Femtosecond laser pulses: nonlinear spectroscopy and microfabrication

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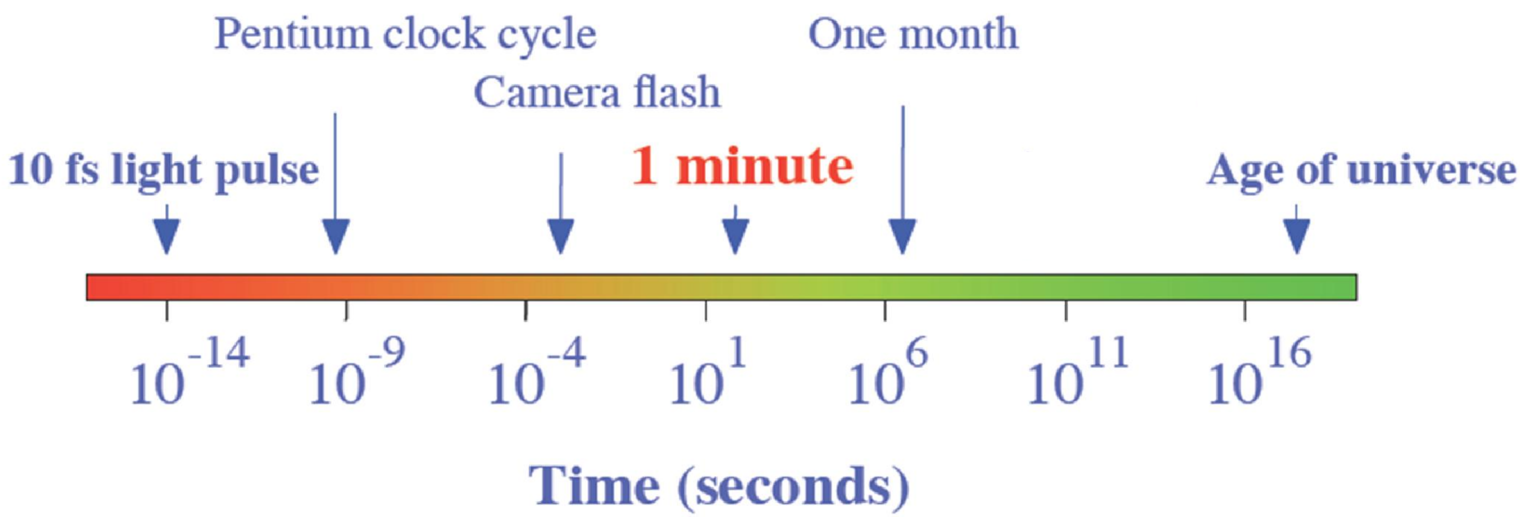
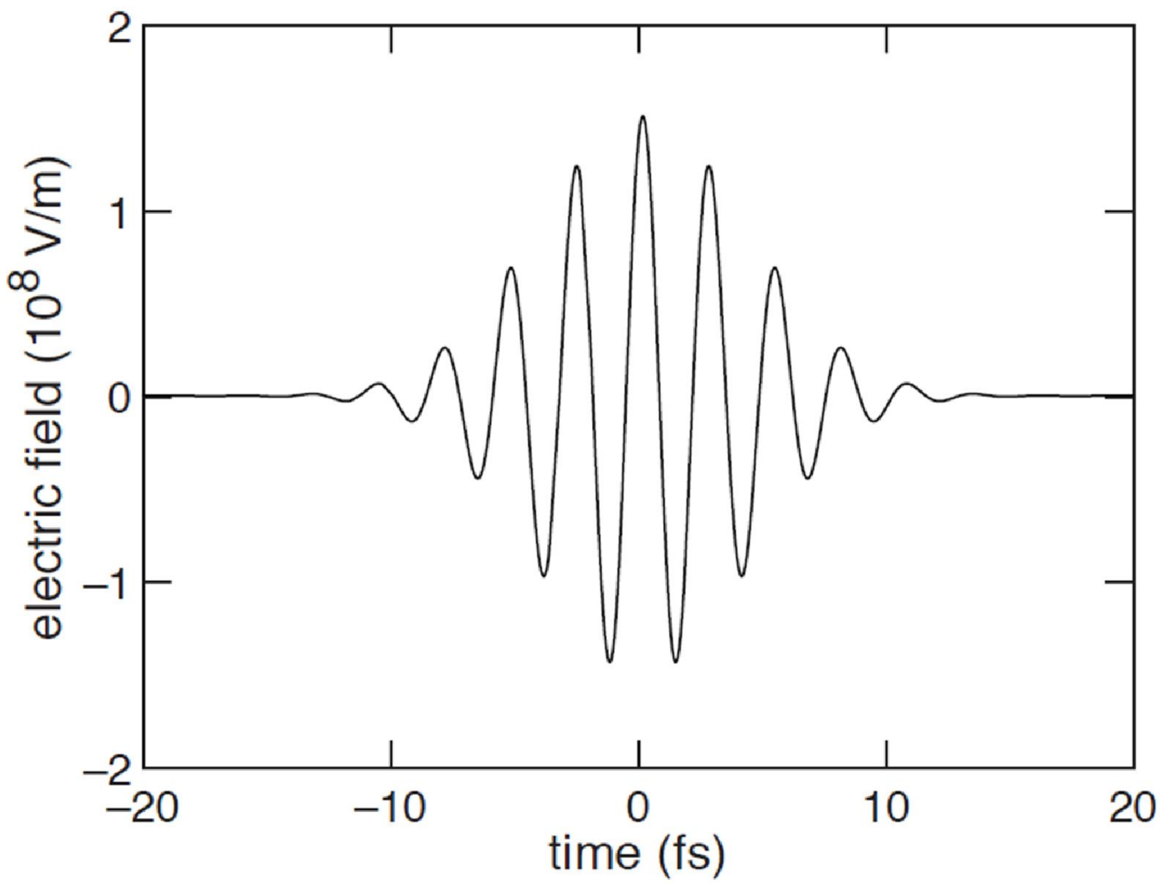
Microfabrication

1 fs = 10^{-15} s



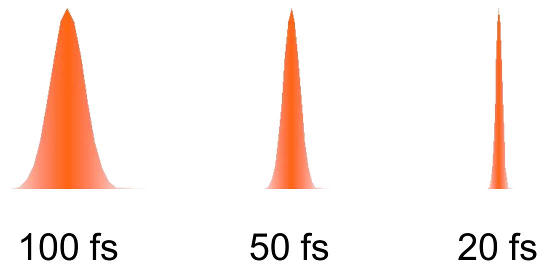
introduction

how short is a femtosecond pulse ?



Microfabrication

Ti:Sapphire lasers



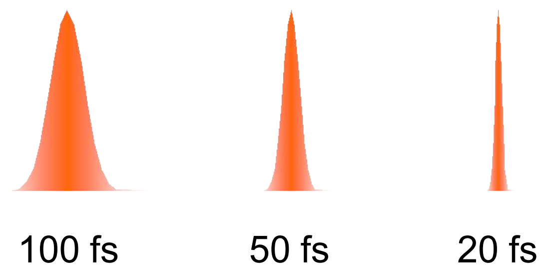
Very intense light

Laser intensities ~ *100 GW/cm^2*
1×10^{11} W/cm^2

Laser pointer: 1 mW/cm^2 (1×10^{-3} W/ cm^2)

fs-laser micromachining

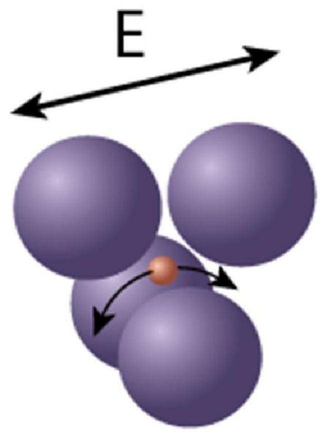
Ti:Sapphire lasers



Very intense light

Nonlinear Optical Phenomena

Nonlinear Optics



anharmonic oscillator

high light intensity

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

nonlinear polarization response

$$P = \varepsilon_0 \left(\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right)$$

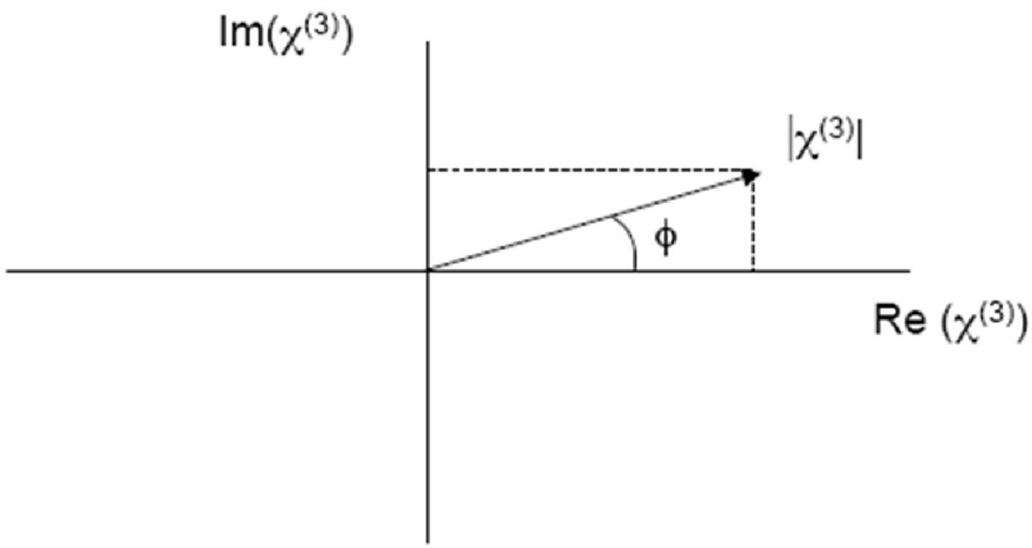
Nonlinear Optics

$\chi^{(3)}$ is a complex quantity

$$\chi^{(3)} = \mathrm{Re}\,(\chi^{(3)}) + i\,\mathrm{Im}(\chi^{(3)})$$

Related to intensity dependent refractive index

Related to two-photon absorption



Nonlinear Optics

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

Refractive process:

$$n = n_0 + n_2 I$$

- self-phase modulation
- lens-like effect

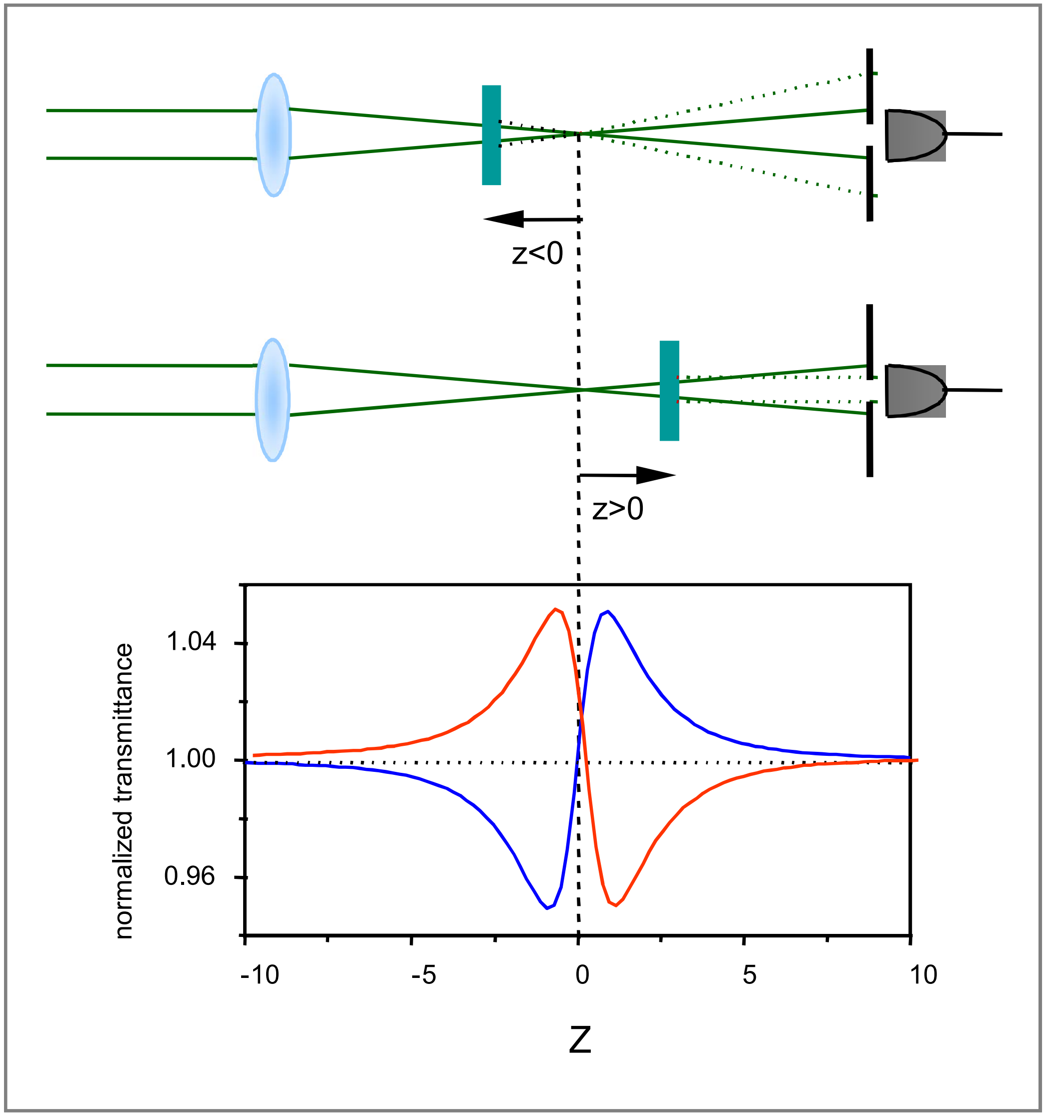
Absorptive process:

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

- nonlinear absorption
- two-photon absorption

Measuring nonlinear refraction

Z-scan: close aperture



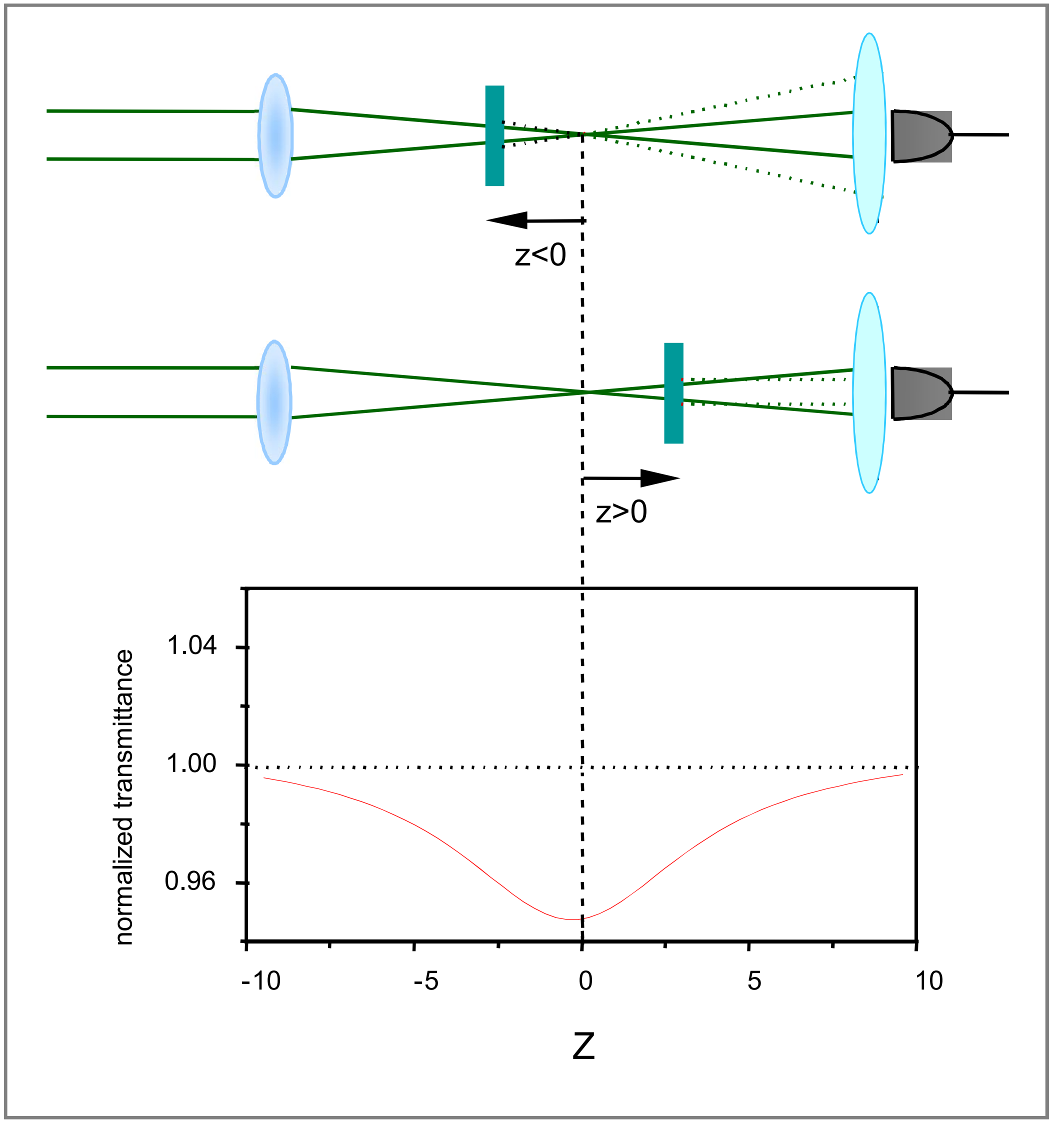
$$n = n_0 + n_2 I$$

$$\left|\Delta Z_{pv}\right| \approx 1.7 Z_0$$

$$\Delta T_{pv} \cong 0.406(1-S)^{0.27}\left|\Delta\Phi_0\right|$$

$$\Delta\Phi_0 = \frac{2\pi}{\lambda} n_2 I_0 L_{eff}$$

Measuring nonlinear absorption



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

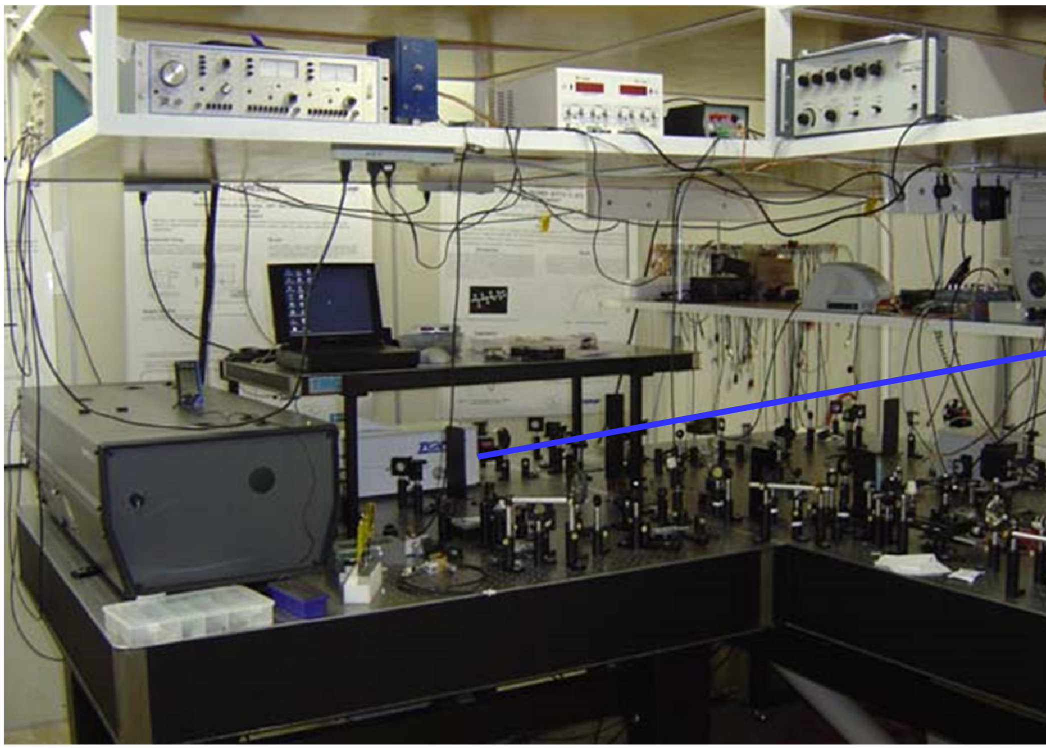
$$\Delta T \propto \beta I$$

$$T(z) = \sum_{m=0}^{\infty} \frac{[-q_0(z,0)]^m}{(m+1)^{3/2}}$$

$$q_0(z,t) = \beta I_0 L / \left(1 + z^2 / z_0^2\right)$$

Nonlinear spectrocopy

nonlinear spectrum



Optical parametric amplifier

τ = 120 fs

λ = 460 - 2600 nm

E= 20-60 μJ

Laser amplifier (Ti:Saphire)

τ = 150 fs

λ = 775 nm

E = 800 μJ

Tungsten Lead-Pyrophosphate + Cu

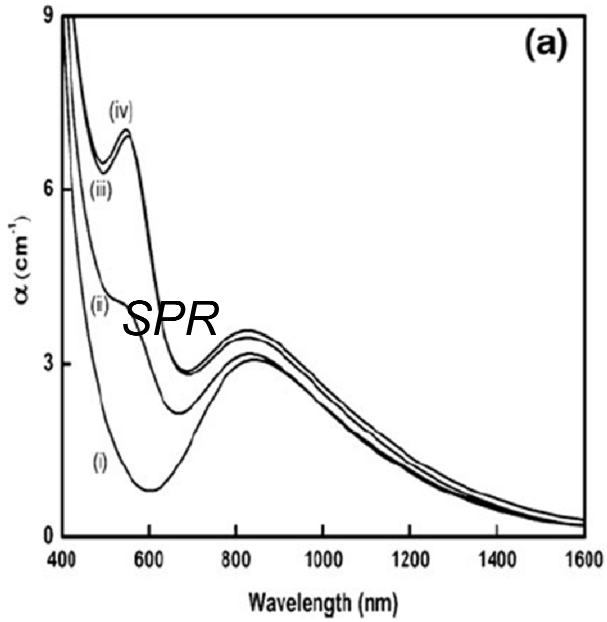
$70Pb_2P_2O_7$-$30WO_3$ (in wt. %) for glass host

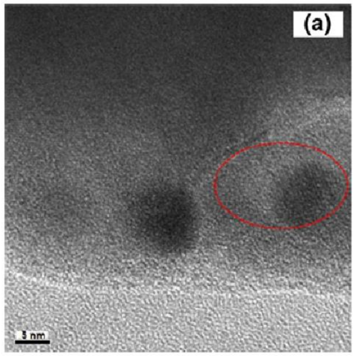
+

CuO (0.5 wt. %)

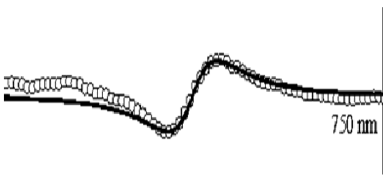
Table 1 Sample labels, synthesis conditions, and characteristic temperatures of PW glasses doped with CuO

	Sample labels	Annealing conditions		Characteristic temperatures	
		T_{ht} (°C)	t_{ht} (min)	T_g (°C)	T_x (°C)
(i)	PW-0		0		
(ii)	PW-5		5		
(iii)	PW-20	410	20	410	575
	PW-60		60		
(iv)	PW-120		120		

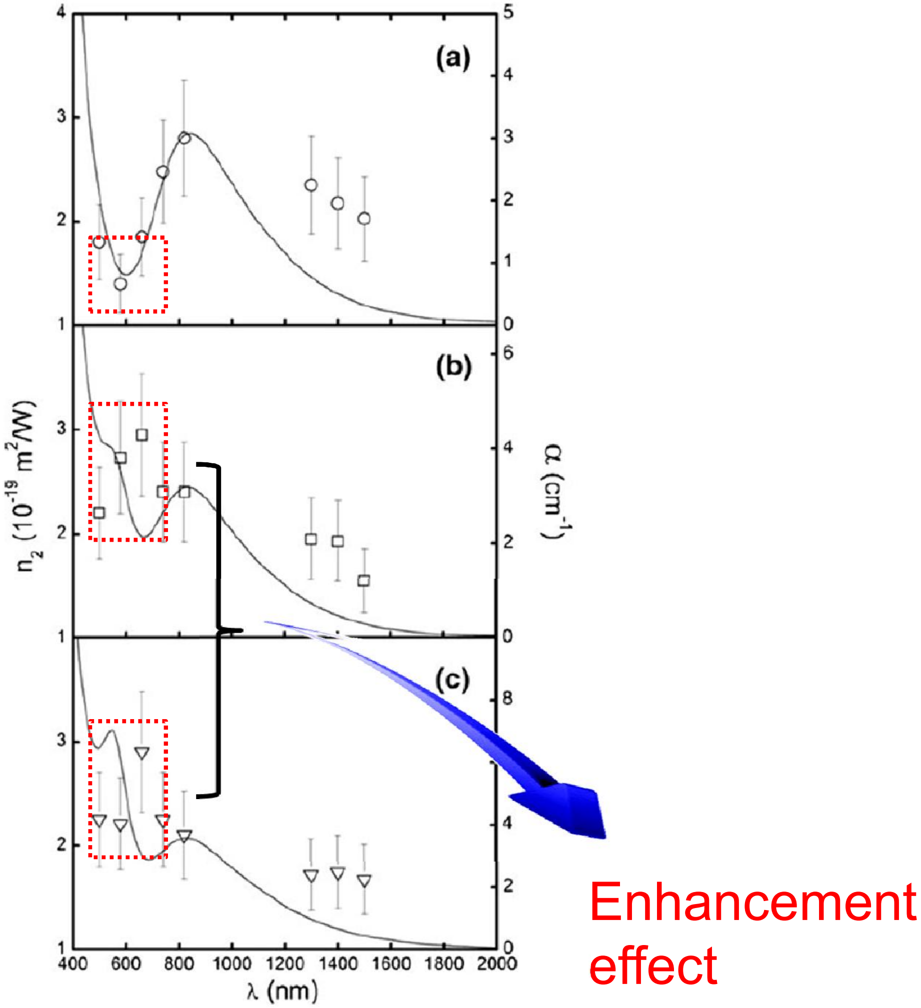




Nonlinear refraction



$$\Delta\phi_0 = kn_2 I_0 L.$$



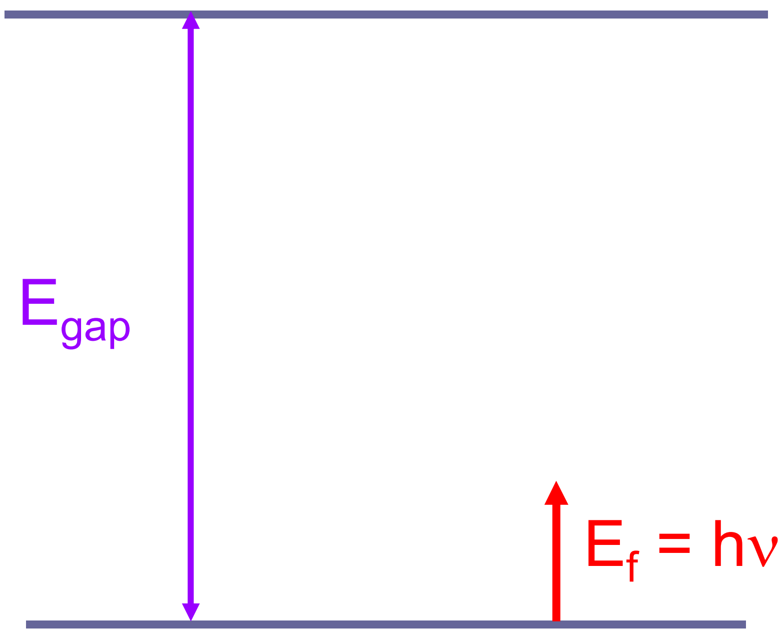
fs-laser microfabrication

photon energy < bandgap

nonlinear interaction

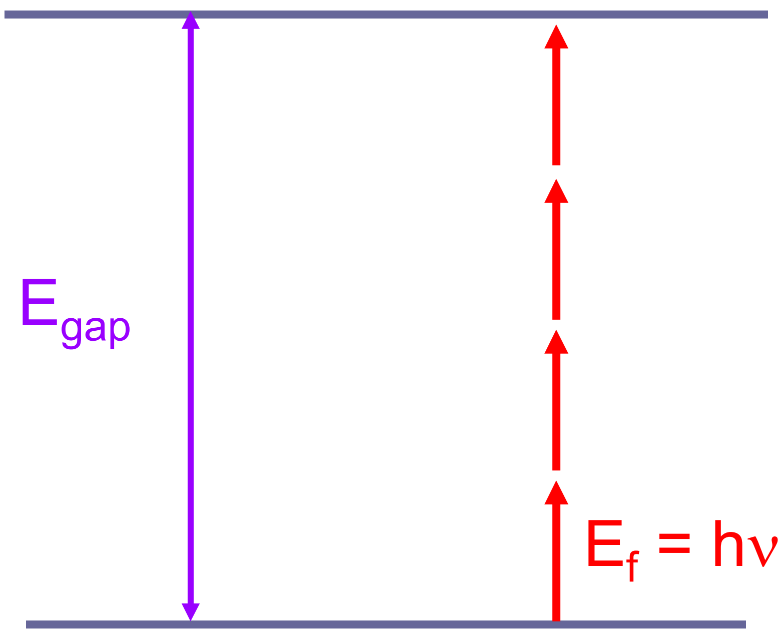
fs-laser microfabrication

nonlinear interaction



fs-laser microfabrication

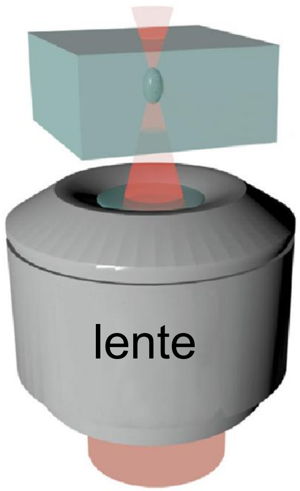
nonlinear interaction



multiphoton absorption

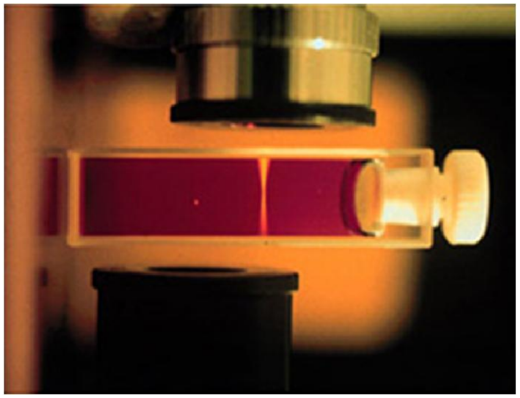
multiphoton absorption

nonlinear interaction



spatial confinement of excitation

two-photon absorption

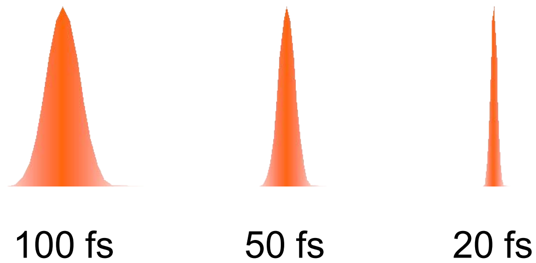


$$\alpha = \alpha_0 + \beta I$$
$$R \propto I^2$$

feature exploited for microfabrication

femtosecond pulses

Ti:Sapphire lasers

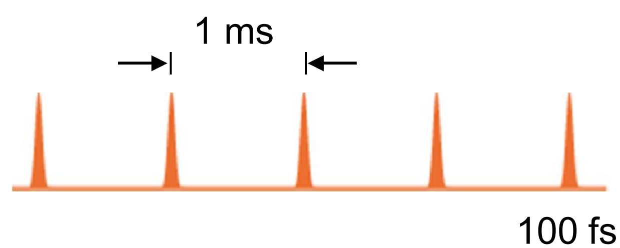


1 fs = 10^{-15} s

Repetition rate

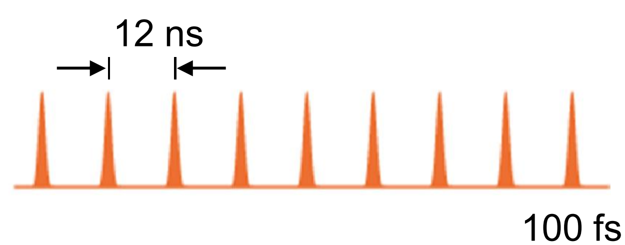
Energy

1 KHz



mJ

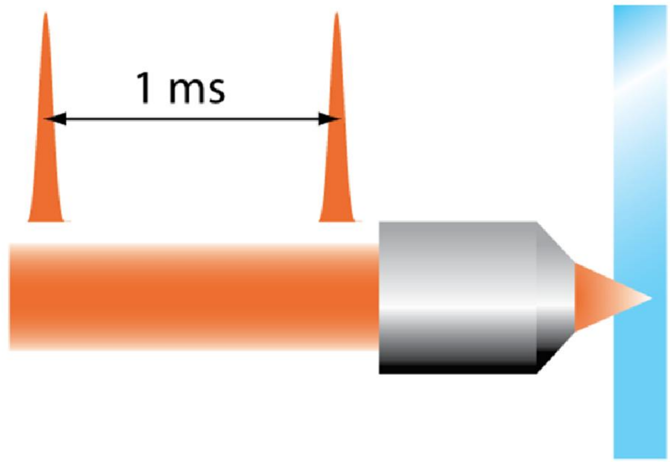
86 MHz



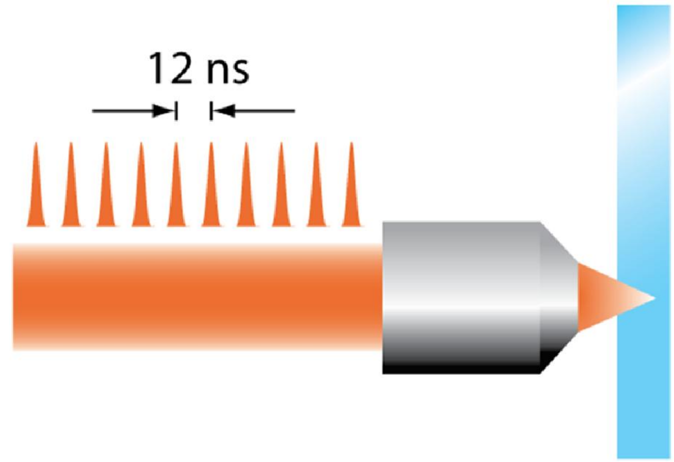
nJ

fs-micromachining

amplified laser

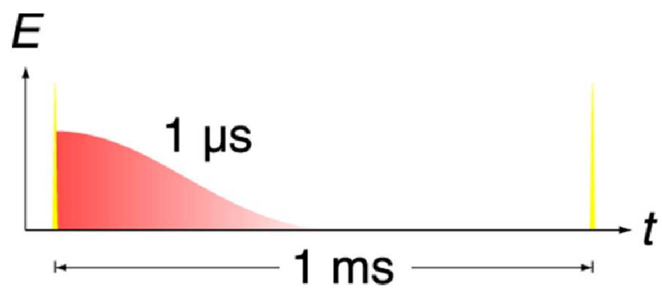
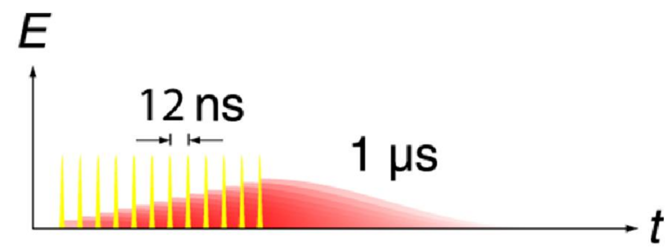


oscillator

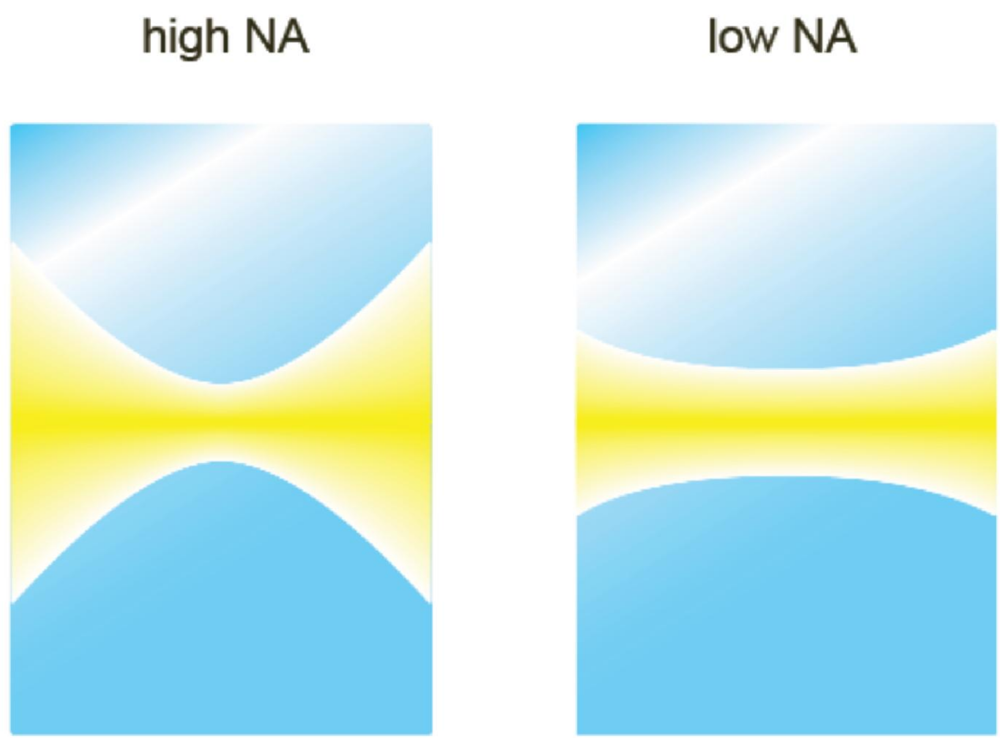


heat diffusion time: $t_{diff} \sim 1\ \mu s$

fs-micromachining

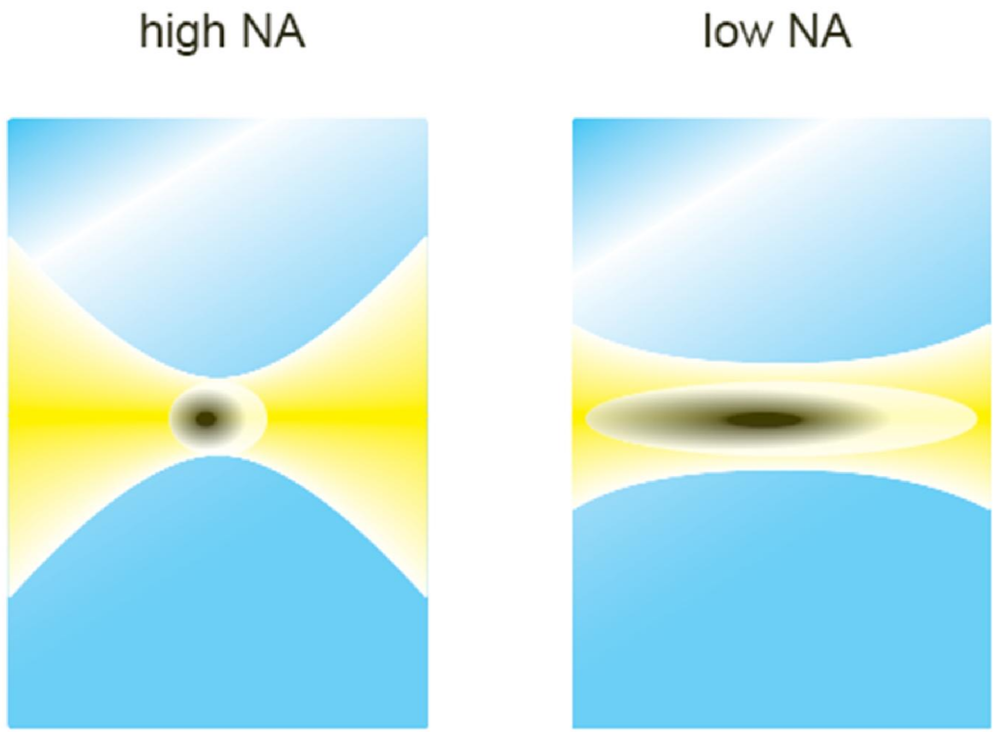
amplified laser	oscillator
low repetition laser	high repetition laser
	
repetitive	cumulative

what is the difference ?



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

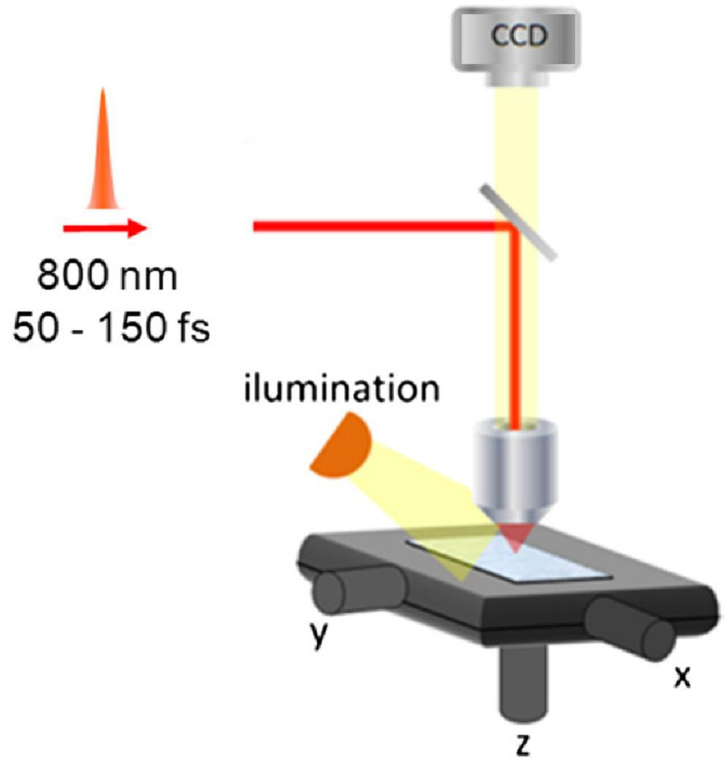
very different confocal lenght/interaction length



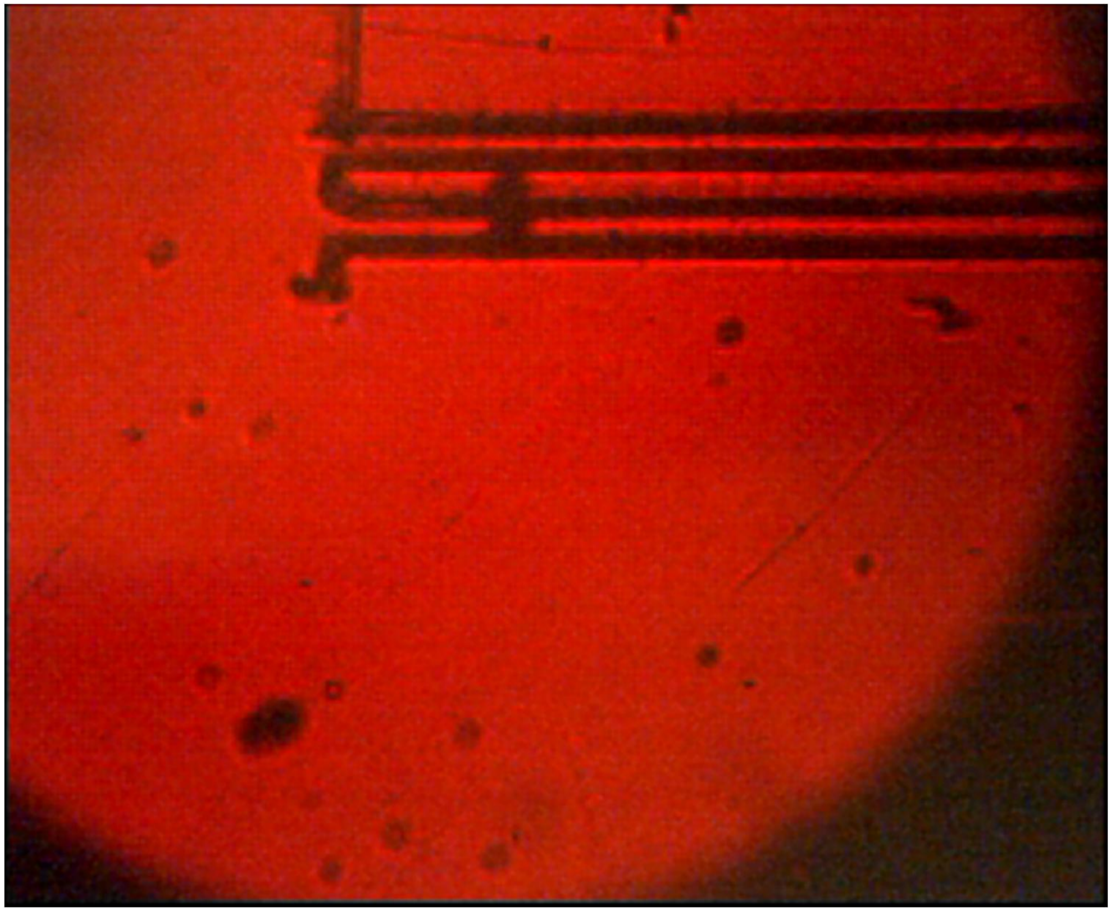
two main techniques

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

fs-laser microstructuring experimental setup

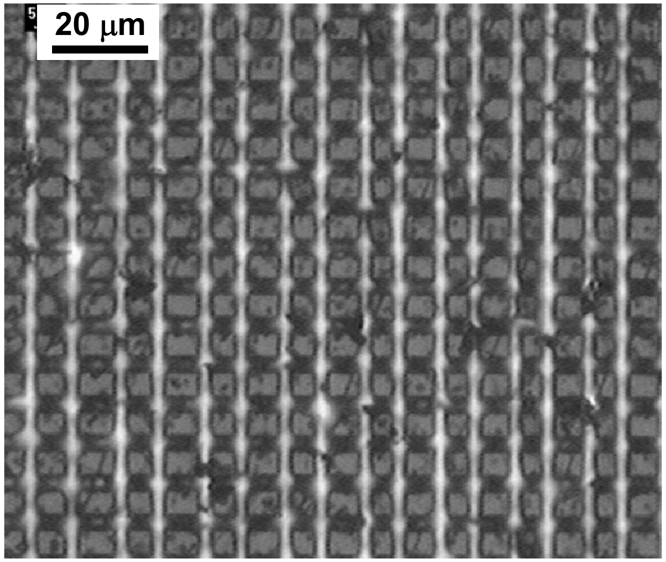


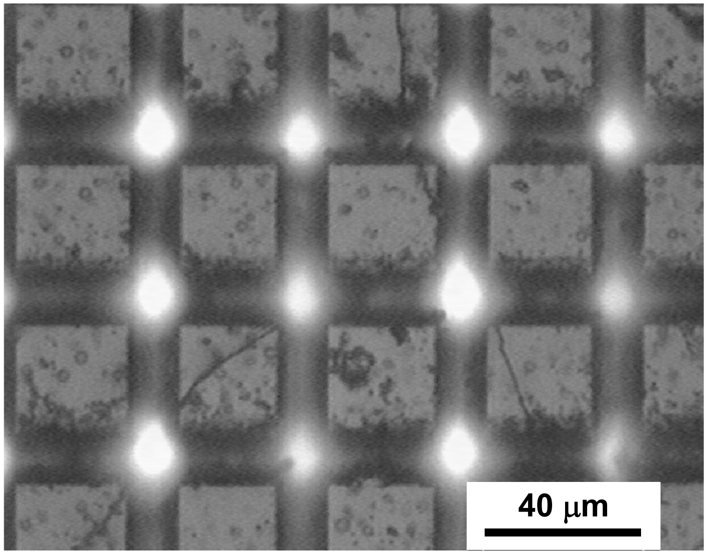
microstructuring polymer: super hydrophobic surface



laser microfabrication: super hydrophobic surface

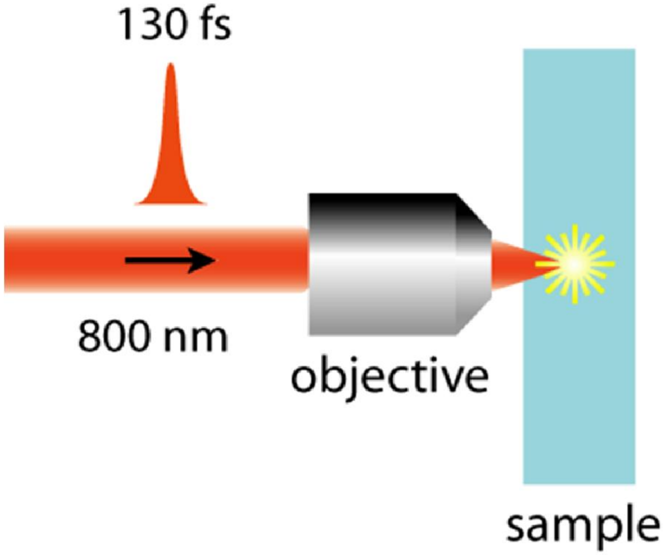
examples of fabricated surfaces



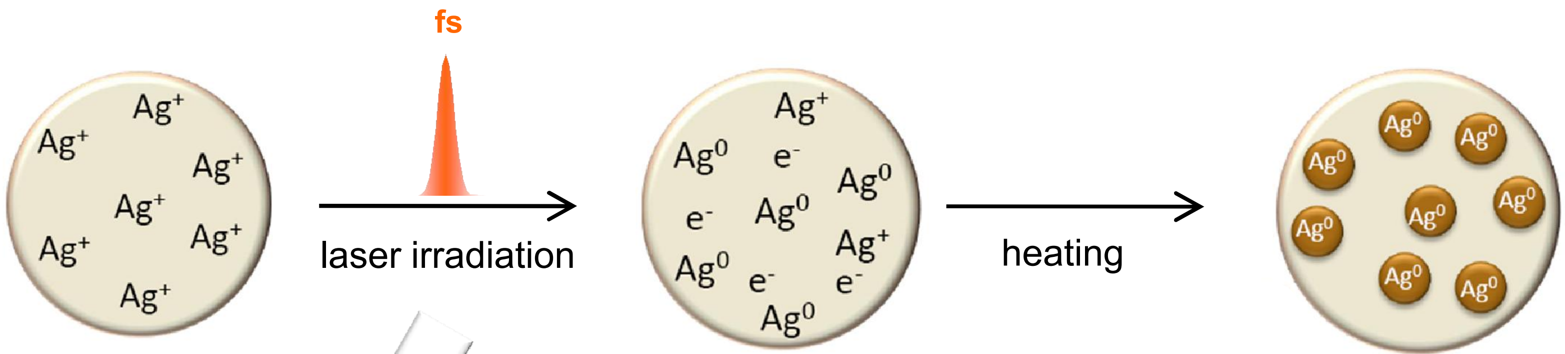


fs-laser micromachining

Volume



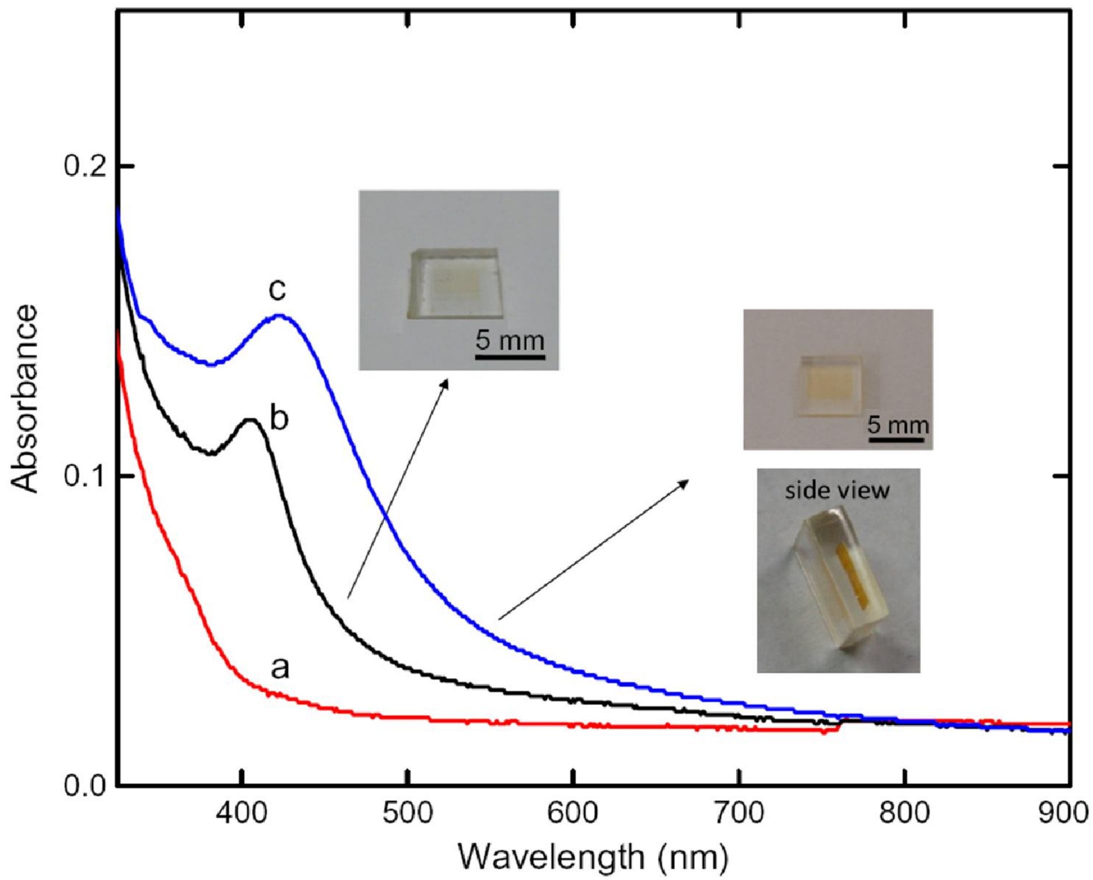
Generation of Ag nanoparticles



Ag nanoparticles are generated only in the irradiated area due to the **fs-laser induced photoreduction**

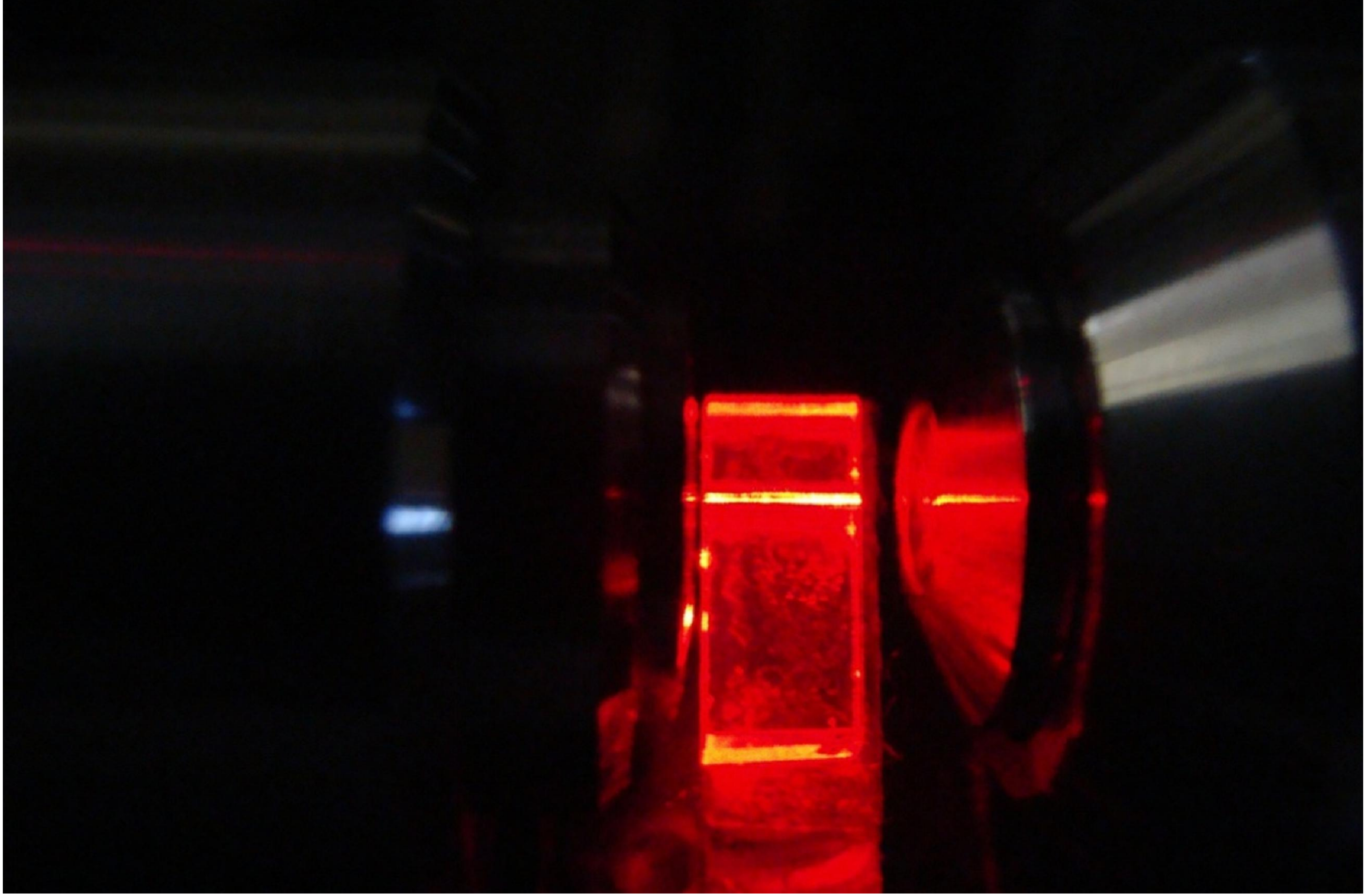
Free electron generation
Photoreduction reaction
$Ag^{+} + e^{-} \rightarrow Ag^{0}$

Generation of Ag nanoparticles



Absorption spectrum of the Ag:BBO sample as prepared (a), after irradiation with the 5 MHz fs-laser (b) and after irradiation with the amplified fs-laser (1 kHz) and subsequent thermal treatment.

fs-laser waveguides fabrication



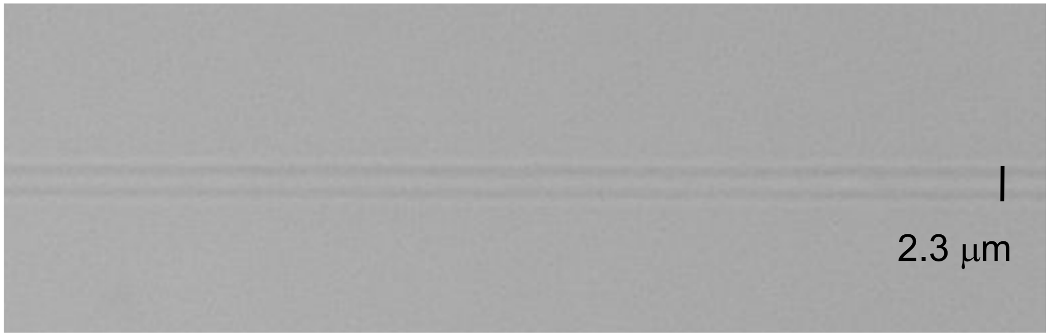
Waveguides fabrication

Sample:

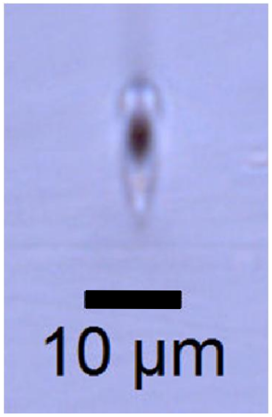
Ag:P7W3

Tungsten lead pyrophosphate glass - $(70Pb_2P_2O_7\text{-}30WO_3)$:1AgCl (%mol)

Waveguides fabricated using the 5-MHz laser system (50 fs) with 37 nJ/pulse and v = 10 µm/s



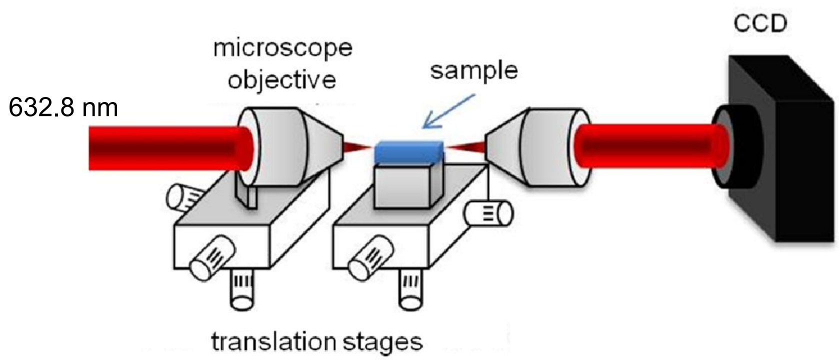
Top view

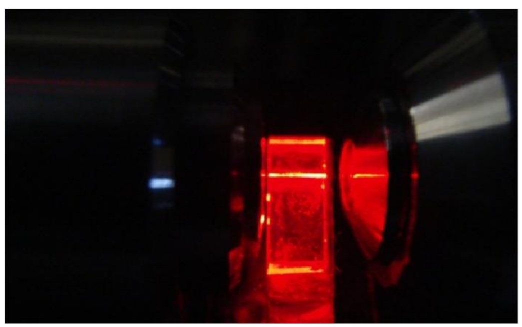


Cross-section view

Waveguides fabrication

Coupling light into the waveguides





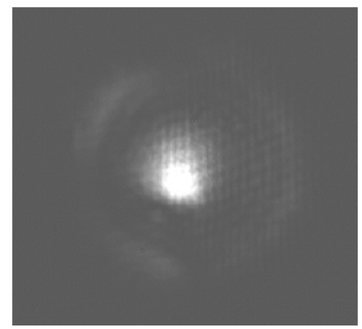
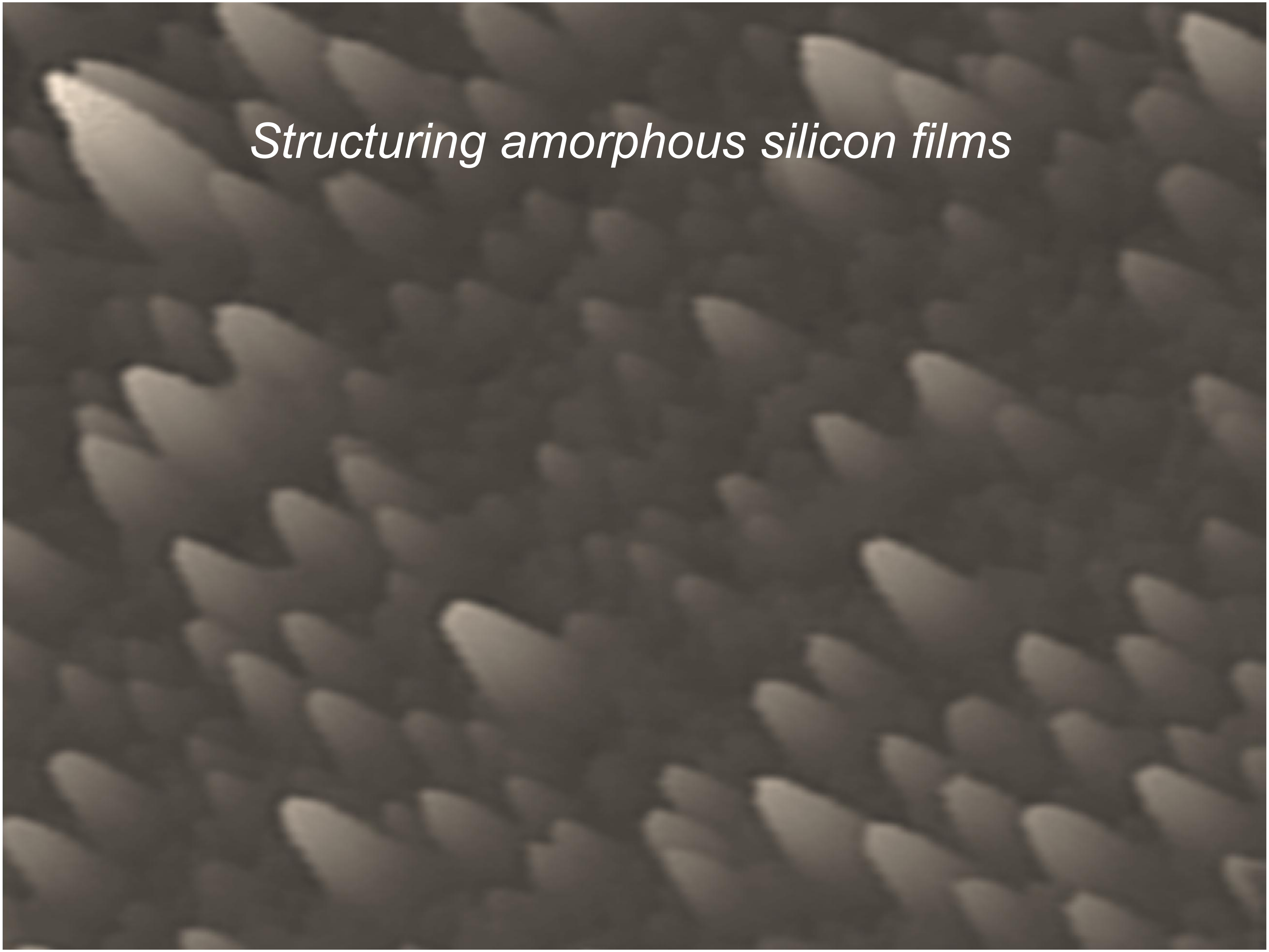


image of the waveguide output

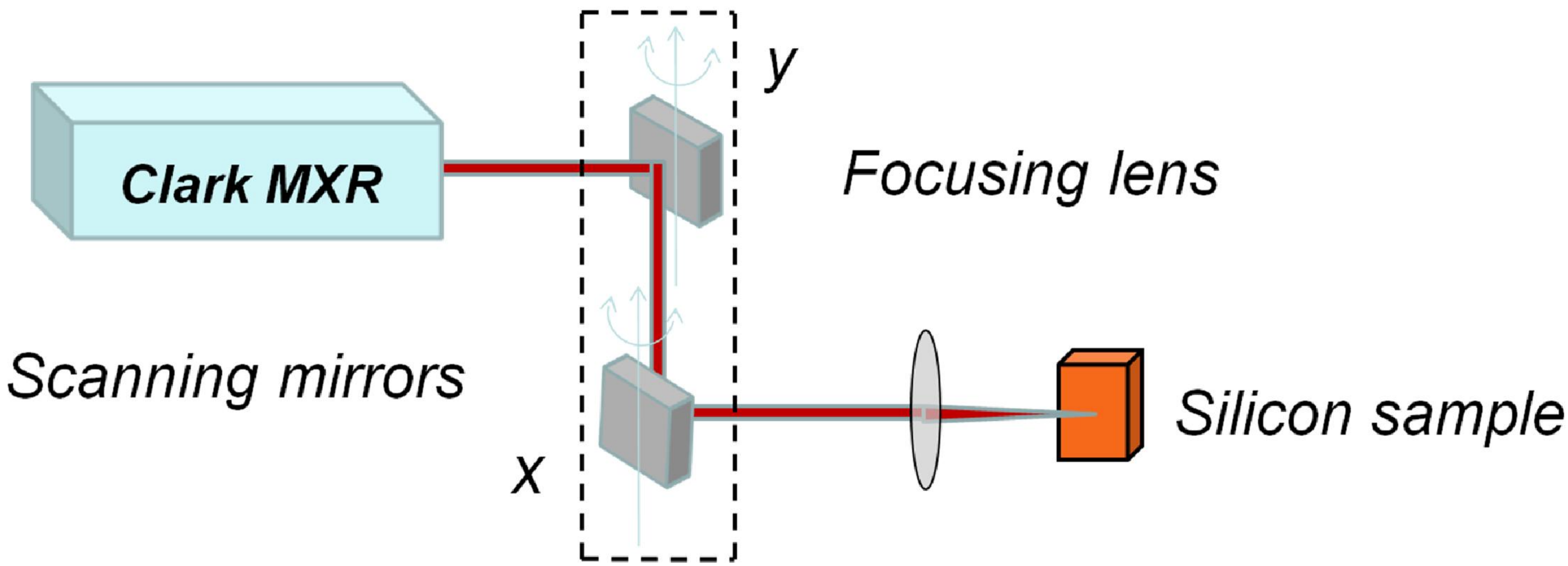
measured waveguide loss L = 1.3 dB/mm

Structuring amorphous silicon films



structuring amorphous Si surface

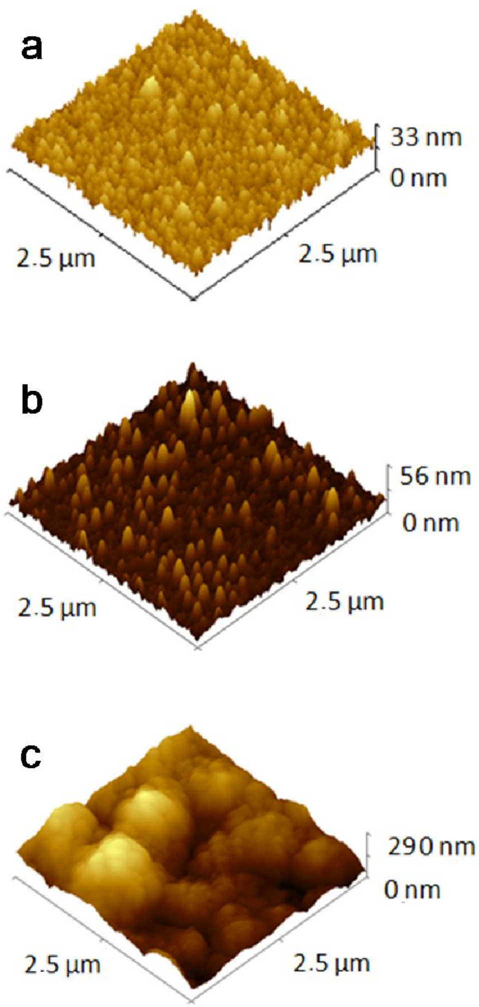
Experimental setup uses a pair of scanning mirrors



150 fs, 775 nm, 1 KHz, v = 5 mm/s, f= 20 cm

structuring amorphous Si surface

AFM micrographs of aSi microstructures at different laser intensities

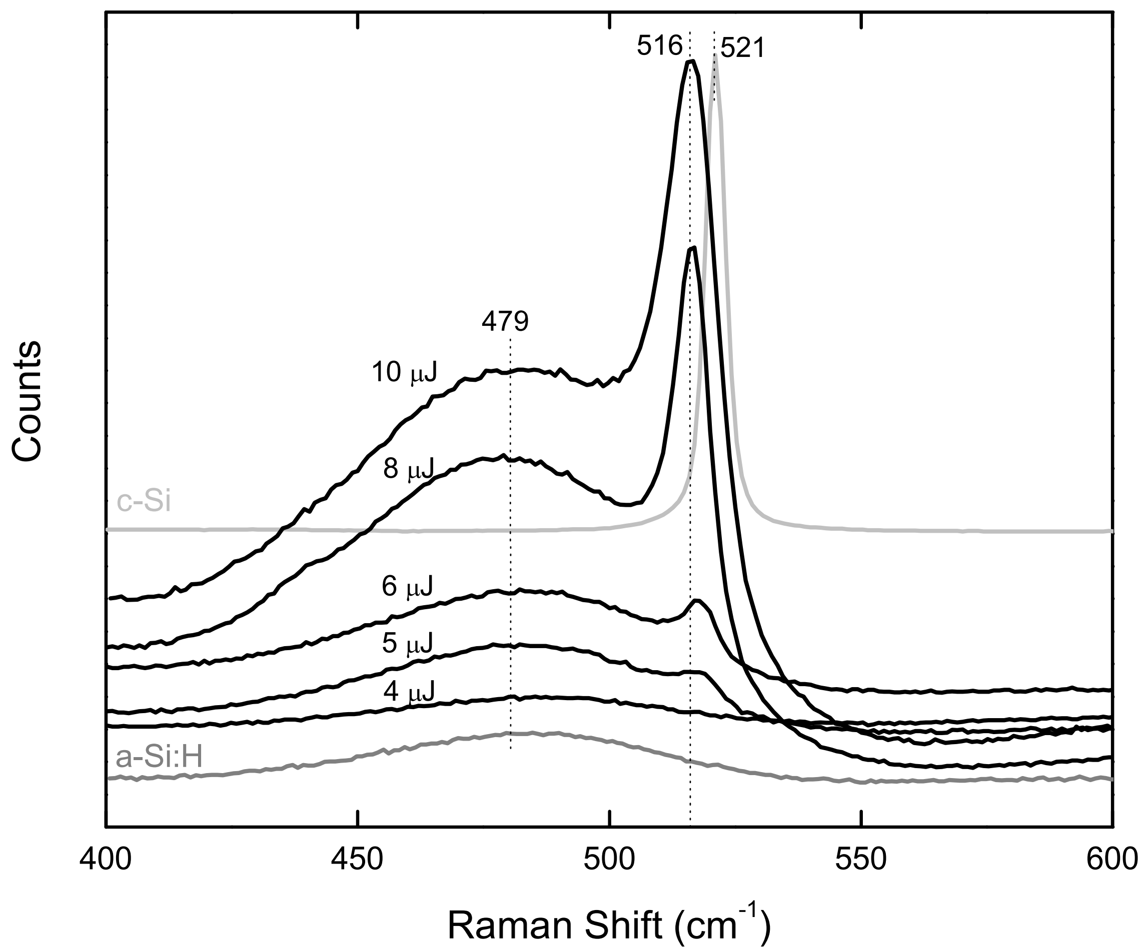


before irradiation

E = 5 µJ/pulse

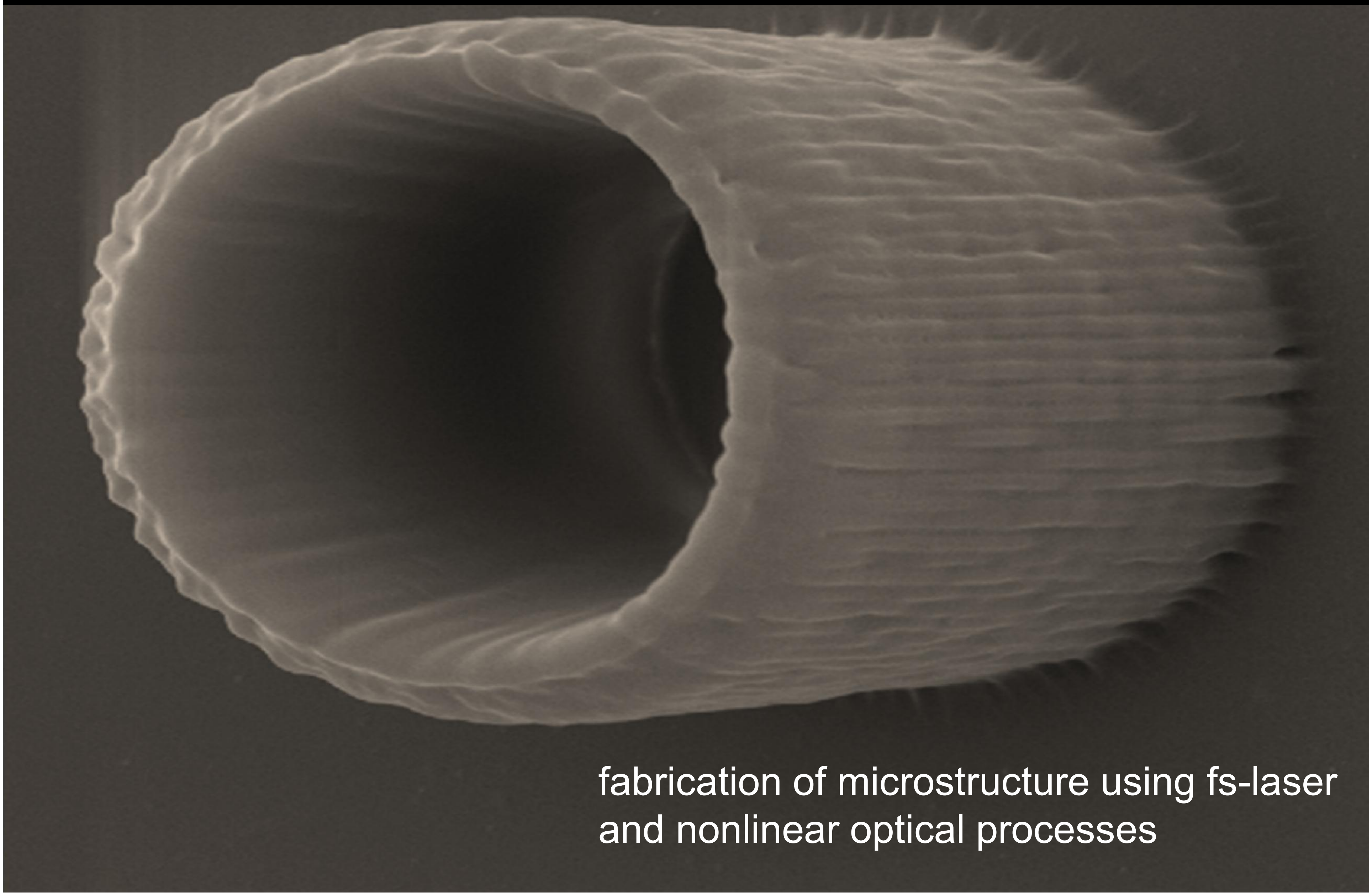
E = 8 µJ/pulse

structuring amorphous Si surface



Micro-Raman analysis reveals the crystallization of the aSi upon fs-laser irradiation

fs-laser microfabrication



fabrication of microstructure using fs-laser
and nonlinear optical processes

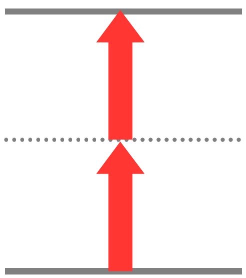
Two-photon polymerization

Monomer + Photoinitiator → Polymer

laser pulse

100 fs

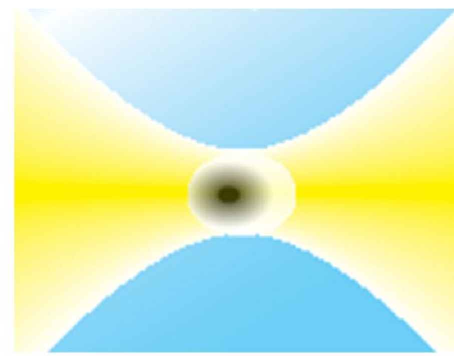
Photoinitiator is excited by ***two-photon absorption***

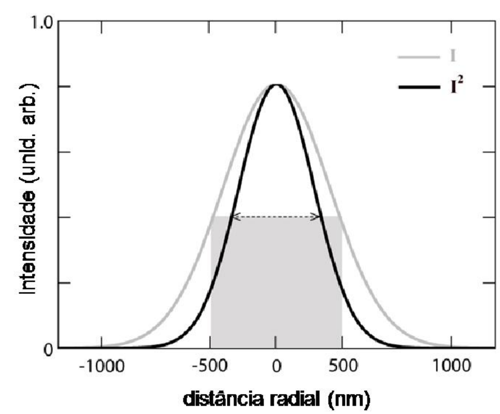


$$R \propto I^2$$

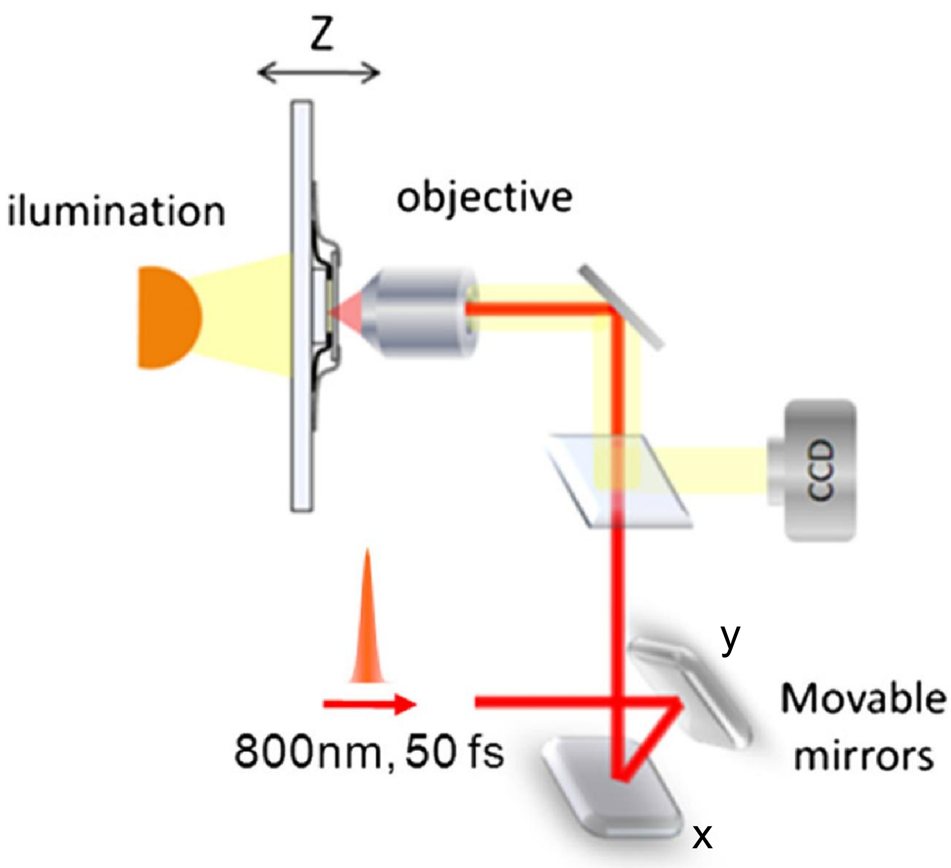
The polymerization is confined to the focal volume.

High spatial resolution





Two-photon polymerization setup



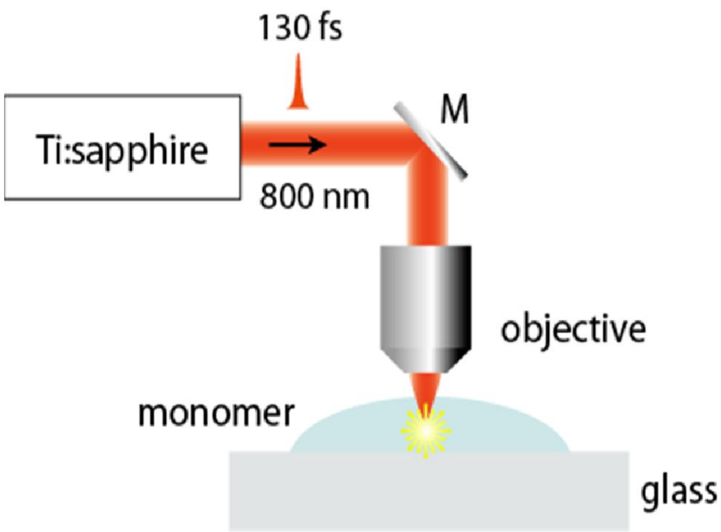
Ti:sapphire laser oscillator

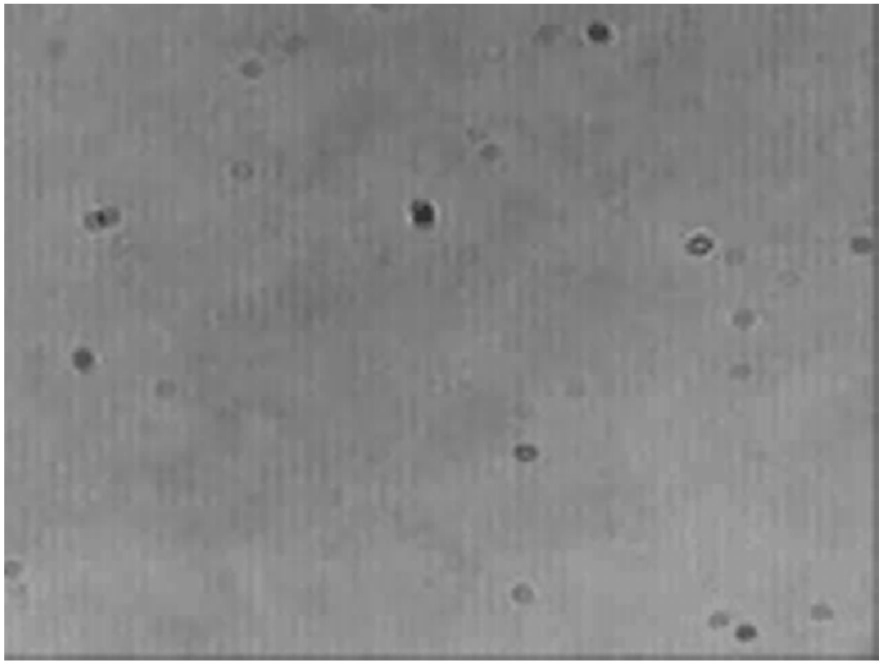
- 50 fs
- 800 nm
- 80 MHz
- 20 mW

Objective

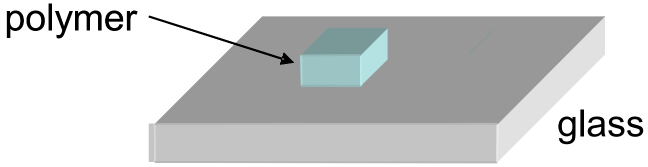
40 x
0.65 NA

Two-photon polymerization



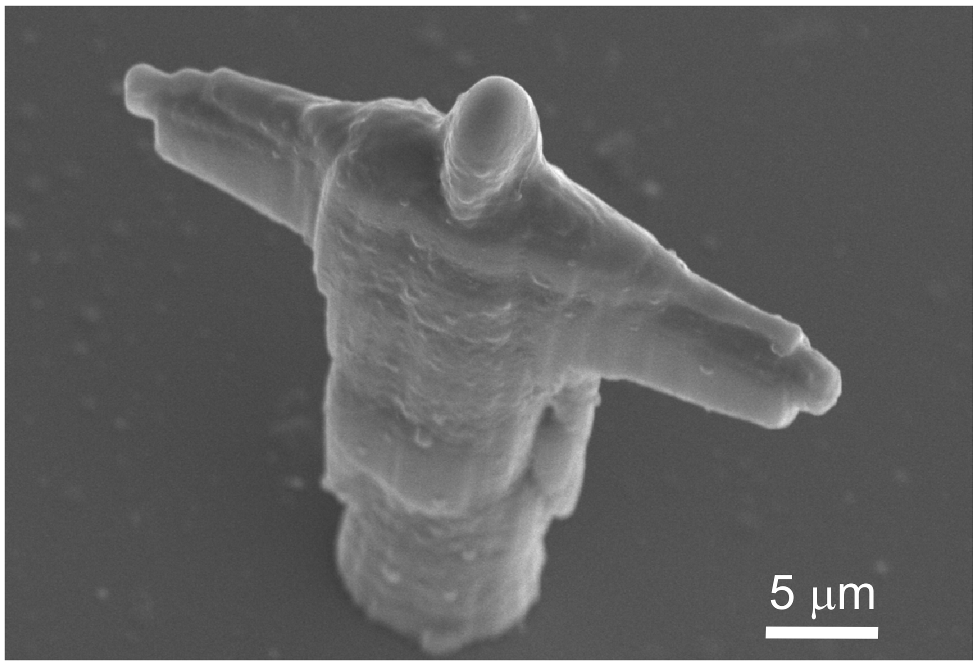


30 µm x 30 µm x 12 µm cube



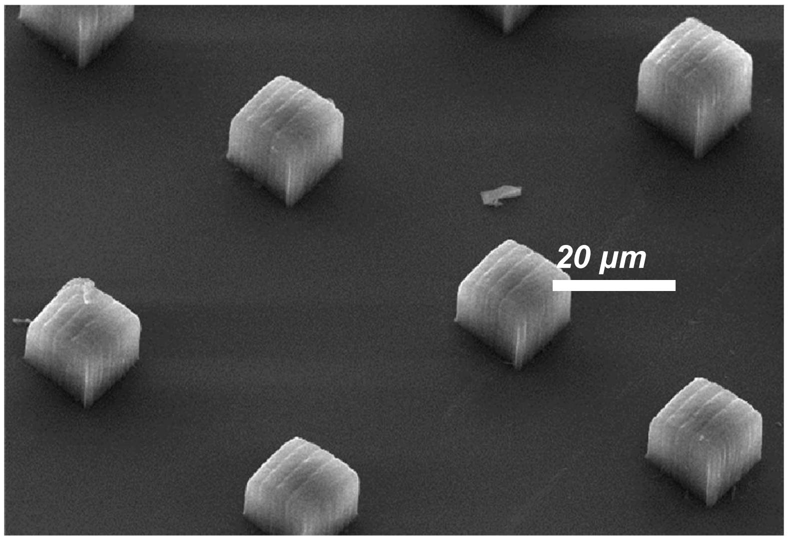
two-photon polymerization

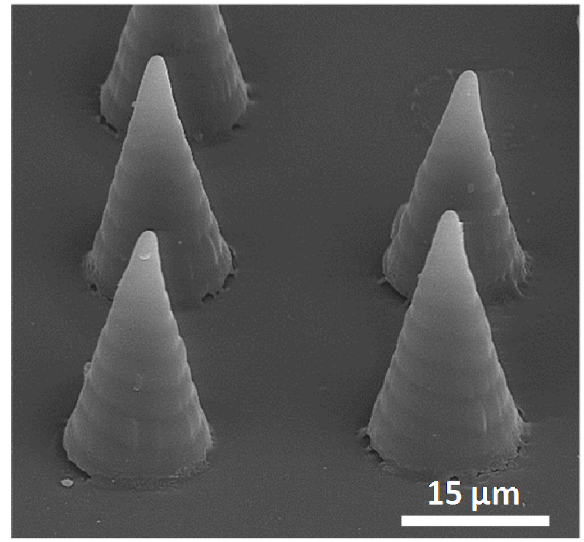
Microstructure fabricated by two-photon polymerization

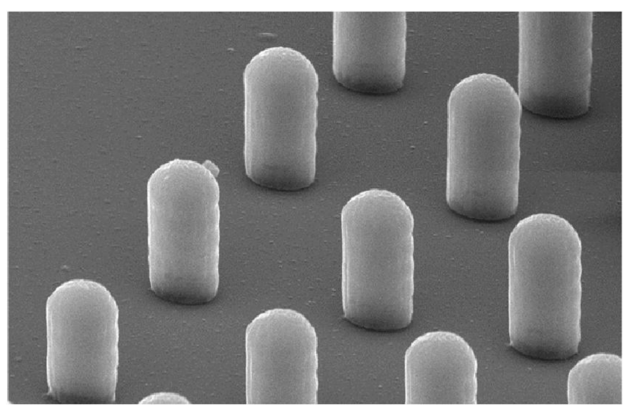


Two-photon polymerization

Microstructures fabricated by two-photon polymerization

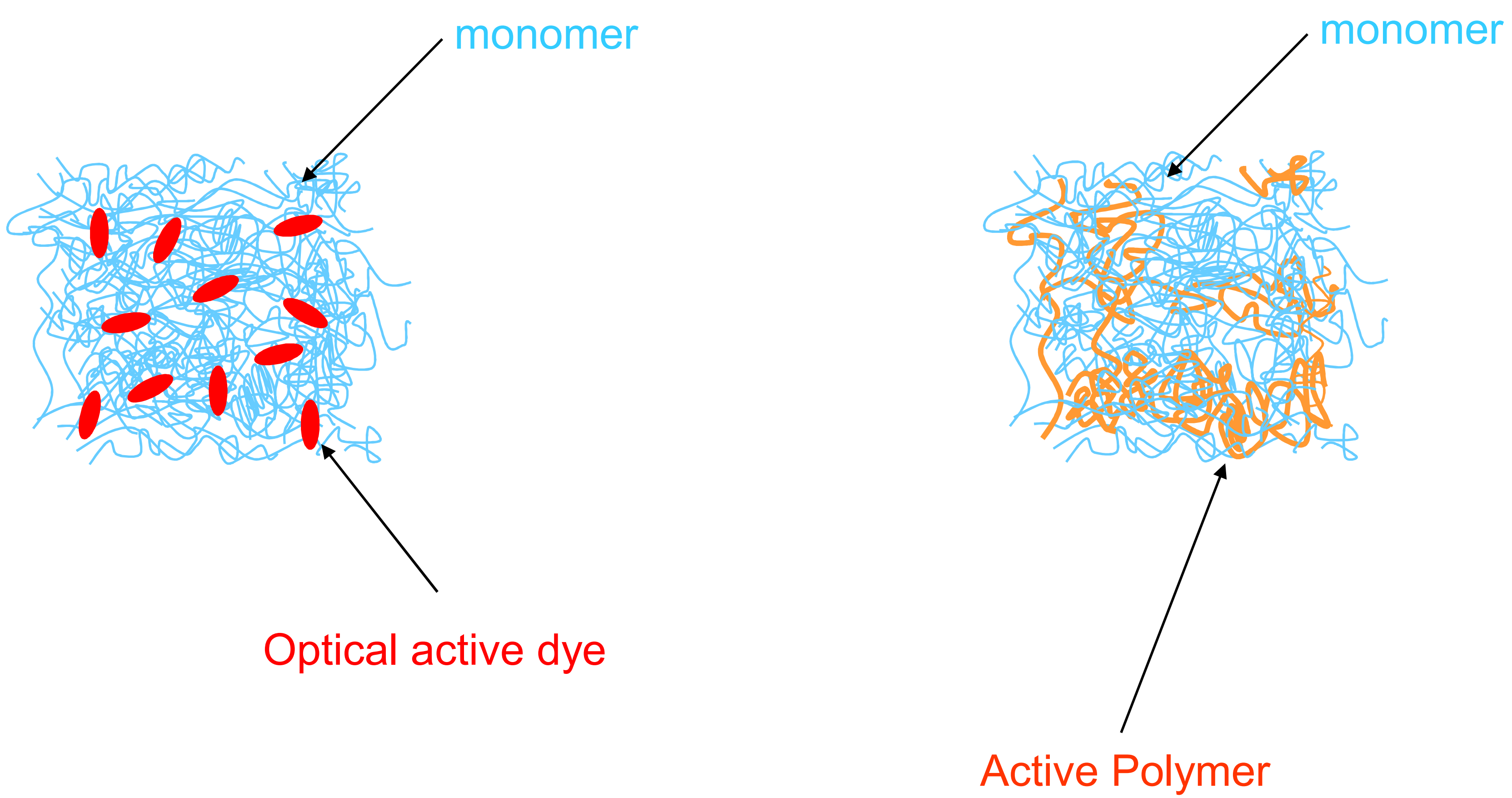






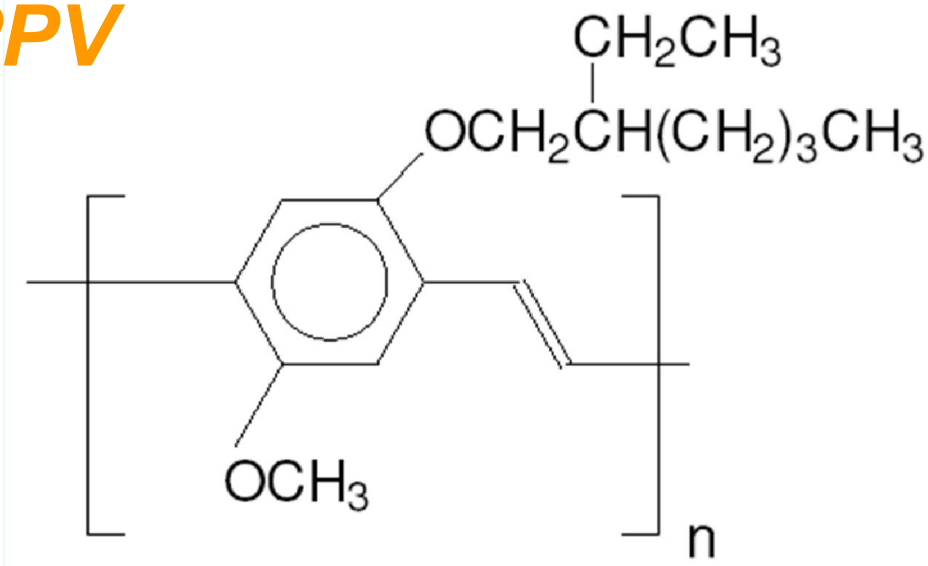
Doping microstructures

Microstructures containing active compounds



Microstructure containing MEH-PPV

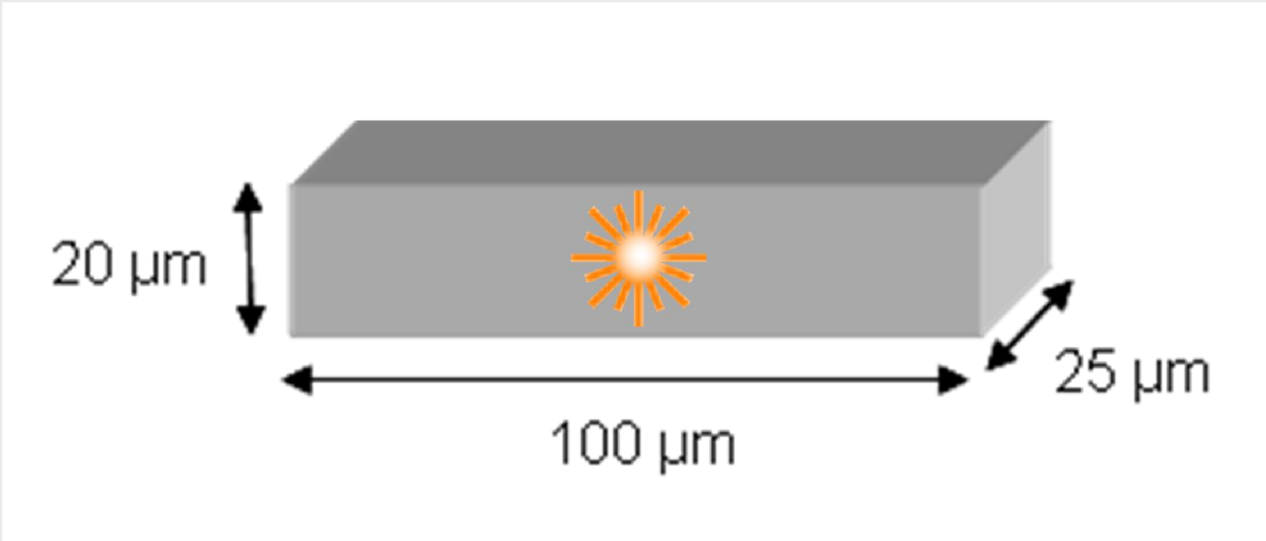
MEH-PPV



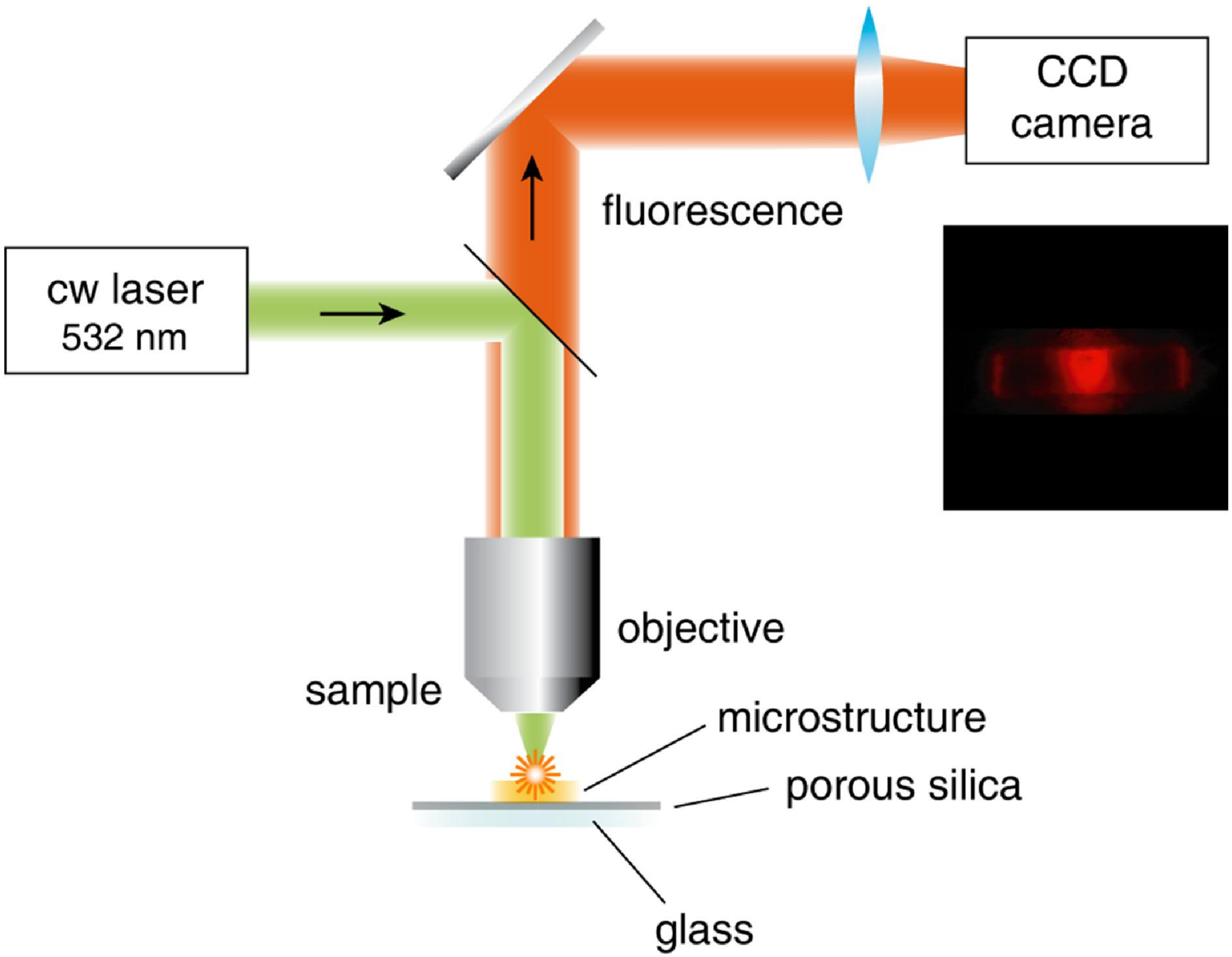
- Fluorescence
- Electro Luminescent
- Conductive

Microstructure containing MEH-PPV

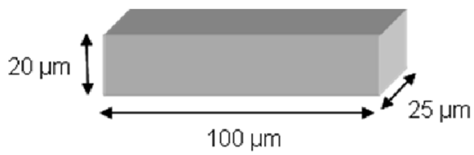
Do we have waveguiding in the microstructure ?

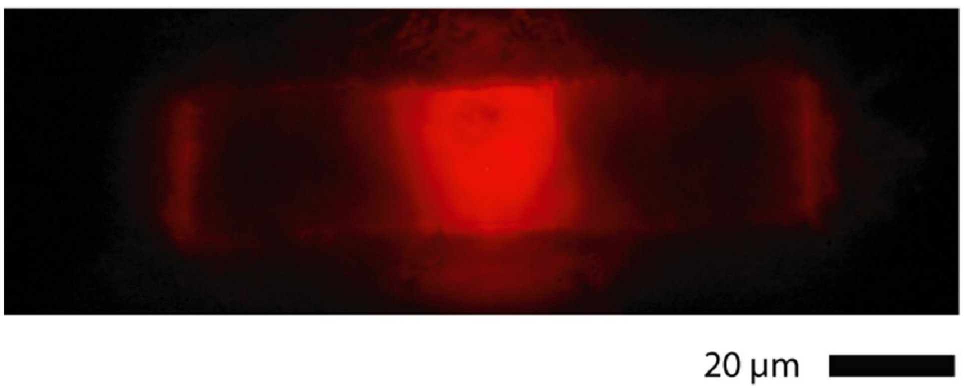


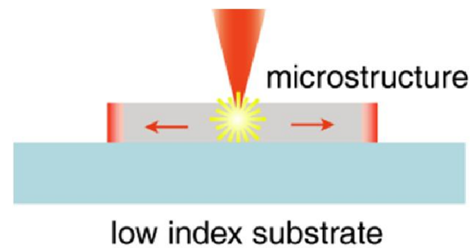
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV



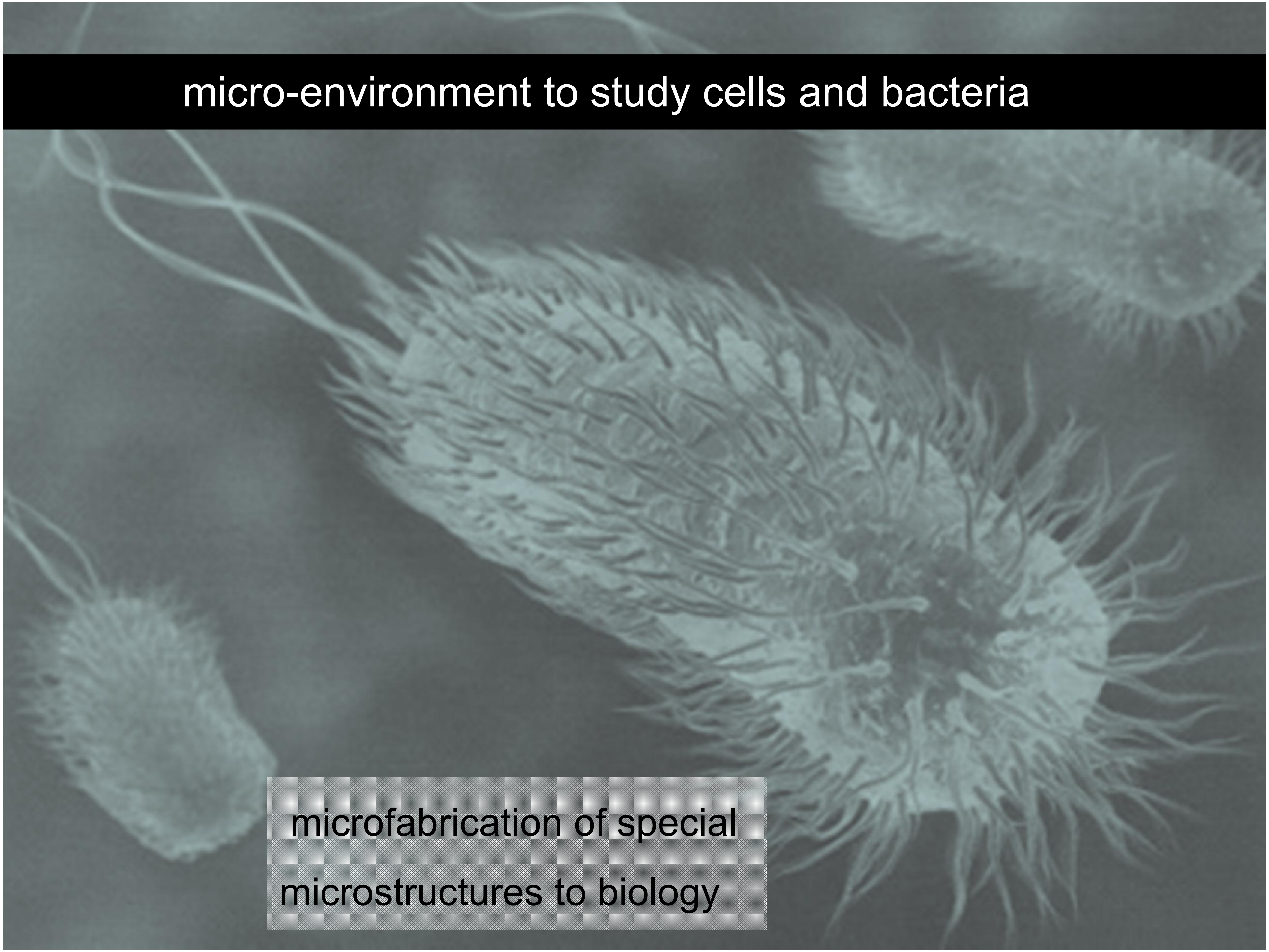




waveguiding of the microstructure fabricated on porous silica substrate (*n*= 1.185)

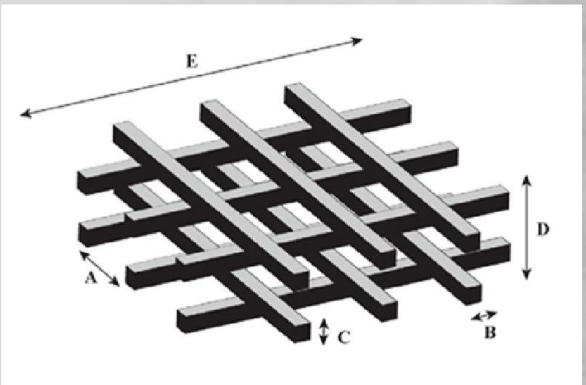
Applications: micro-laser; fluorescent microstructures; conductive microstructures

micro-environment to study cells and bacteria

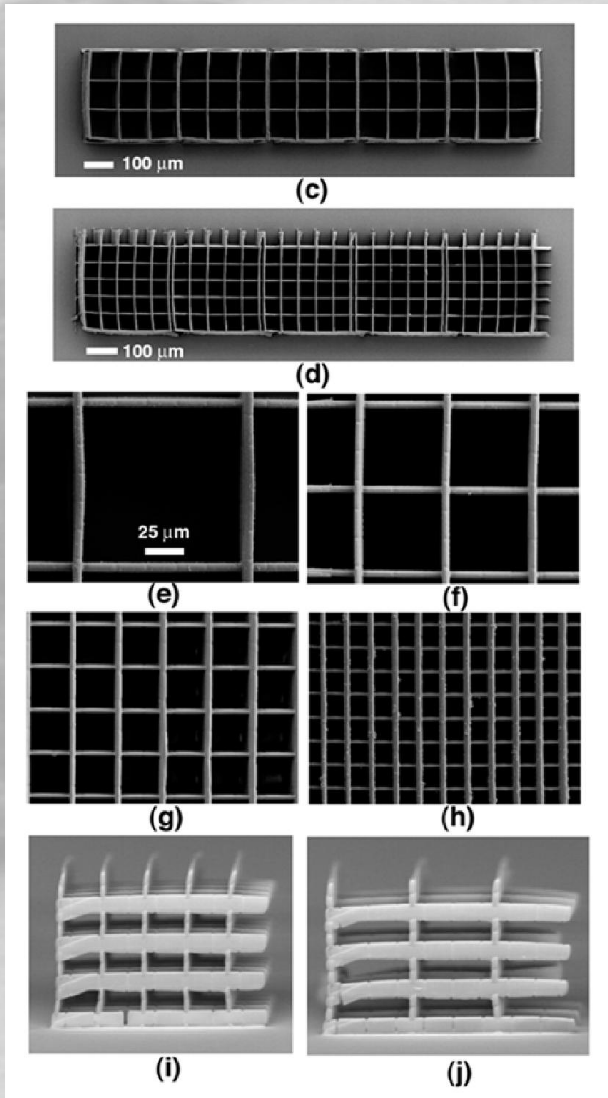


3D cell migration

- 3D cell migration studies in micro-scaffolds



SEM of the scaffolds



110 µm pore size

52 µm pore size

Top view

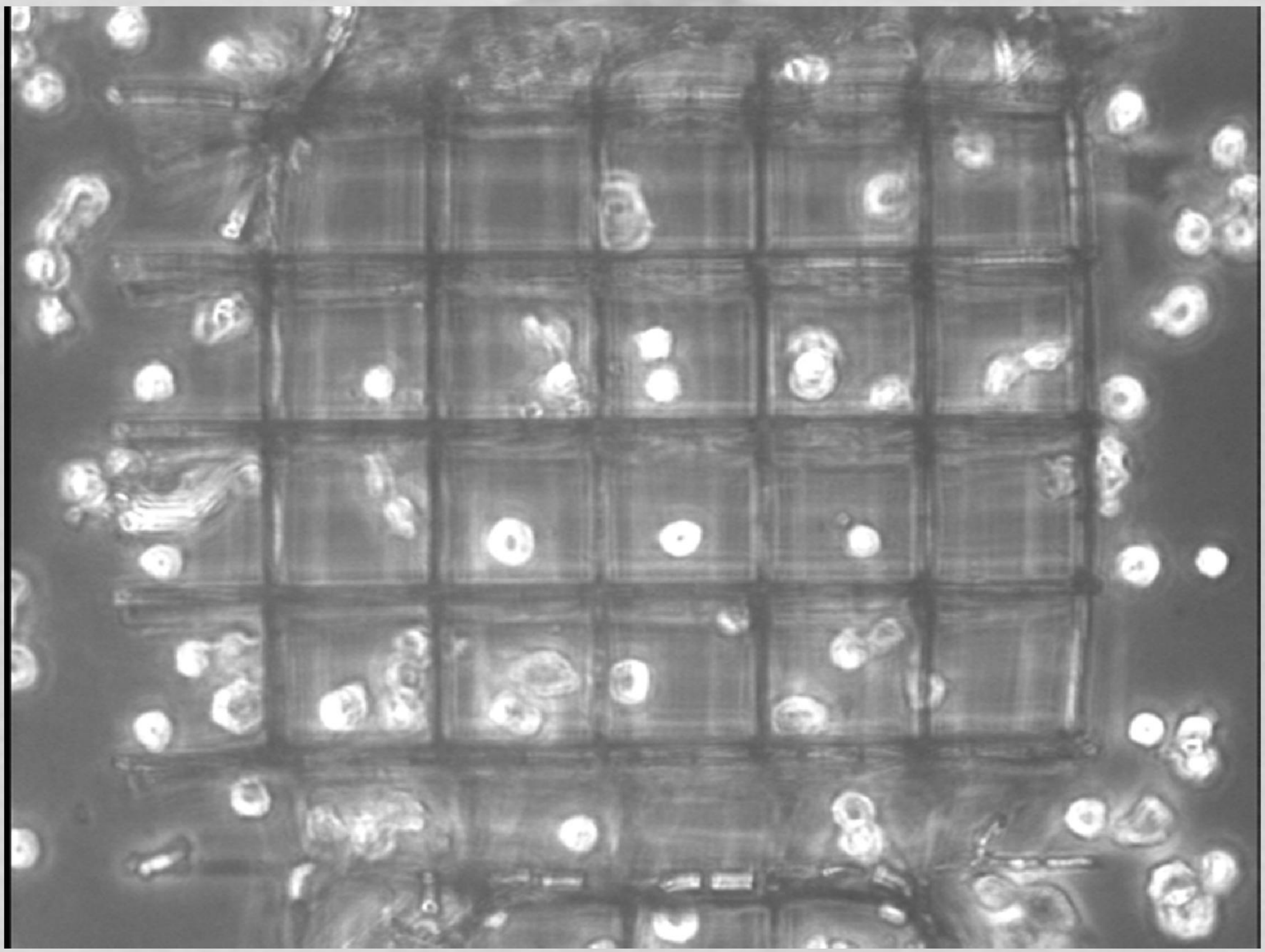
110, 52, 25, 12 µm pore size

Side view

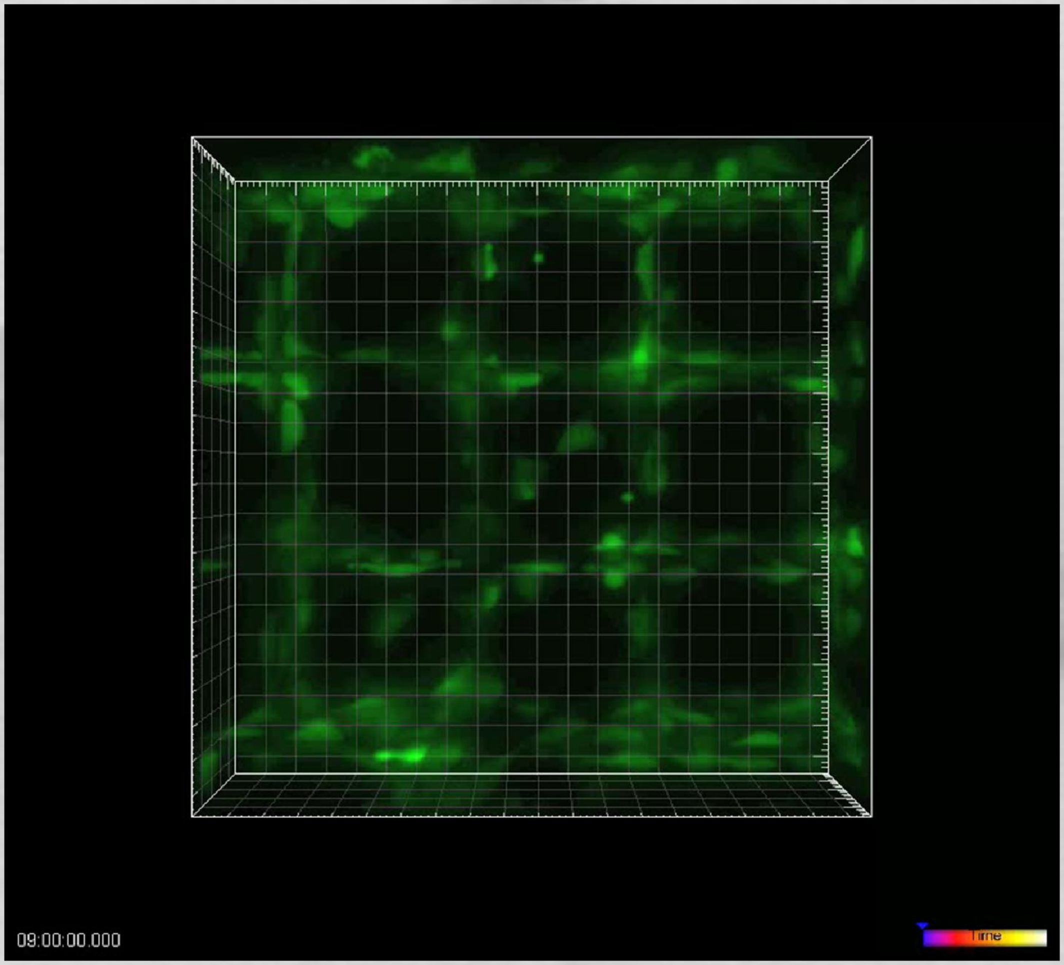
25, 52 µm pore size

3D cell migration

50 μm pore size

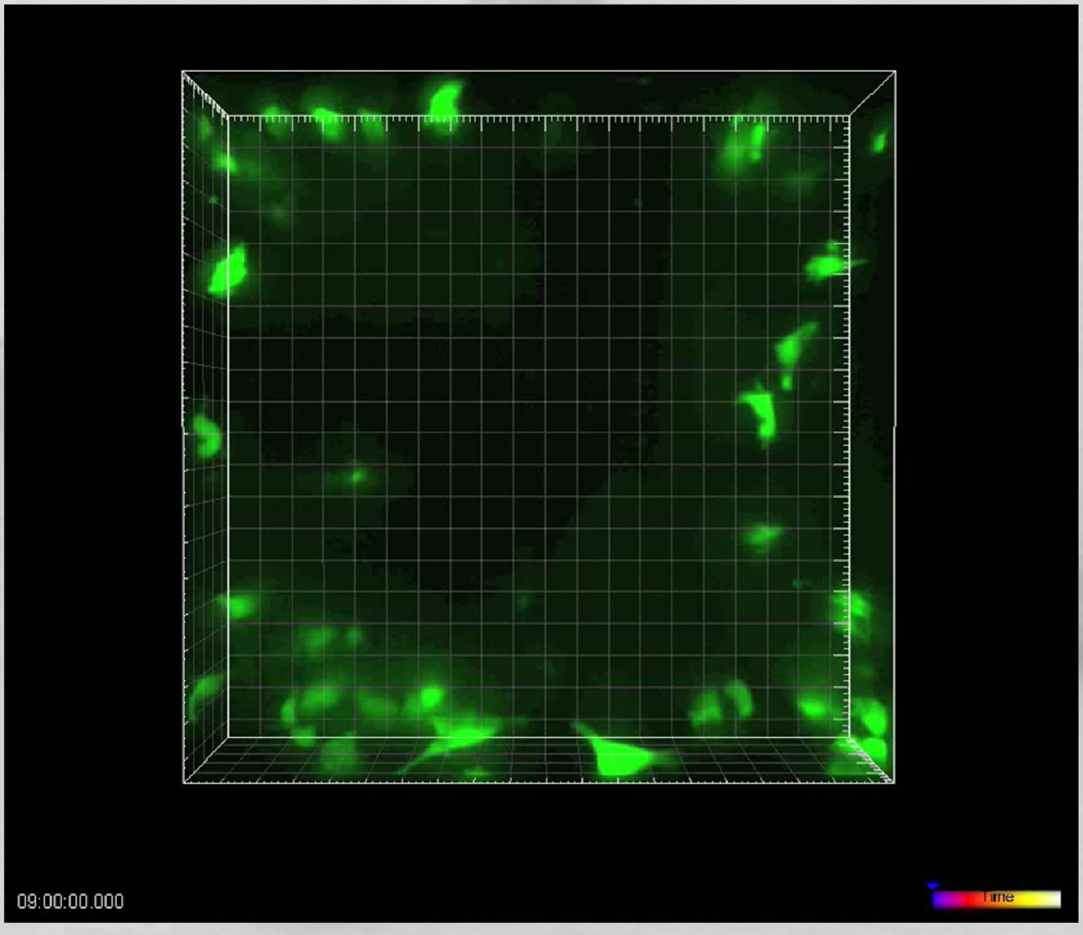


3D cell migration



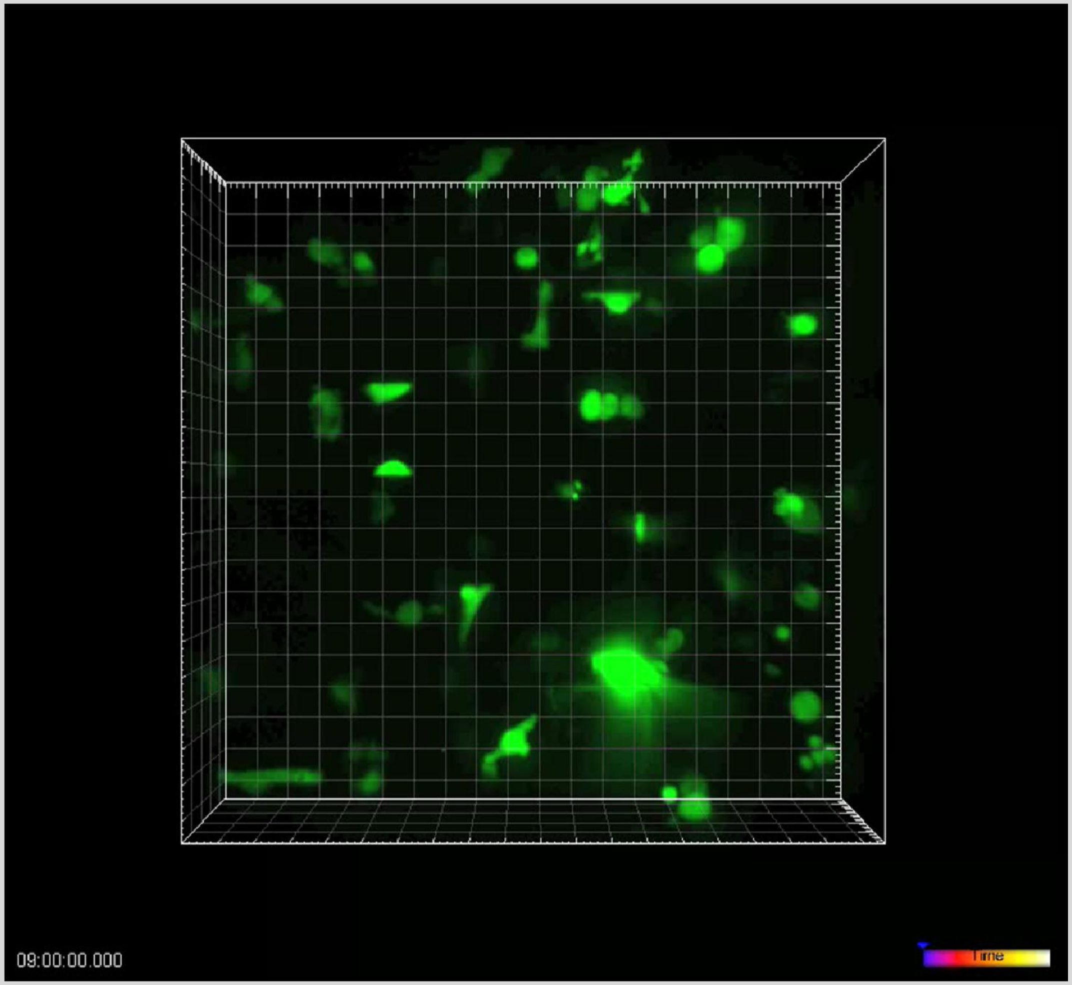
110 μm pore size

3D cell migration



12 µm pore size

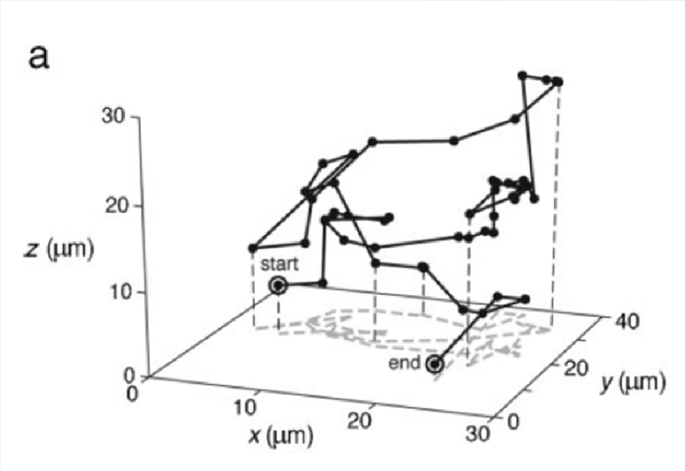
3D cell migration

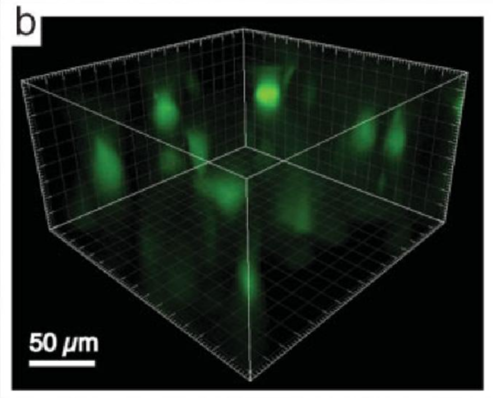


52 μm pore size

3D cell migration

- 3D cell migration studies in micro-scaffolds





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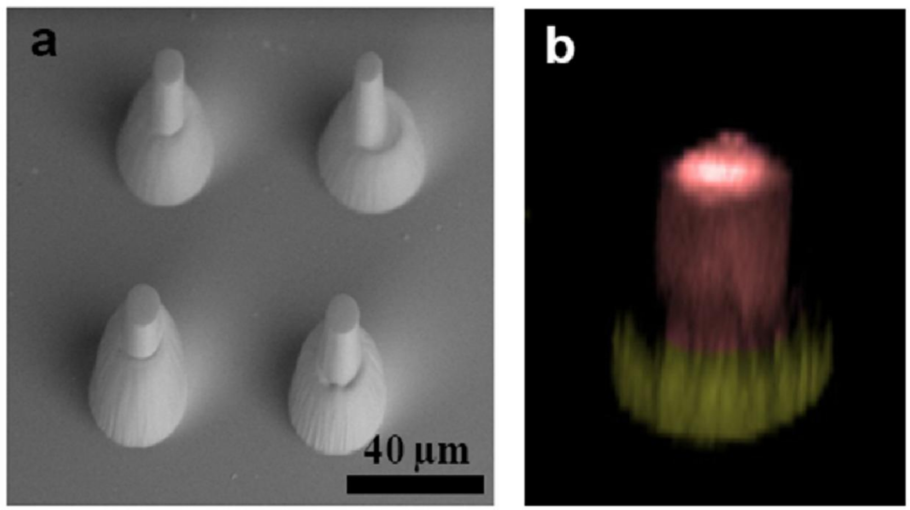
Guiding bacterial growth in a micro-environment

to study bacterial growth it was needed to develop
double doped microstructures

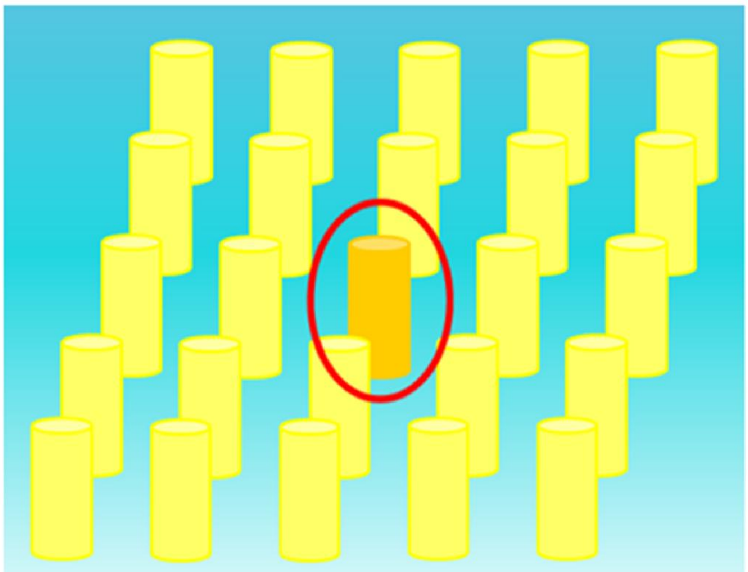
microstructure containing Fluorescein and Rhodamine

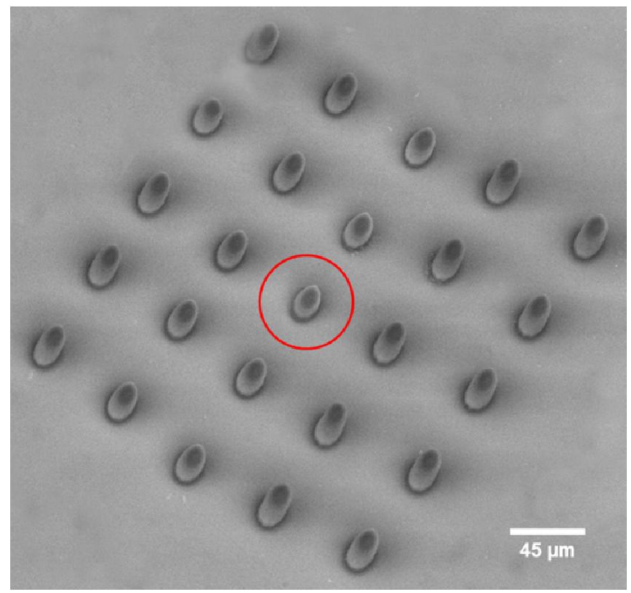


(a) SEM of a double-doped microstructure (top view).
(b) Confocal fluorescent microscopy image of the same microstructure.

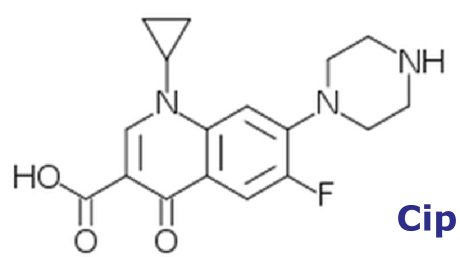
Guiding bacterial growth in a micro-environment

Study the development of E. coli in micro-environments:





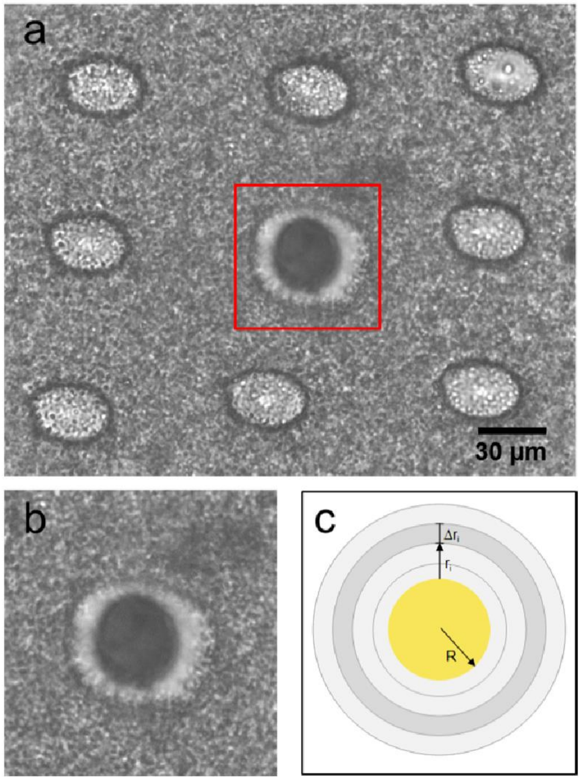
micro-environment in which the central structure contains antibiotic.



Ciprofloxacin

Guiding bacterial growth in a micro-environment

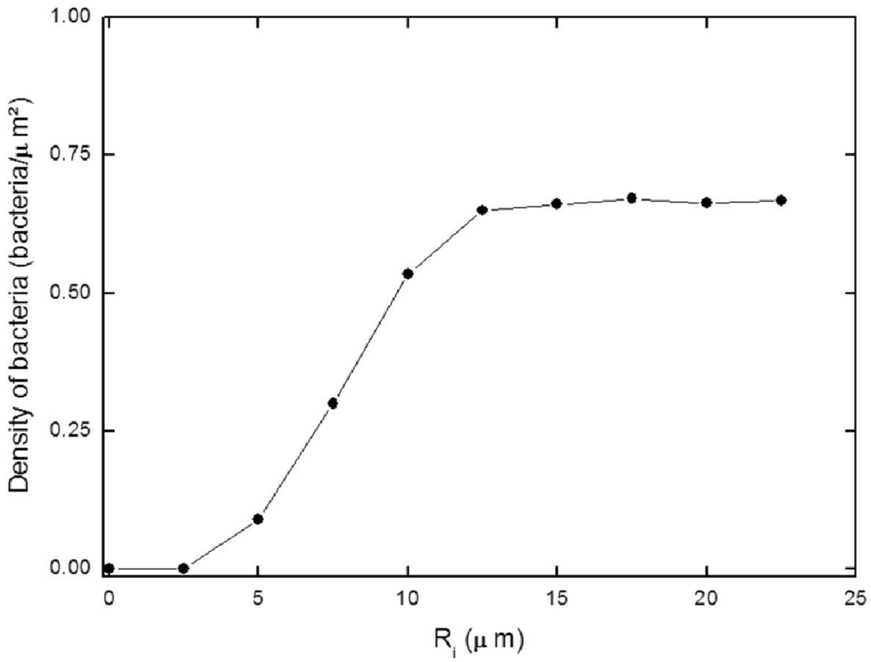
Study the development of E. coli in micro-environments:



after 3 hours, we observed that a small region around the doped structure does not show bacterial growth.

such inhibition zone was analyzed by determining the bacterial density in concentric rings

Guiding bacterial growth in a micro-environment



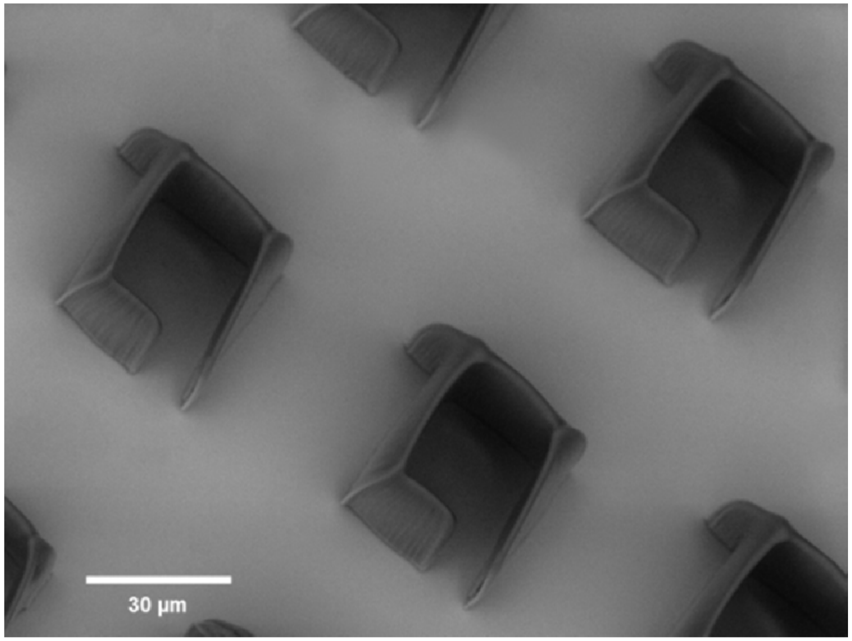
the density of bacteria grows monotonically with r_i

saturating when r_i reaches approximately 12 µm in about 0.7 bacteria/μm^2

the inhibition zone has a maximum range of approximately 10 µm, being more effective as one gets closer to the microstructure impregnated with ciprofloxacin

Guiding bacterial growth in a micro-environment

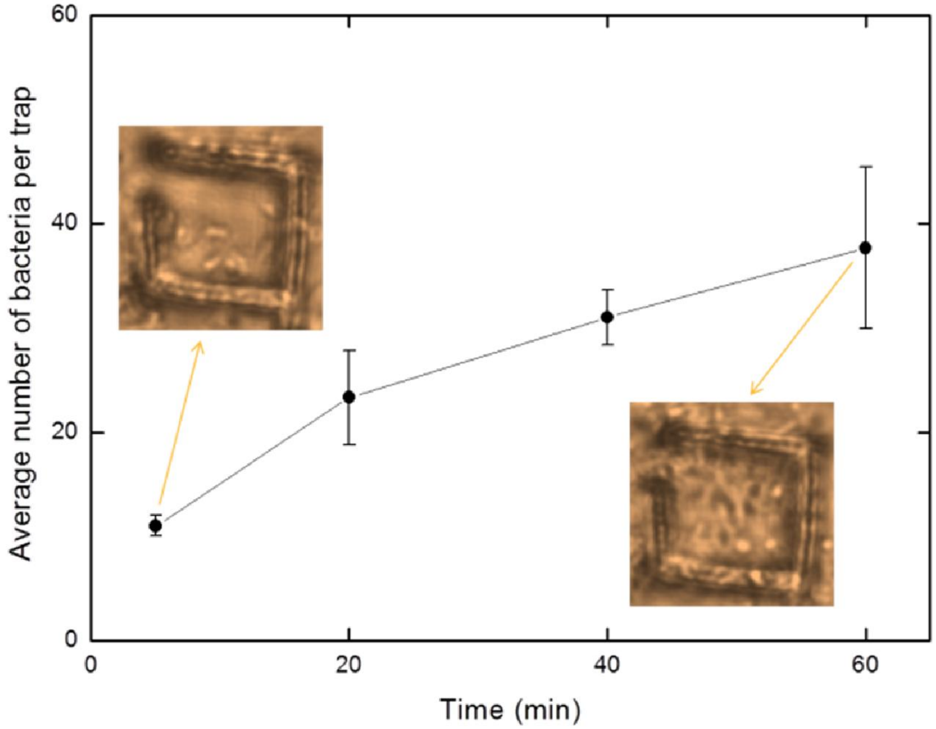
Bacteria microtraps



using micro-environments to study the dynamics of bacterial migration

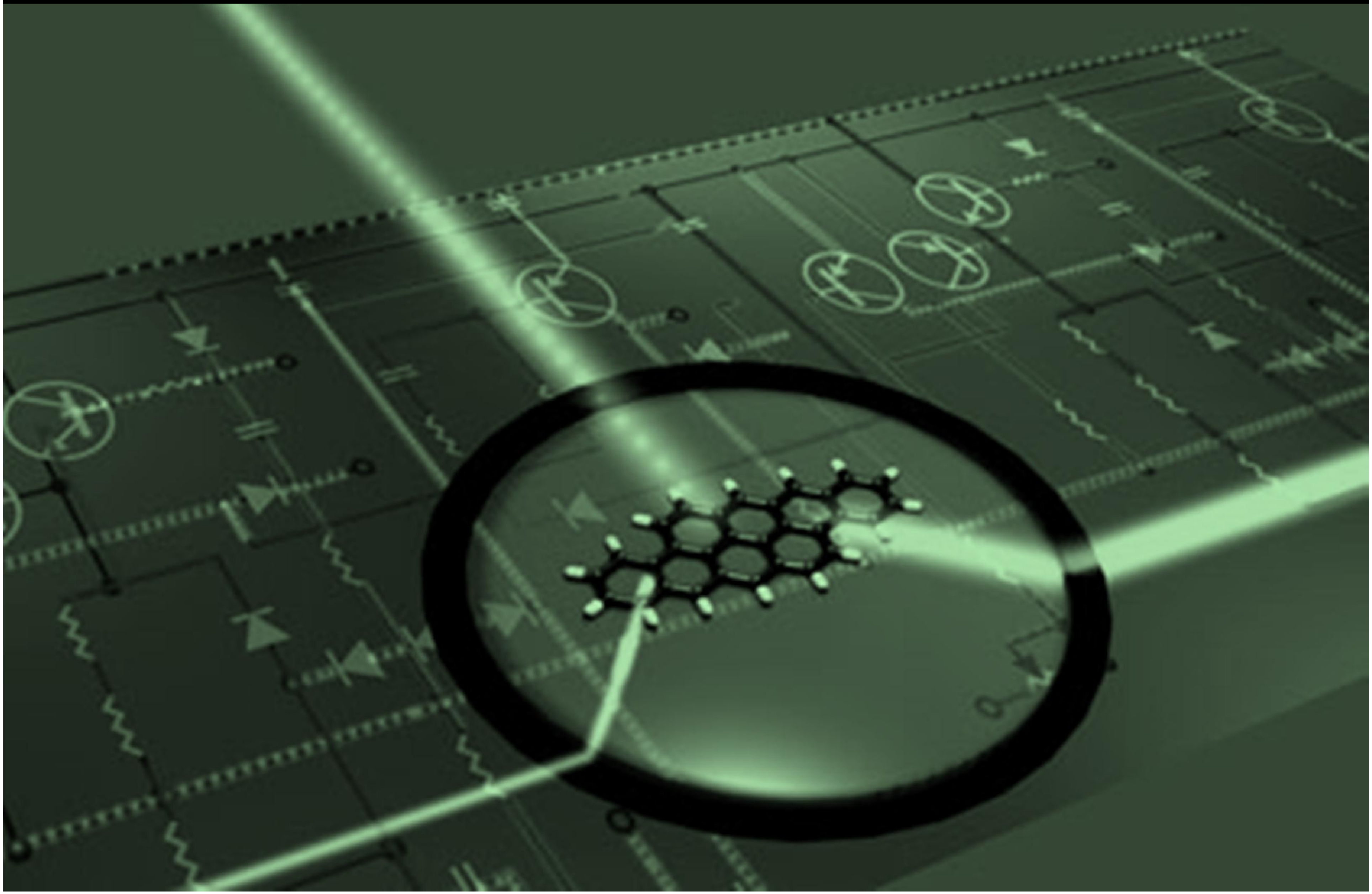
Guiding bacterial growth in a micro-environment

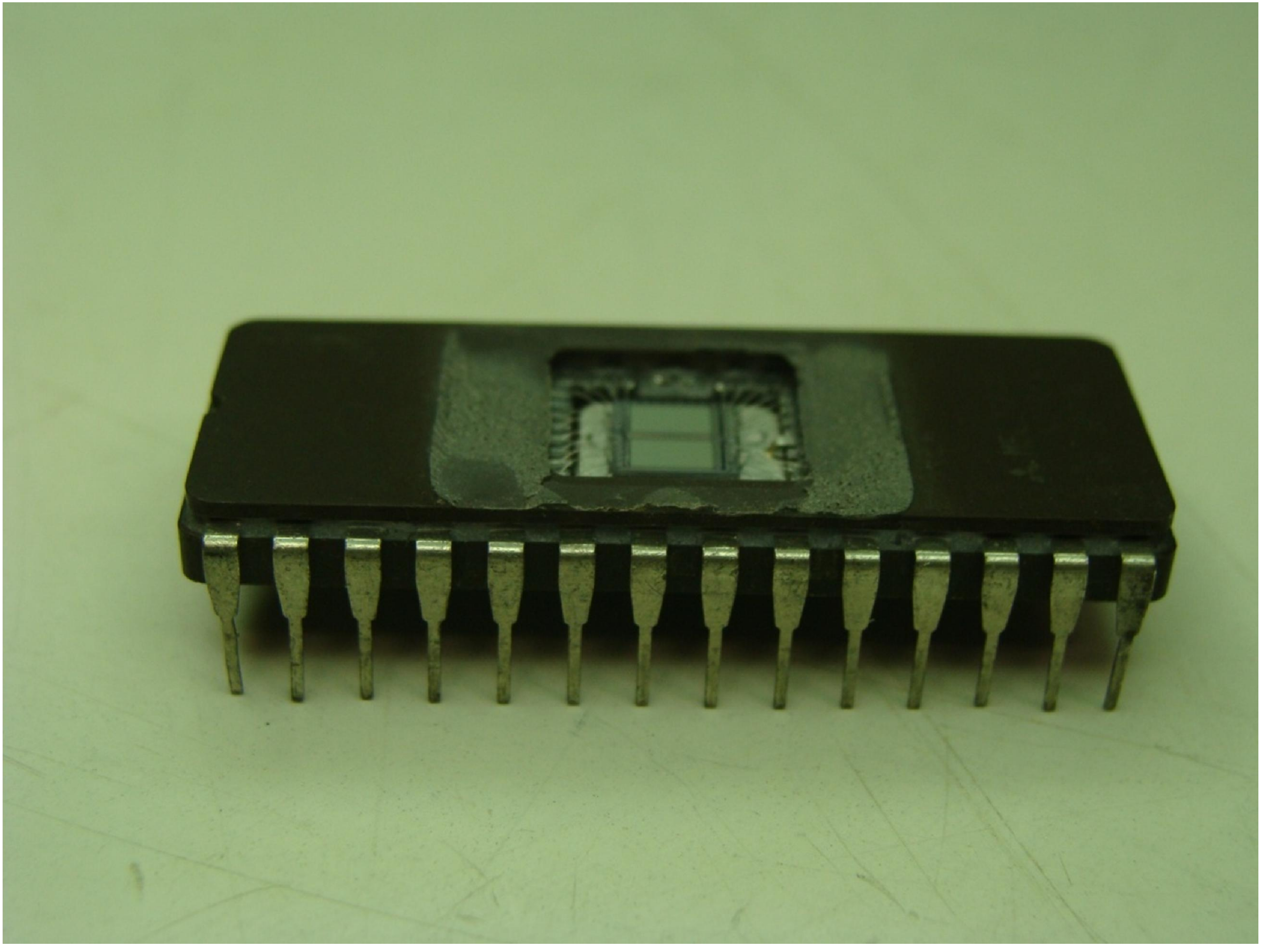
Bacteria microtraps

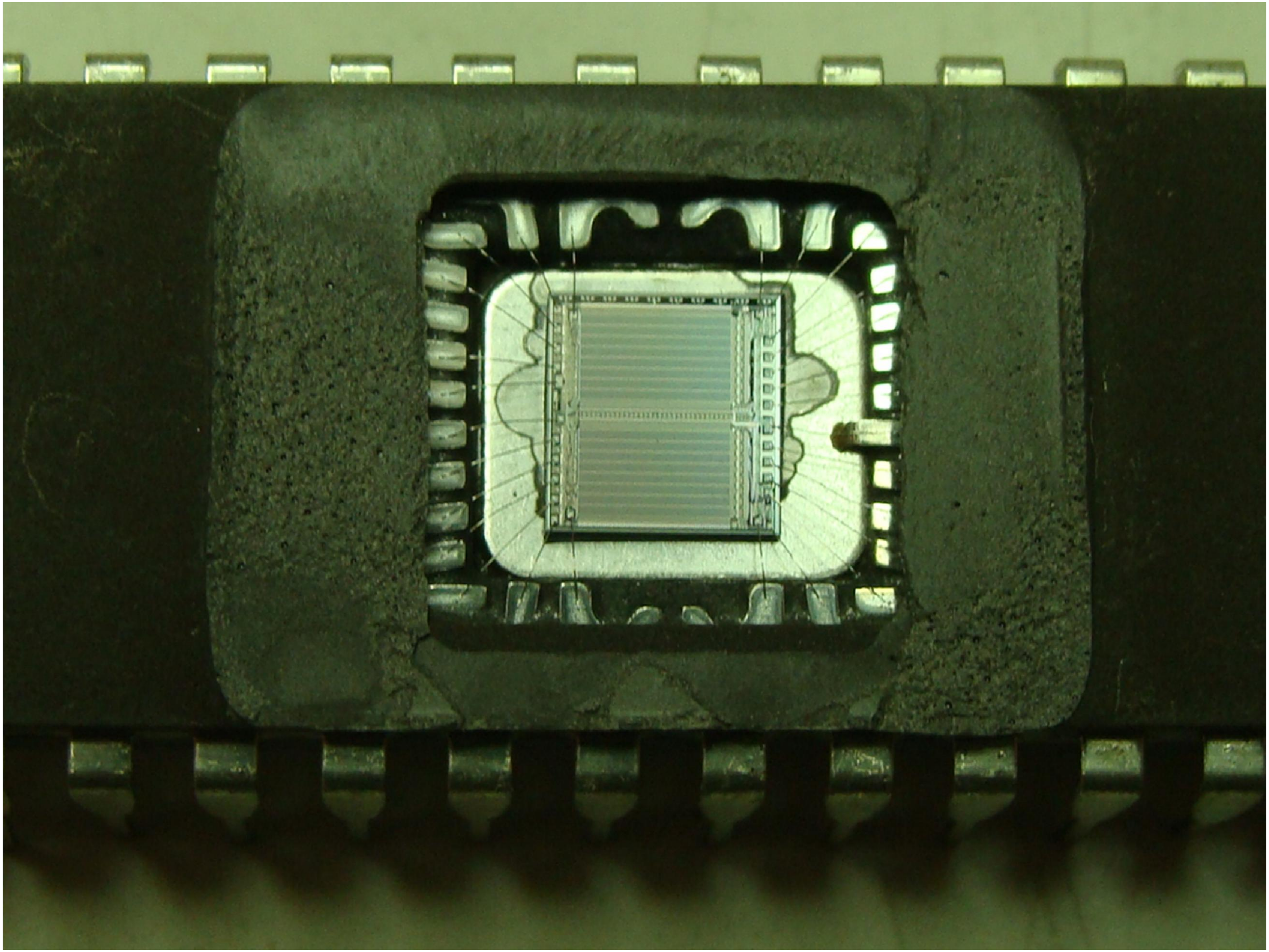


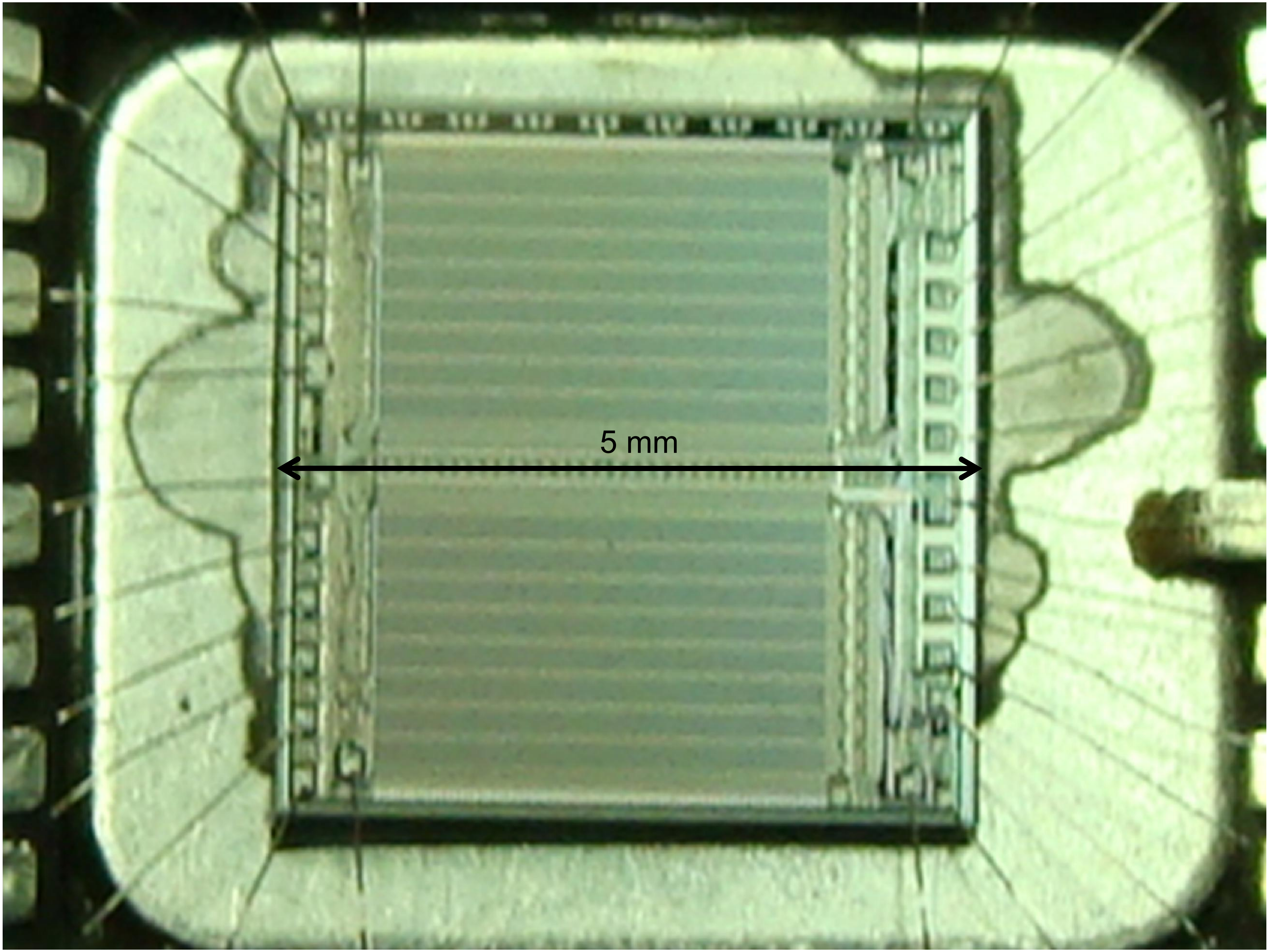
using micro-environments to study the dynamics of bacterial migration

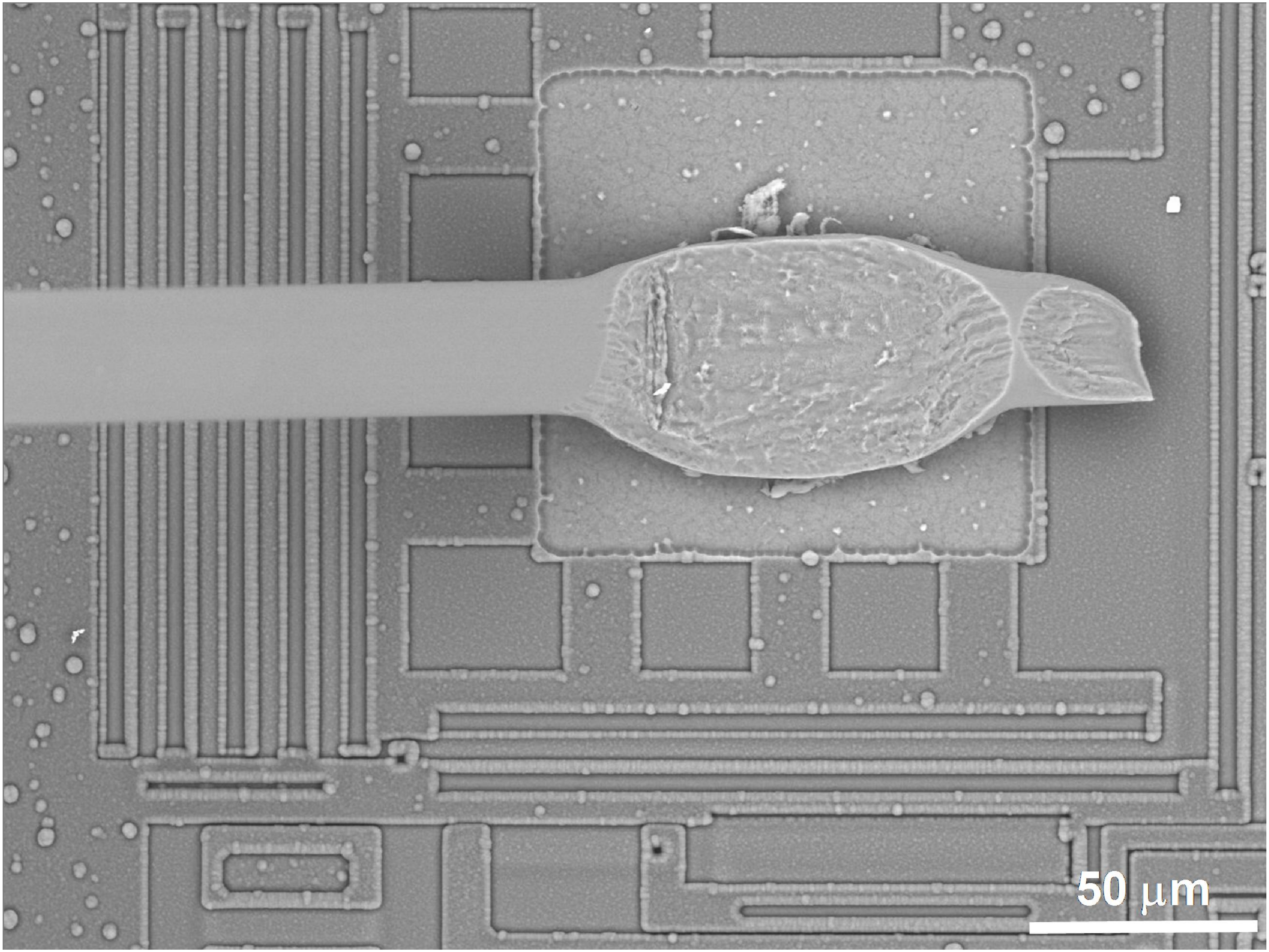
Optical circuit





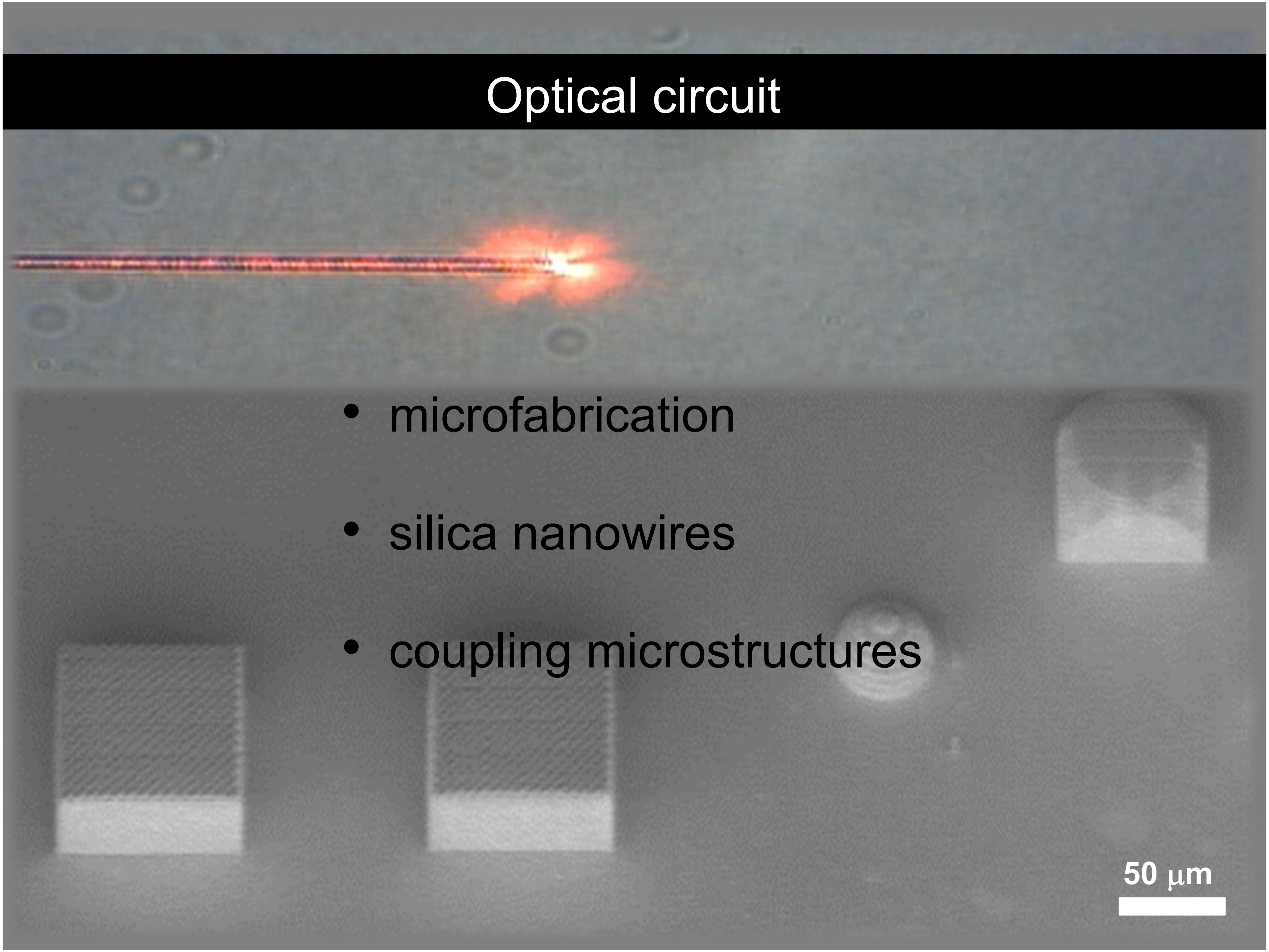



5 mm


50 μm

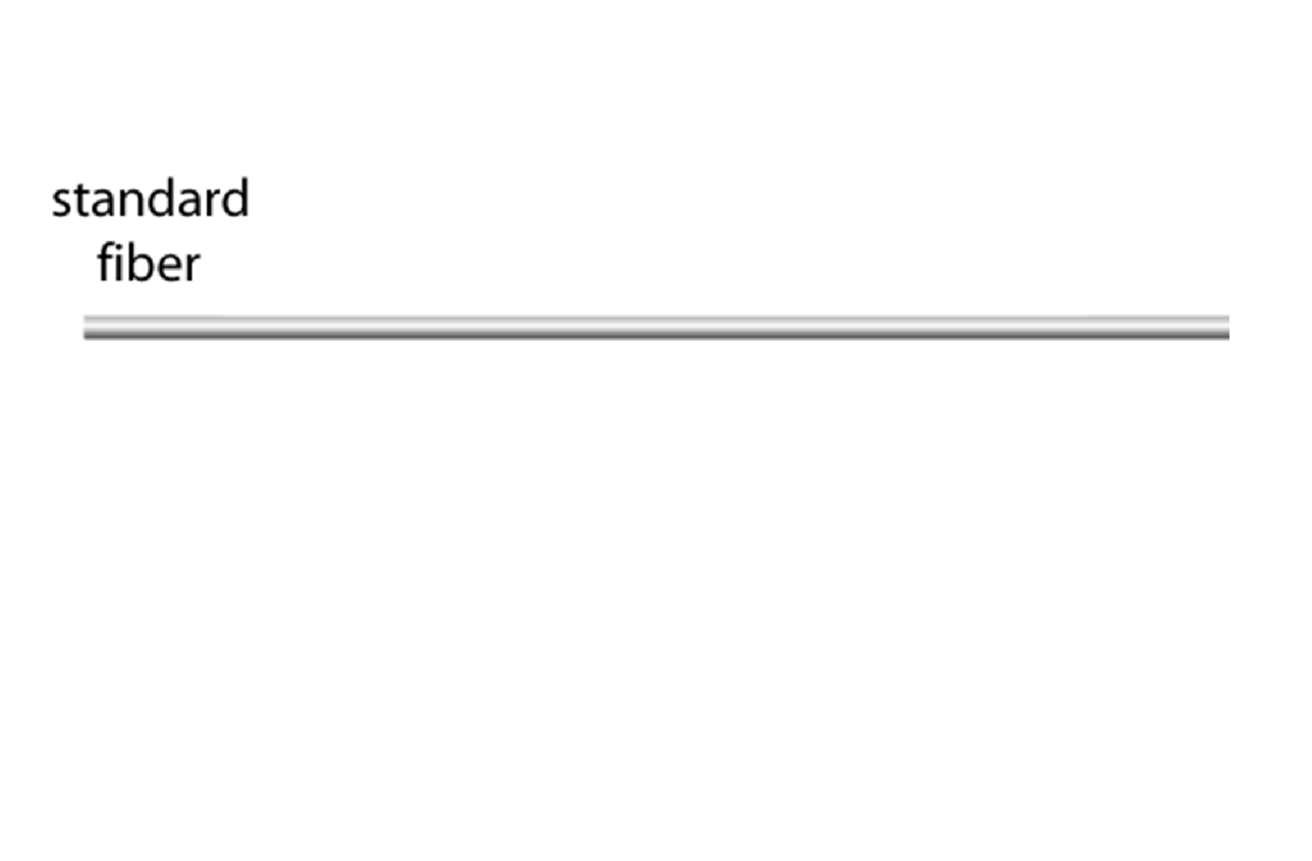
Optical circuit

- microfabrication
- silica nanowires
- coupling microstructures



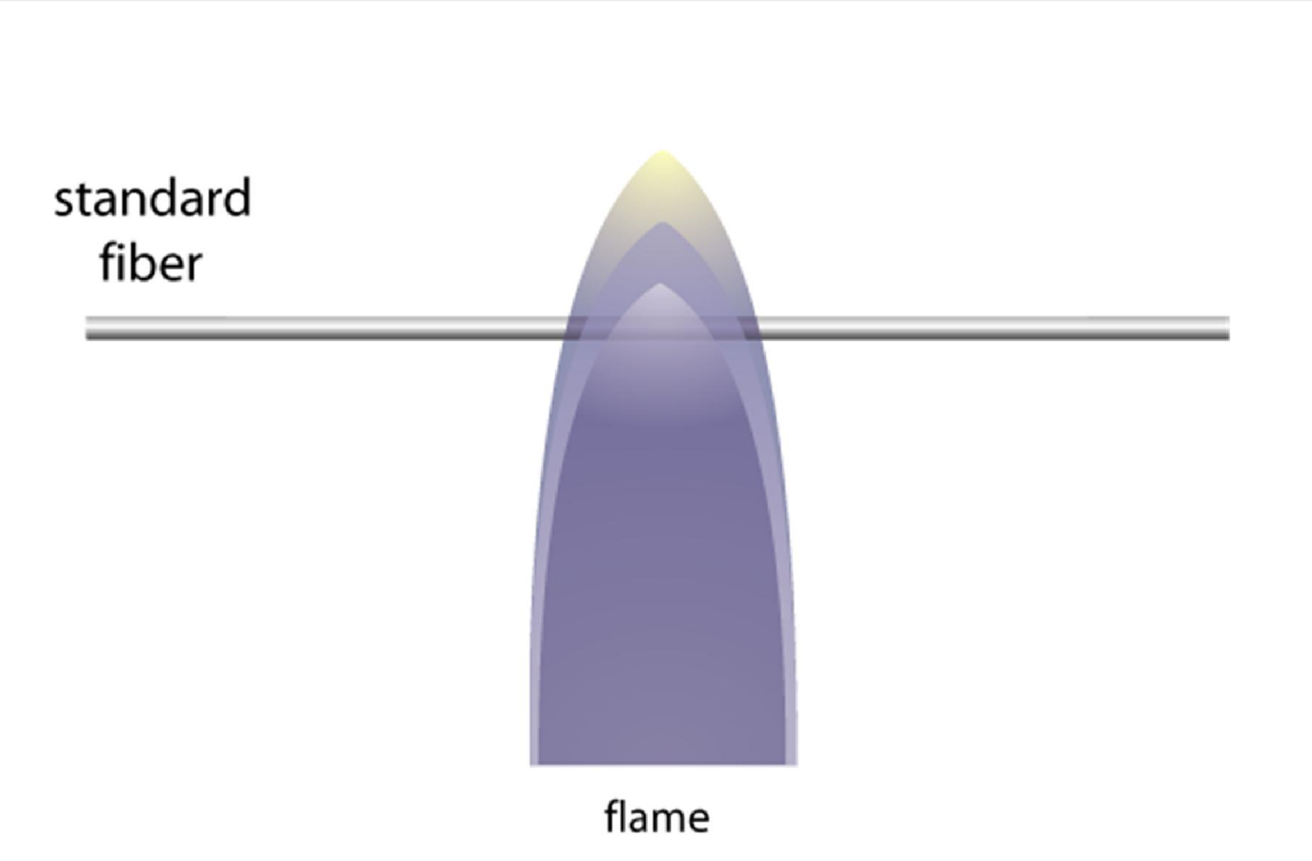
Silica nanowires

nanowires fabrication process



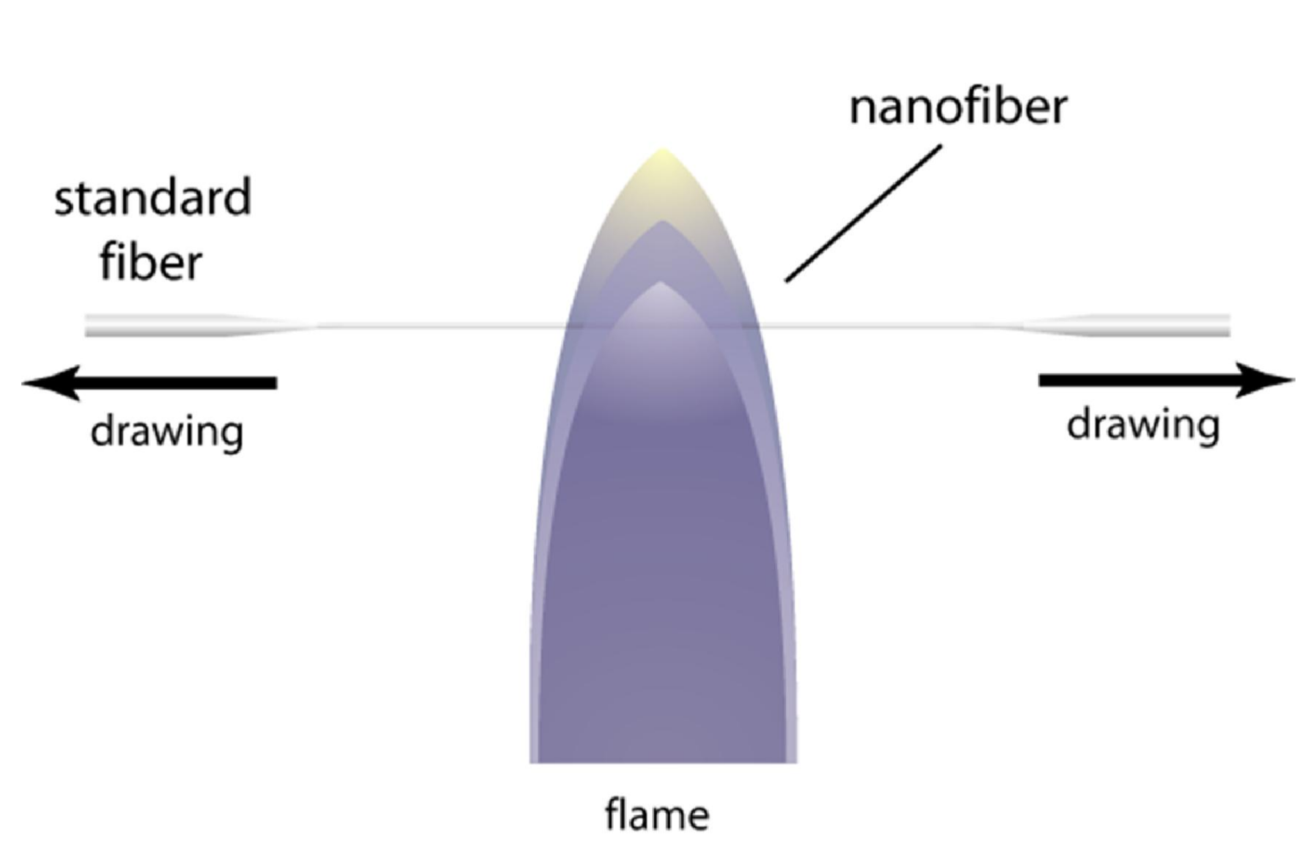
Silica nanowires

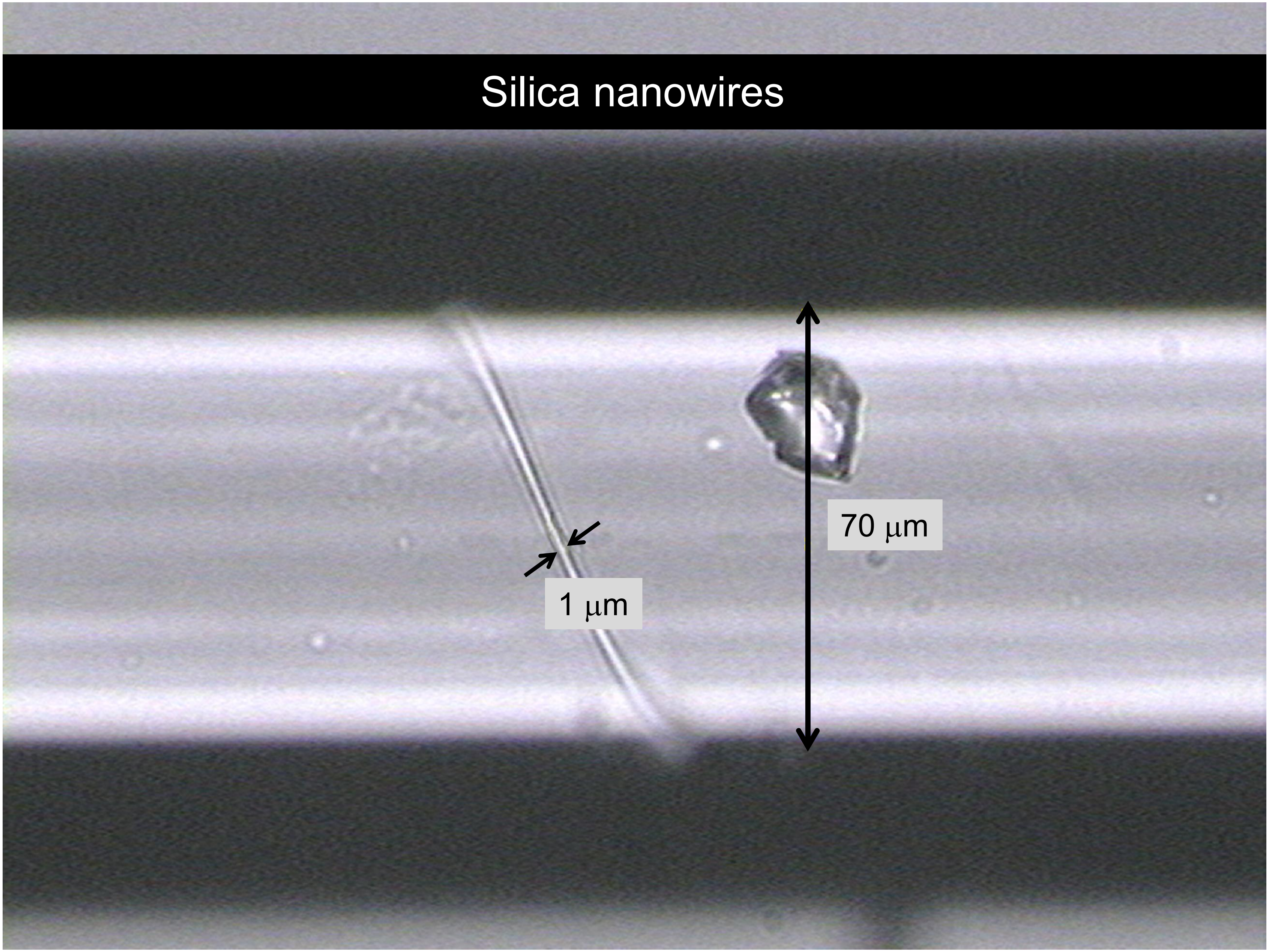
nanowires fabrication process



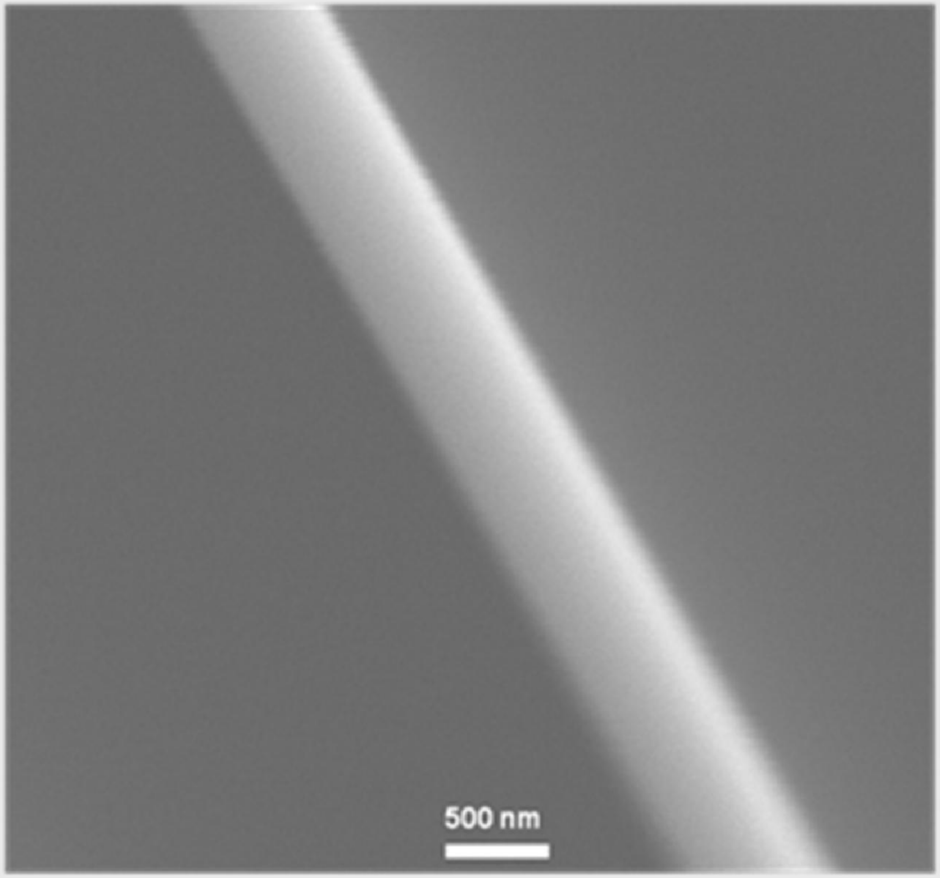
Silica nanowires

nanowires fabrication process



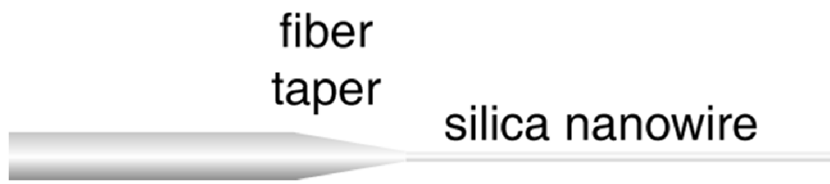

Silica nanowires
70 μm
1 μm

Silica nanowires



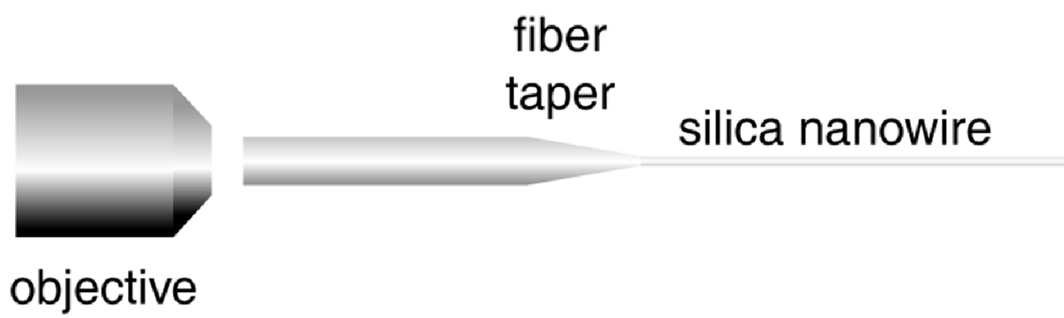
Silica nanowires

coupling light into nanowires



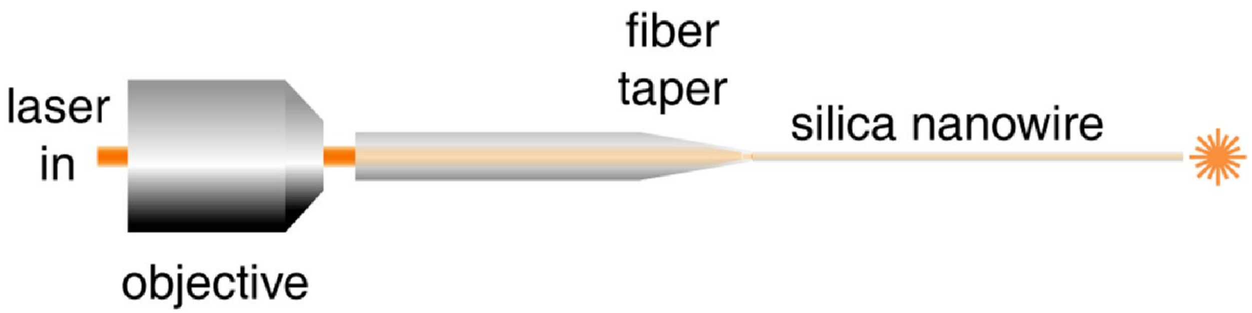
Silica nanowires

coupling light into nanowires



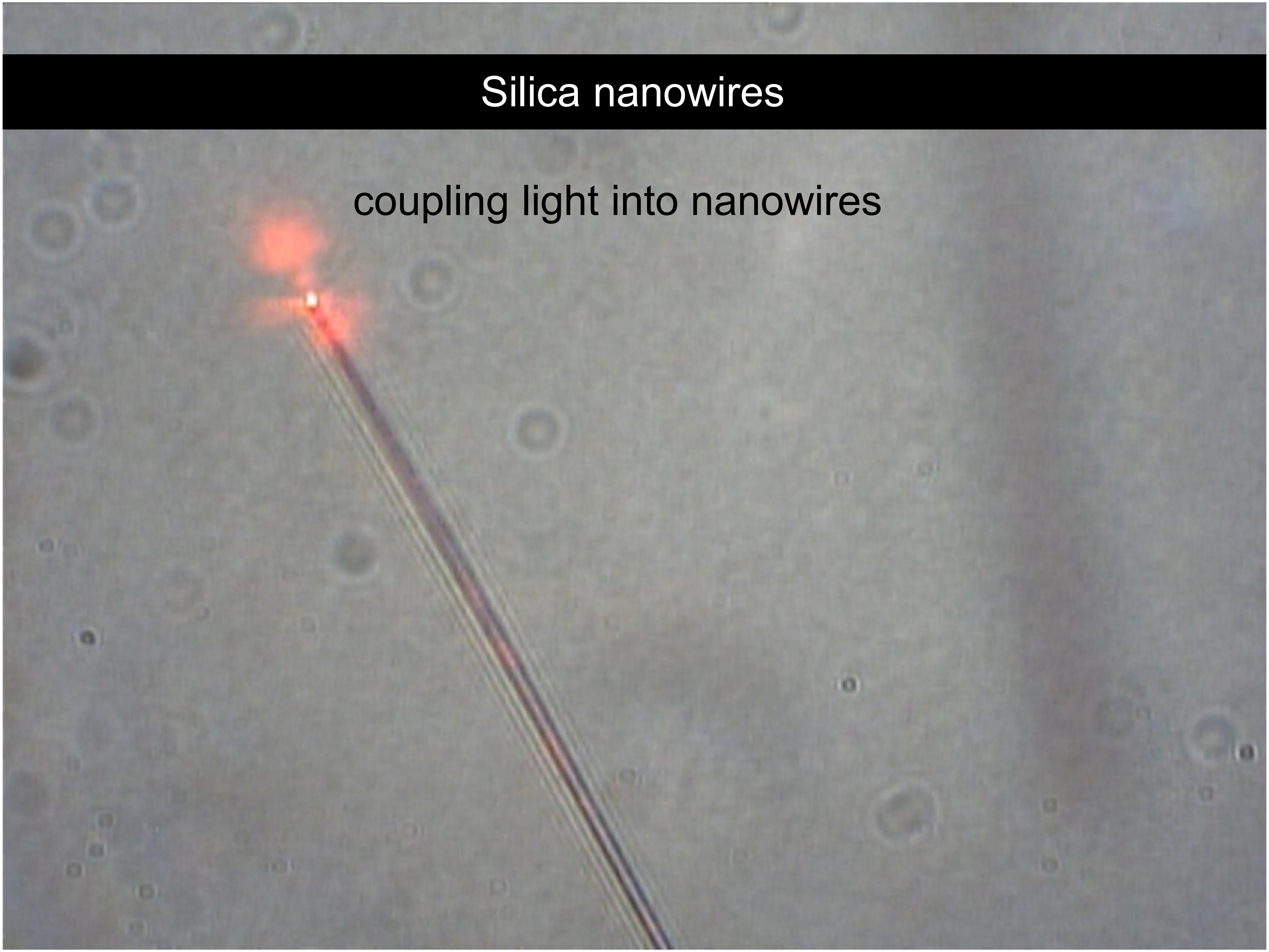
Silica nanowires

coupling light into nanowires

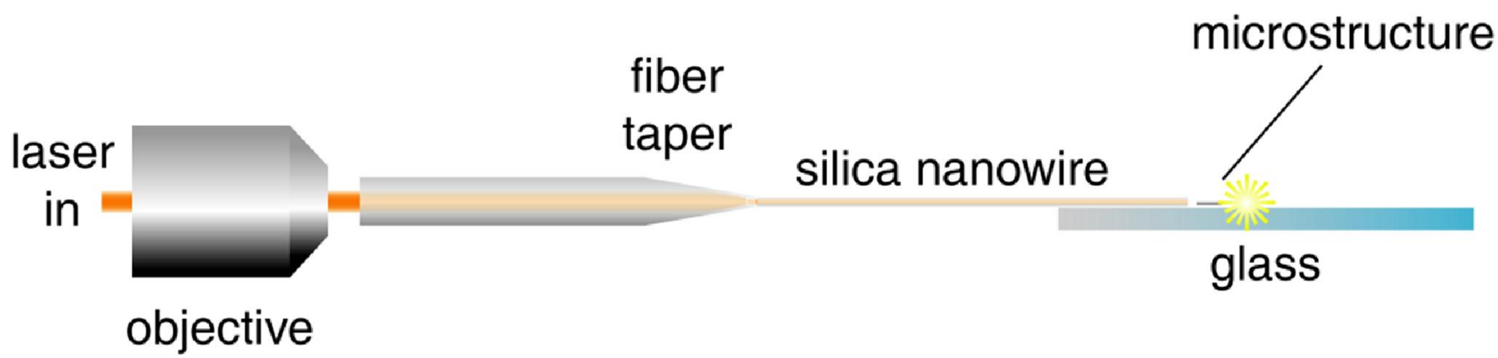


Silica nanowires

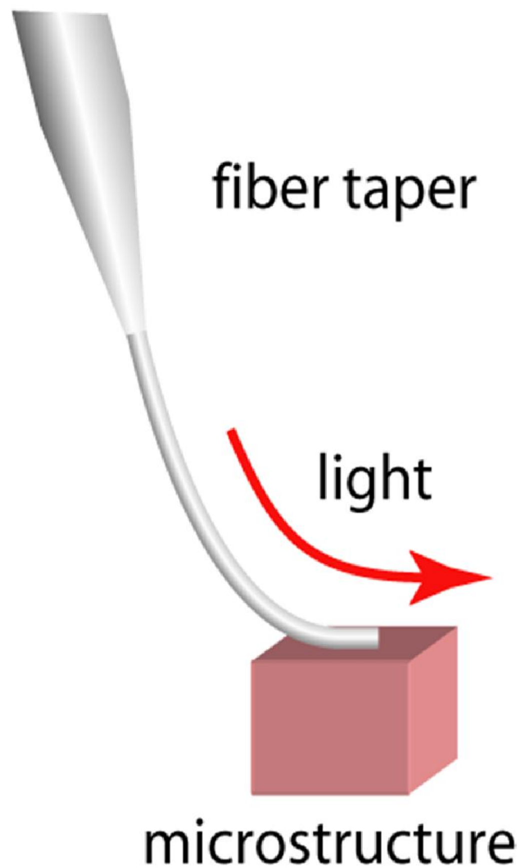
coupling light into nanowires



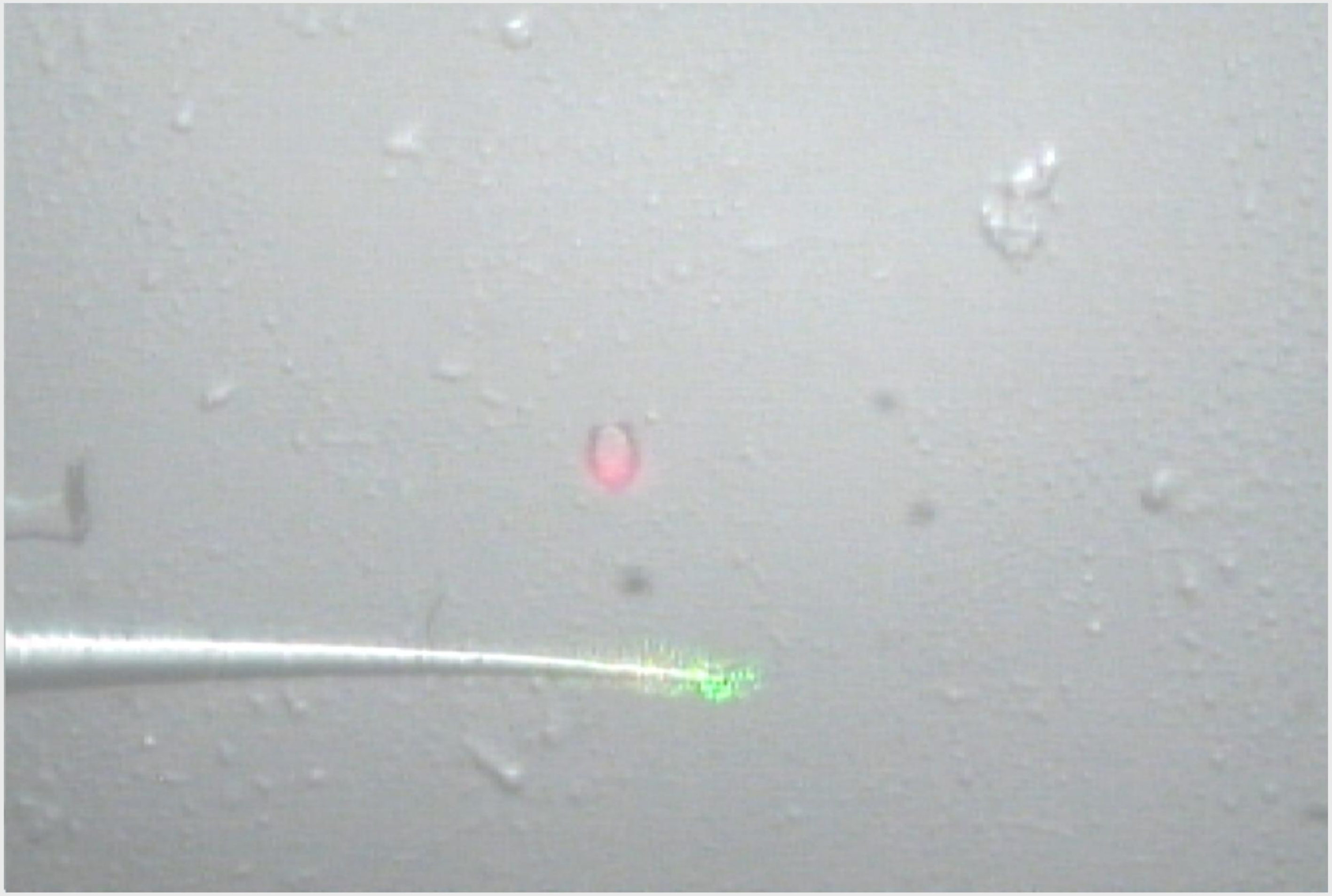
Coupling microstructures



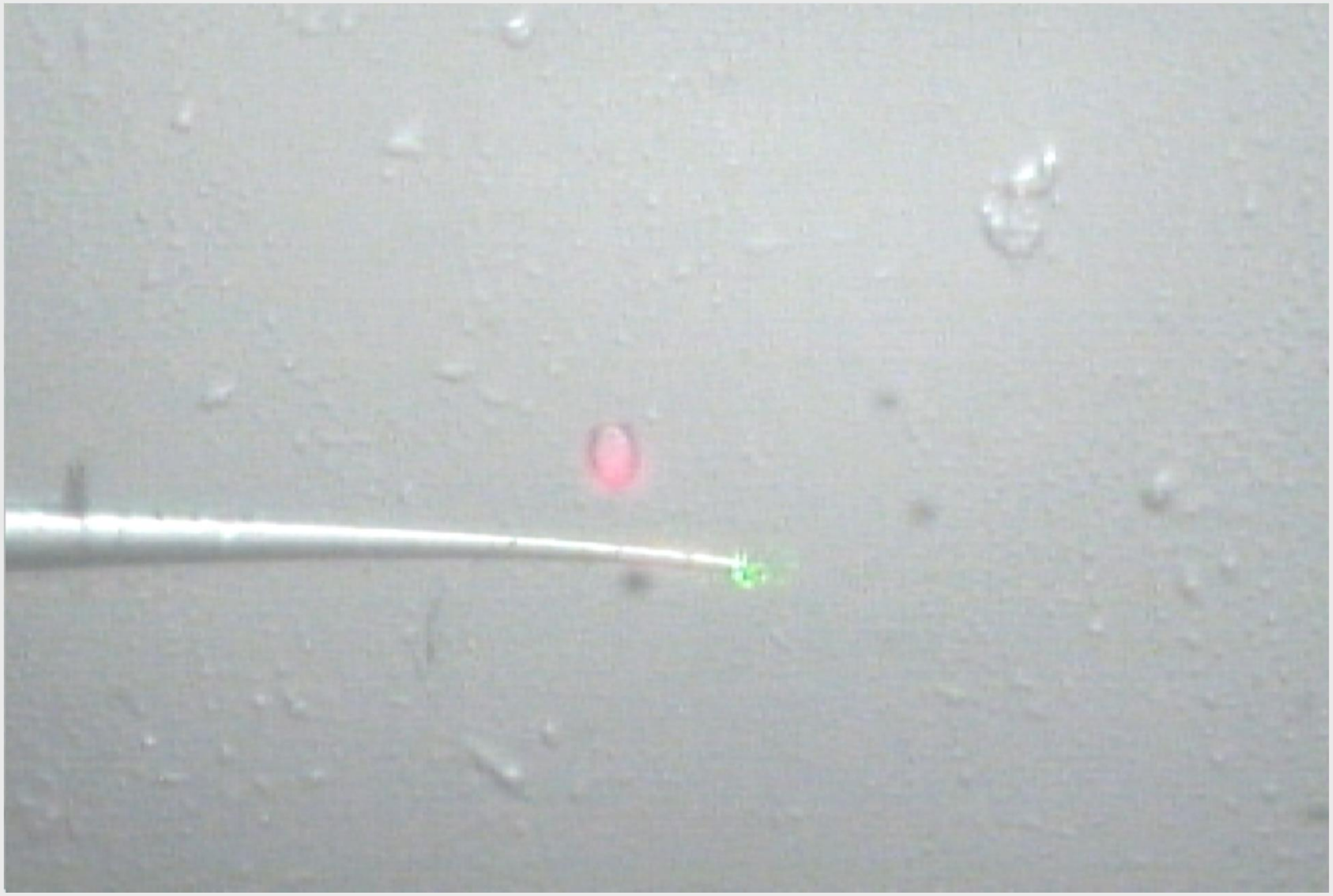
Coupling microstructures



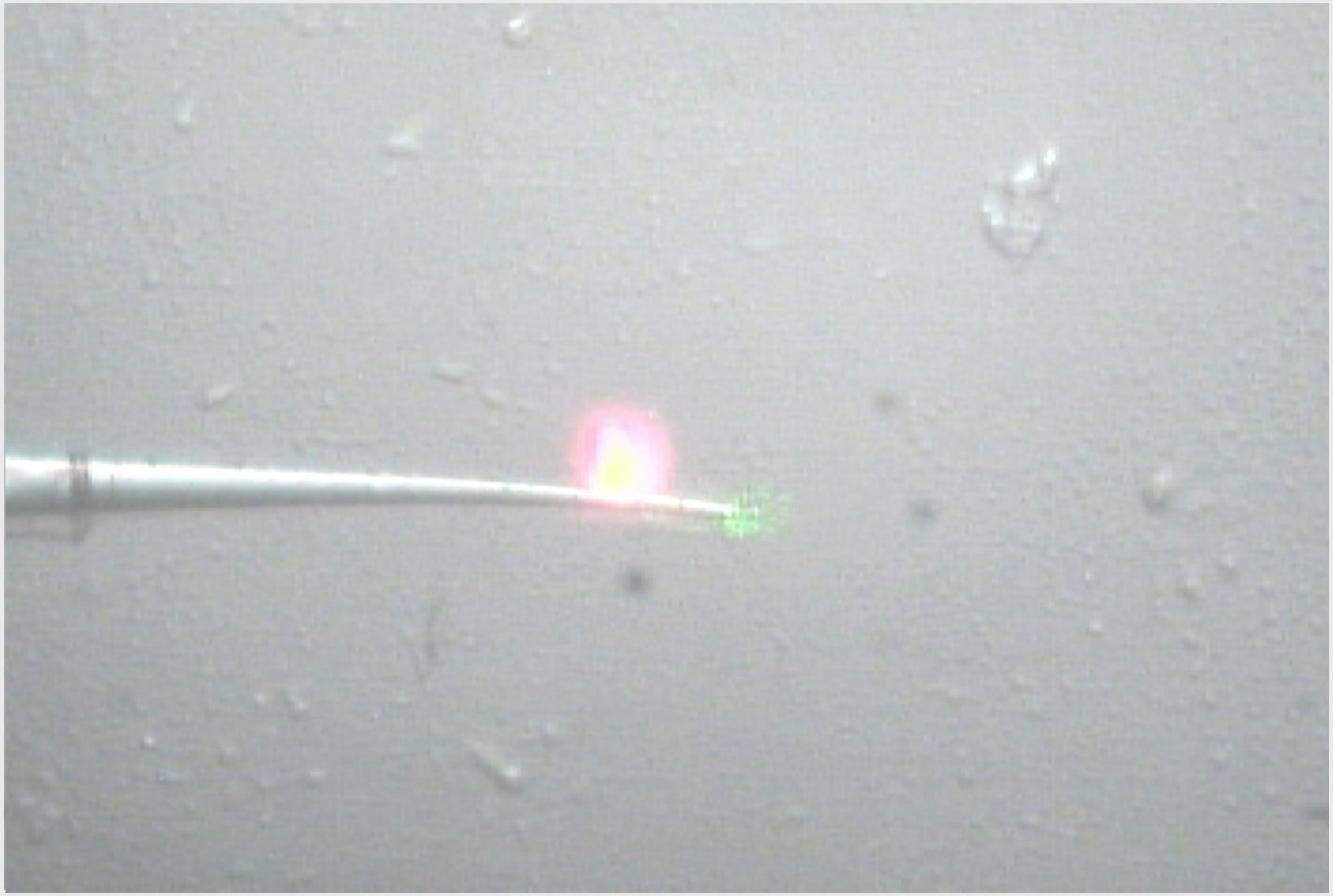
Coupling microstructures



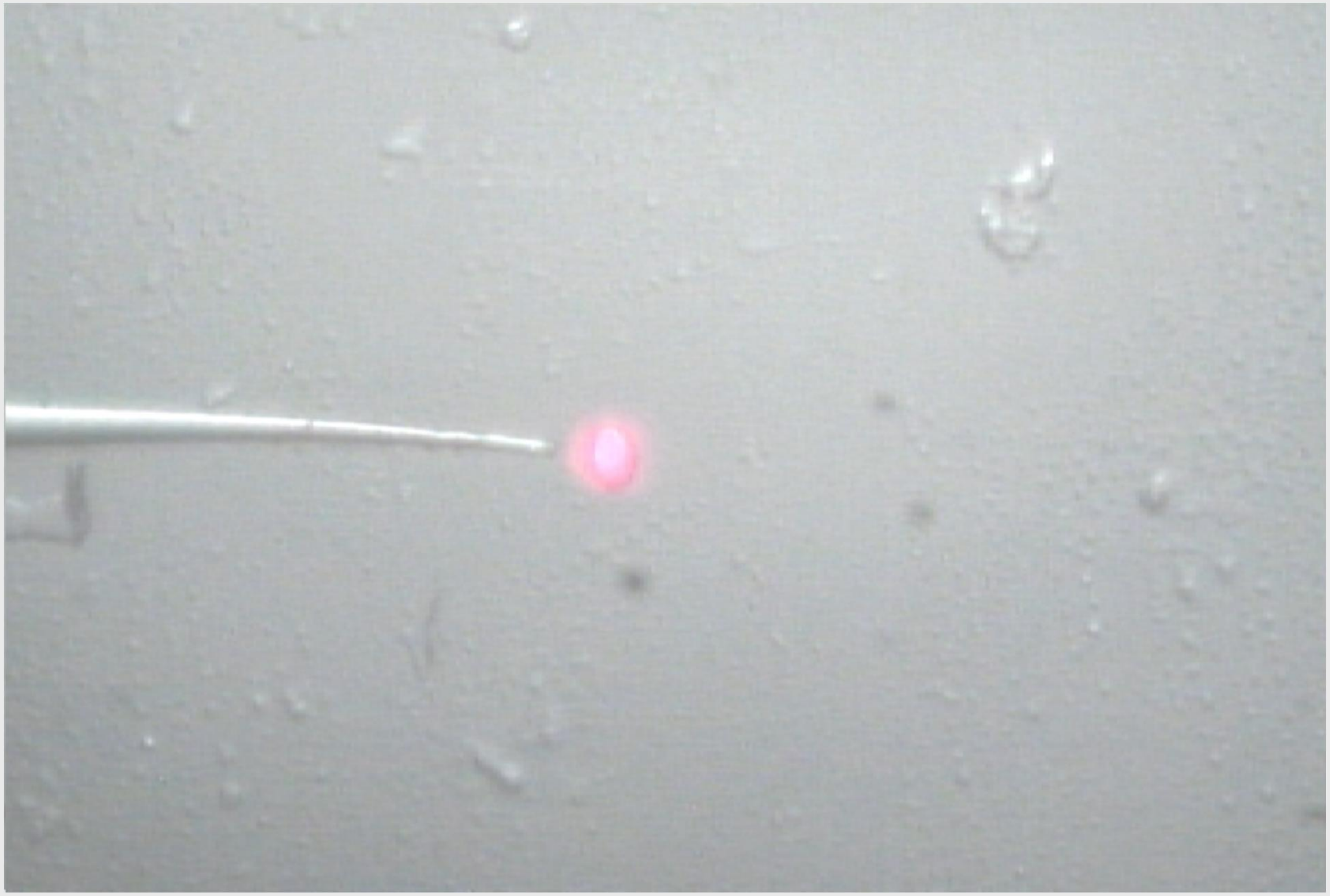
Coupling microstructures



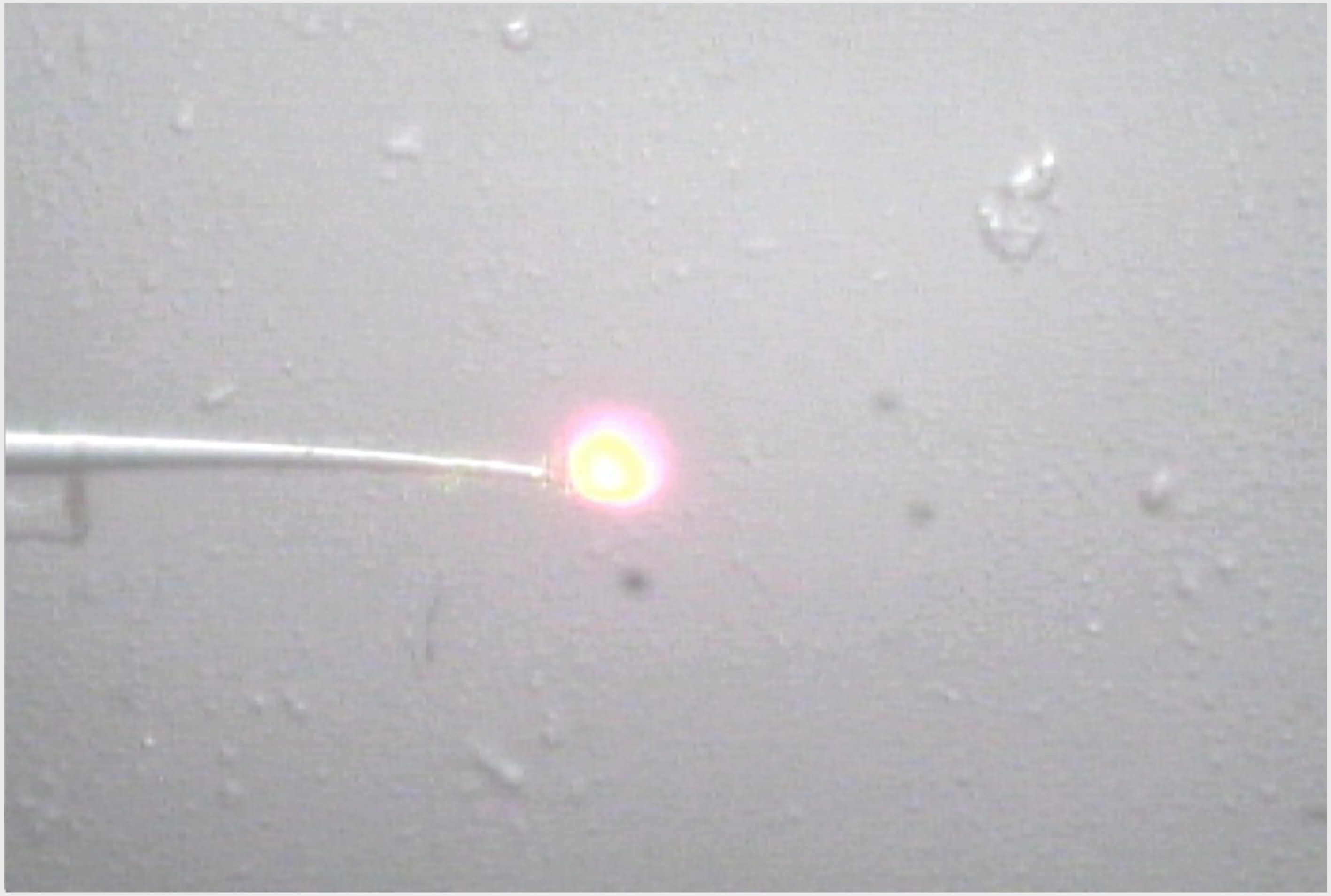
Coupling microstructures



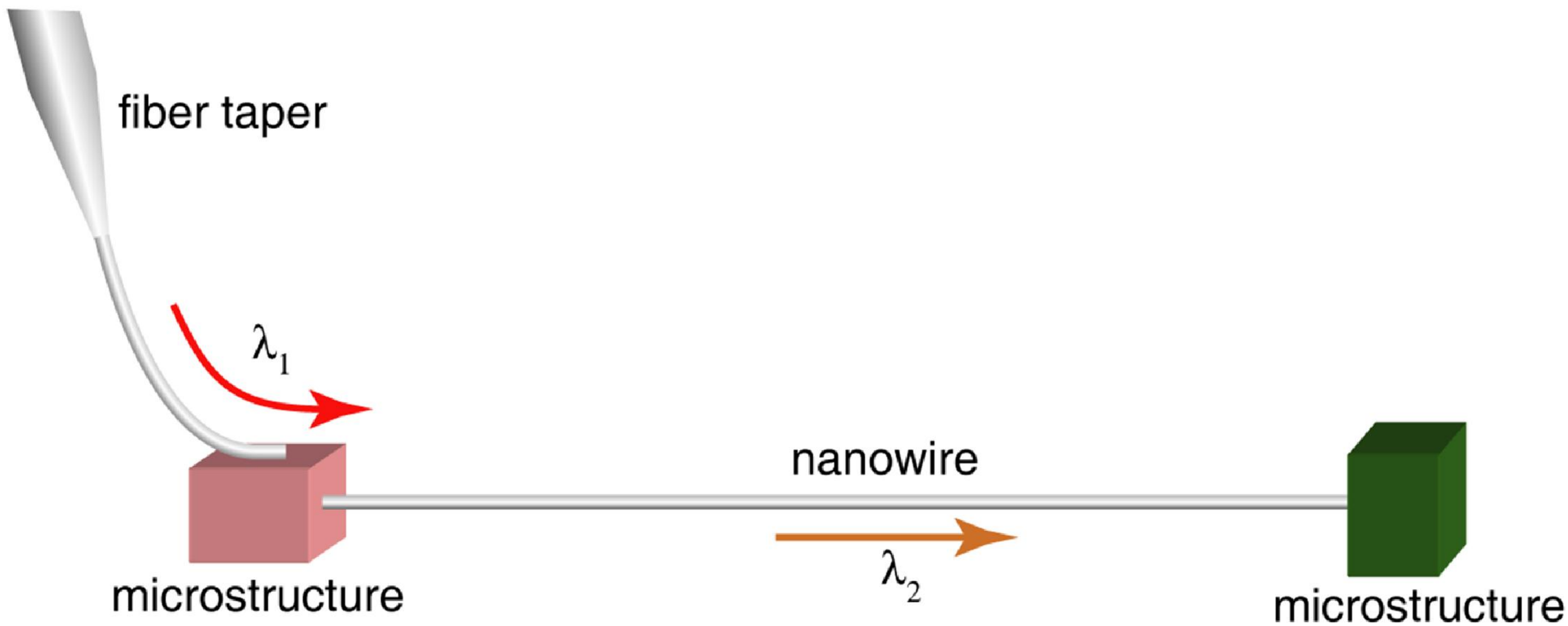
Coupling microstructures



Coupling microstructures



Coupling microstructures



Acknowledgments

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