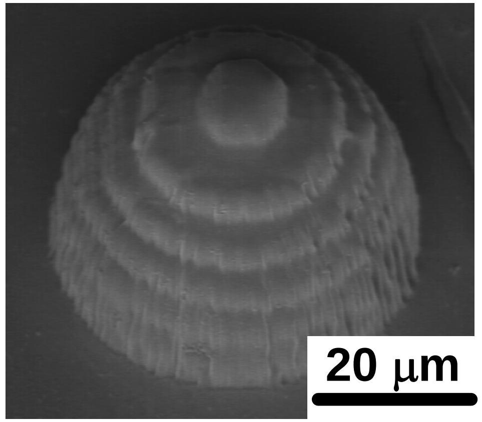


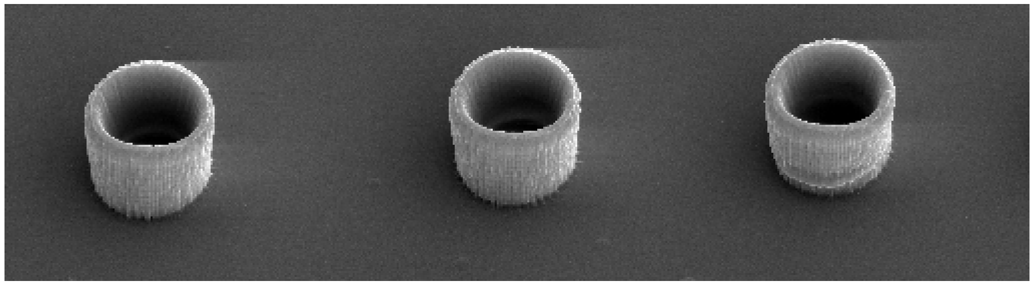
Two-photon polymerization

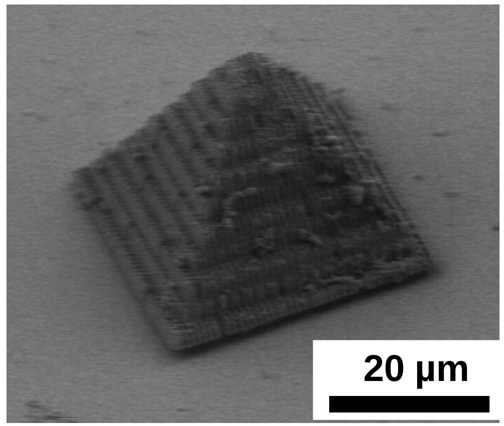
Microstructures fabricated by two-photon polymerization



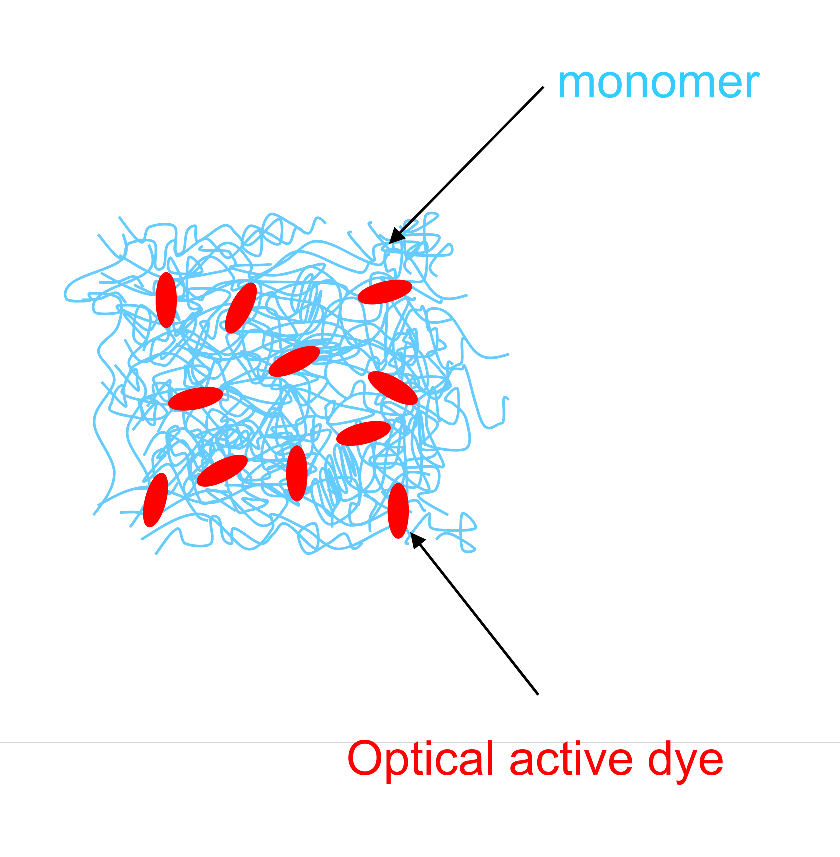


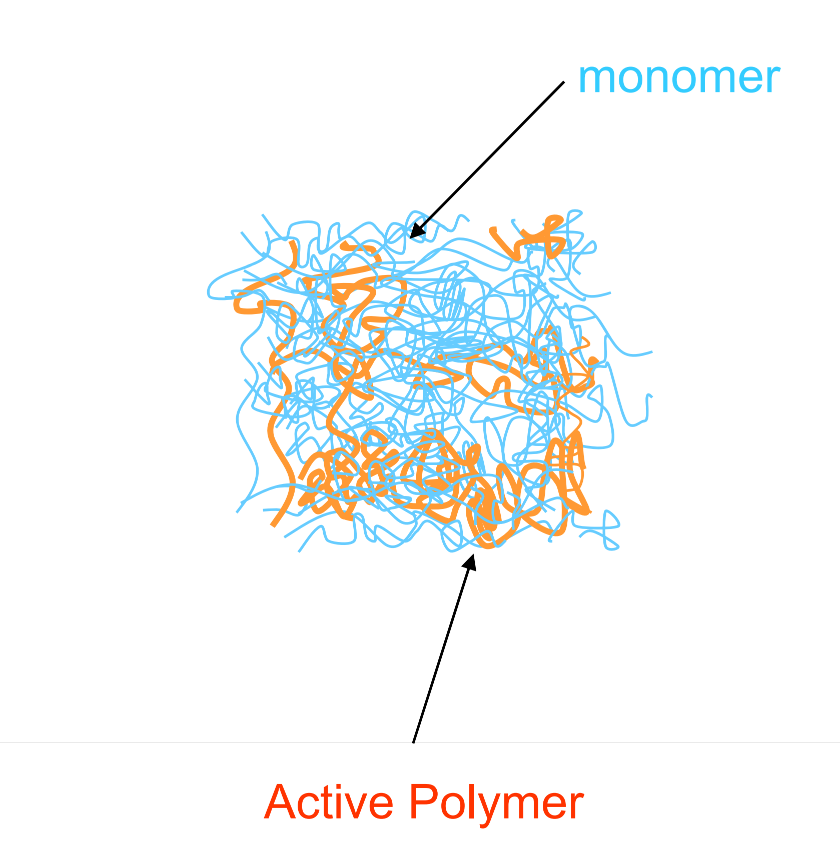






Microstructures containing active compounds





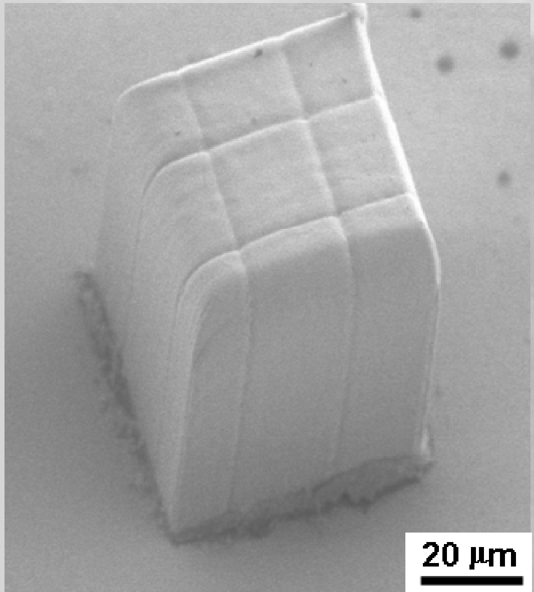
two-photon polymerization

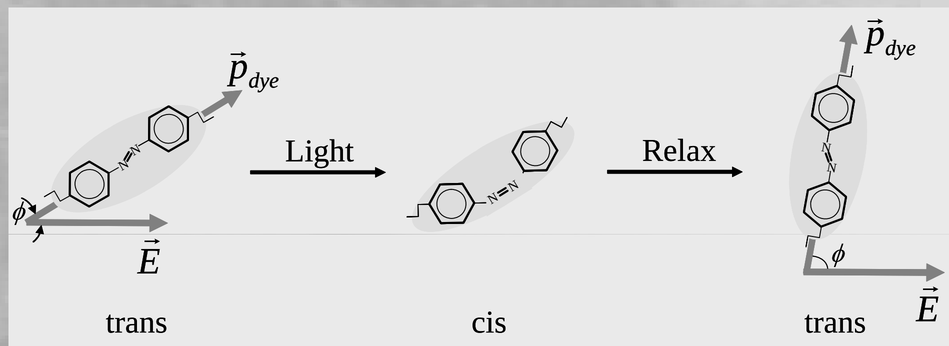
applications

- micromechanics
- waveguides
- microfluidics
- biology
- optical devices

Other studies

- microstructures for optical storage – birefringence

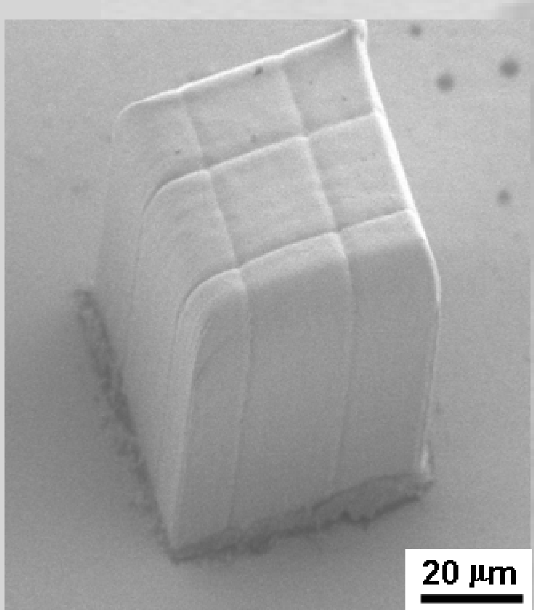




J. Appl. Phys., 102, 13109-1-13109-4 (2007)

Other studies

- microstructures for optical storage – birefringence



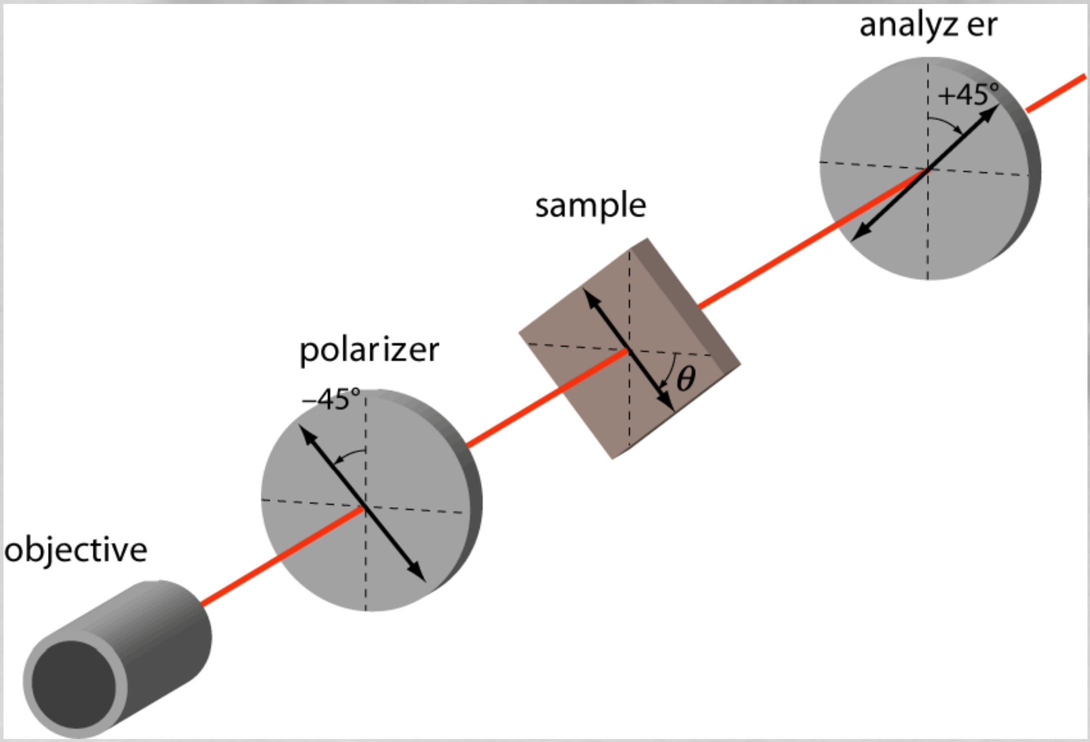
Ar^+ ion laser irradiation

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

Other studies

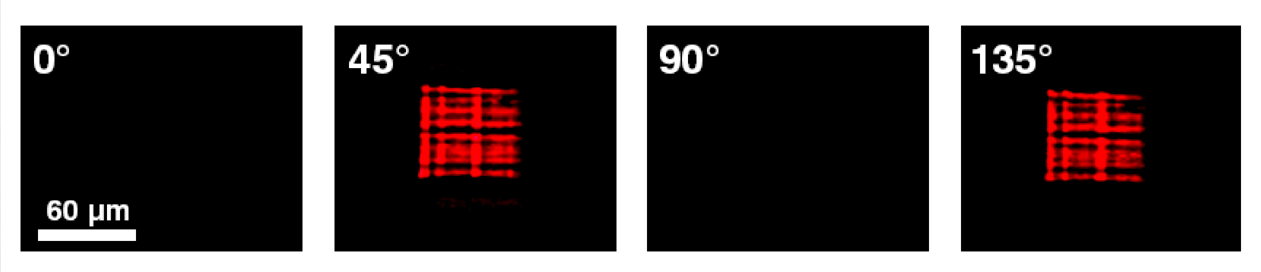
- microstructures for optical storage – birefringence

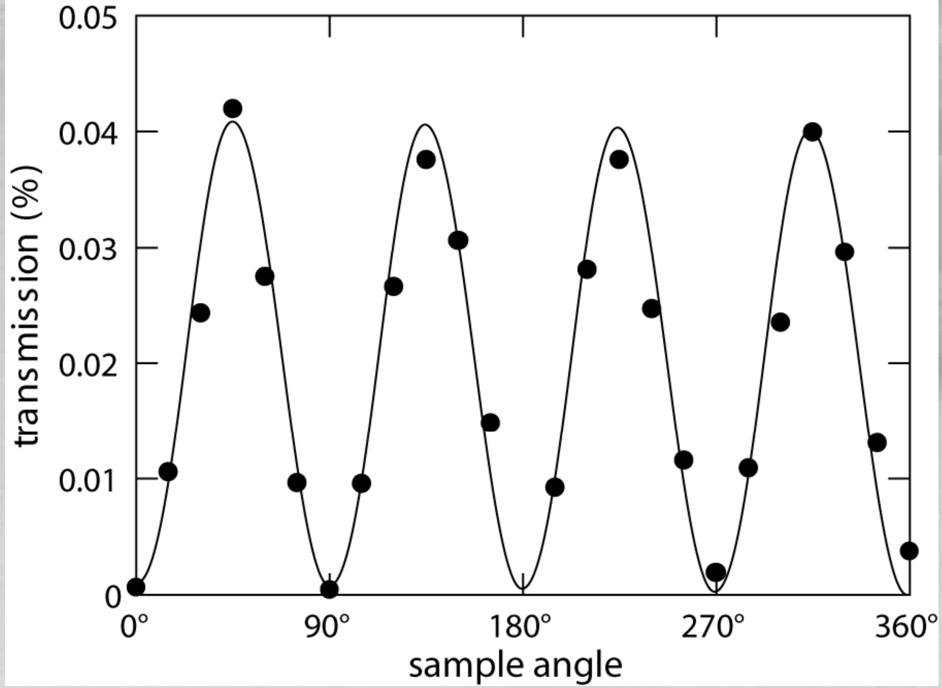
The sample was placed under an optical microscope between crossed polarizers and its angle was varied with respect to the polarizer angle



Other studies

- microstructures for optical storage – birefringence

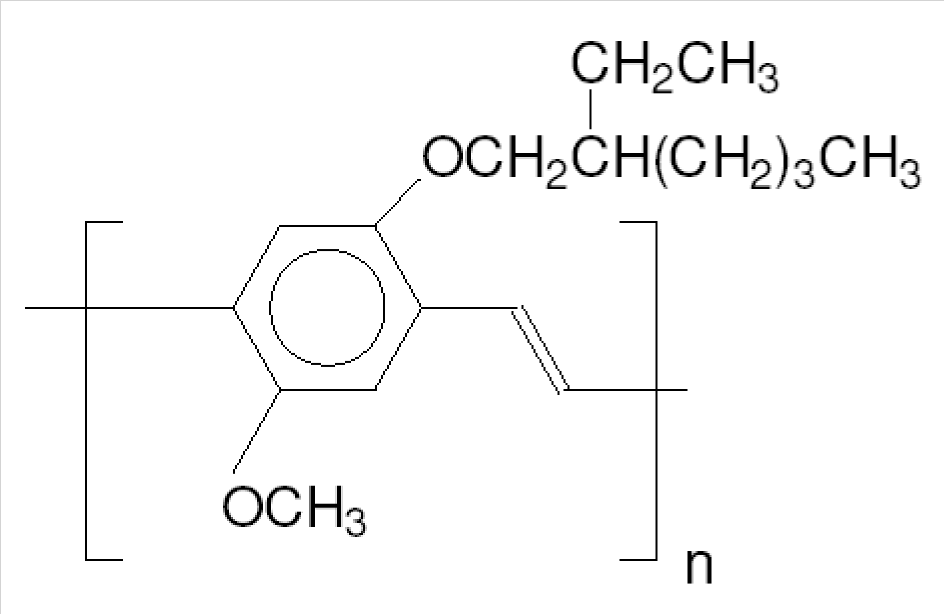




J. Appl. Phys., 102, 13109-1-13109-4 (2007)

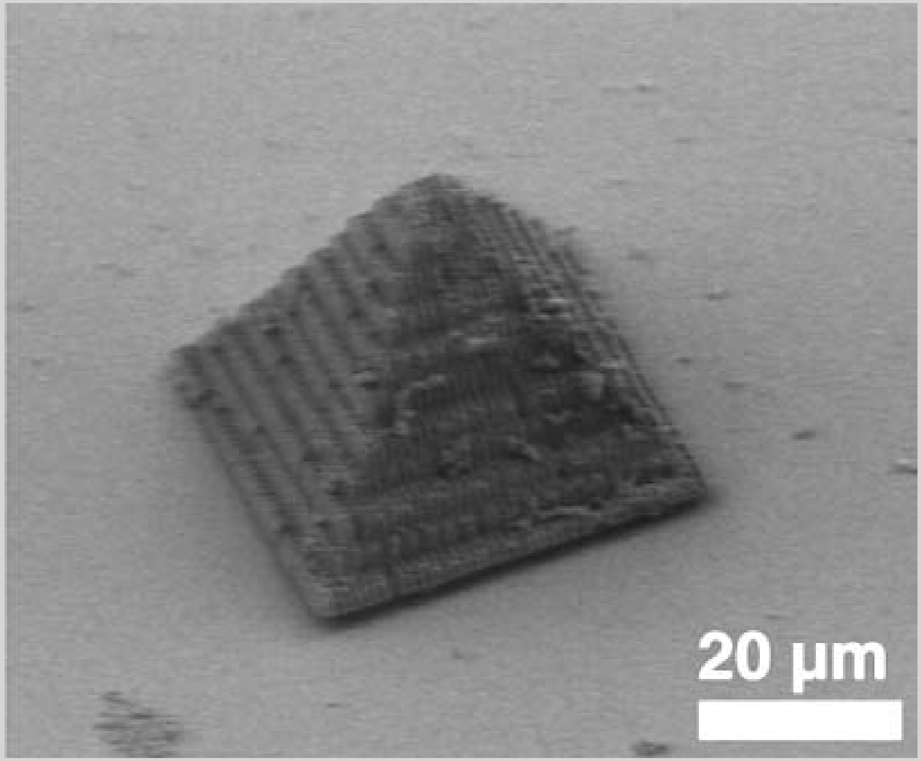
Microstructures containing MEH-PPV

MEH-PPV



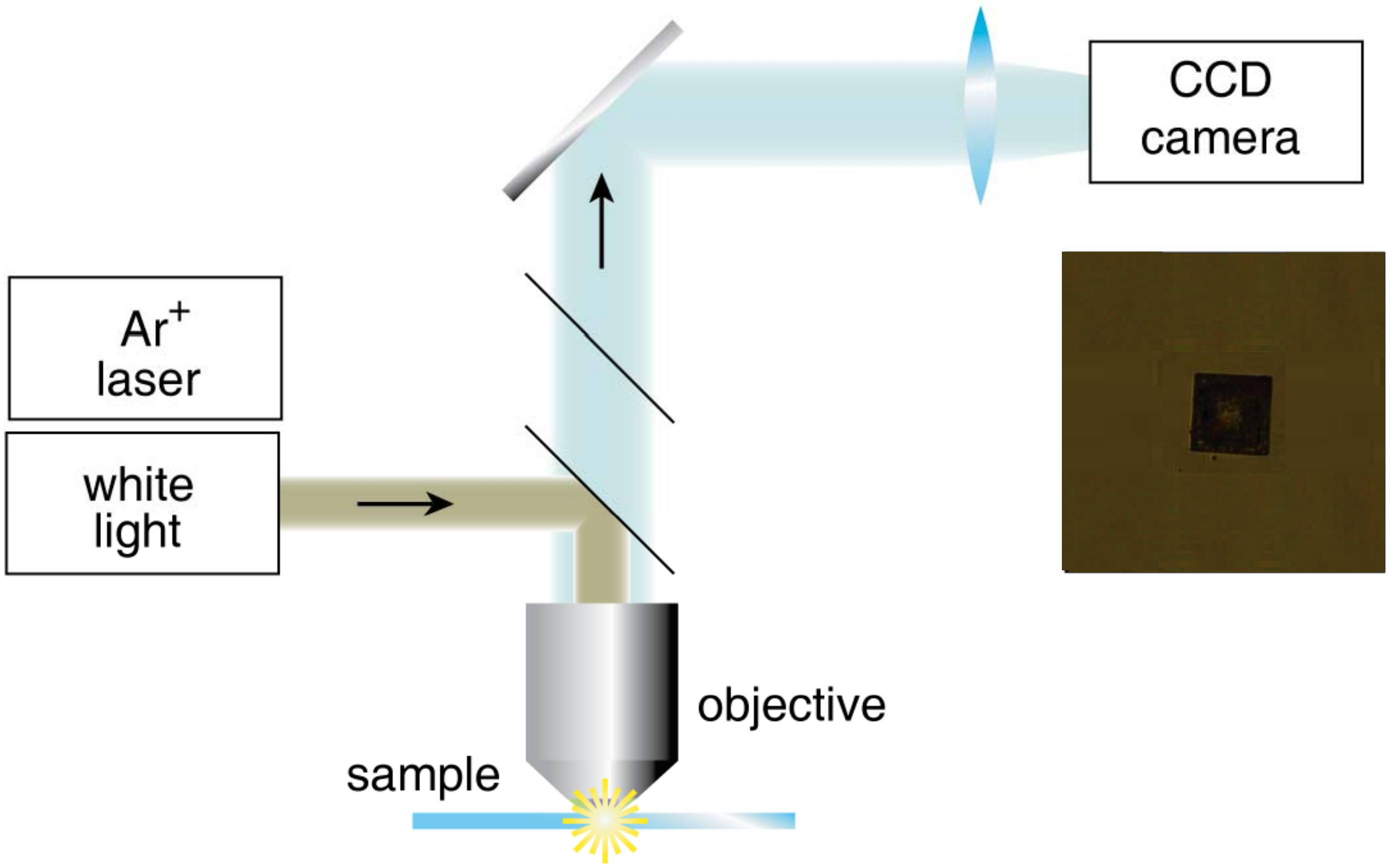
Fluorescence
Electro Luminescent
Conductive

Microstructure containing MEH-PPV

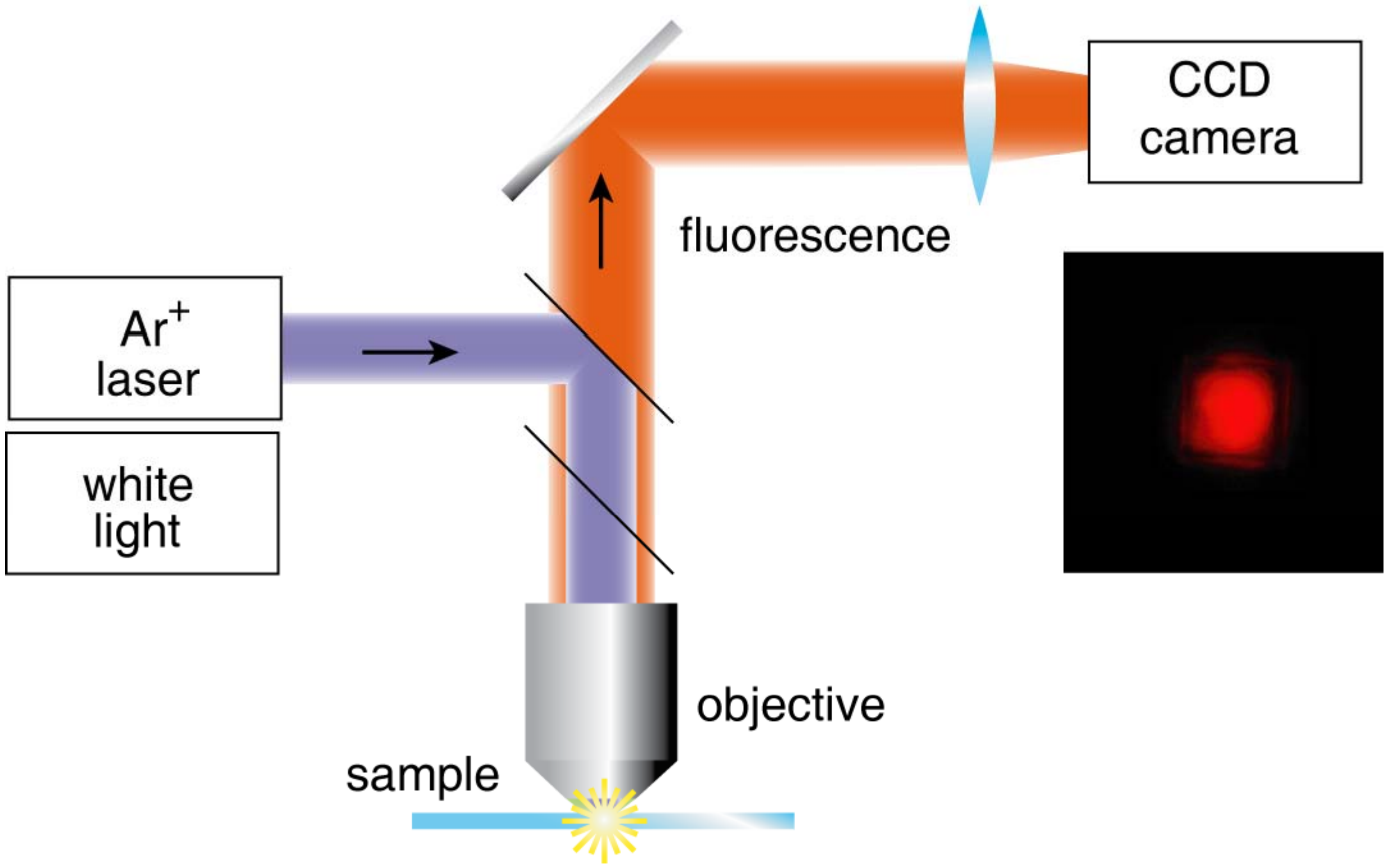


Appl. Phys. Lett., 95 1133091-3 (2009)

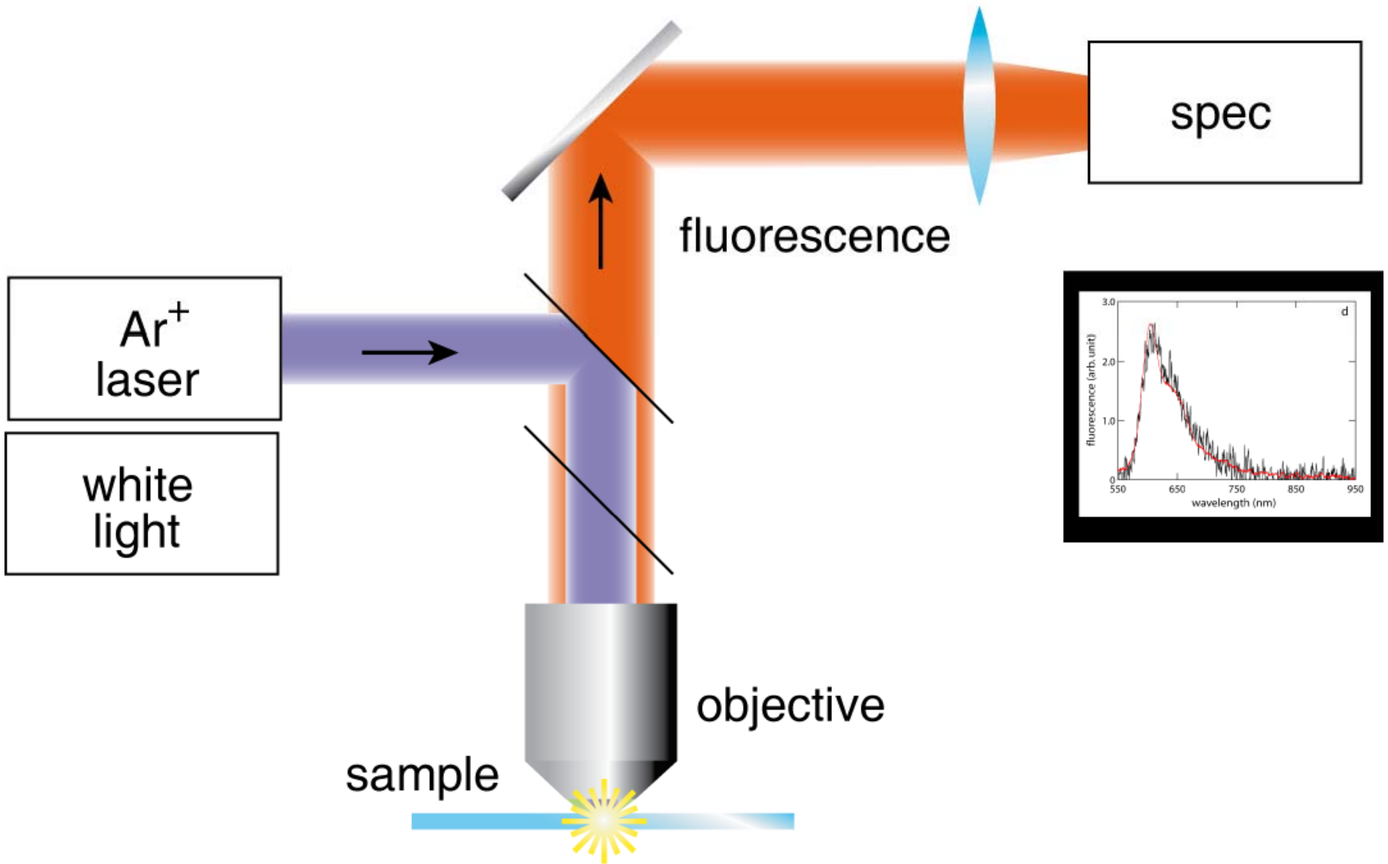
Microstructure containing MEH-PPV



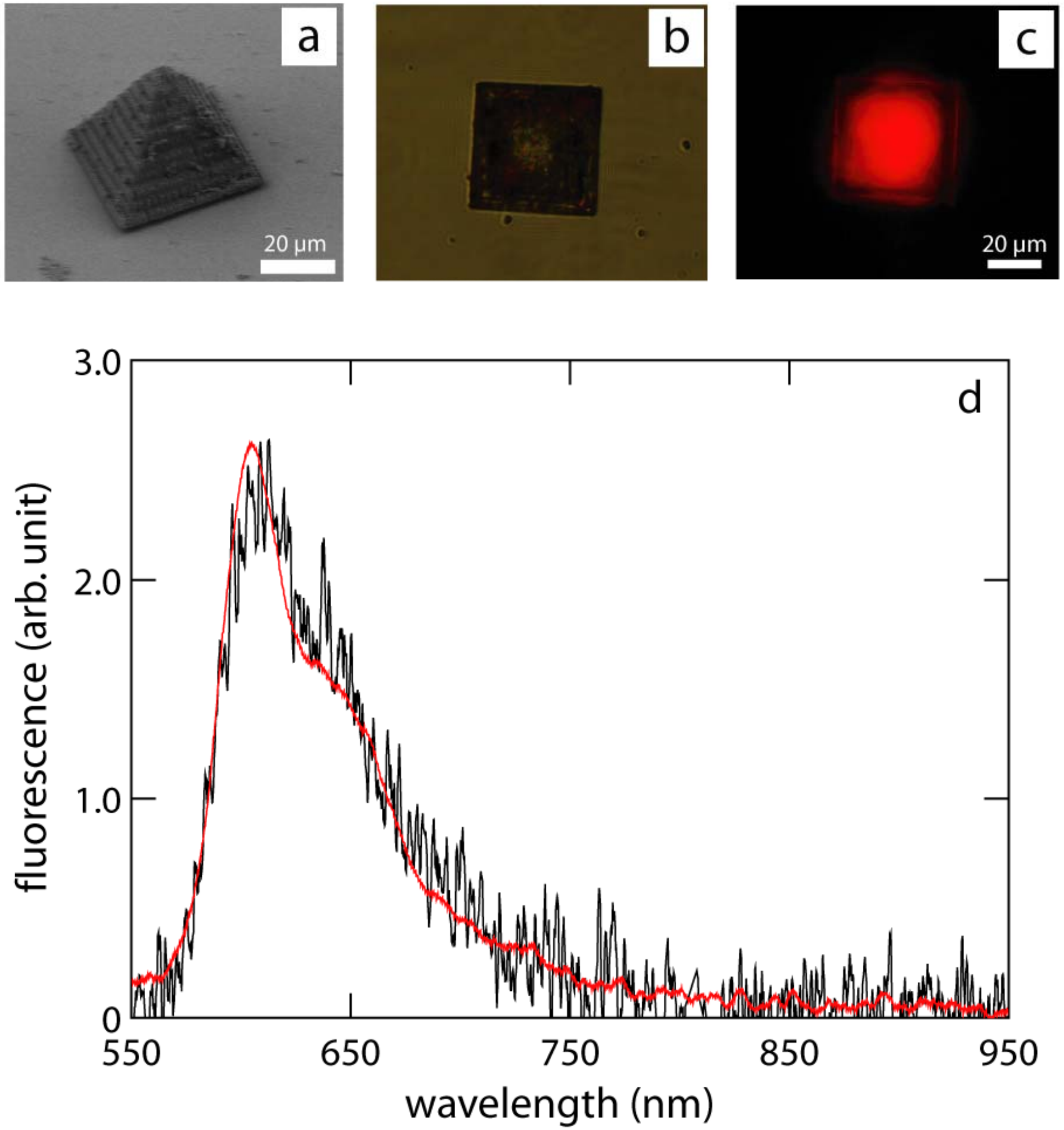
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV



Microstructure containing MEH-PPV



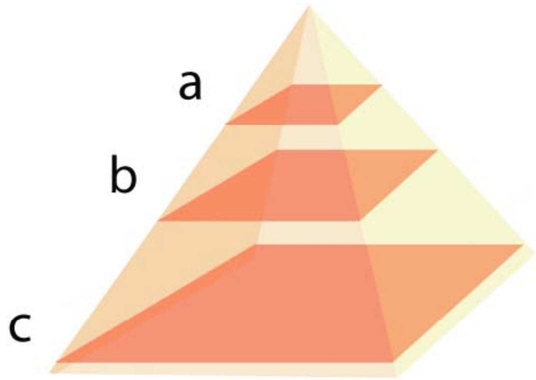
(a) Scanning electron microscopy

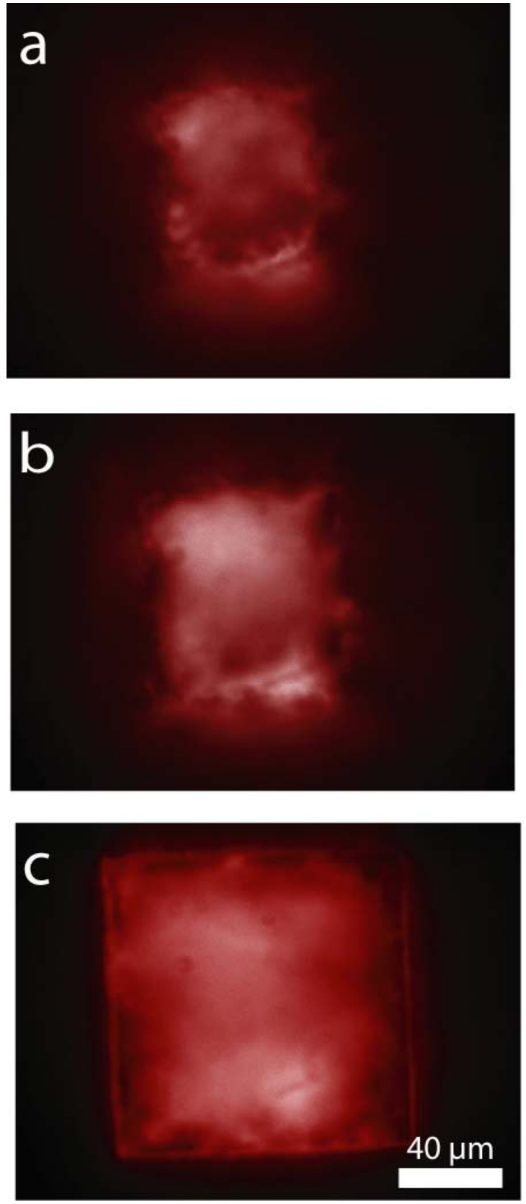
(b,c) Fluorescence microscopy of the microstructure with the excitation OFF (b) and ON (c)

(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

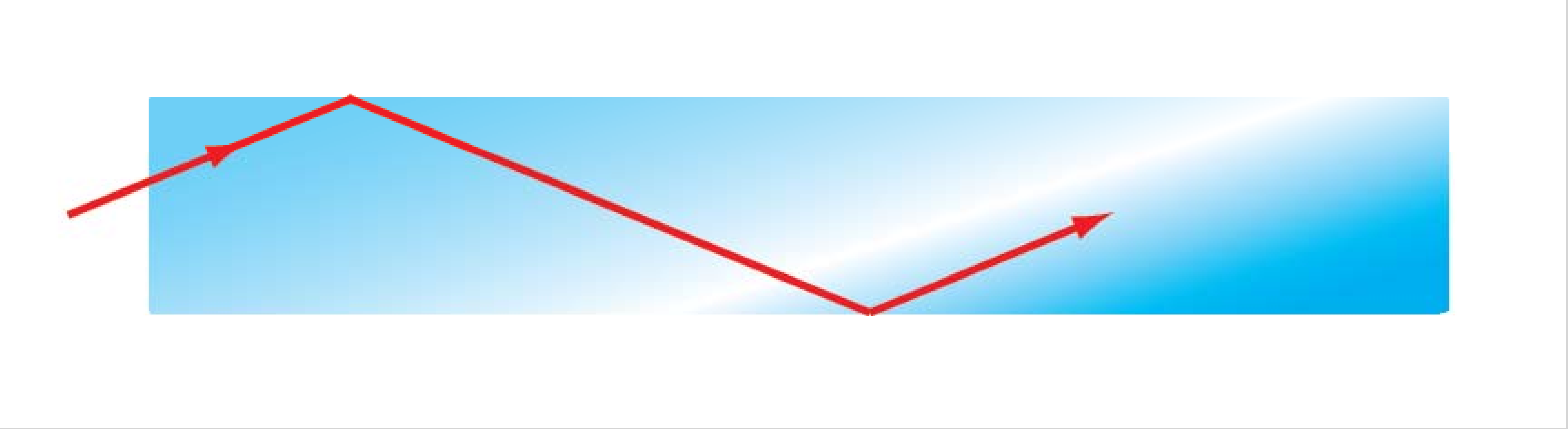




Fluorescent confocal microscopy images in planes separated by 16 μm in the pyramidal microstructure.

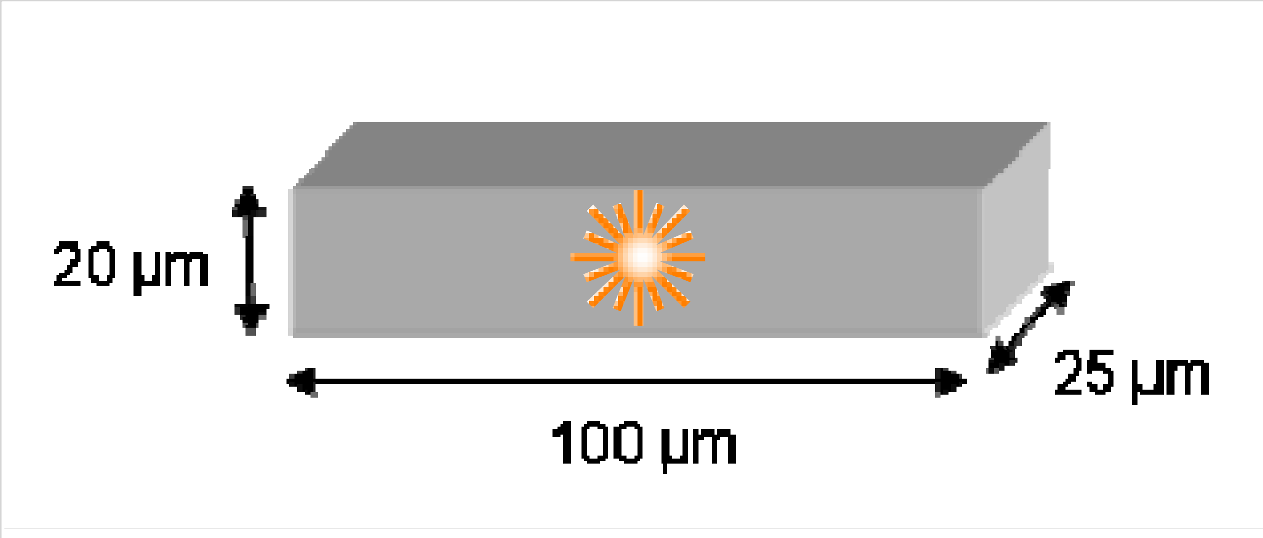
Microstructure containing MEH-PPV

Do we have waveguiding in the microstructure ?

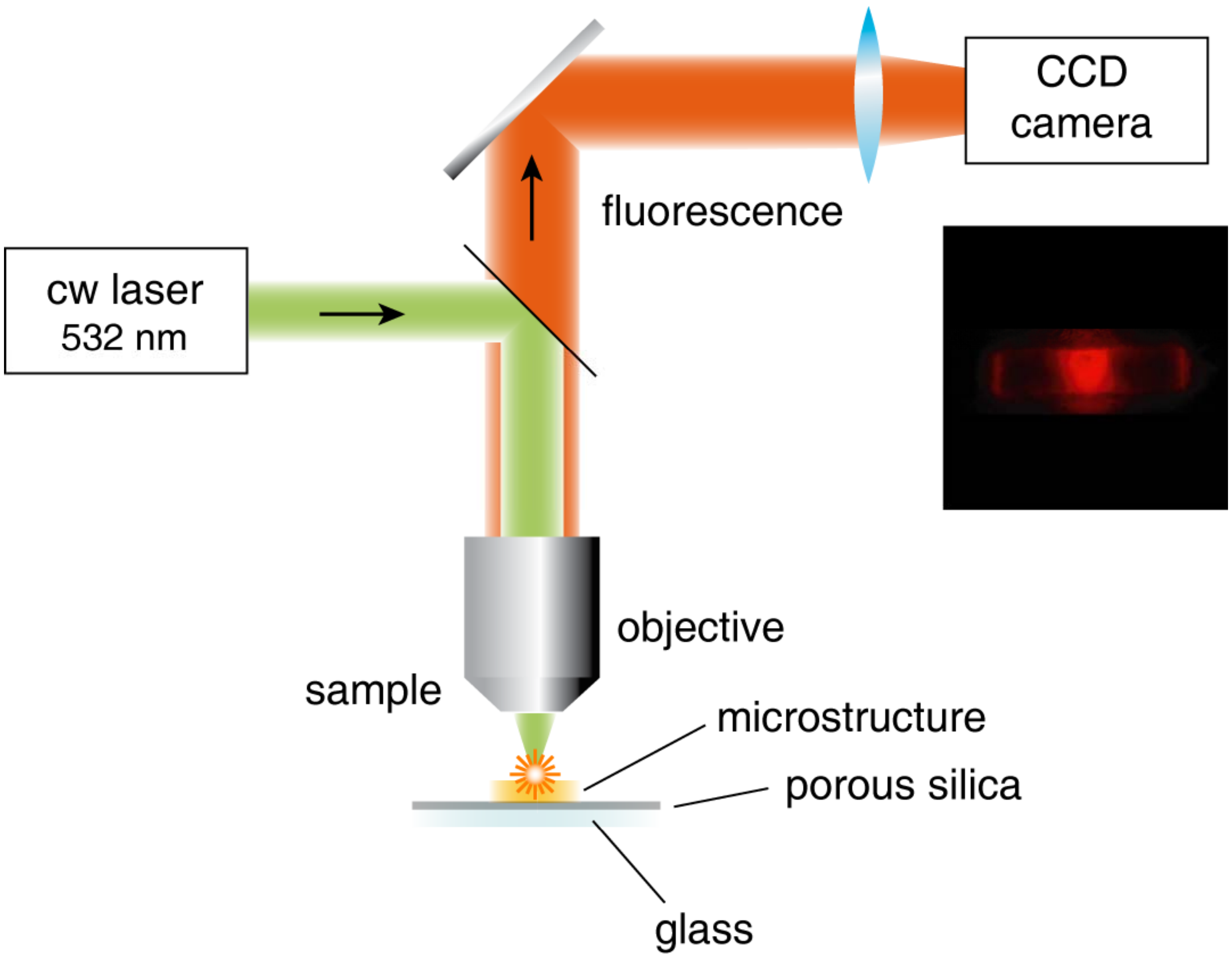


Microstructure containing MEH-PPV

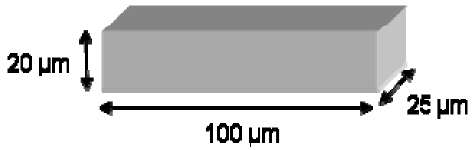
Do we have waveguiding in the microstructure ?

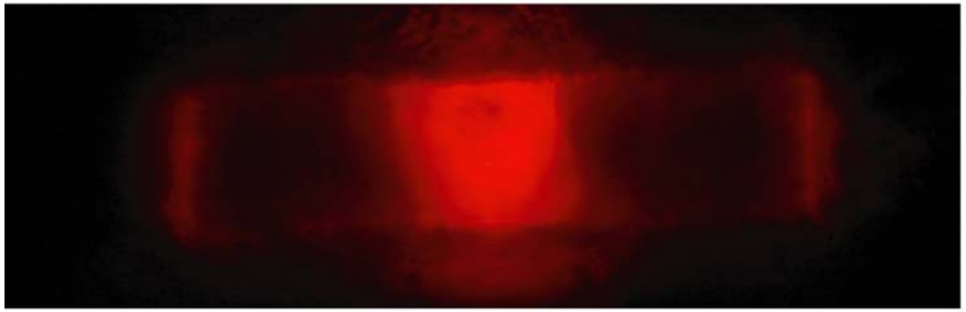


Microstructure containing MEH-PPV

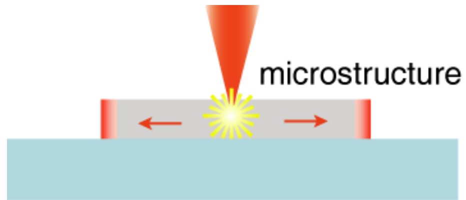


Microstructure containing MEH-PPV





20 µm



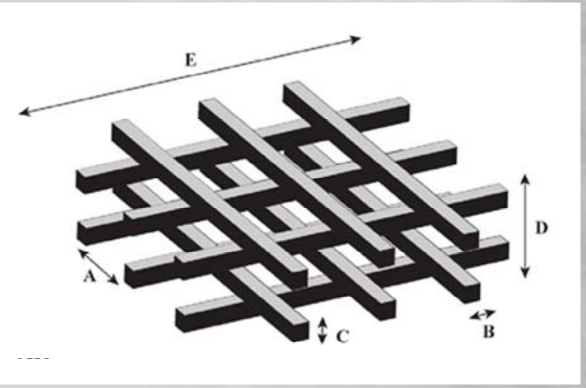
waveguiding of the microstructure fabricated on porous silica substrate (n= 1.185)

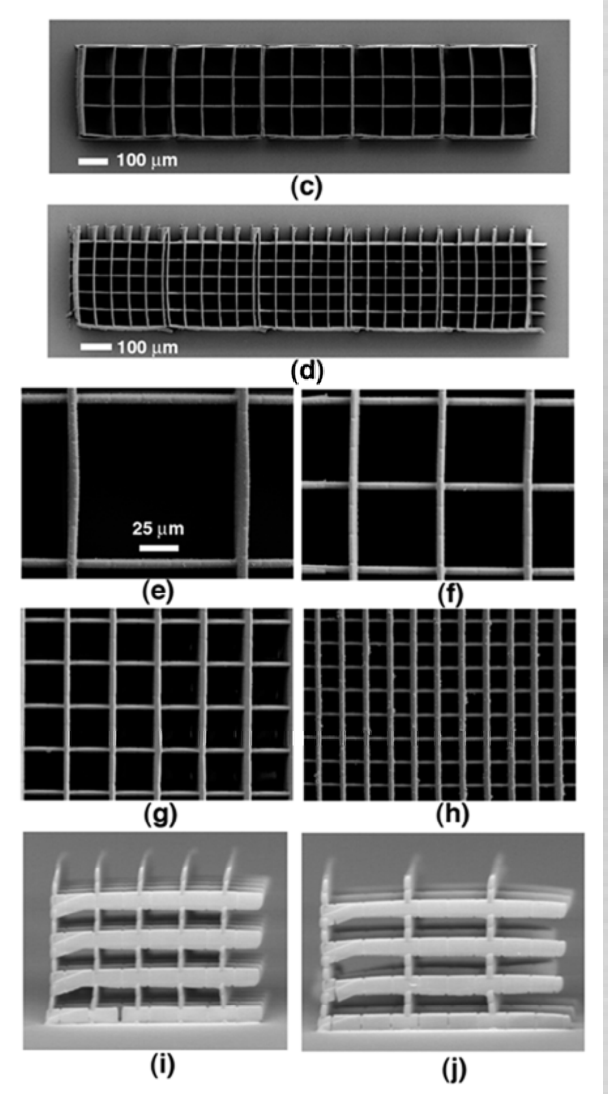
Applications: micro-laser; fluorescent microstructures; conductive microstructures

3D cell migration

- 3D cell migration studies in micro-scaffolds

SEM of the scaffolds





110 µm pore size

52 µm pore size

Top view

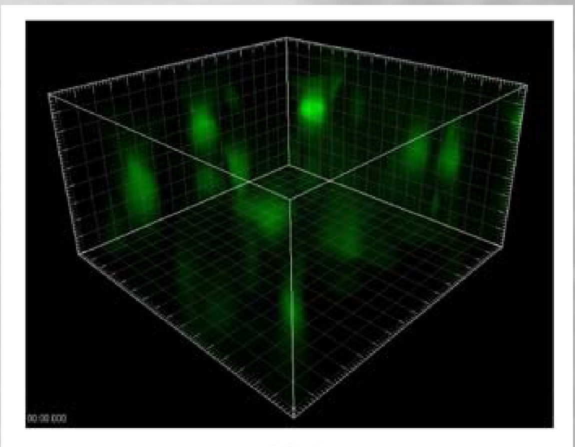
110, 52, 25, 12 µm pore size

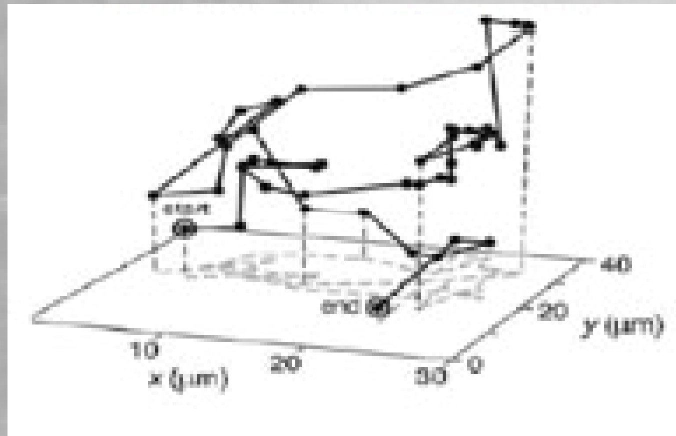
Side view

25, 52 µm pore size

3D cell migration

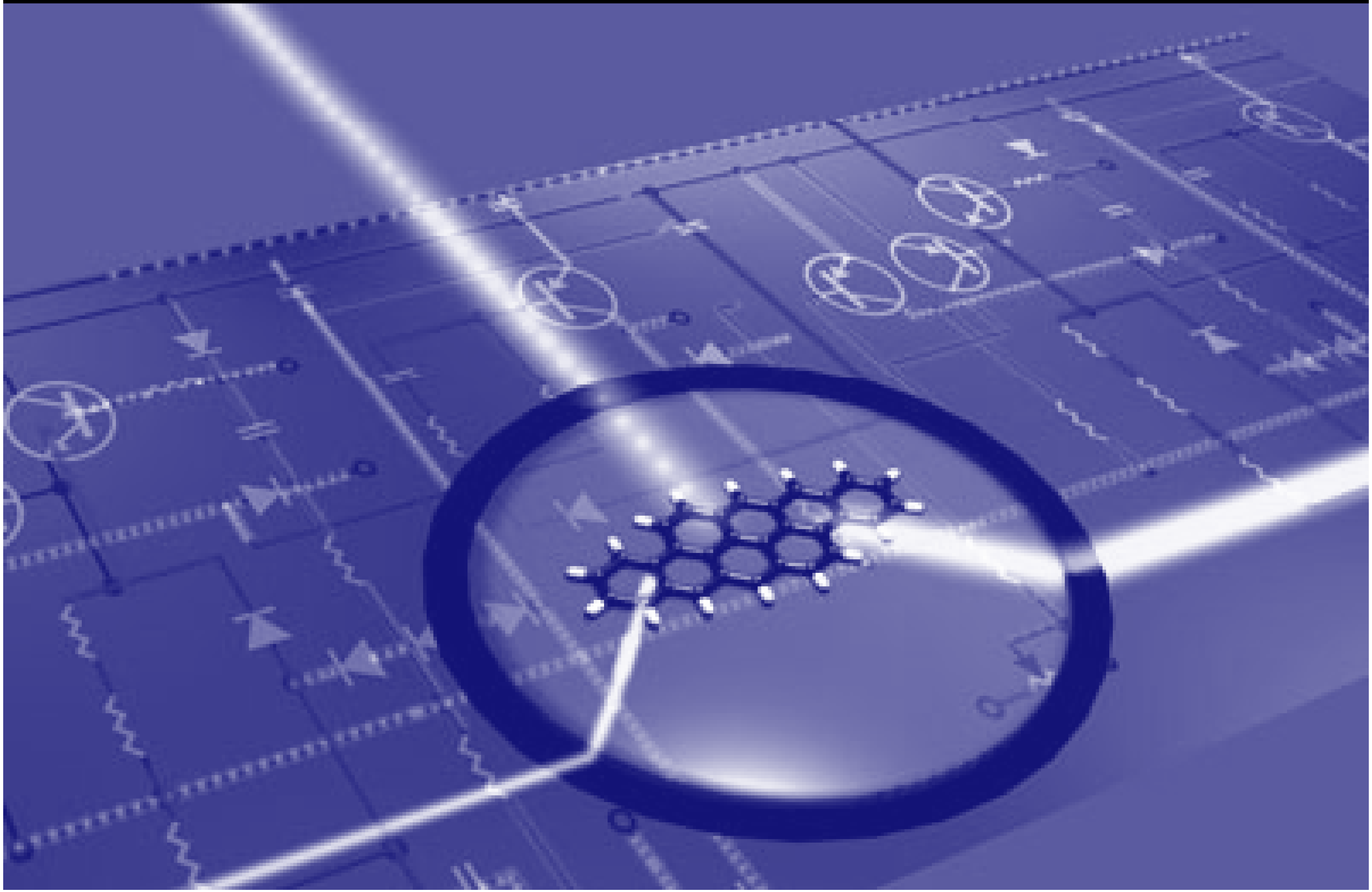
- 3D cell migration studies in micro-scaffolds





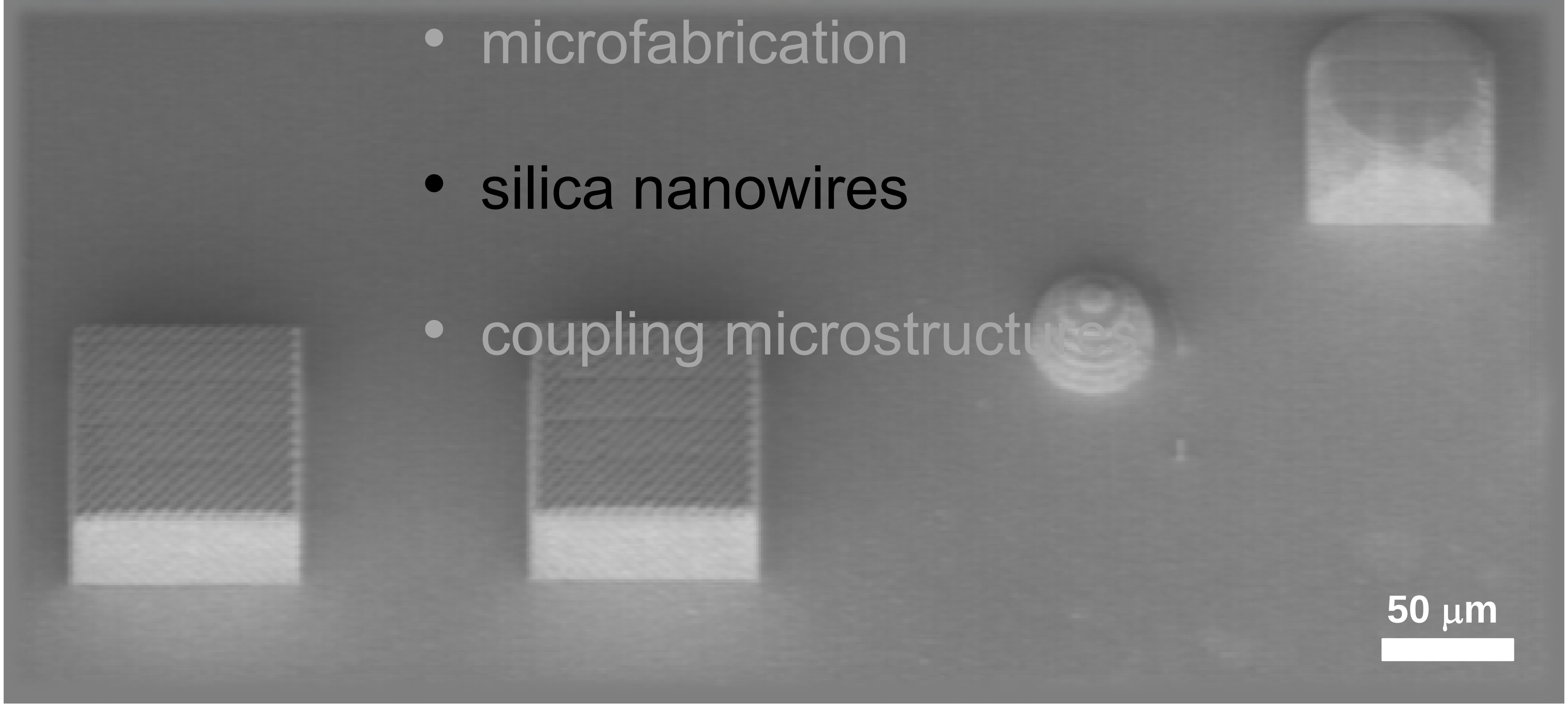
Advanced Materials, 20, 4494-4498 (2008)

Optical circuit



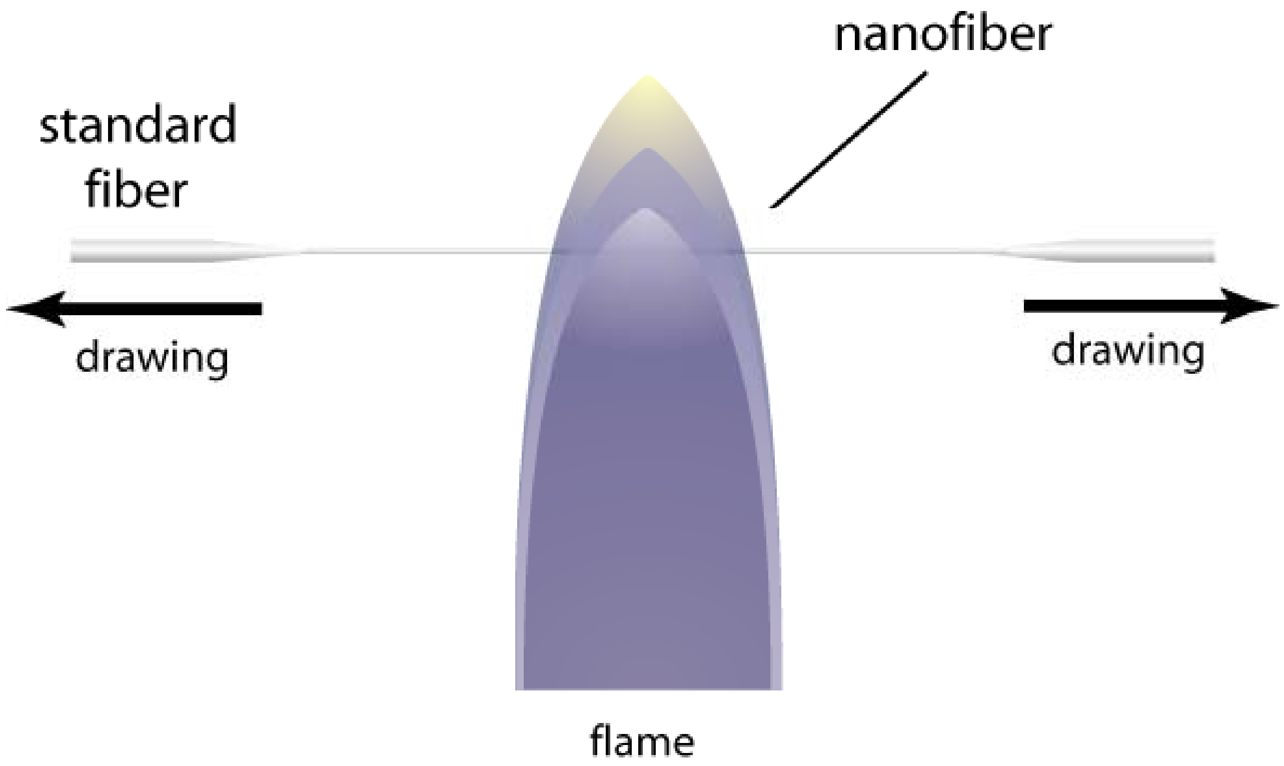
Optical circuit

- microfabrication
- silica nanowires
- coupling microstructures



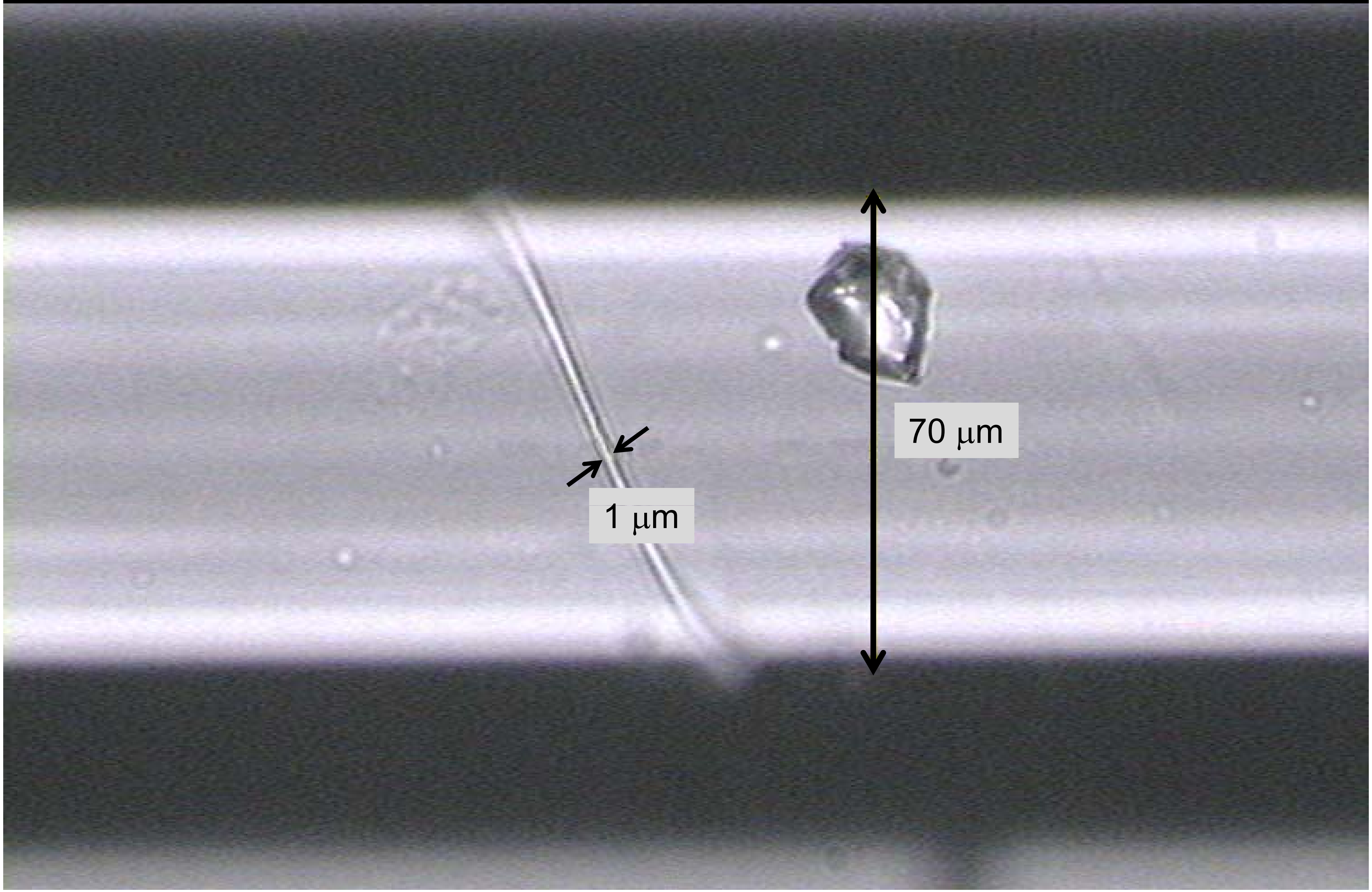
Silica nanowires

nanowires fabrication process

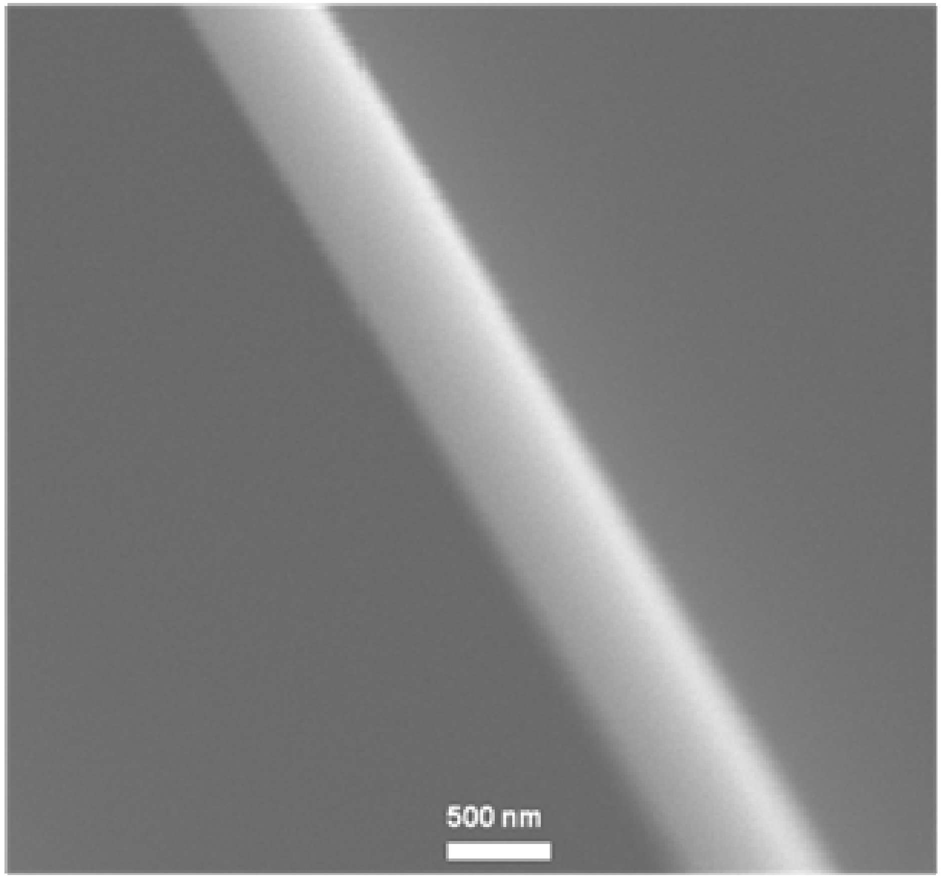


Silica nanowires

Silica nanowires

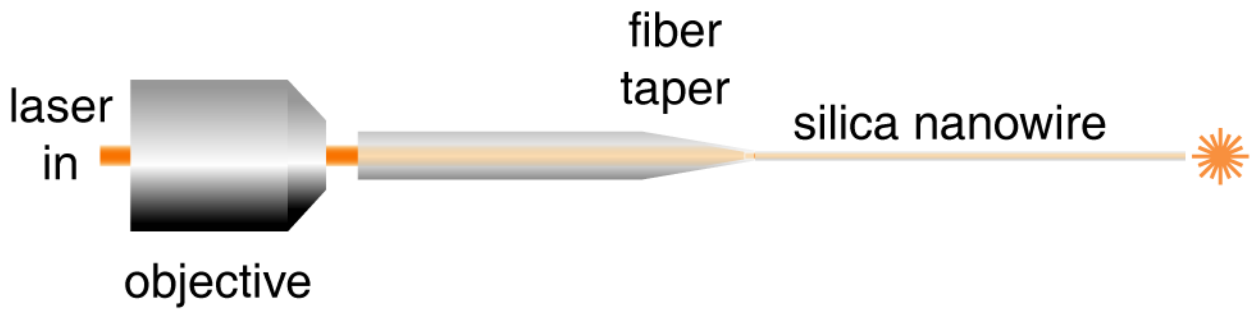


Silica nanowires



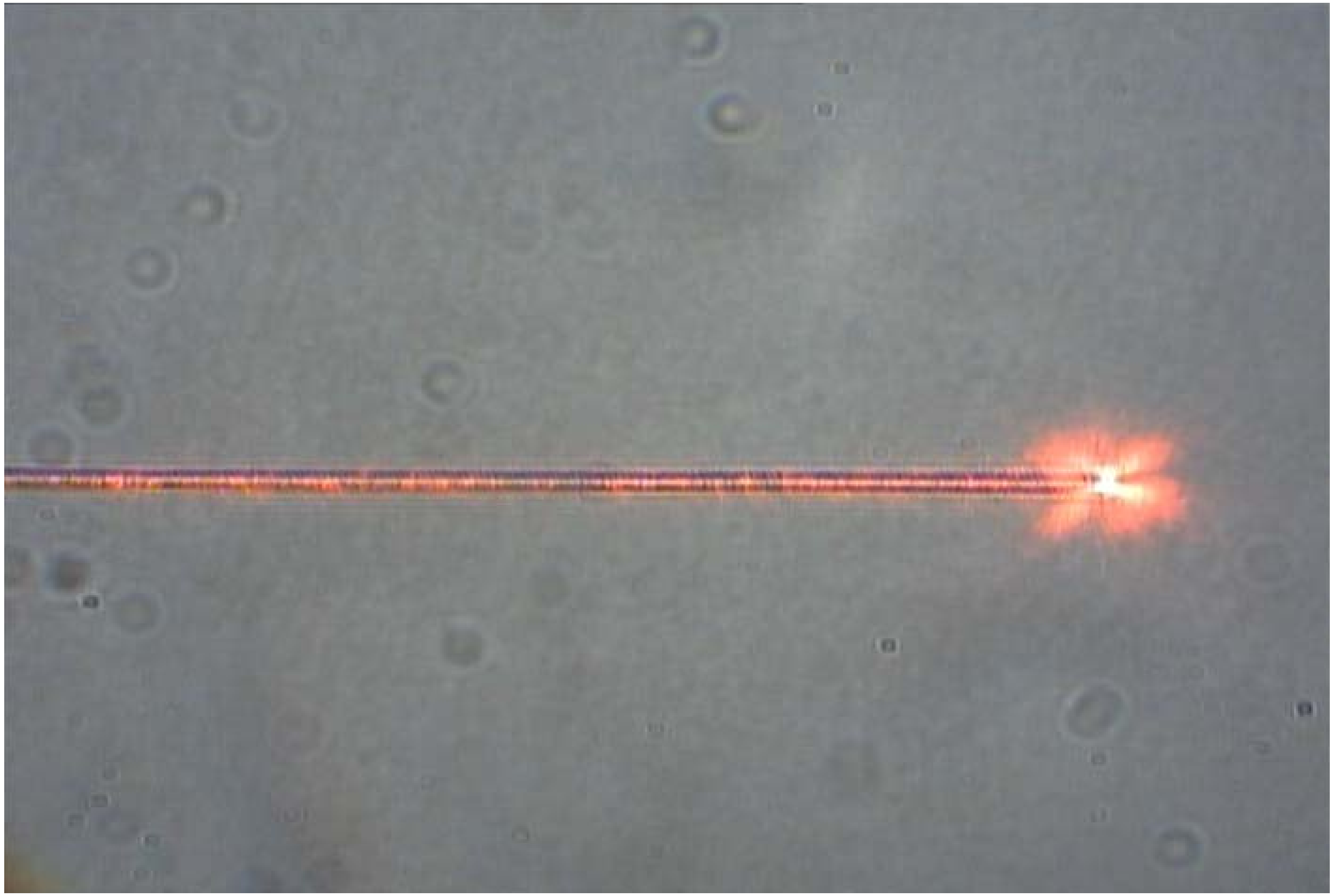
Silica nanowires

coupling light into nanowires

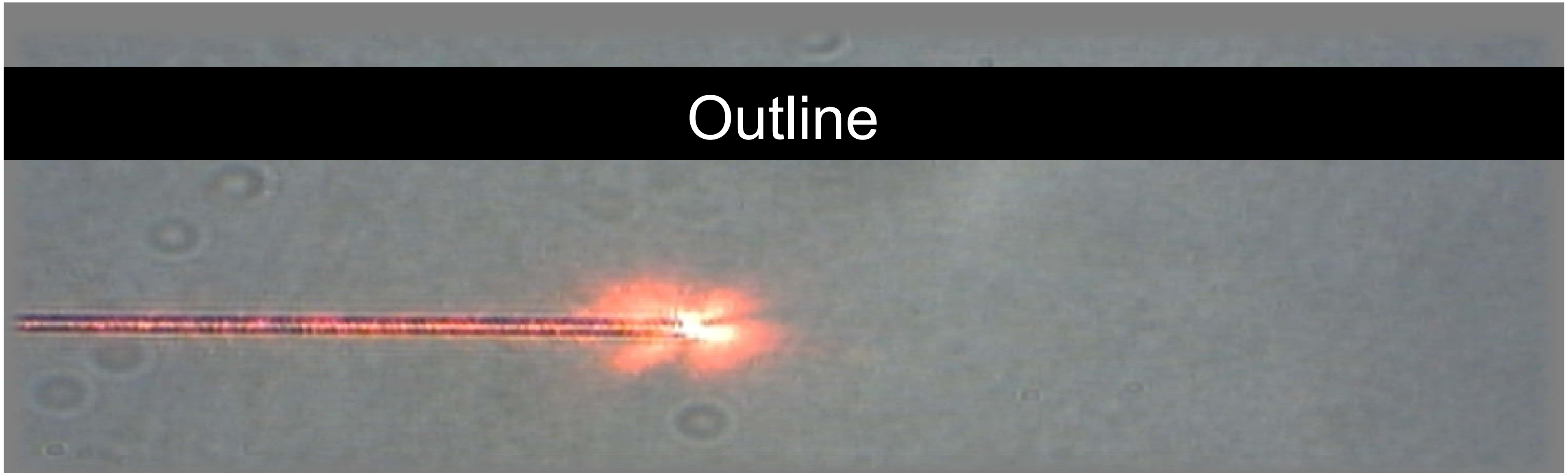


Silica nanowires

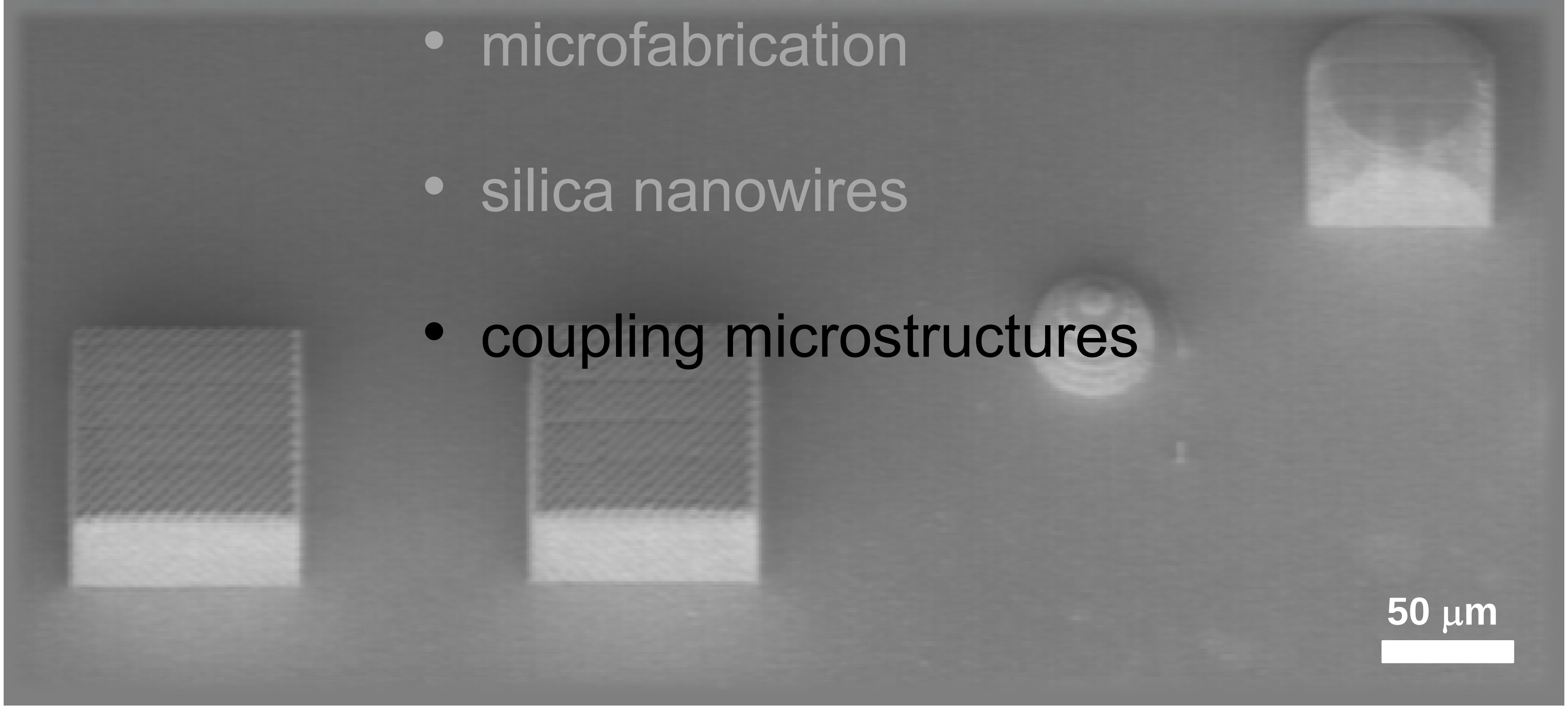
coupling light into nanowires



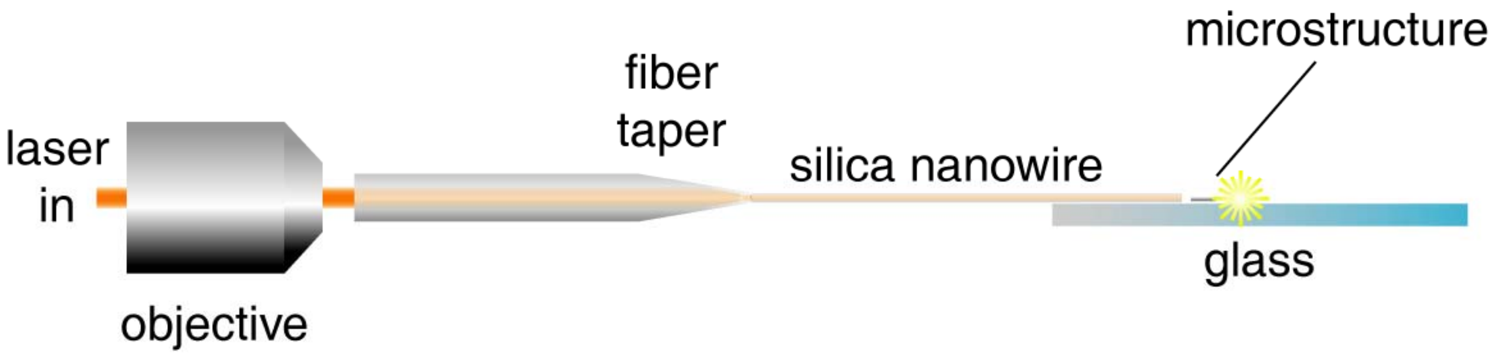
Outline



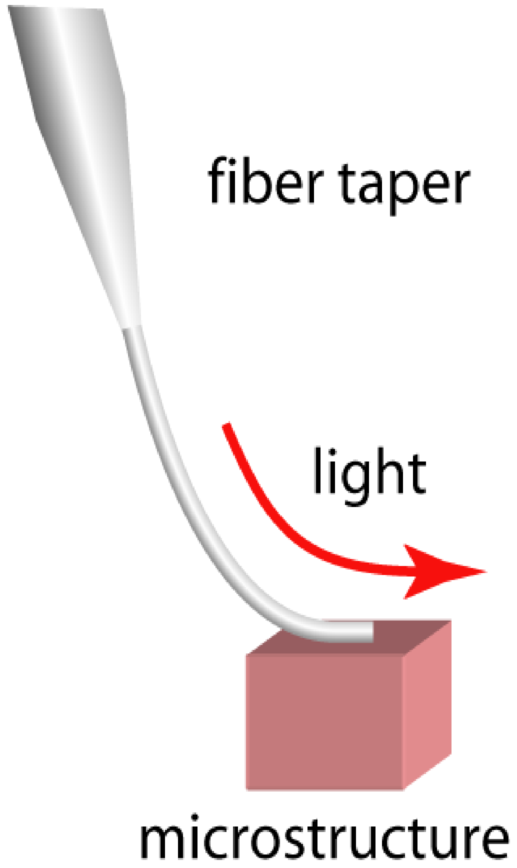
- microfabrication
- silica nanowires
- coupling microstructures



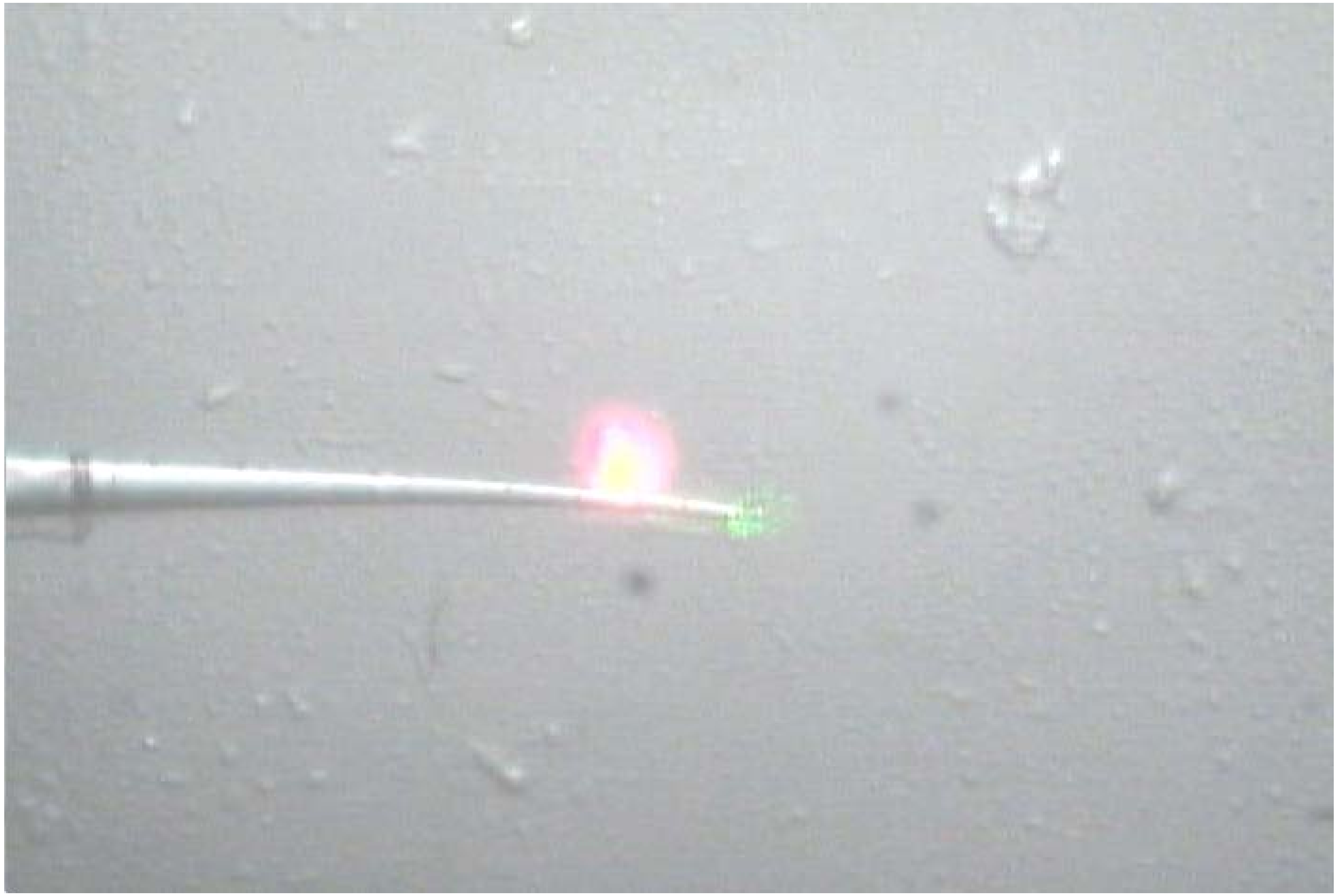
Coupling microstructures



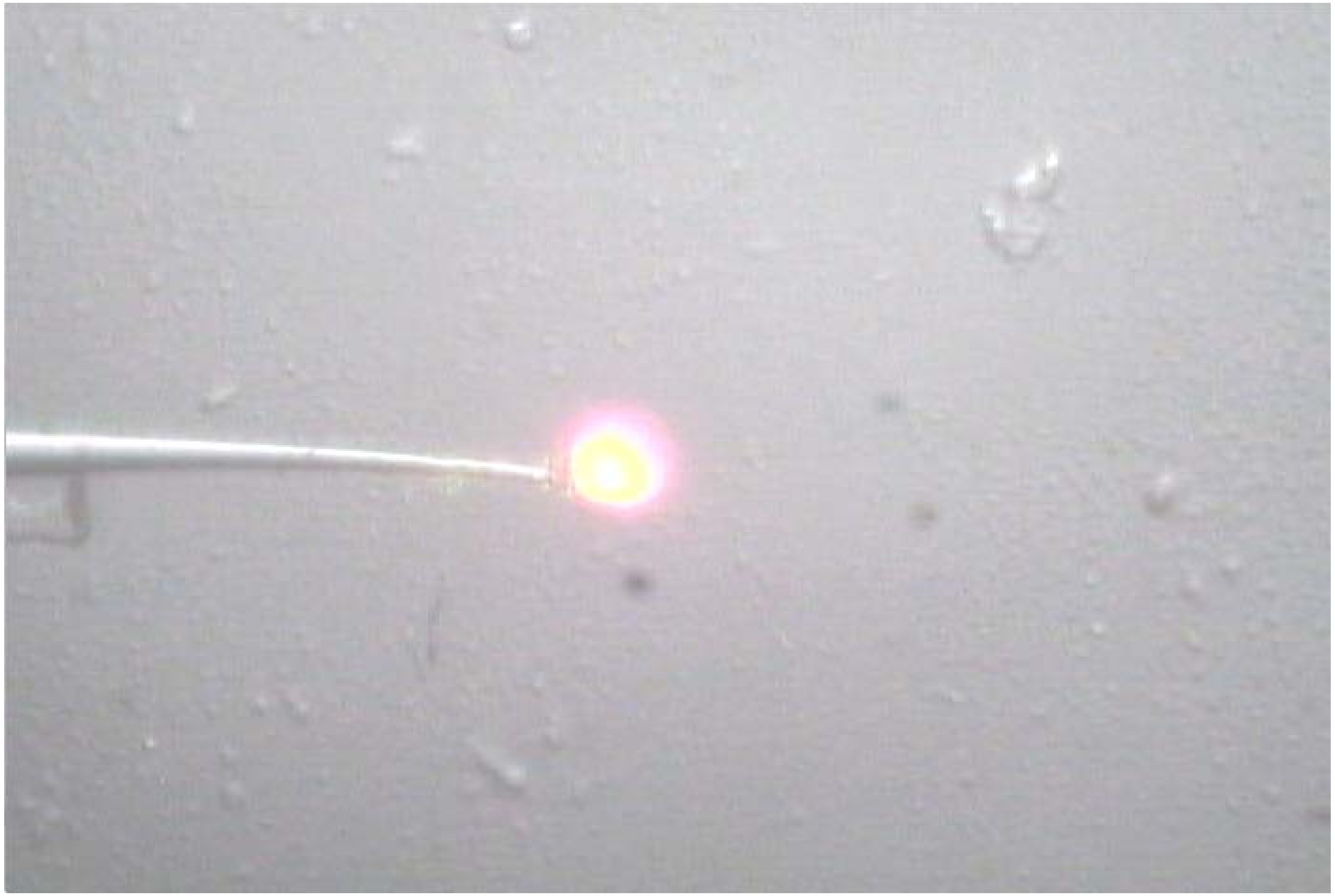
Coupling microstructures



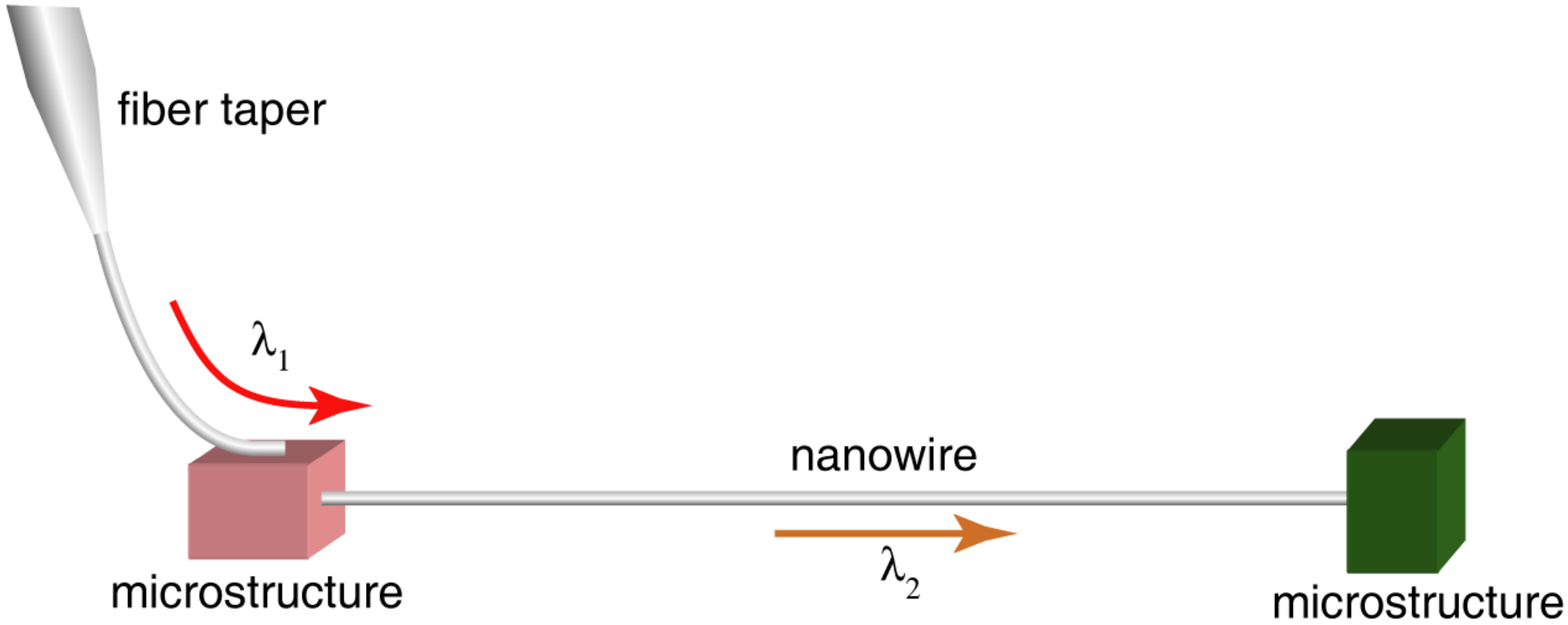
Coupling microstructures



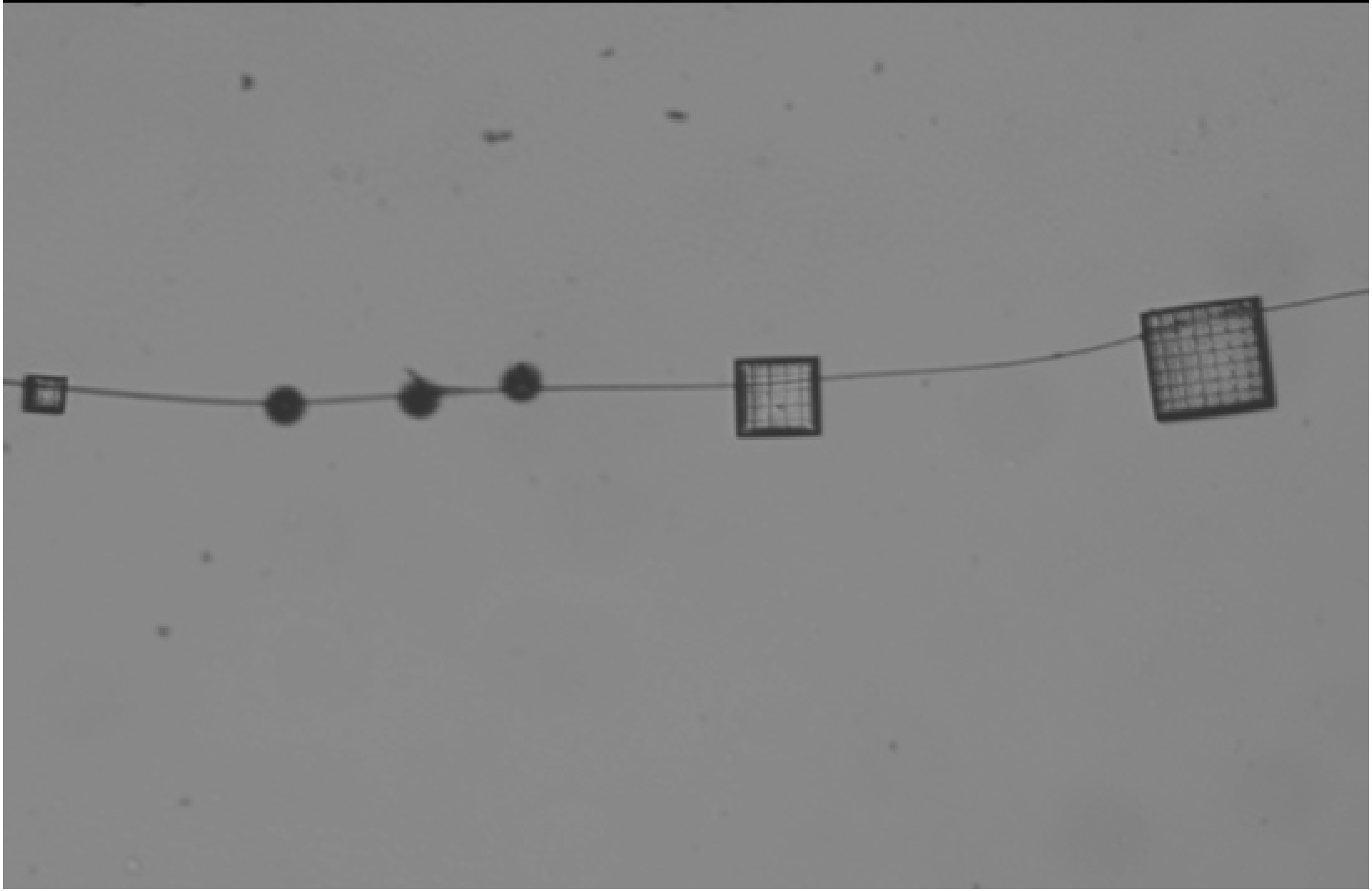
Coupling microstructures



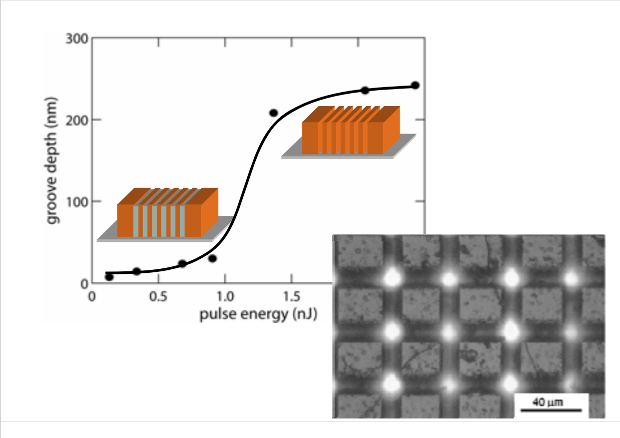
Coupling microstructures



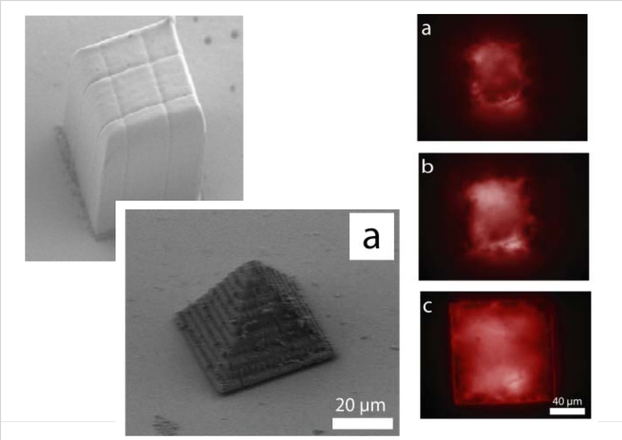
Coupling microstructures



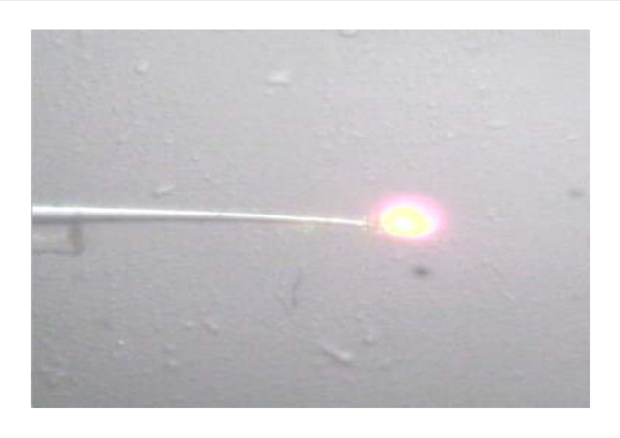
Summary

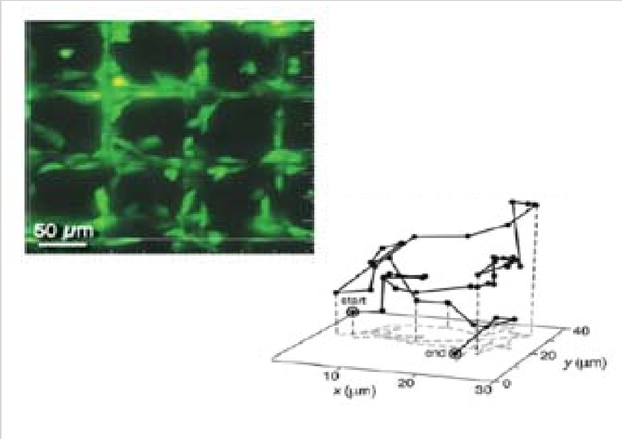


300
200
100
0
groove depth (nm)
0
0.5
1.0
1.5
pulse energy (nJ)
40 µm



a
20 µm
a
b
c
40 µm





50 µm
start
end
40
20
y (µm)
0
10
20
30
x (µm)

Acknowledgments

FAPESP
CAPES
CNPq

US AirForce
NSF
ARO

www.fotonica.ifsc.usp.br

for a copy of this presentation

www.photonics.ifsc.usp.br

presentations