



The Abdus Salam
International Centre
for Theoretical Physics



2443-17

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

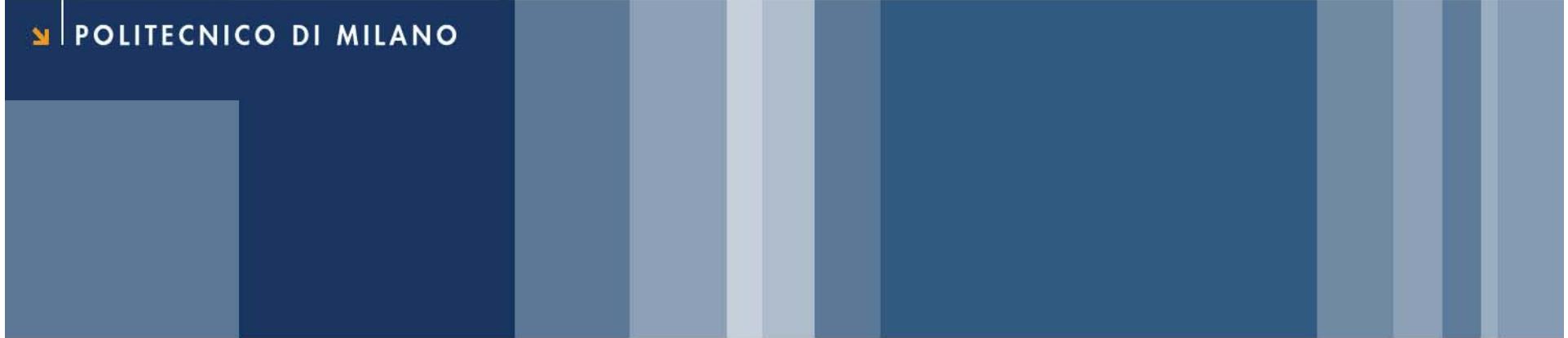
4 - 15 February 2013

Femtosecond laser micromachining (part 3)

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Politecnico di Milano
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POLITECNICO DI MILANO



Femtosecond laser micromachining (3)

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Outline of the presentation

- Femtosecond laser microstructuring for solar cells
- Fabrication of microoptical components: Fresnel lenses
- Two-photon polymerisation

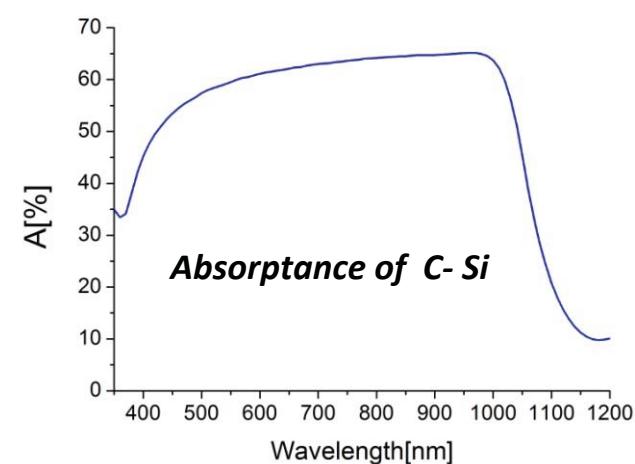
Femtosecond laser microstructuring for solar cells

- Introduction
- Optimization of fabrication process at 1 kHz
- Microstructuring of c-Si at low repetition rates (< 20 kHz)
- Microstructuring at high repetition rates (up to 1000 kHz)
- Conclusions and future perspectives

Introduction



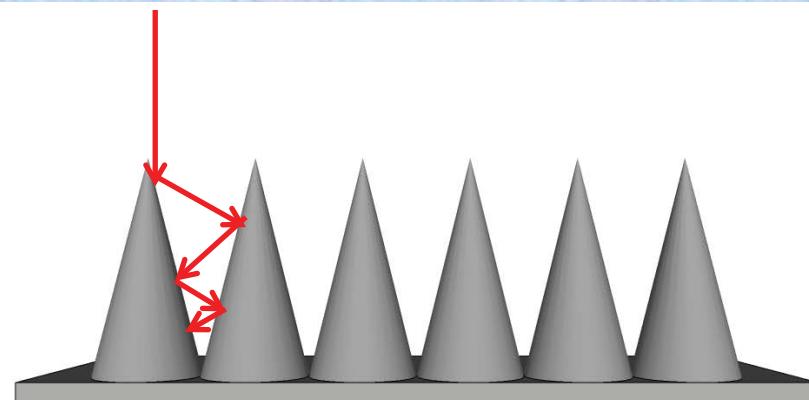
Silicon



Motivation: why microstructuring?

Maximum absorbance
of c – Si is 65%.

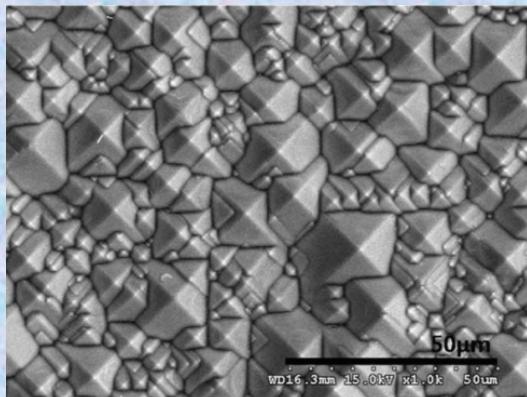
The principle of reduction of
reflectivity



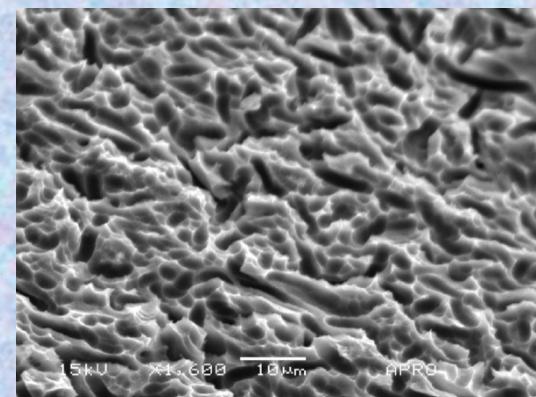
Introduction

Micro-texturing by Chemical Etching

- ✗ the reduction of reflectivity is around 10* - 15 %*** (AR coating)
- ✗ dependence on type of the Si wafer (c or mc)
- ✗ usage of non-environmental friendly chemical reagents
- ✗ difficult to control the homogeneity of structures



► Microstructures (c-Si) produced by *KOH***



► Microstructures (*mc-Si*) produced by *HF* and *HNO₃****

* K. Barada et al, Prog. Photovolt: Res. Appl. (2011)

**H. Park et al, SolEnergMater & SolCells 93 (2009) 1773–1778

*** K. Kim et al, SolEnergMat & SolCells 92 (2008) 960–968

Introduction

Femtosecond laser microstructuring

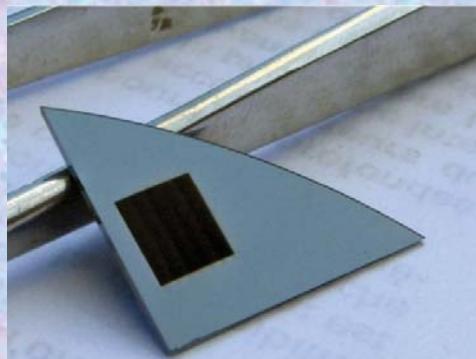
T.H. Her et al., "Microstructuring of silicon with femtosecond laser pulses," APL 73, 1673-1675 (1998).

- ✓ Reflection reduced to < 3 % - "**black silicon**"
- ✓ Fabrication process independent of the type of Si wafer and doping
- ✓ Can be processed in ambient air
- ✓ Reported increase in PV efficiency \approx 1% (Sionyx)

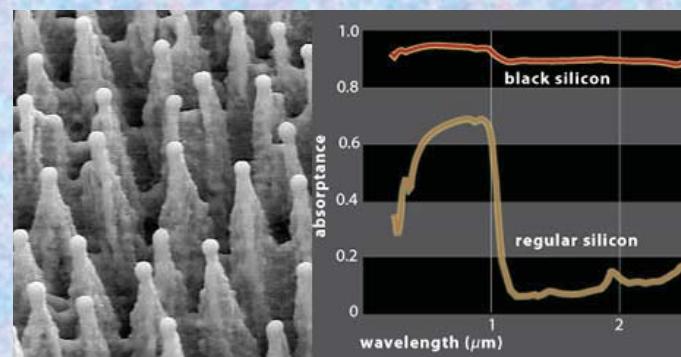
(<http://sionyx.com/2011/10/sionyx-solar-achieves-record-results-for-black-silicon-solar-cells-2/>)

High repetition rate fs laser pulses to improve processing speed

Thermal cumulative effects?



► "black silicon"

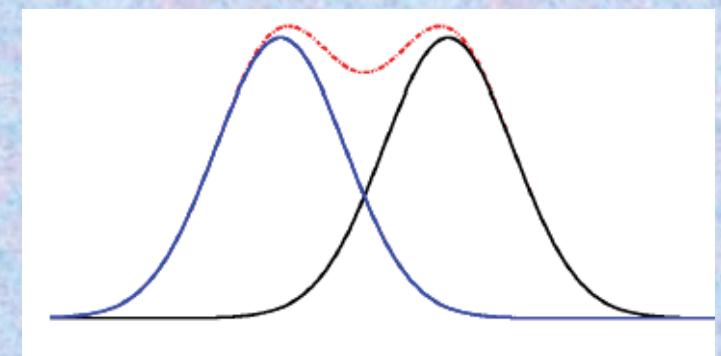
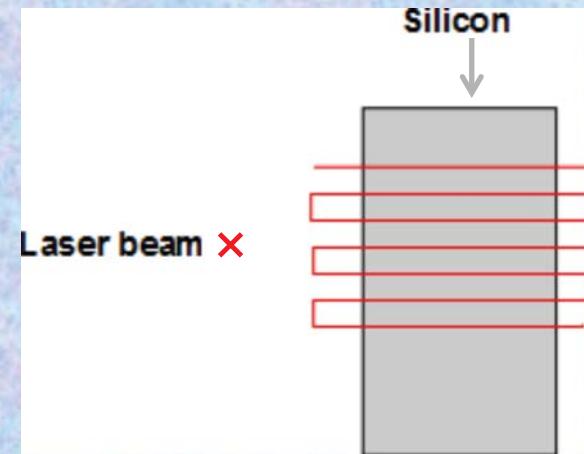


Comparision: Absorbance of Black Silicon and Silicon

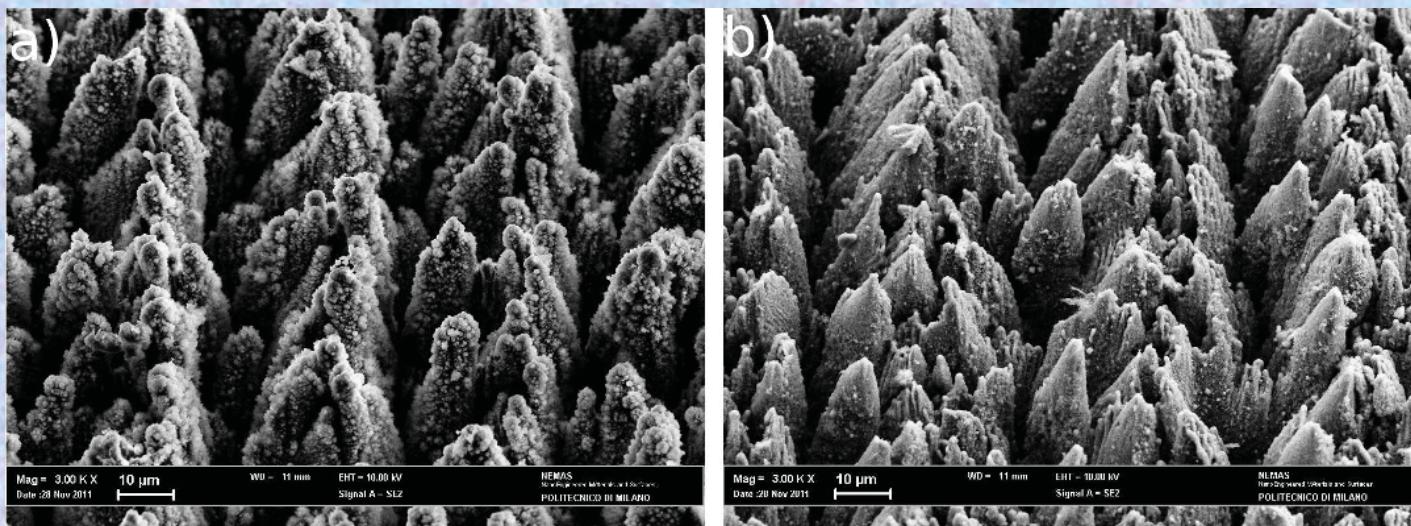
Introduction

The laser microstructuring

- Irradiation along equi-spaced parallel lines
- Main processing parameters:
 - Laser Fluence at the sample surface
 $(0.29 \text{ J/cm}^2 < F < 1.64 \text{ J/cm}^2)$
 - Repetition rate, sample scanning speed
 - Interline spacing, focal depth



Cleaning



Laser Fabrication System



Laser System: Yb:KGW active medium
Pharos Laser (Light Conversion, Lithuania)

OSCILLATOR

Average Power : 2 W

Pulse width: 80 fs

Repetition rate: fixed; 60 MHz

AMPLIFIER

Average Power : 10 W

Pulse width: 250 femtoseconds

Wavelength: 1030 nm (fundamental)

Repetition rate: variable; up to 1 MHz

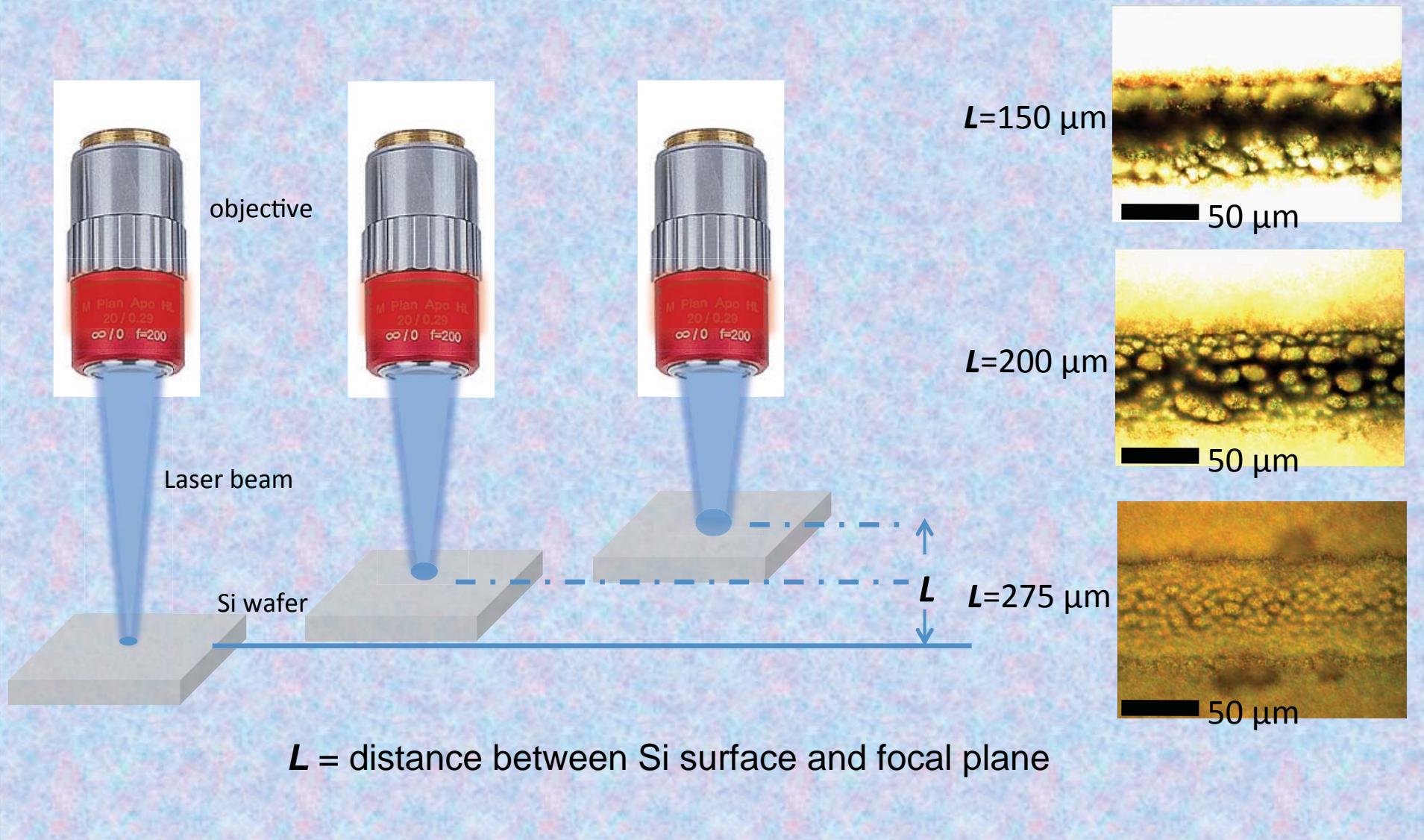
Harmonic generator: HIRO (Light Conversion, Lithuania)
(Second, third and fourth)

Sample translation stage:

Fiberglide - 3 D (Aerotech, USA) stage with a resolution of 2 nm.

Optimization: @1 kHz repetition rate

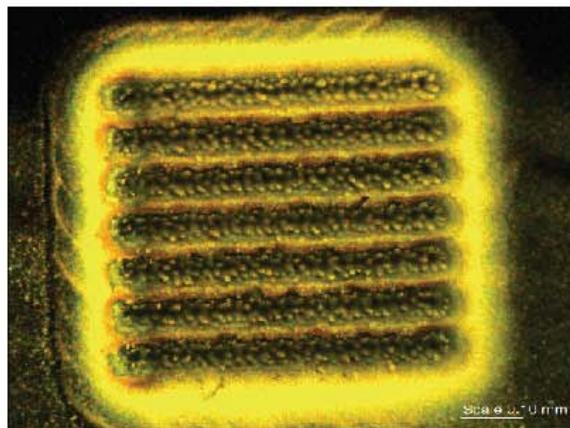
Optimization of the laser fluence (pulse energy 100 μ J):



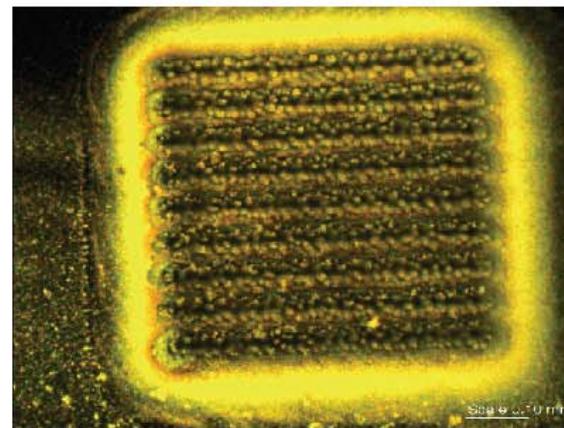
Optimization: @1 kHz repetition rate

Optimization of interline spacing for uniform area modification

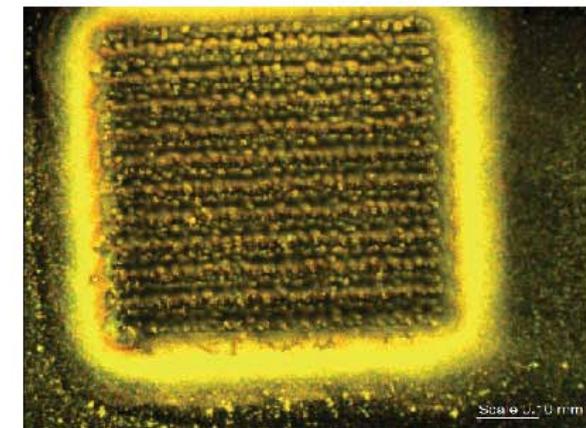
70 μm



55 μm

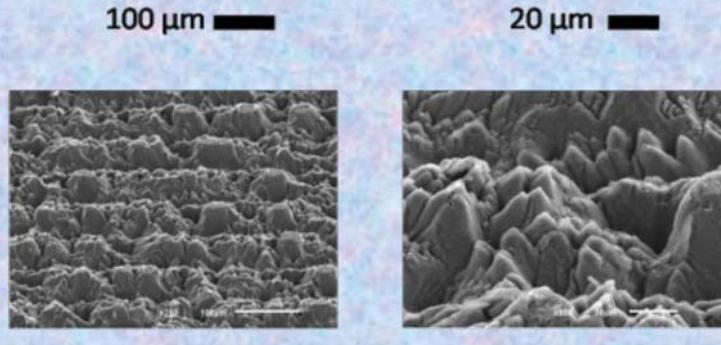


45 μm

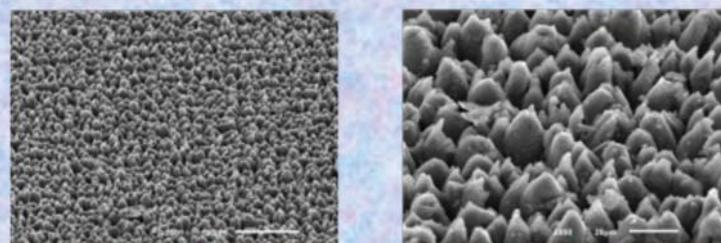


Results @ 1 kHz Repetition rate

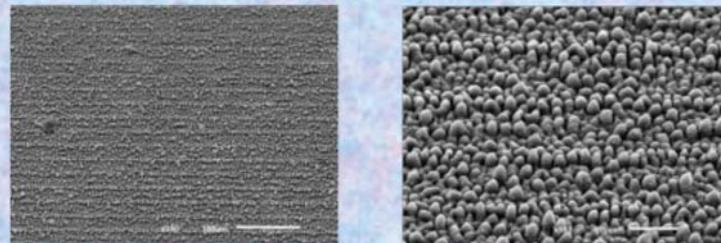
Regime I
0.1 mm/s



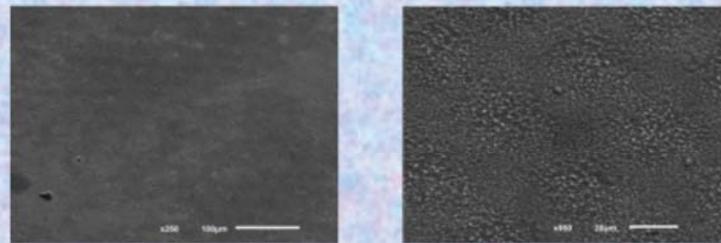
Regime II
0.35 mm/s



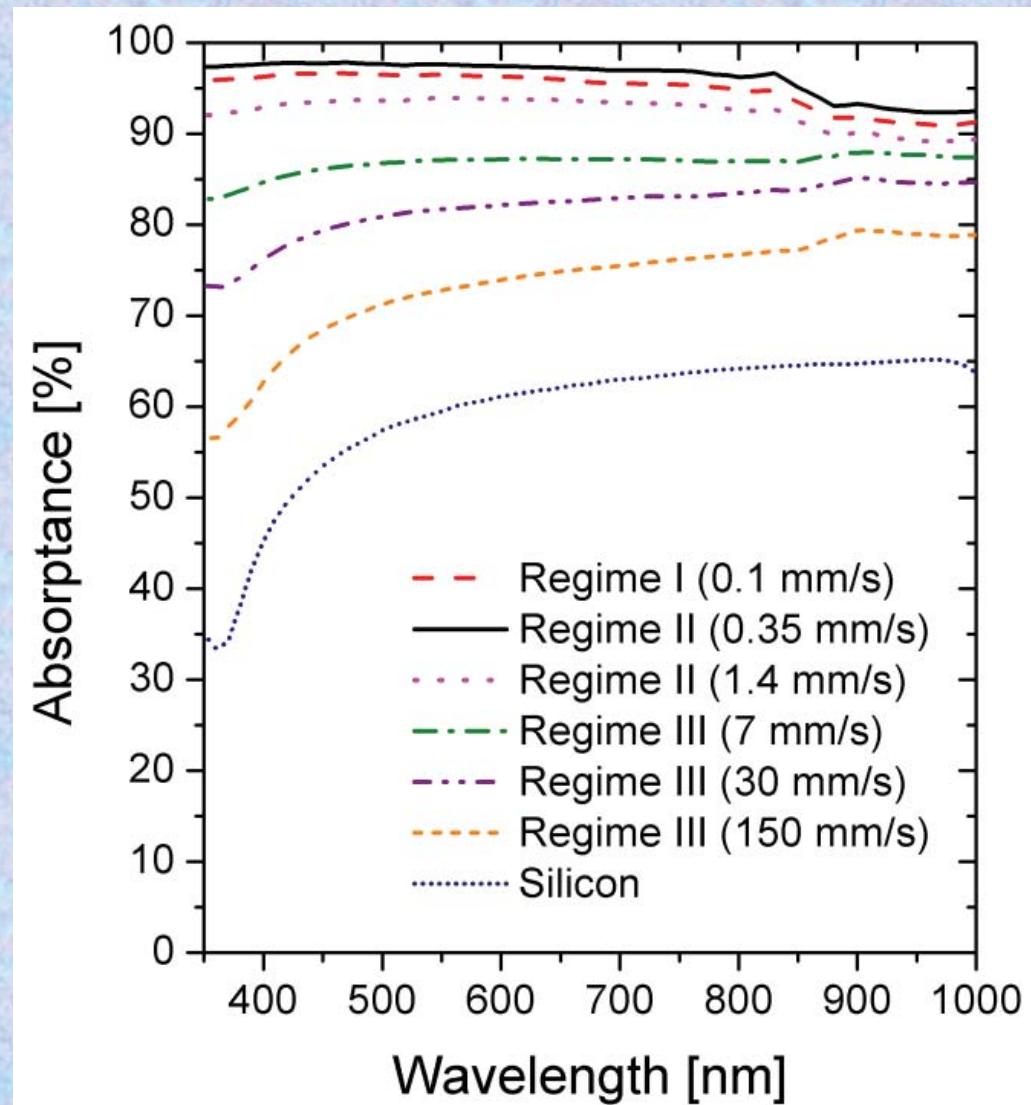
1.4 mm/s



Regime III
150 mm/s



Results @ 1 kHz Repetition rate



Optimization: @1 kHz repetition rate

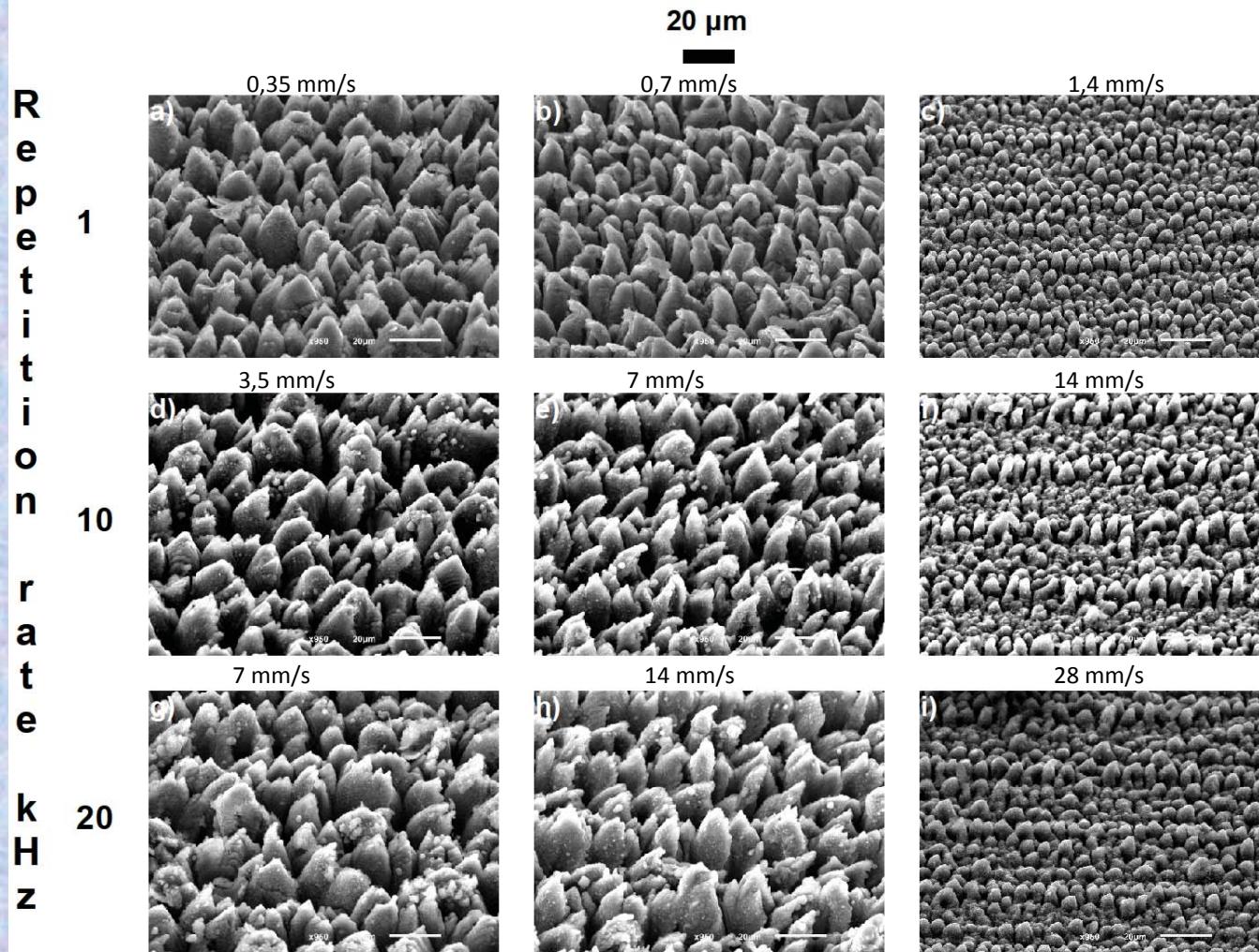
Optimized Parameters	
Pulse Energy [μJ]	100
Scanning speed [$\mu\text{m/s}$]	350
Focal plane depth [μm]	200
Interline spacing [μm]	35

Low repetition rates 1-20 kHz

Repetition rate [kHz]	1, 2, 4, 8, 10 e 20
Energy per pulse [μ J]	100
Focal plane depth [μ m]	200
Interline spacing [μ m]	35
Sample scanning speed [mm/s]	0.35 – 28

Low repetition rates

Scalability of process



High repetition rate >100 kHz

Calculated
fluence

(a)
100 kHz
30 mm/s

100 μm

20 μm

(b)
200 kHz
60 mm/s

0.82 J/cm^2

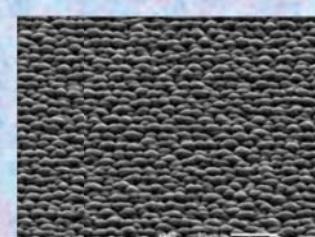
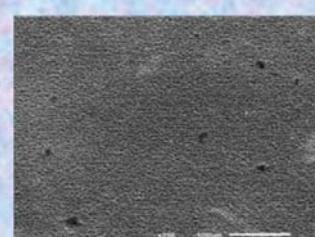
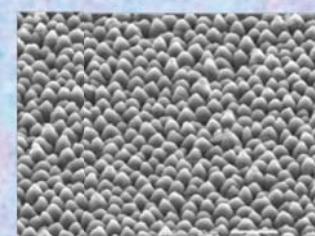
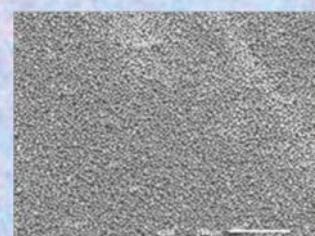
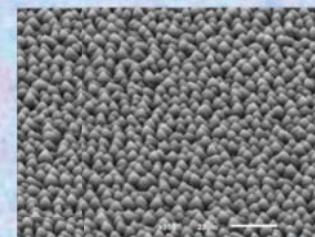
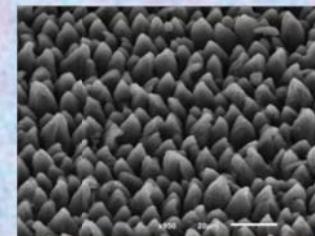
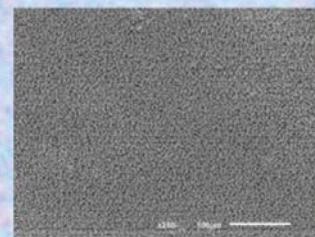
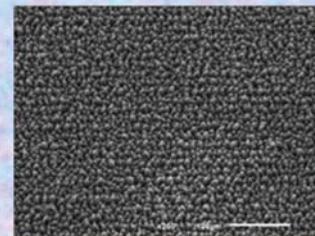
(c)
500 kHz
60 mm/s

0.41 J/cm^2

(d)
1 MHz
60 mm/s

0.59 J/cm^2

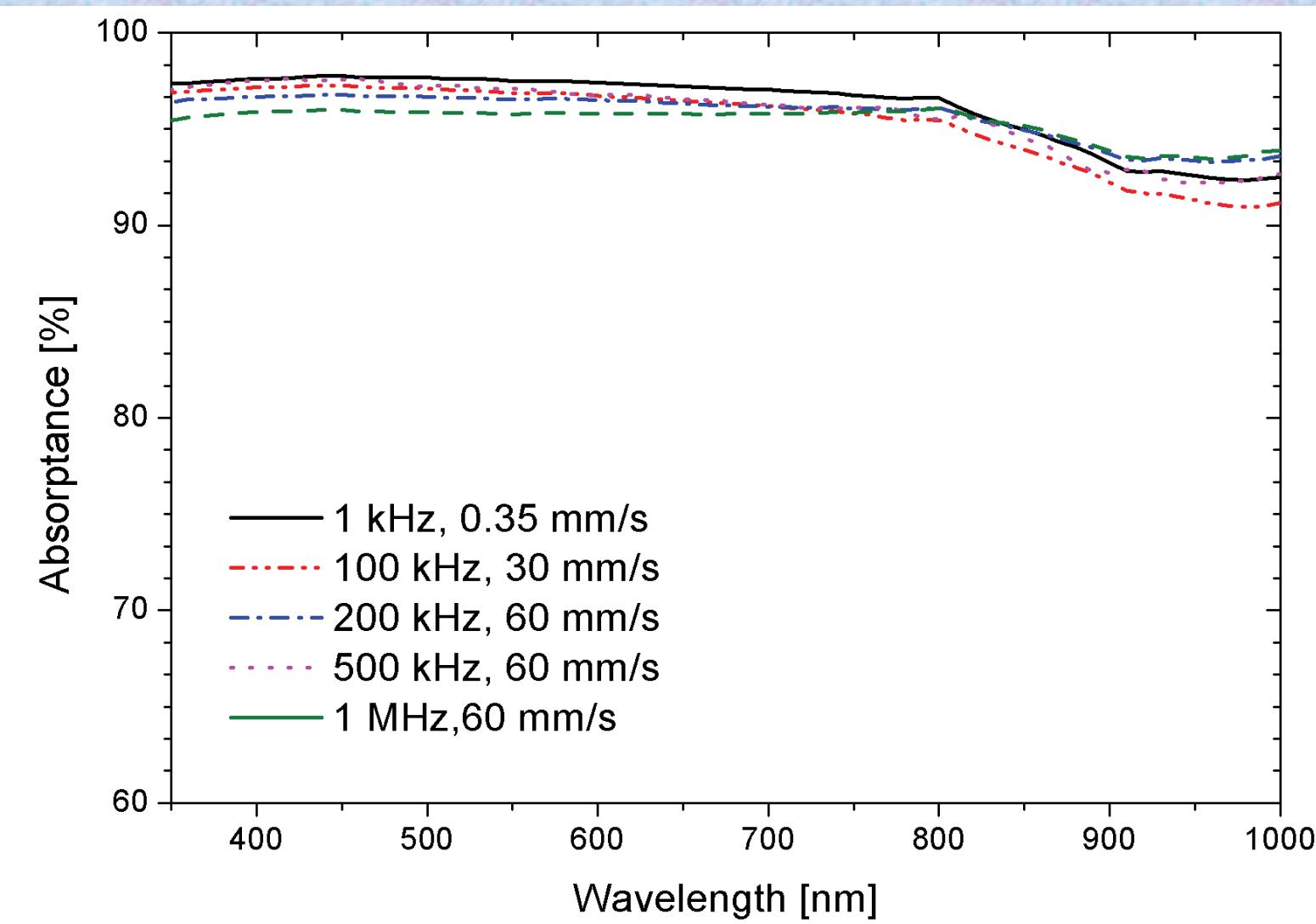
0.29 J/cm^2



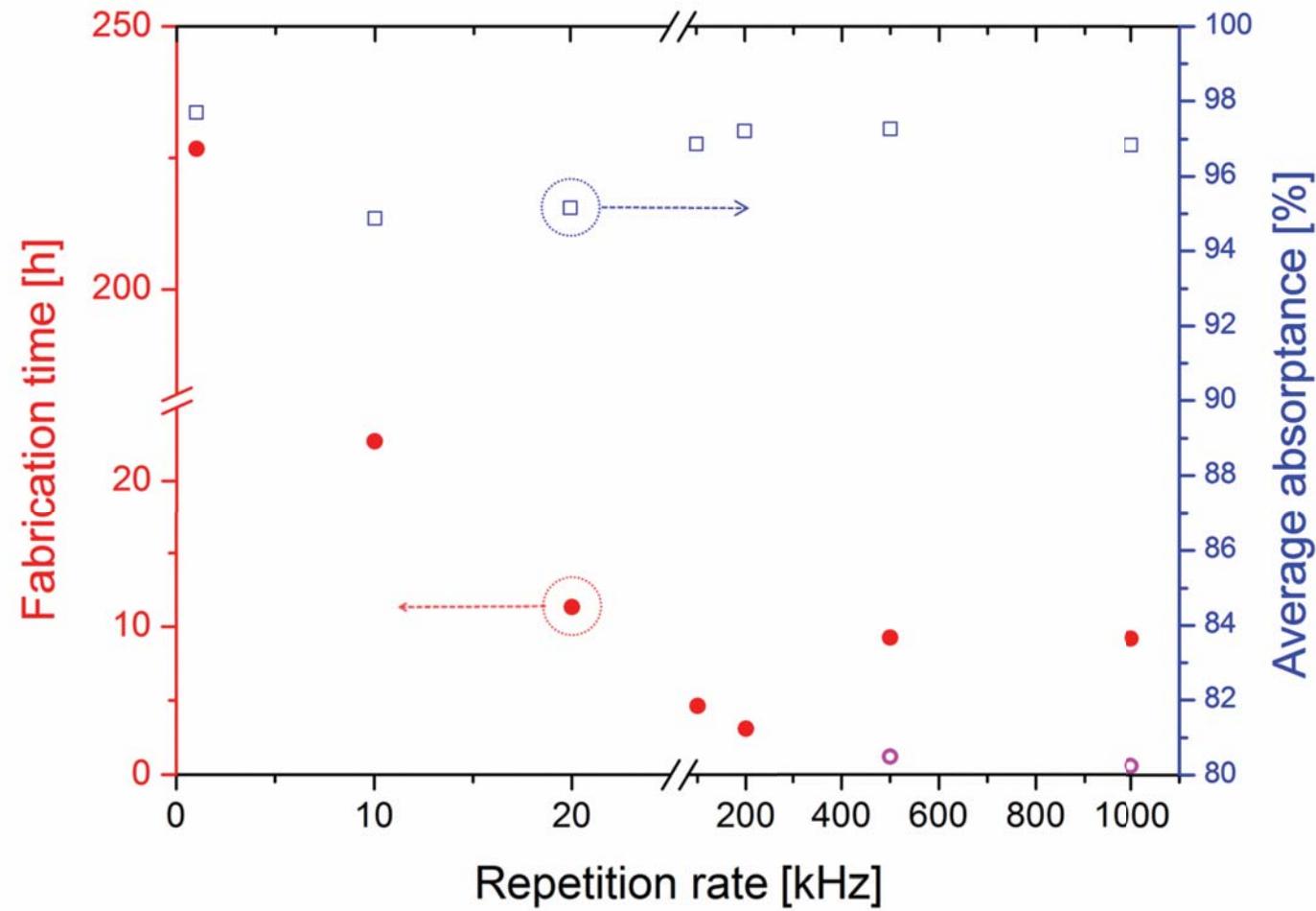
Parameters at a glance

Repetition rate [kHz]	Pulse energy [μJ]	Focal plane depth L [μm]	Beam waist w [μm]	Calculated fluence [J/cm^2]	Interline spacing [μm]	Scanning speed [mm/s]
1	100	200	44	1.64	35	0.35 to 1.4
10	100	200	44	1.64	35	3.5 to 14
20	100	200	44	1.64	35	7 to 28
100	50	200	44	0.82	20	30
200	25	200	44	0.41	15	60
500	10	105	23	0.59	5	60
1000	5	105	23	0.29	5	60

High repetition rate

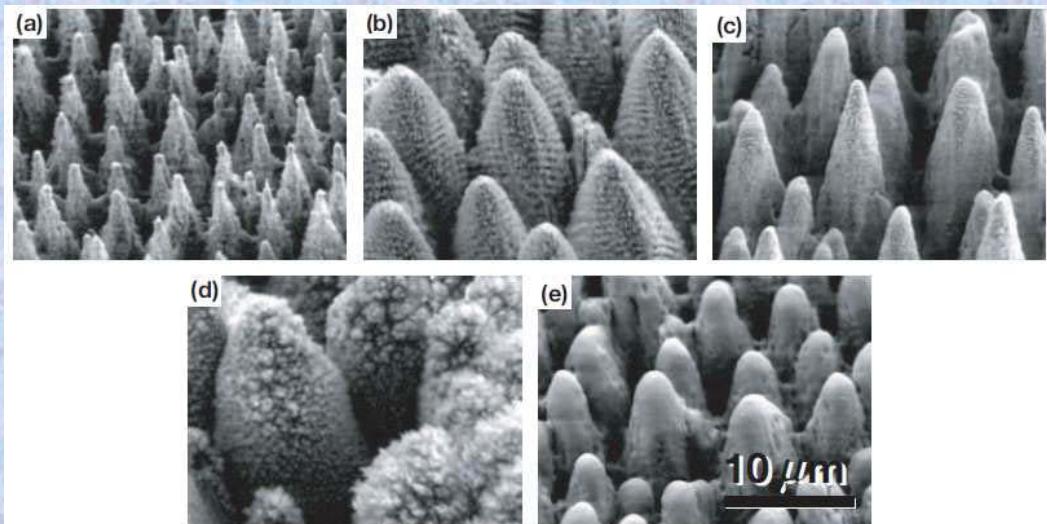


Conclusions



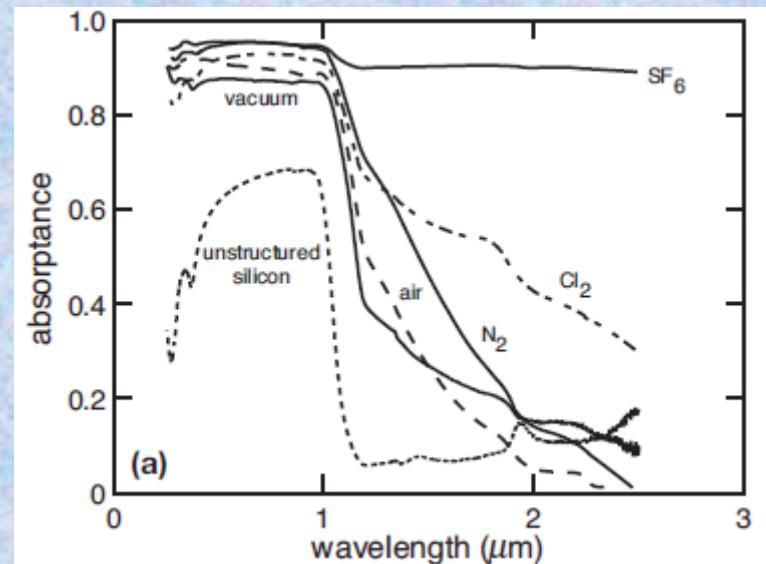
Effect of Gases

Morfology*



(a) SF₆, (b) N₂, (c) Cl₂, (d) aria, (e) vuoto

Absorbance**



*James Edward Carey III. Femtosecond-laser Microstructuring of Silicon for Novel Optoelectronic Devices. PhD thesis, 2004

**R. Younkin et al, Journal of Applied Physics Volume 93, Number 5

Conclusions

- ❖ fs-laser surface texturing of silicon can be performed at different repetition rates (1 kHz - 1 MHz)
- ❖ Optimal parameters for black silicon formation were determined
- ❖ No thermal effects were observed at high repetition rates
- ❖ Processing time 70x lower was demonstrated with potential for further 5x reduction
- ❖ Applications to high-efficiency detectors can be foreseen

Fabrication of Fresnel lenses

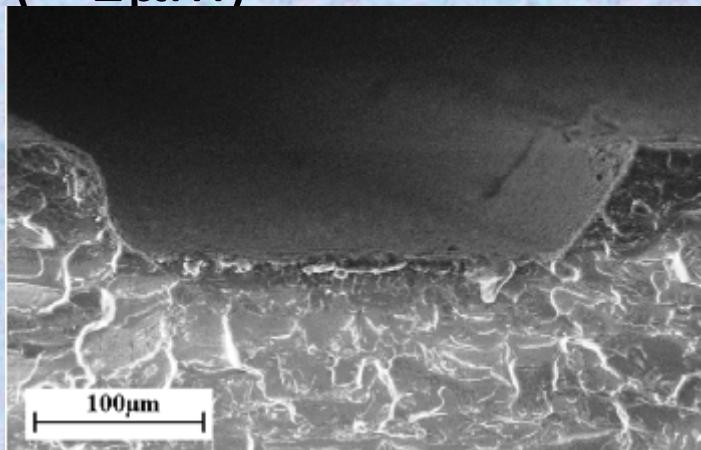
- Introduction and motivation
- Fabrication of Fresnel zone plates
- Characterization of the lenses
- Integration of the lenses in an optofluidic chip
- Conclusions

Motivation: Optofluidic chip

- **Polymer Lab-on-Chip** are low-cost (**disposable**), easy to manufacture (**soft lithography**)
- **Optical detection difficult** to integrate without increasing the cost and complicating the manufacturing
- **Femtosecond lasers** promising tool for **rapid prototyping** of devices
- **Design** should consider **easy replication** by soft lithography

fs Laser micromachining

- No wavelength dependence: any material can be machined with the same laser
- No thermal damage: high machining quality
- Low ablation threshold: high precision processing ($< 1\mu\text{m}$)



R. Suriano et al., Appl. Surf. Sci. 257, 6243 (2011)

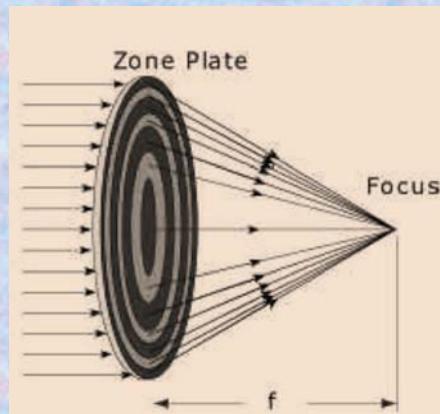
Motivation: Fresnel Lenses

- Compact lenses (thickness $< 1\mu\text{m}$): easy integration in microfluidic chips.
- High Numerical aperture
- Short focal length
- High efficiency (2 level 40%; 4 level ~81%)

Fresnel zone plates



Top view

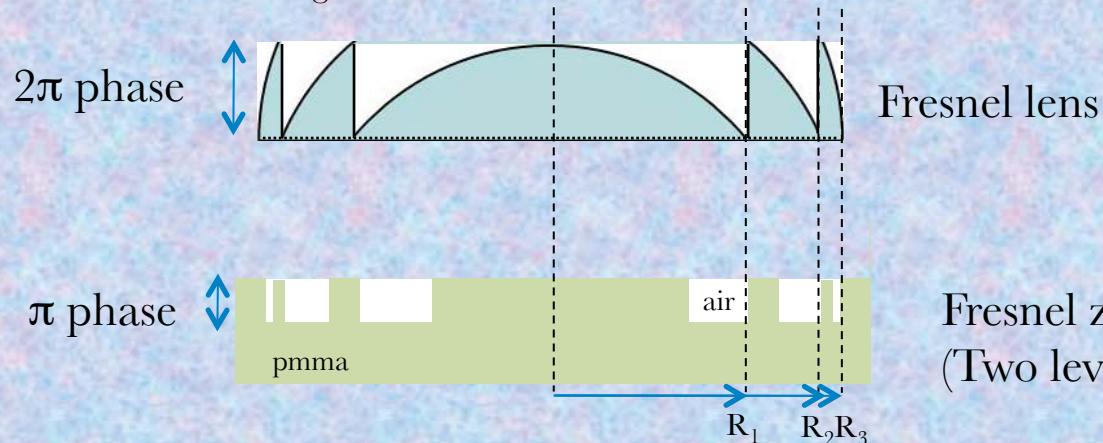


Focusing a monochromatic
incident beam

$$R_m^2 = 2 m \lambda f$$

$$\text{NA} = \lambda / (2\Lambda)$$

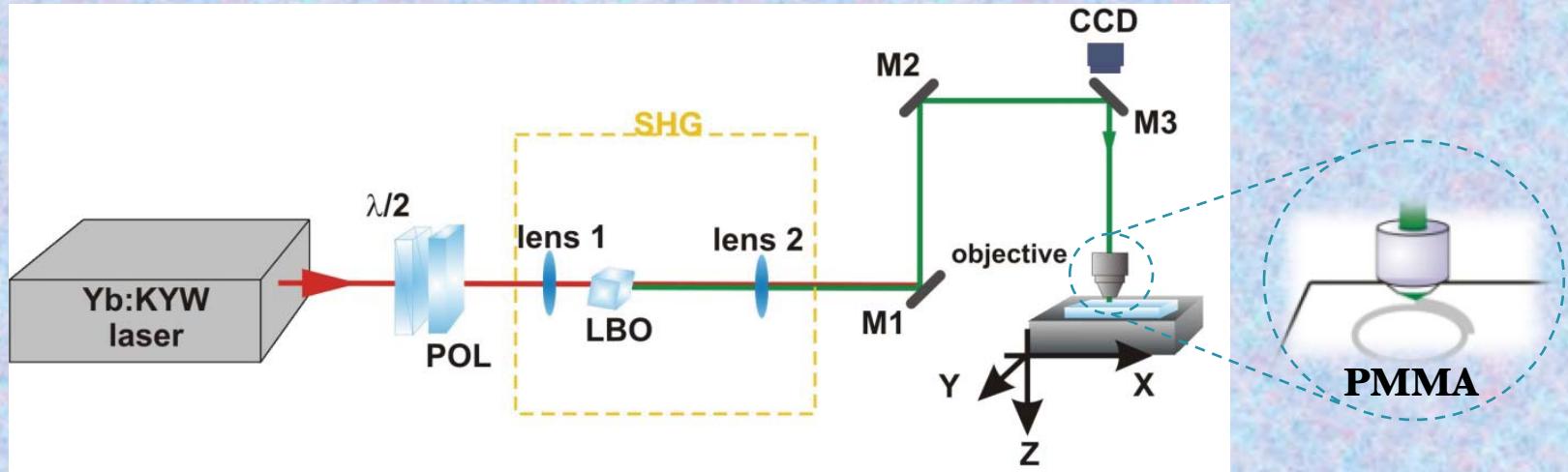
Edge view



Fresnel zone plate
(Two level Fresnel lens)

Fresnel zone plates fabrication

Surface ablation: high index change; small feature size; easy reproducibility by soft lithography



Cavity-dumped Yb laser

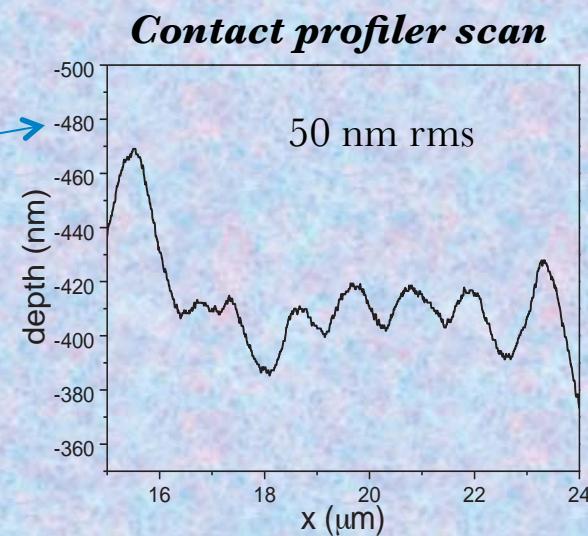
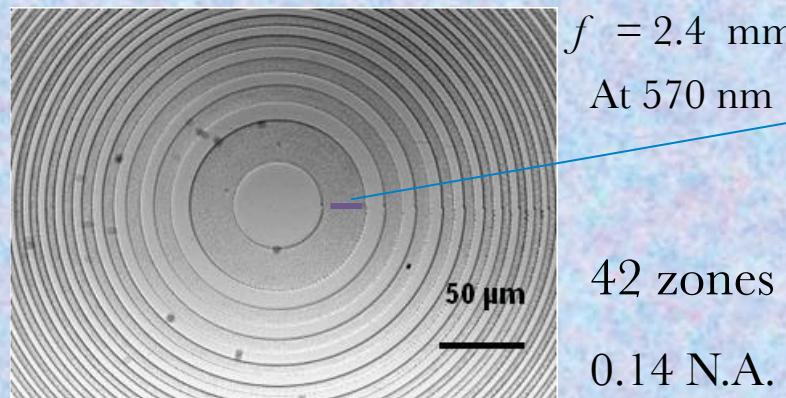
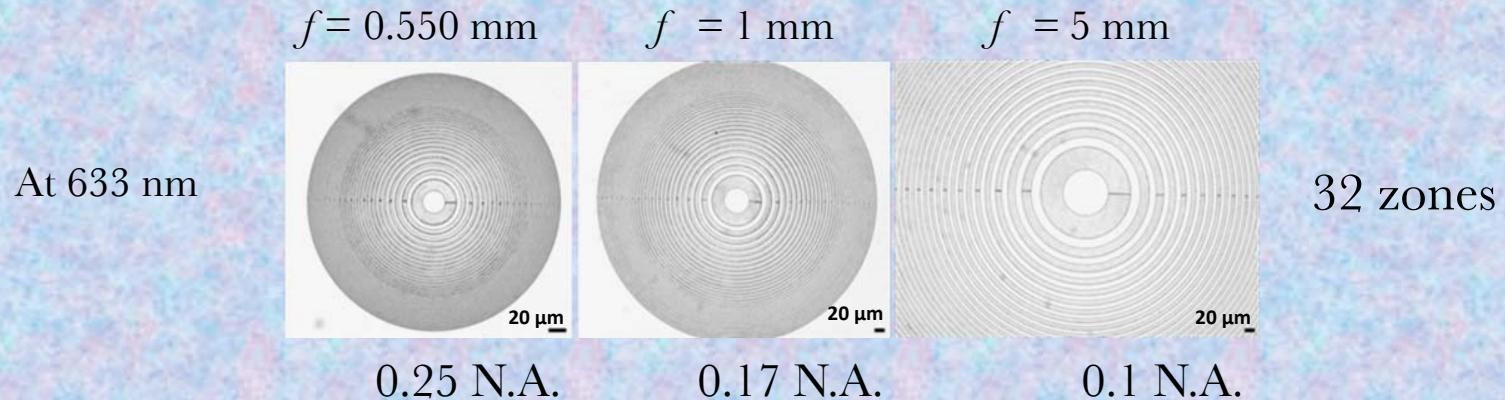
- Wavelength 1030 nm
- Pulse energy < 1 μ J
- Repetition rate < 1MHz
- Pulse width: \cong 350 fs

Fabrication parameters

- Pulse energy: 25 nJ
- Repetition rate 10 kHz
- Focusing objective: 100x (0.95 NA)
- Translation speed: 0.2 mm/s
- 600 nm radial step

FZPs in PMMA

Fabrication time ~20 - 30 minutes

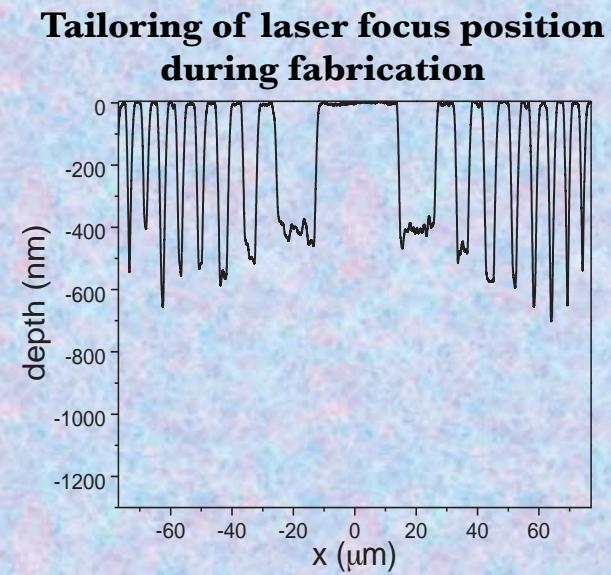
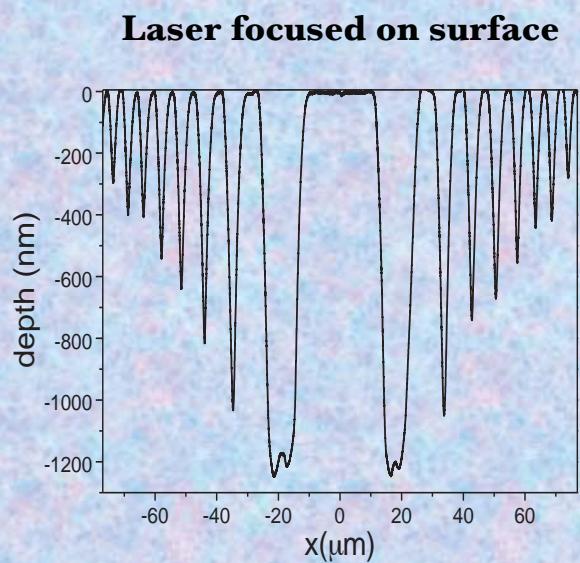


R. Martínez Vázquez et al., Optics Express, 19 (2011).

Depth control

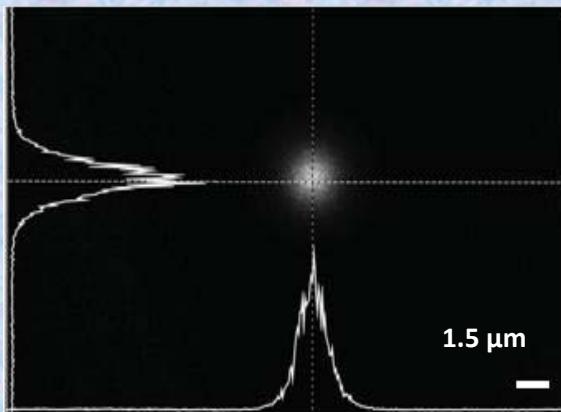
$$d = \lambda / (2(n-1))$$

Groove depth to obtain π phase shift
 $n = 1.492$, (Vistracryl CQTM non UV)



Similar depth within 200 nm

FZPs characterization



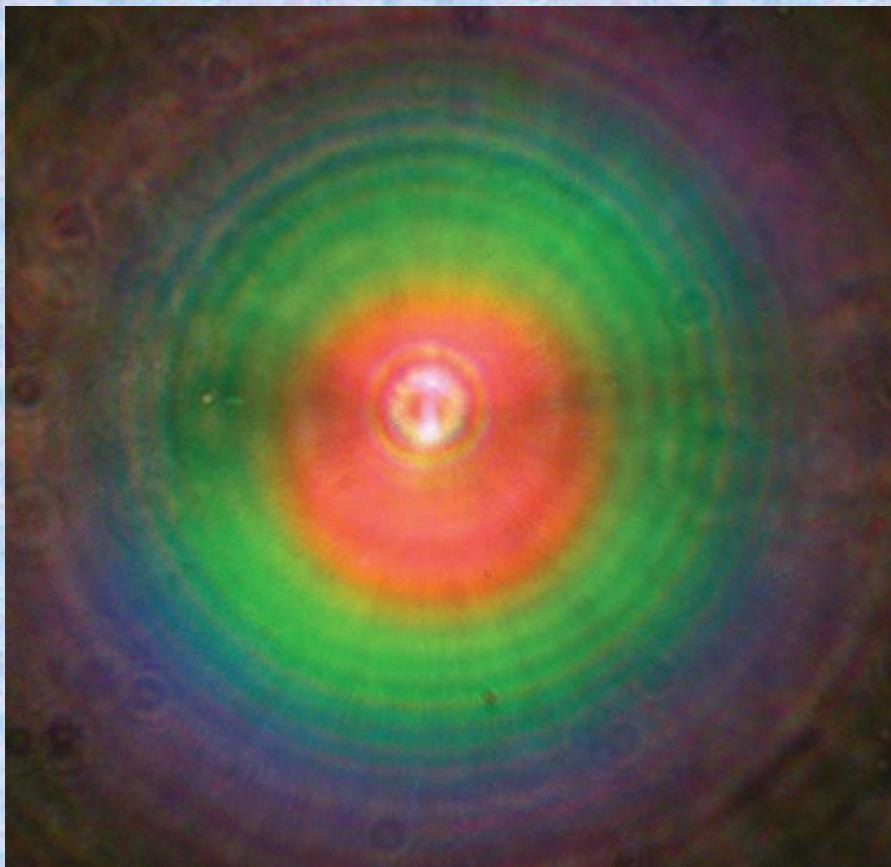
<i>Lens focal length @632 nm</i>	
Theoretical (mm)	Measured (mm) (±0.01mm)
0.55	0.61
1.5	1.62
5	5.13

Efficiency for lenses fabricated without depth compensation: 10%

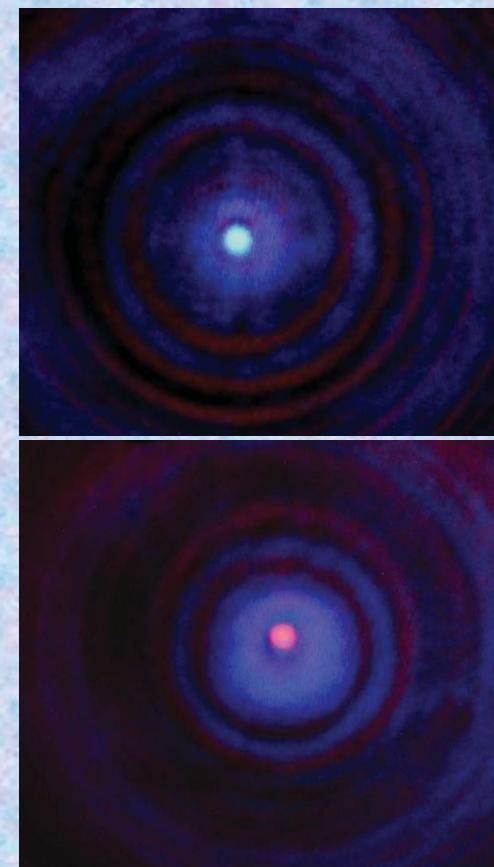
Efficiency for lenses fabricated with depth compensation: 30%
(Theoretical efficiency: 40 %)

Chromatic dispersion

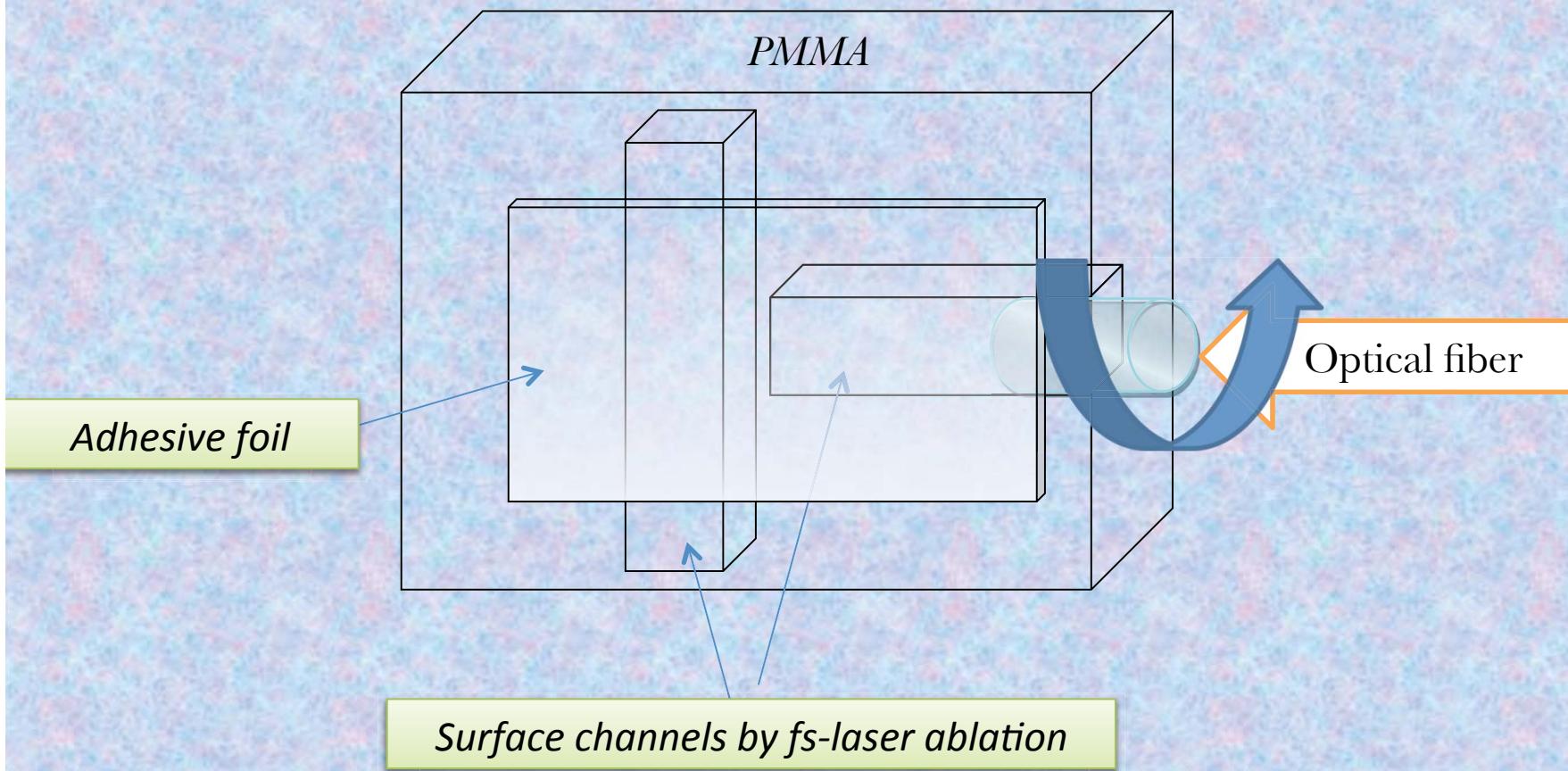
WHITE LIGHT
ILLUMINATION



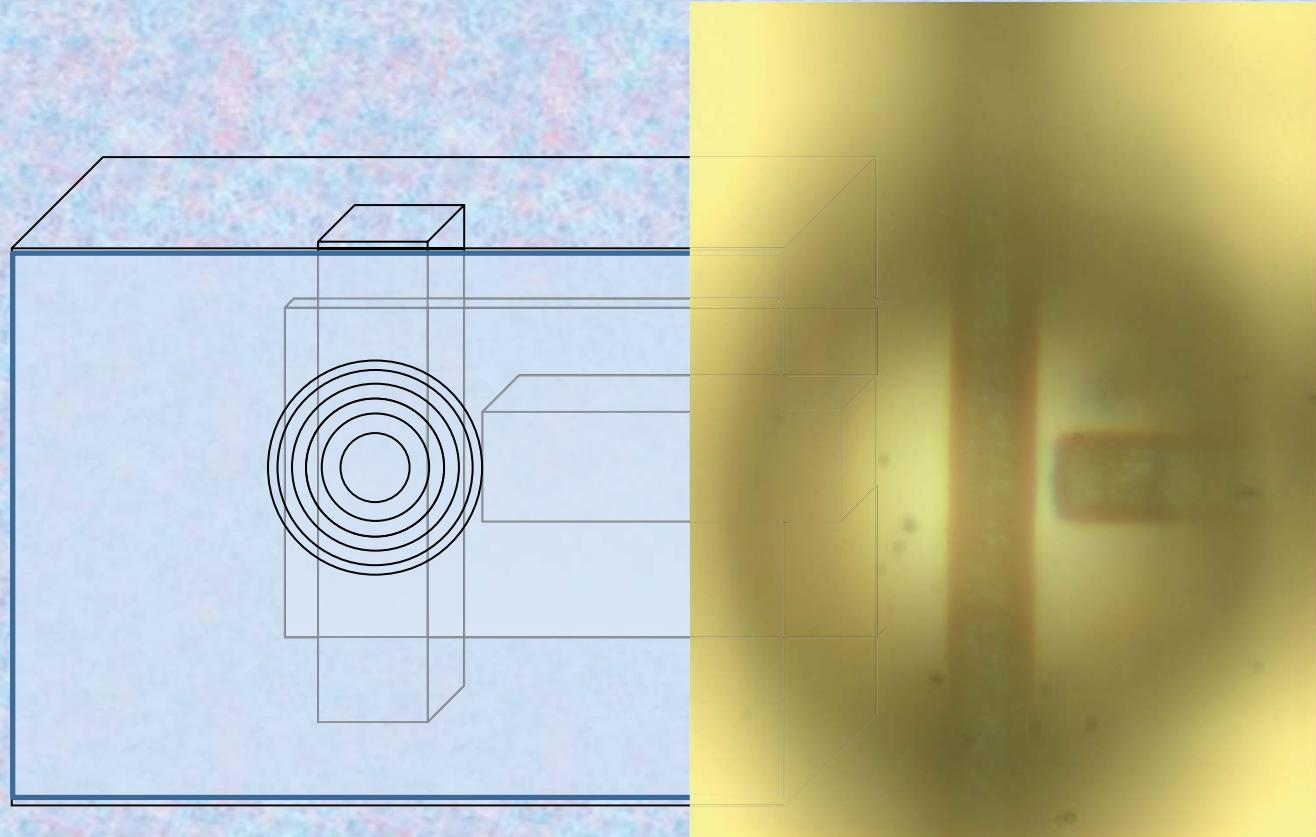
BLUE & RED LIGHT
ILLUMINATION



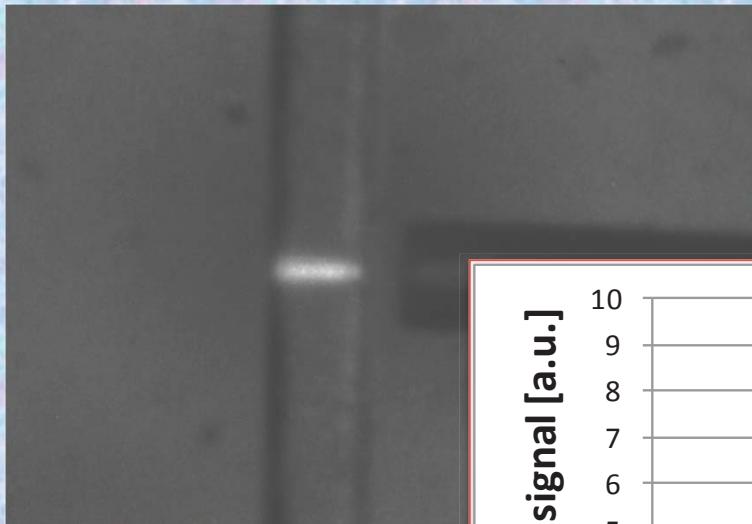
Optofluidic chip fabrication



Optofluidic chip fabrication

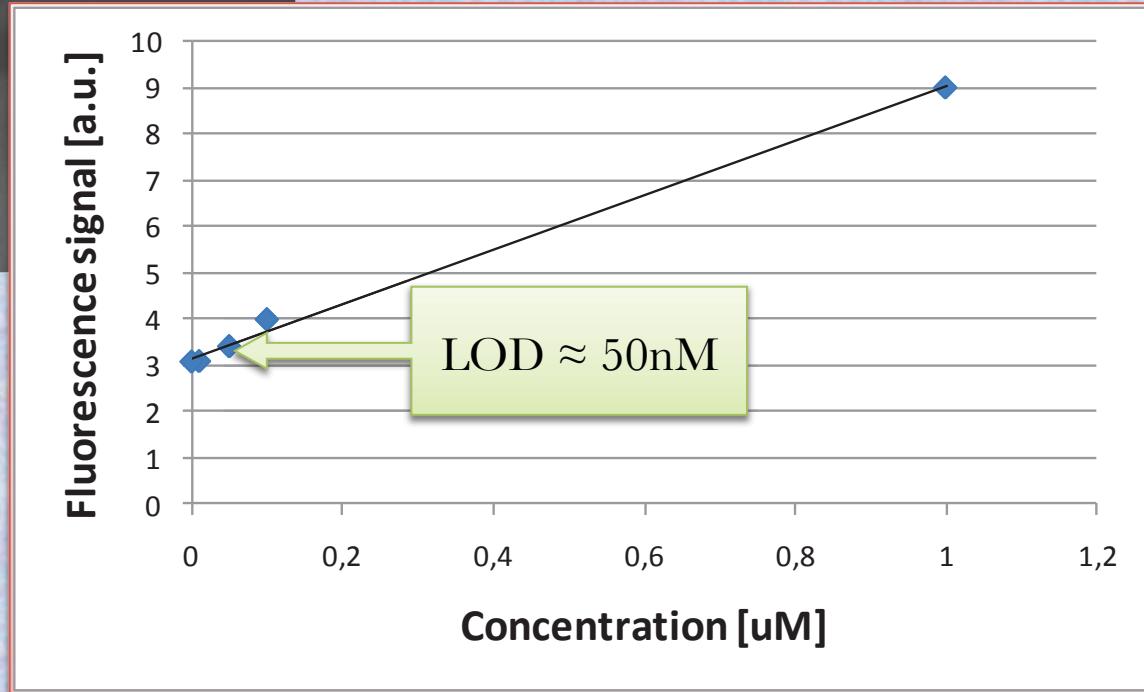


On-chip fluorescence detection



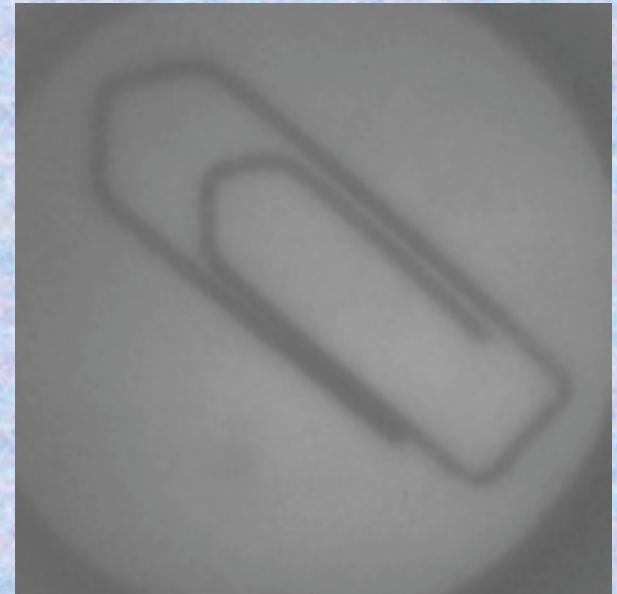
Rhodamine 6G solution

Green laser excitation



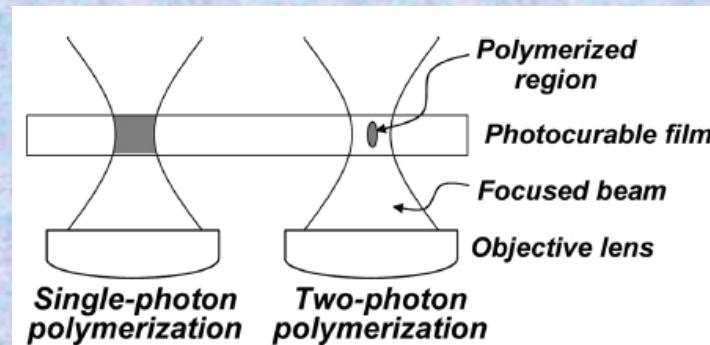
Conclusions

- fs laser ablation effective tool for fabrication of microchannels and optical diffractive elements in polymers
- Demonstration of lenses with high NA and low focal lengths
- Focusing efficiency near the theoretical value
- First experiments of integrated detection in polymer Lab on Chips



TWO-PHOTON POLYMERIZATION

Femtosecond laser pulses are focused inside a UV photosensitive resin. Near-IR laser beams undergo two-photon absorption

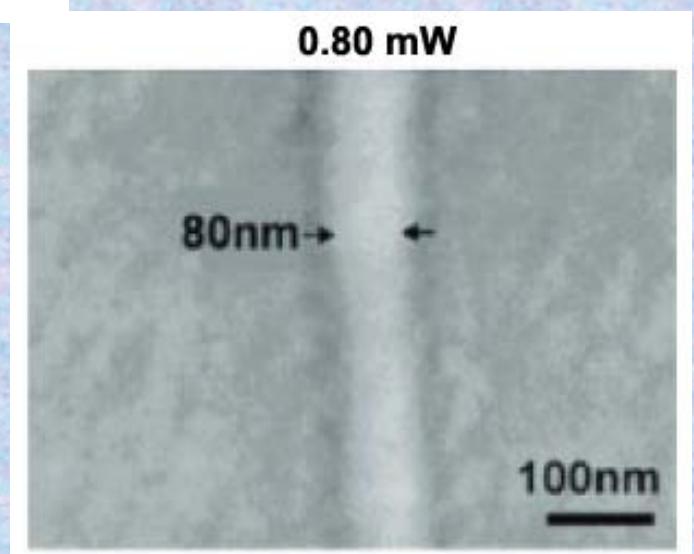


Two-photon absorption:

- Absorption is proportional to the square of the intensity
- It's a process with a threshold

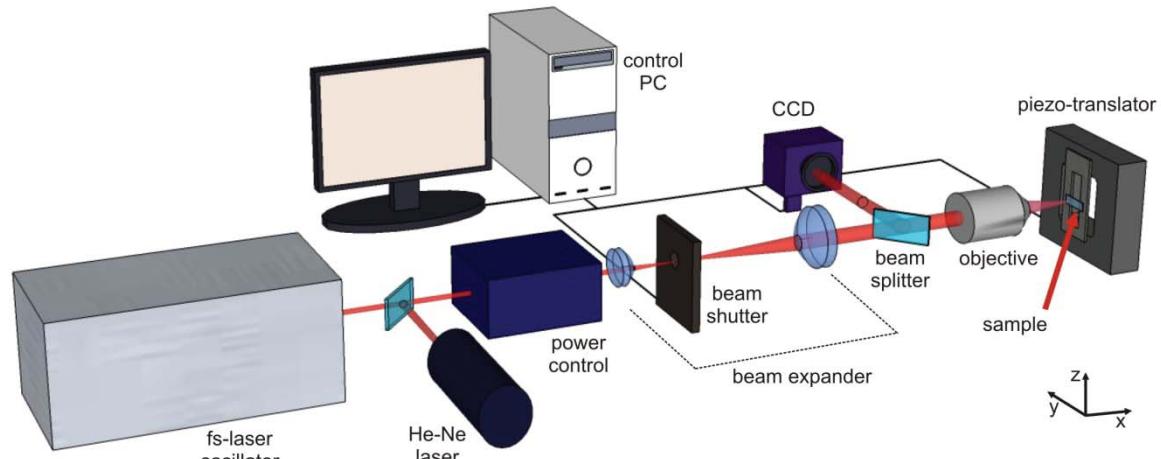


Resolution well-below the diffraction limit

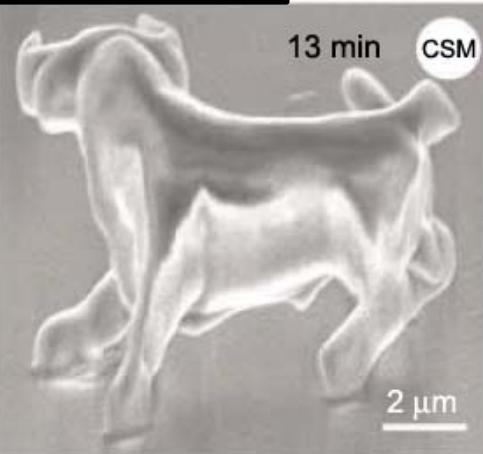
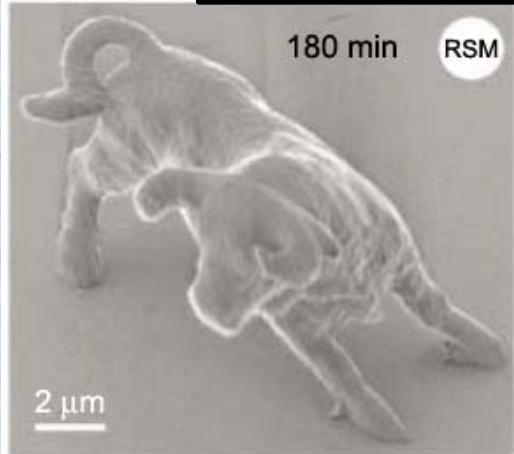


TWO-PHOTON POLYMERIZATION

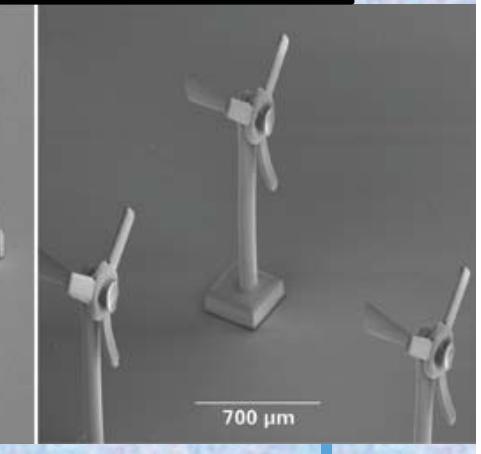
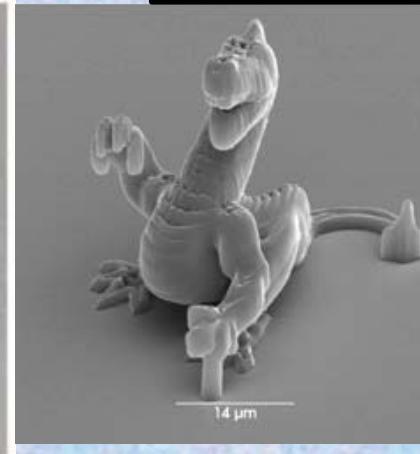
a)



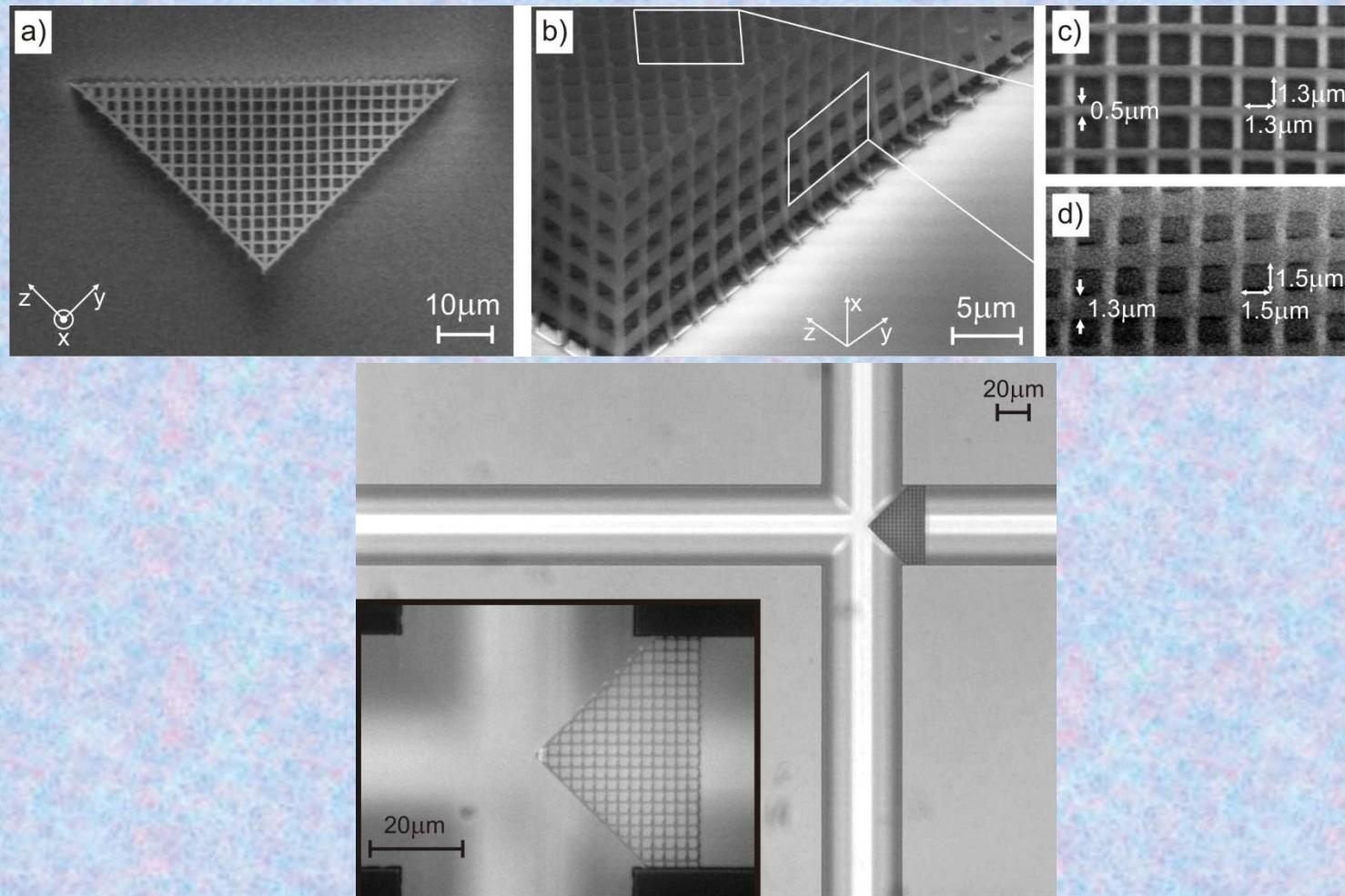
Kawata et al. *Nature* **412**, 697 (2001)



Laser Zentrum Hannover

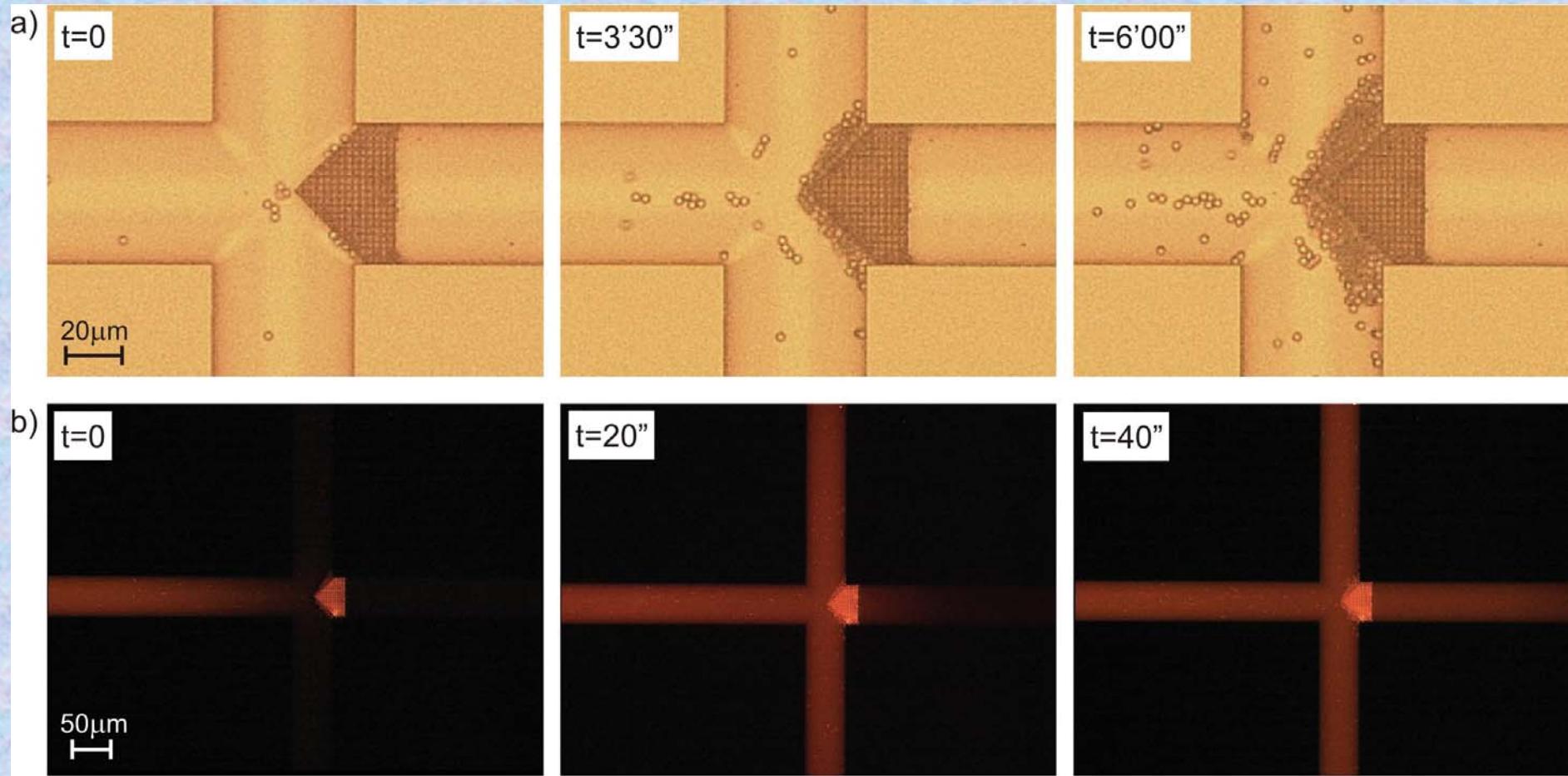


FILTERS IN MICROCHANNELS



L. Amato et al., Lab Chip, (2011)

FILTERS IN MICROCHANNELS



FILTERS IN MICROCHANNELS

Cleaning of the filter

