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Recent applications of fibers for optical sensors and particles manipulation in lab-on chip systems

C. Sada

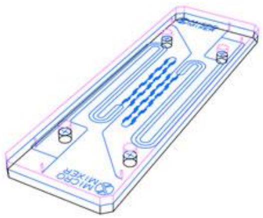
A. Zaltron, G. Bettella, G. Pozza, R. Zamboni

Lab on a chip

Optofluidics

Microscope

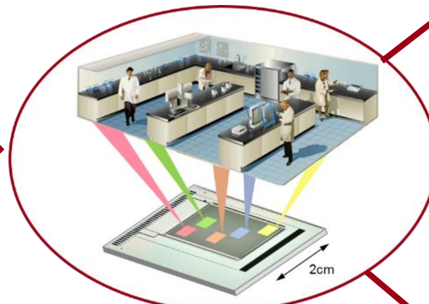
Fast Camera



Microfluidic chip

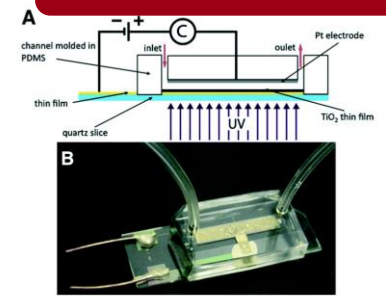
Syringe Pumps

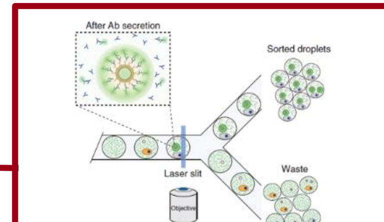
Lack of integration



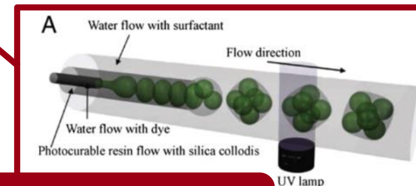
Lab-on-a-Chip

Chemical synthesis





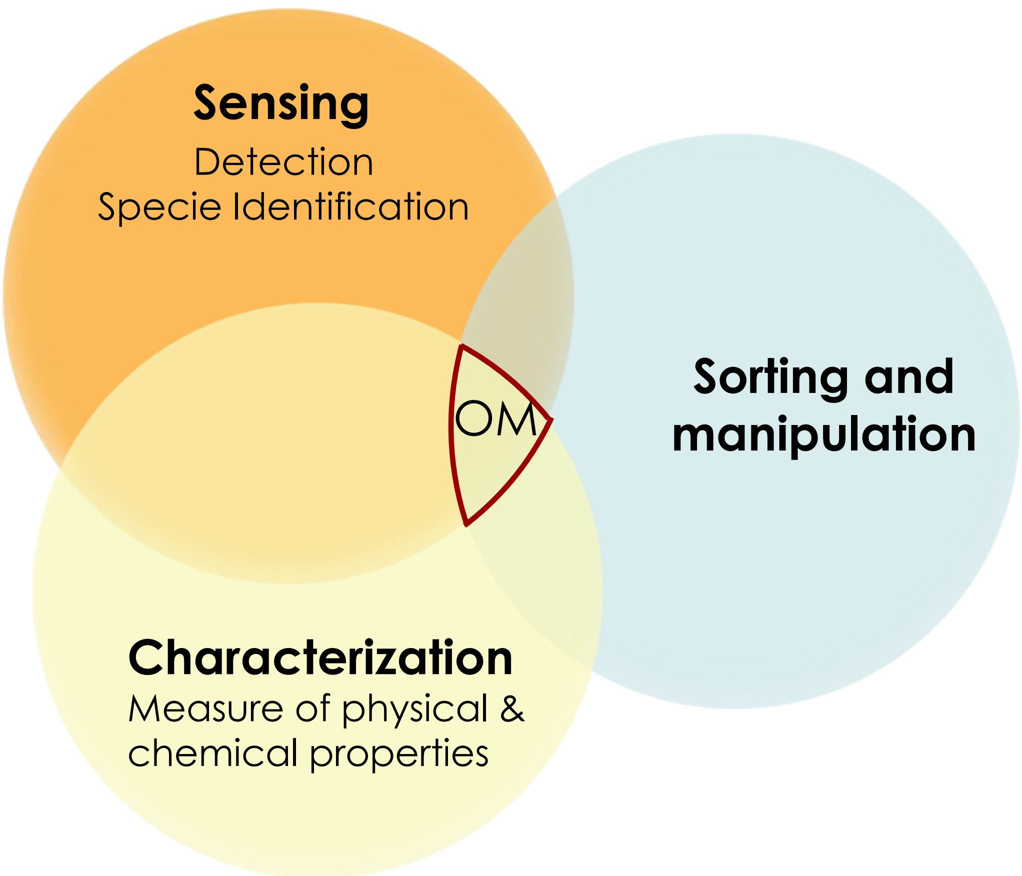
Cells Manipulation



Drug delivery

Lab on a chip

“*Frame*” of reference



OM:Opto-microfluidics

- Small efficient device
- Multifuctional
- Portable
- Low cost

Opto-Microfluidics Integration

Microfluids circuit

- Laser ablation
- Laser irradiation+ chemical etching
- Casting
- Molding

Substrates

- Glass/silica
- Silicon + ..
- PDMS, PPMA, …
- Hybrids

Optical circuit

- Laser irradiation
- Local doping
- Incorporation/Bonding
- **Fibers coupling**

External Coupling& Detection **(Fibers)**

Issue: optimisation of the coupling between optical and microfluidics stages on the same substrate

Outline

Fibers always needed for :

- Waveguiding;
- Guaranteeing portability and flexibility of the device;
- Laser sources coupling.

Outline of this talk:

- Examples of **fibers applications** (coupling and beyond coupling);
- Limits of current results;
- What is needed next.

Absorption Analysis

Outline 6

- Introduction
- Fibers for coupling
- Fibers beyond coupling
- Optical sensing
- Conclusions

Fiber coupling

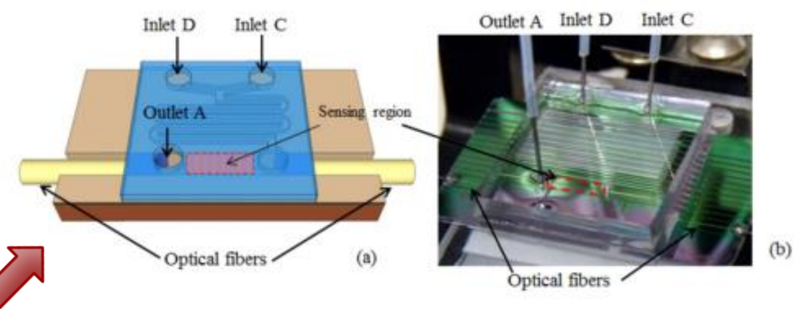
A hybrid silicon-PDMS optofluidic platform for sensing applications

Genni Testa,[1,*] Gianluca Persichetti,[1] Pasqualina M. Sarro,[2] and Romeo Bernini[1]

[1] *Institute for Electromagnetic Sensing of the Environment (IREA), National Research Council, (CNR), Via Diocleziano 328, 80124 Napoli, Italy*

[2] *DIMES-ECTM, Delft University of Technology, Feldmannweg 17, 2628 CT Delft, The Netherlands*

[*] *testa.g@irea.cnr.it*



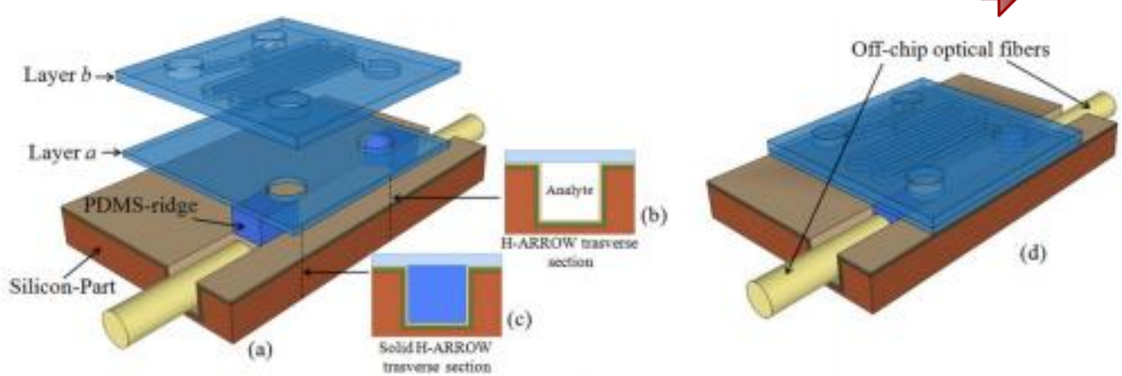
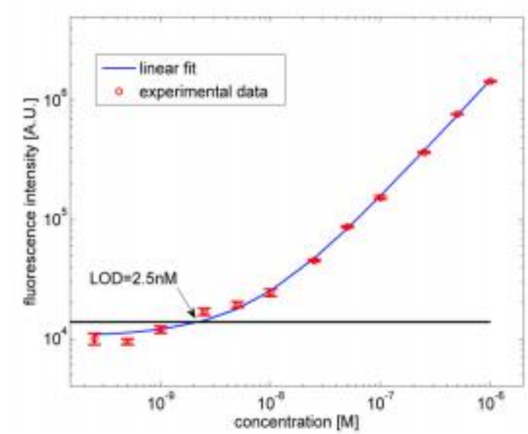


Fig. 1. (a) Exploded view drawing of the proposed hybrid ARROW optofluidic platform with transverse section of (b) liquid h-ARROW and (c) solid h-ARROW. (d) Schematic of the assembled device.

Fluorescence of Cy5 in H_2O

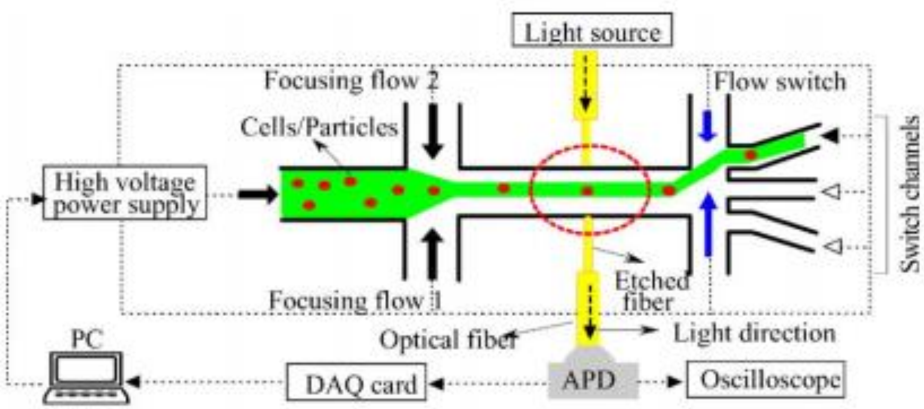


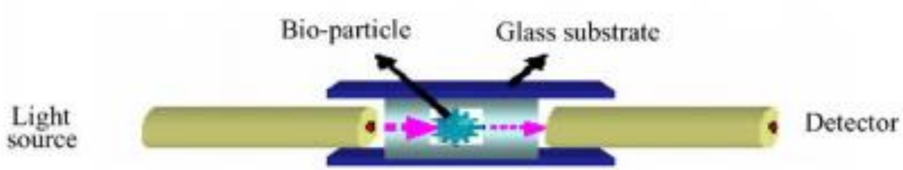
*Biomedical Optics Express vol.14 n.2, 417, 2014

Particle sorting

Flow cytometer: an integrated device

L.-M. Fu et al. / Analytica Chimica Acta 507 (2004) 163–169





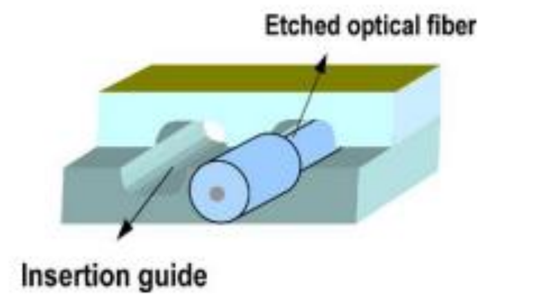
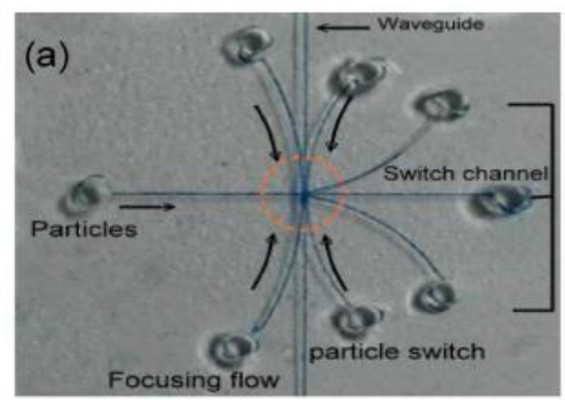


Fig. 3. Schematic of "insertion guide" for etched optical fibers.

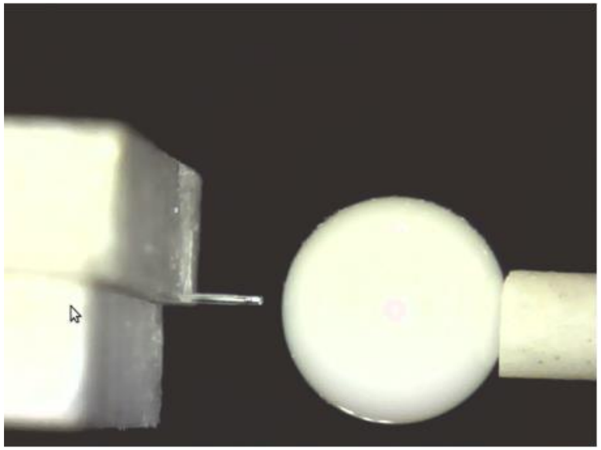


Fiber shaping: feasibility

Fiber Cavity

Alternative techniques to shape a fiber tip with concave curvature

Fiber shaped on a sphere at 1200 – 1600∘C

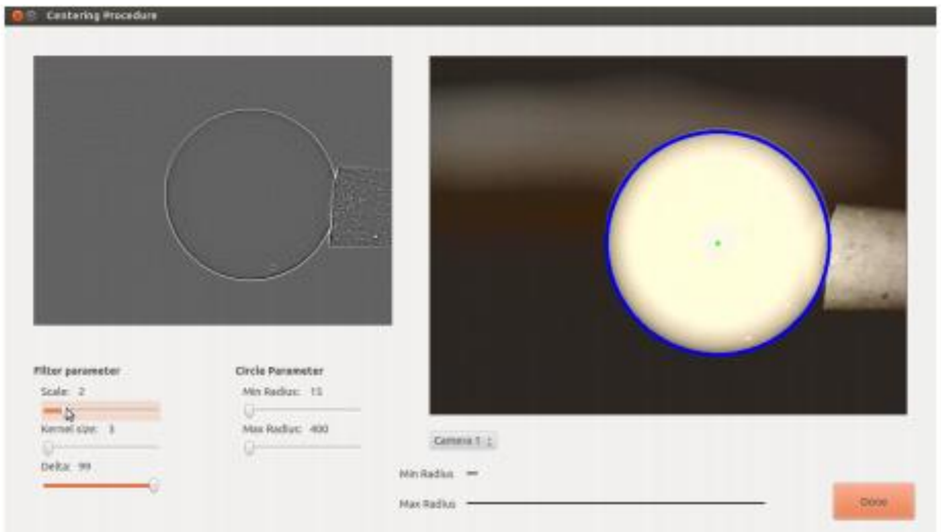


Produce really concave spherical tips
with a larger useful diameter
(and so more stable cavities)

*Work in collaboration with Tracy Northup @ UIBK - Austria

Fiber shaping: feasibility

Fiber made Cavity:



*Dario Fioretto @ UIBK - Austria

Process optimization

When cavity are used sensitivity increases of at least 2 orders of magnitude

Particle manipulation

An integrated optofluidic device for single-cell sorting driven by mechanical properties†

T. Yang,‡[a] P. Paiè,‡[bc] G. Nava,[a] F. Bragheri,[c] R. Martinez Vazquez,[c] P. Minzioni,*[a] M. Veglione,[d] M. Di Tano,[d] C. Mondello,[d] R. Osellame[bc] and I. Cristiani[a]

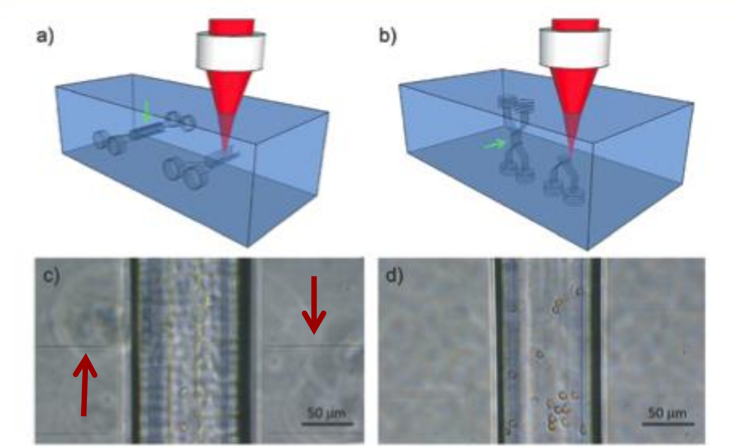
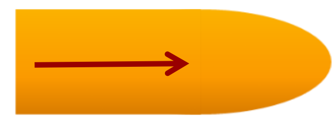


Fig. 1 Schematic rendering of the double-Y-shaped microfluidic circuit irradiation patterns and phase-contrast microscopy images of swollen red blood cells in the microchannels fabricated with the two geometries: (a, c) transverse and (b, d) longitudinal writing geometries.

*Lab Chip vol.15 1262 (2015)

Fibers to couple light in/out the device

SUITABLE SHAPE



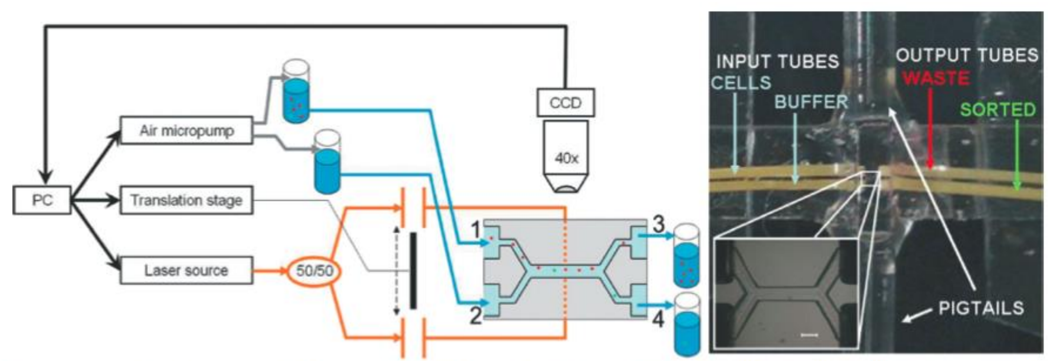


Fig. 2 Left: schematic representation of the experimental setup used to validate our novel optofluidic microchip. Cell stretching and sorting are based on the optical forces exerted by the same waveguides, which are connected with a fiber-to-fiber U-bench to realize the automatic sorting. Right: picture of the optofluidic chip connected to external capillaries and fiber pigtails. The locally enlarged image shows the inside structure of the microchannel network (scale bar, 100 µm).

Beyond light coupling?

Fibers as a tool for sensing and manipulation of particle

Exploitation of the **evanescent** field at the core-cladding interface

➡ Electric field can induce dielectrophoresis / electrophoresis

➡ Surface plasmon resonance (SPR)

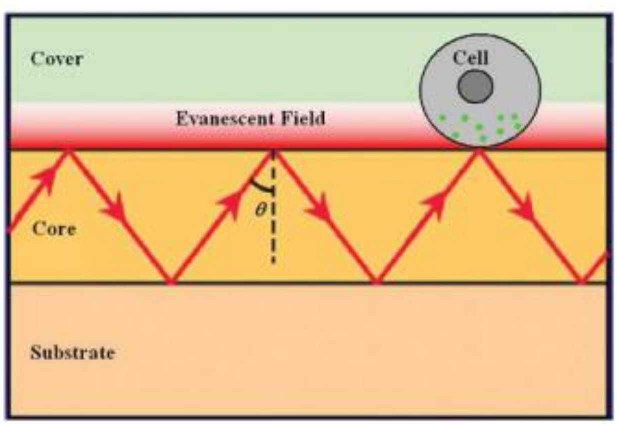
Modification of the **tip shape** to improve/tailor the fiber output

- Tapering
- Rounding
- faceting

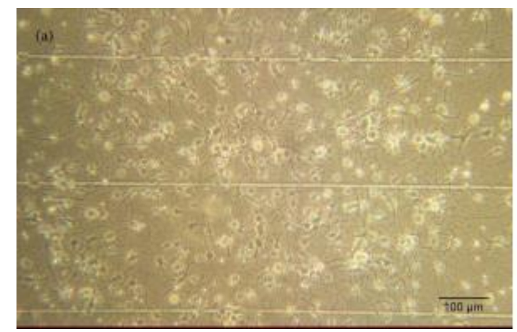
Evanescent fields (EF)

Evanescent-Field Excitation of Fluophores in Cultured Neural Networks by Integrated Polymer Waveguides

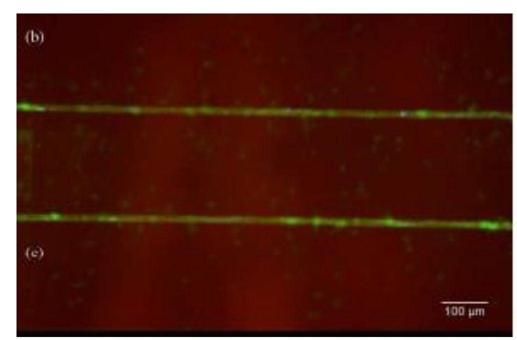
R. Adam Seger, *Student Member, IEEE*, Dominik G. Rabus, *Senior Member, IEEE*, Yasuhisa Ichihashi, Mathias Bruendel, and Michael S. Isaacson, *Member, IEEE*



Neural cells

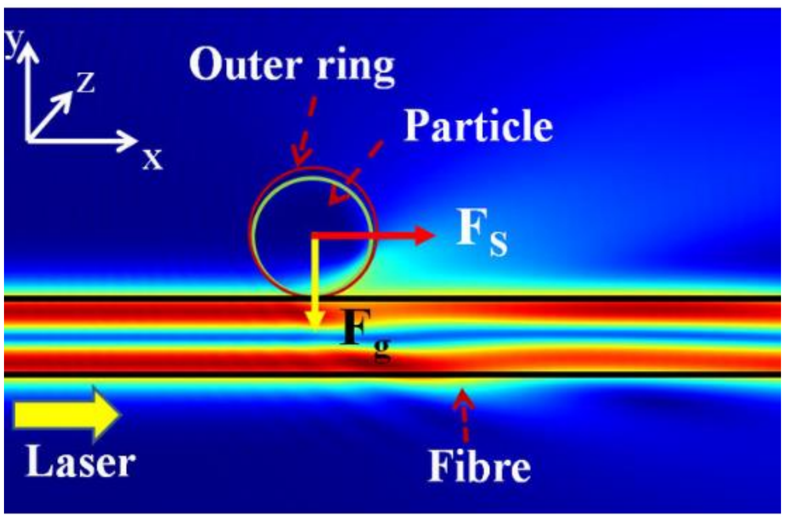


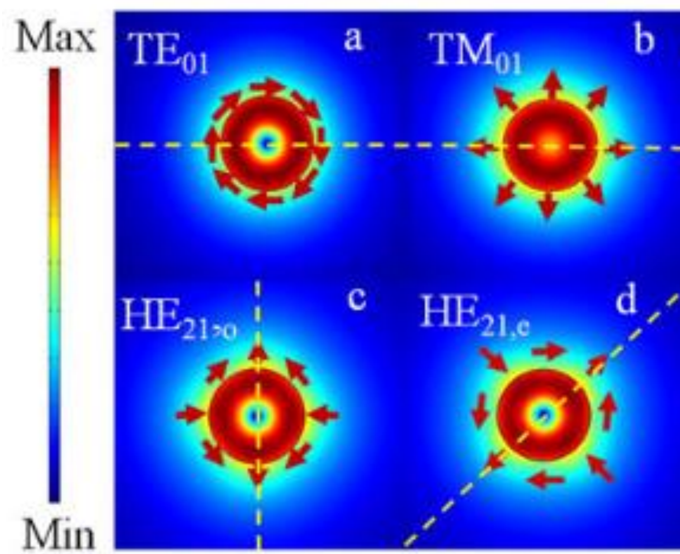
Evanescent field excitation



EF: Fibers as driver

Higher order microfibre modes for dielectric particle trapping and propulsion





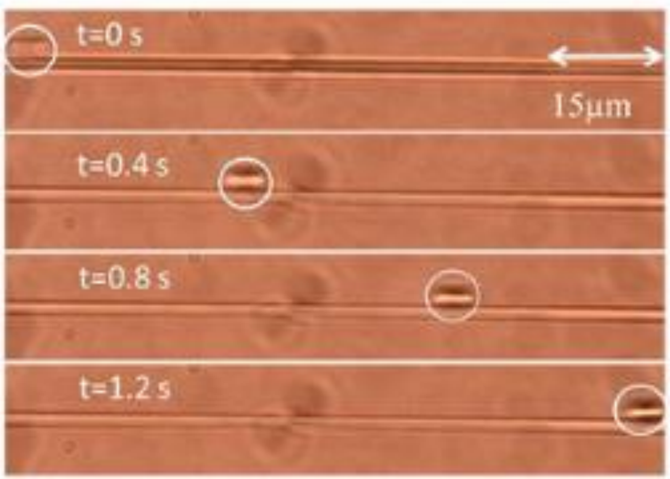
*Aili Maimaiti et al Scientific Reports 5, n. 9077 (2015)

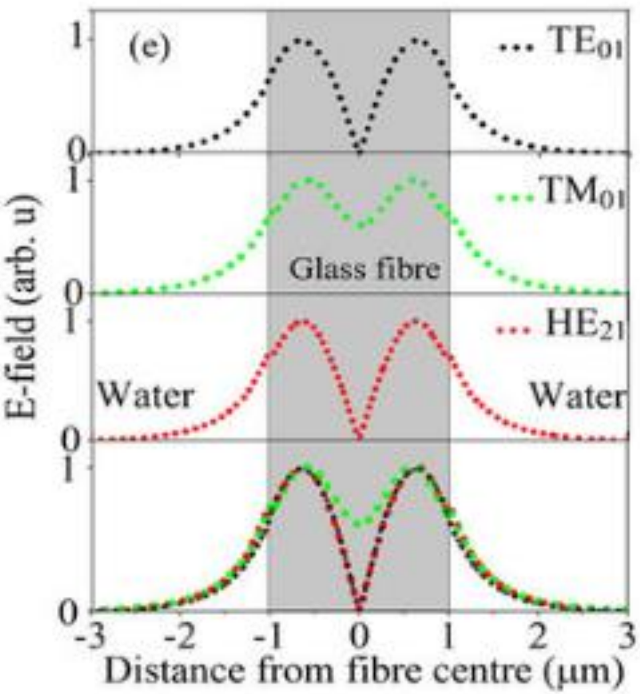
Fiber for particle propulsion

Particle Propulsion

Evanescent field drives charged and polarised particles

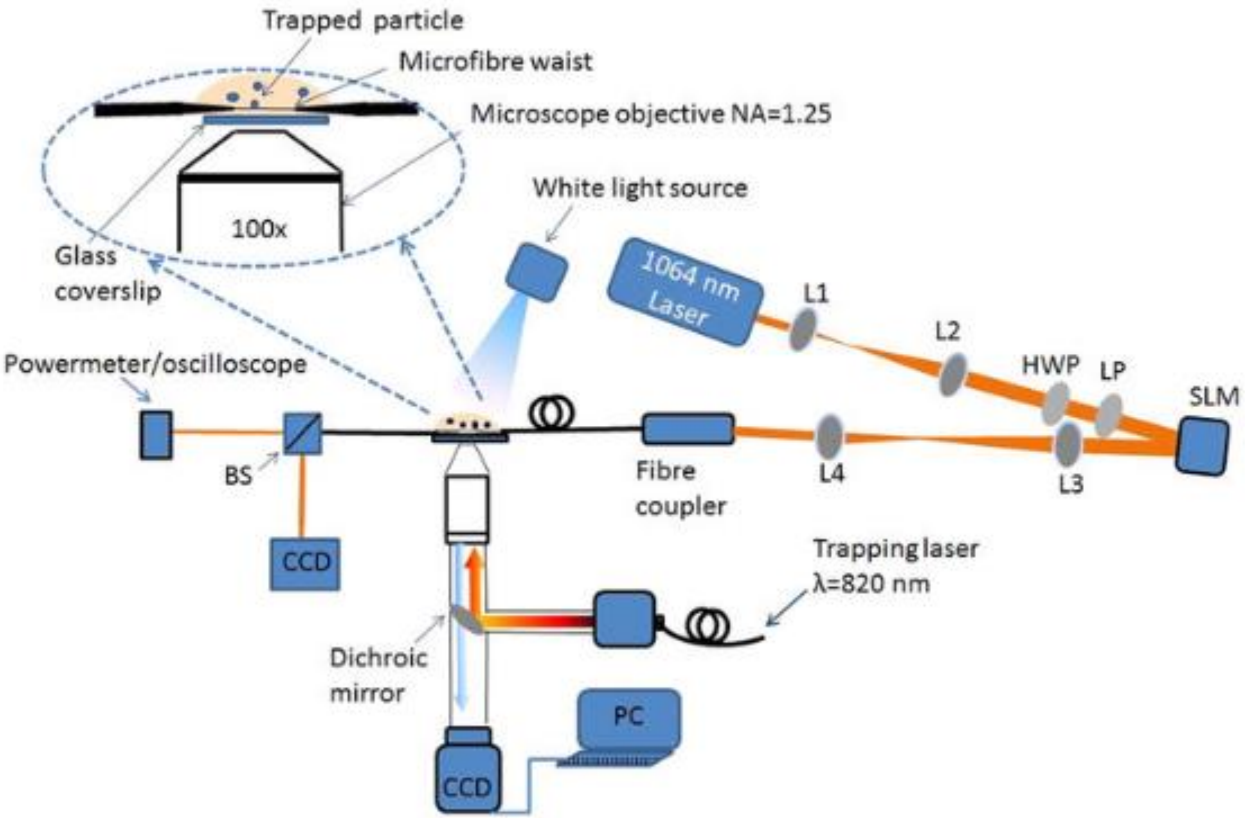
Example 3 μm polystyrene particles





*Aili Maimaiti et al Scientific Reports 5, n. 9077 (2015)

Fiber for particle propulsion



Need of integration:

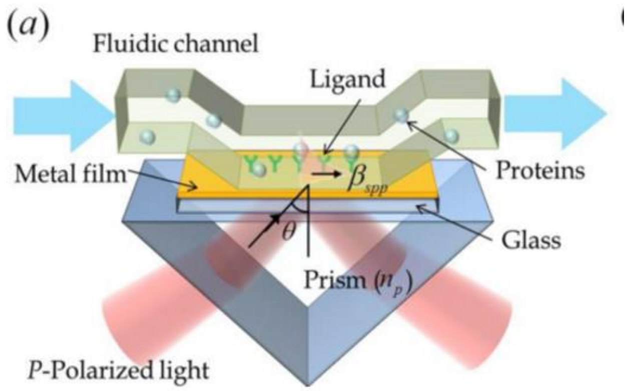
High power Fiber laser?
Fiber detection?

Table 1 | Hydrodynamic velocities of single 3 μm polystyrene beads. Speed of particles is calculated using different correction factors for the LP_{01} and LP_{11} microfibre modes. The power at the fibre waist regions P_{waist} was fixed at 25 mW

Modes	Particle radius a (μm)	Distance from particle centre to fibre surface, h (μm)	Scattering force F_s (pN)	Correction	Velocity (μm/s)
LP_{01}	1.5	1.52	0.75	Stokes	29.0
		1.52	0.75	Krishnan	8.9
		1.56	0.67	Faxen	9.6
				Experiment	8.5
LP_{11}	1.5	1.52	4.15	Stokes	160.5
		1.52	4.15	Krishnan	49.2
		1.56	3.90	Faxen	56.0
				Experiment	72.5

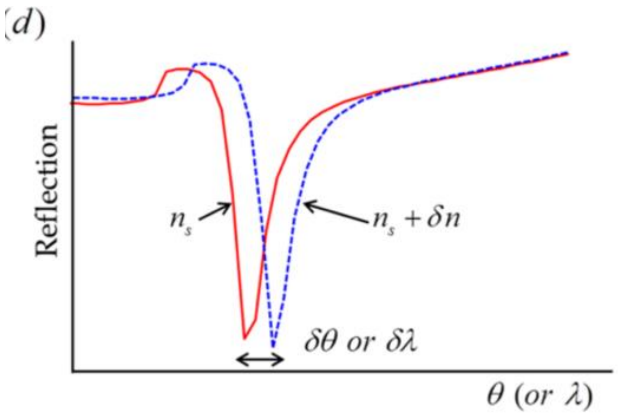
EF: tool for sensing

Surface Plasmon resonance as a sensing method



Kretschmann configuration based coupling

- **Angle scanning** ($5 \cdot 10^{-7}$ RIU – 500 deg/RIU^{-1})
- Wavelength scanning (30000 nm/RIU^{-1})
- Often **gratings are implemented**

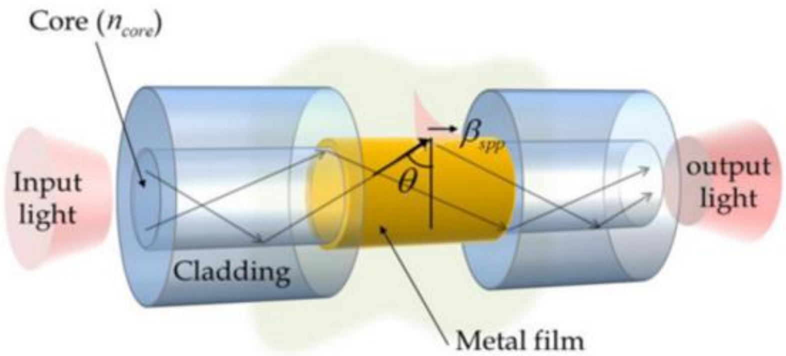


The measure of the **reflectance** carries infos on:

- Refractive index of the fluid
- Concentration of components
- In same cases particle identification

LOD close to pM

EF: fibers for sensing



$$\frac{2\pi}{\lambda} n_p \sin\theta = \beta_{ev} = \mathrm{Re}\left(\beta_{spp}\right);$$

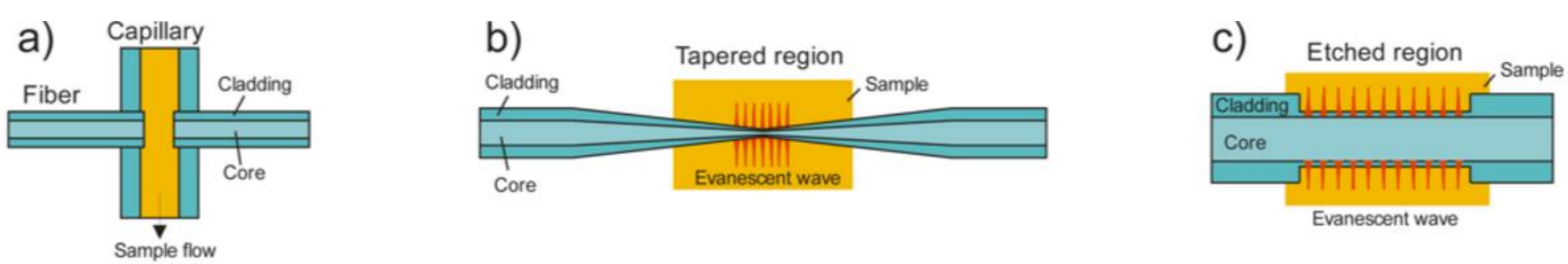
$$\beta_{spp0} + \Delta\beta,\ \beta_{spp0} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m n_s^2}{\varepsilon_m + n_s^2}};$$

Fiber core deposited with metal
mimes Kretschmann configuration based coupling

S= 4000 nm/RIU^{-1}

Problems in angle scanning
Wide range of configurations

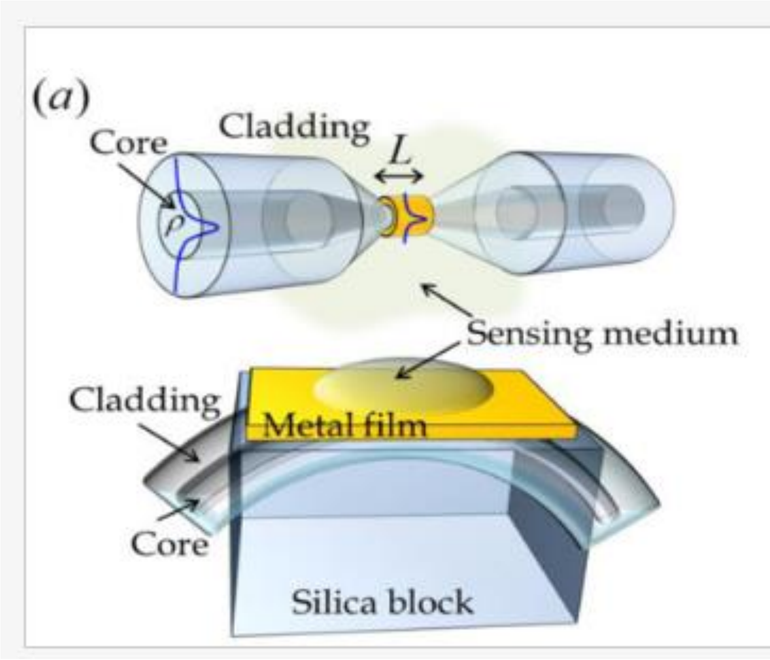
In grating coupling S close to 200-600 deg/RIU^{-1} at 950nm (λ=350nm)



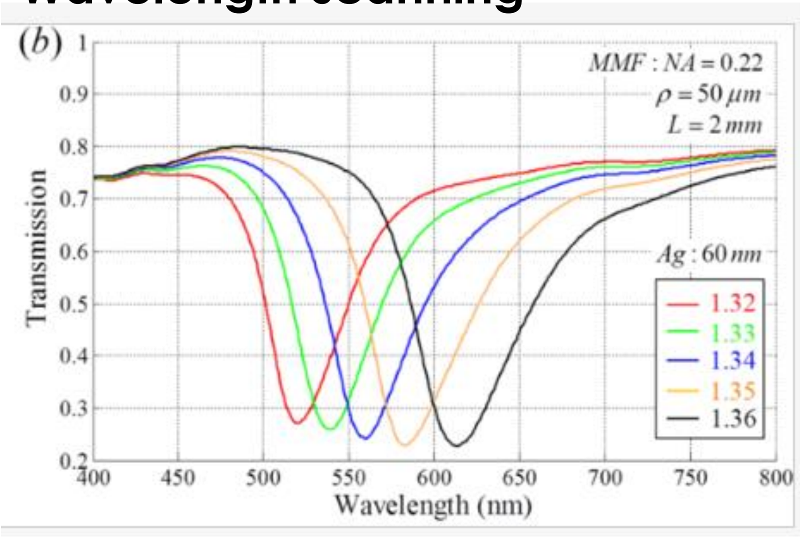
*Sensors 2010, 10(3), 1716-1742

EF: fibers for sensing

Micro- and Nano-Structured Surface Plasmon Resonance Sensors



Wavelength scanning

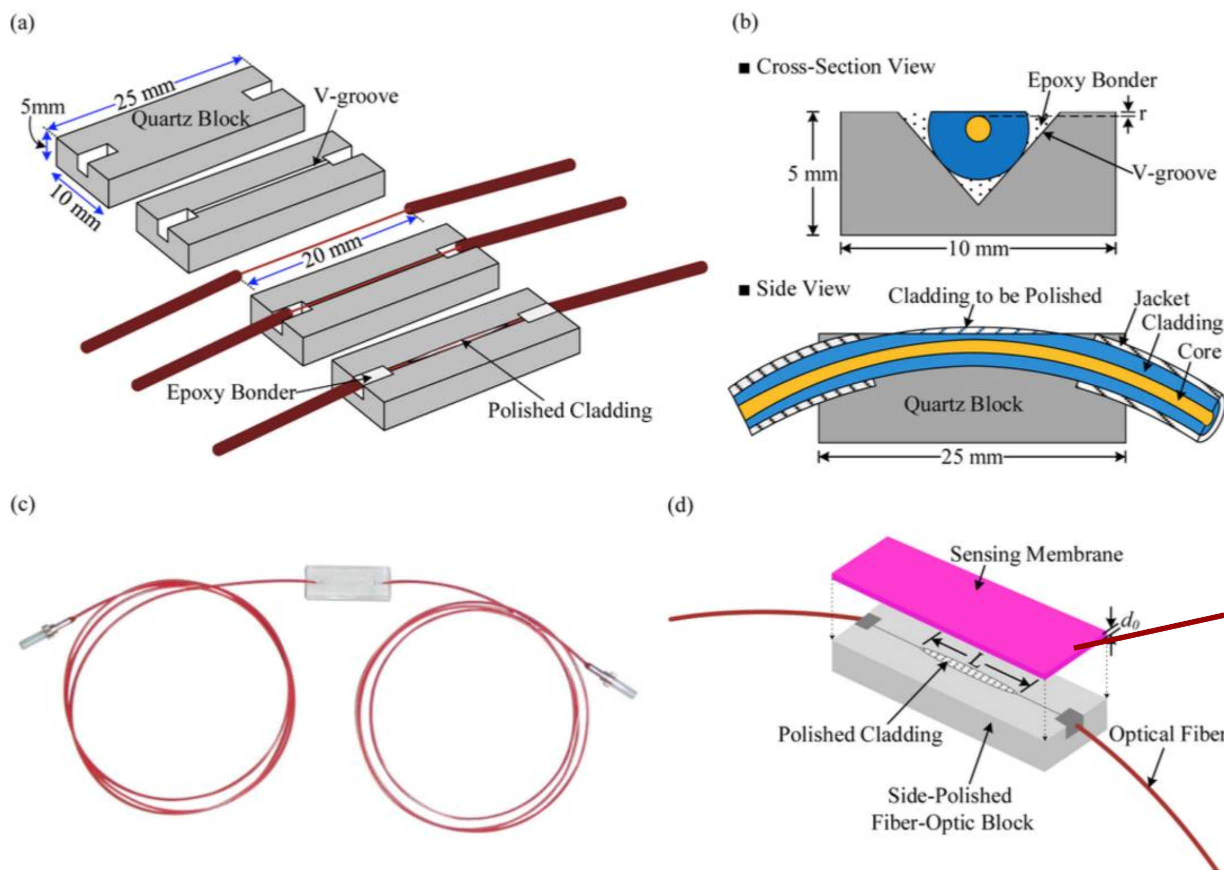


Sookyoung Roh et al.
Sensors 2011, 11(2), 1565-1588

Refractive index resolution
9.9×10^{-4} at n=1.410
4.2×10^{-4} at n=1.440

Fibers for sensing VOC gas

A High Sensitivity and Wide Dynamic Range Fiber-Optic Sensor for Low-Concentration VOC Gas Detection

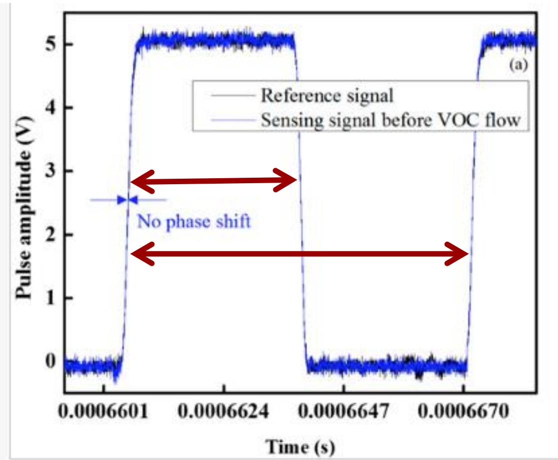


Sensors 2014
14(12) p.23321-23336

$$d_p = \frac{\lambda}{2\pi n_1}\left\{ sin^2\theta - \left(\frac{n_2}{n_1}\right)^2 \right\}^{-0.5}$$

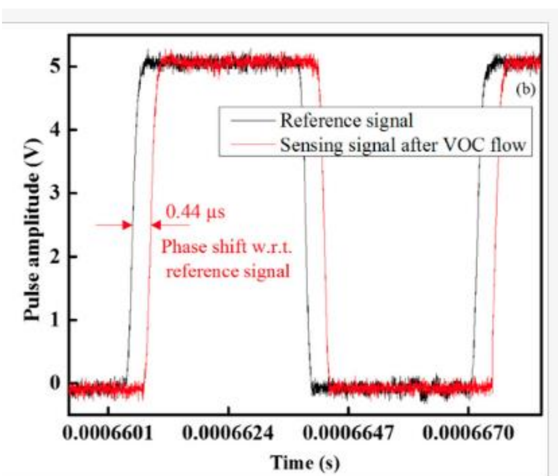
$$P_L = P_0 \exp\left(-\gamma C L\right)$$

Fibers for sensing VOC gas



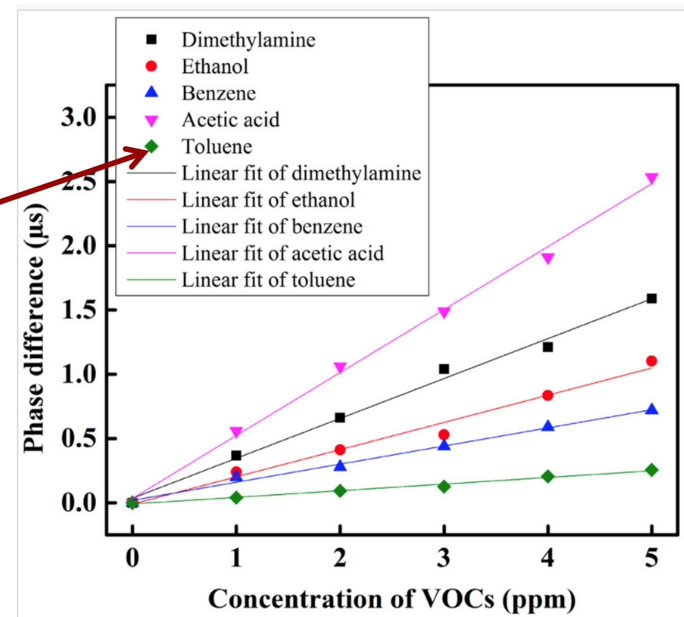
Pulsed Width modulation technique

Volatile organic compounds (VOCs) are common air pollutants: ppm detection sensitivity



$$d_p = \frac{\lambda}{2\pi n_1}\left\{ sin^2\theta - \left(\frac{n_2}{n_1}\right)^2 \right\}^{-0.5}$$

$$\phi = \frac{2\pi n}{\lambda\gamma C}\left(\frac{T}{T_H}\right)^2$$



Focus: opto-fluidics for sensing

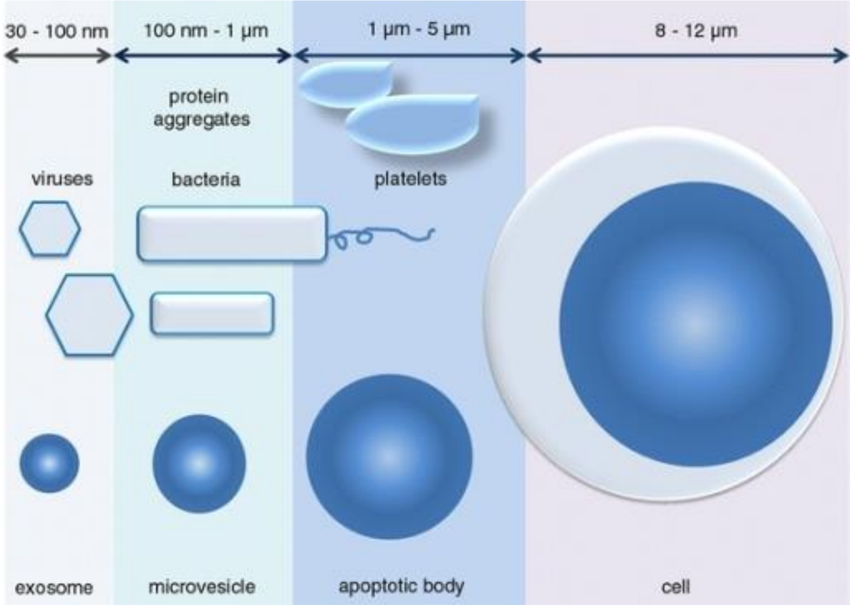
ISSUE: Target counting and identification

Working principle

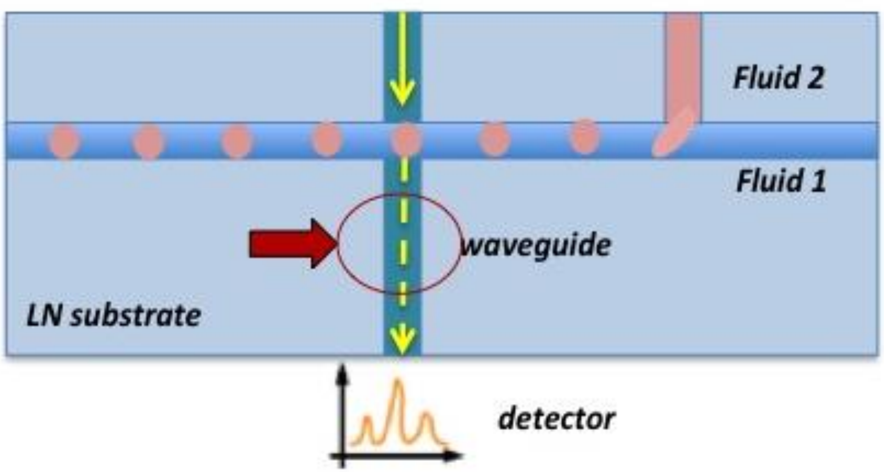
- Target Quantification
- Size measurement
- Sorting

Key parameters

- High sensitivity
- Size domain < 12 μm
- Complementary to other techniques



Integrated Opto-microfluidic prototype



- Droplets generator: controlled diluition
- Droplets counter and analysis

Applications to:

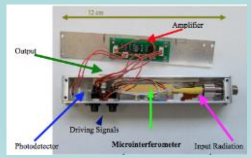
- Targets counting
- Target dimension
- Target identification

"Integrated opto-microfluidics platforms in lithium niobate crystals for sensing applications"
G. Bettella ; G. Pozza ; A. Zaltron ; C. Sada ; M. Chauvet et al. Submitted to LabOnChip 2015

Why not using $LiNbO_3$?

Electro-optic

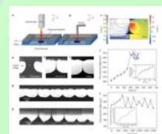
EO modulators
(MZ interferometers)
EO lenses



Transparent
≈330÷3450 nm

Optical waveguides

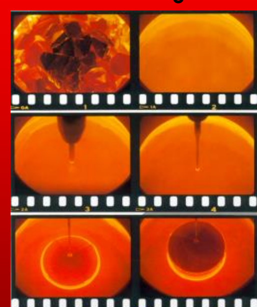
Pyroelectric



*P.Ferraro Group

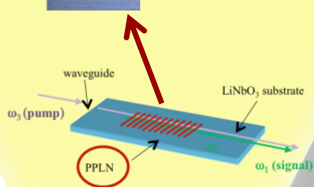
Particle trapping,
nano-droplet
dispensing ….

$LiNbO_3$

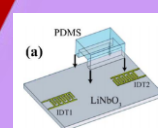


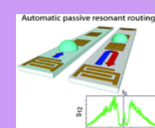
Ferroelectric

Periodically
Poled LN
For SHG



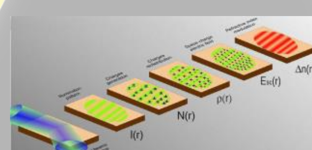
Piezoelectric





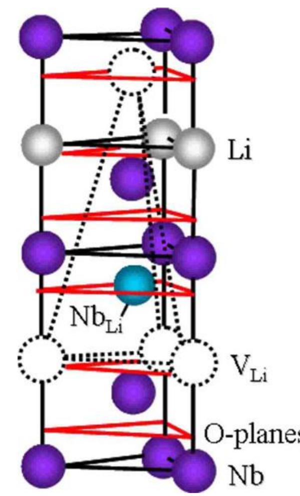
*S.Girardo et al. *M.Travagliati et al.
Microfluidics Pump by Surface Acoustic Waves

Photorefractive



Holographic recording
Bragg filters
Particle trapping

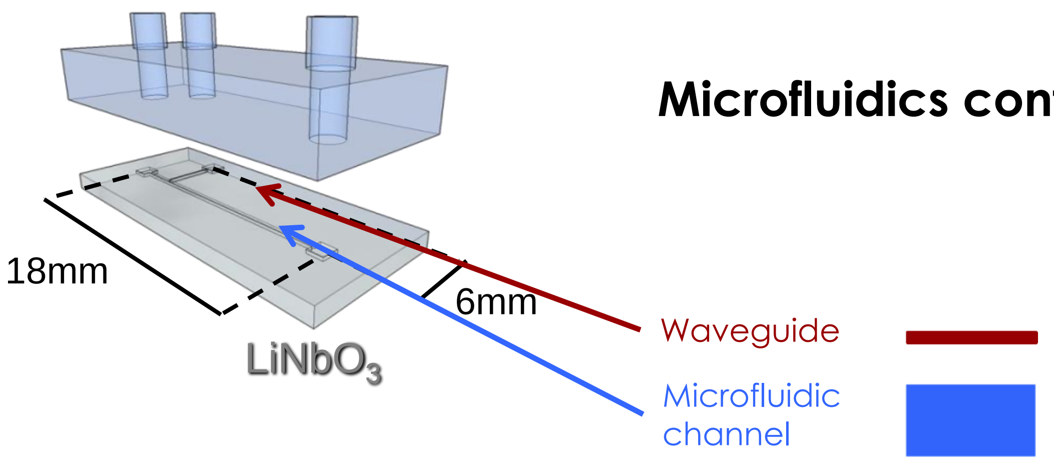
$LiNbO_3$



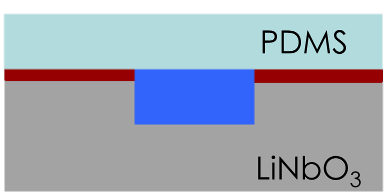
Local and bulk doping

Opto-microfluidic prototype

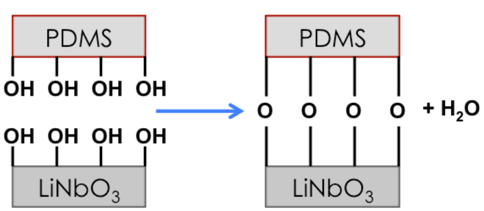
Sealing

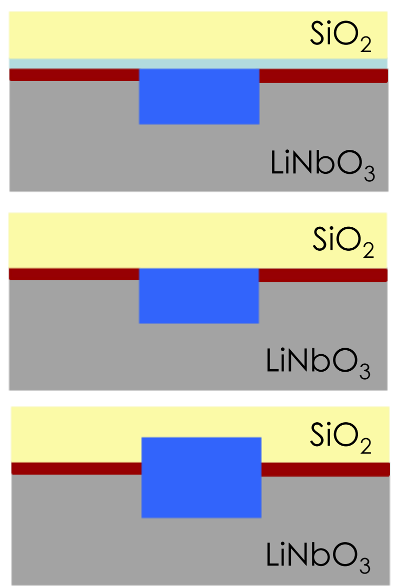


Microfluidics configurations

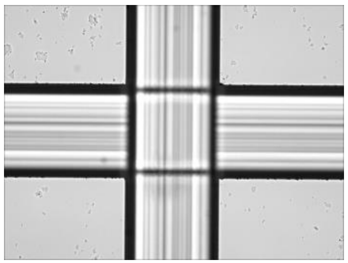


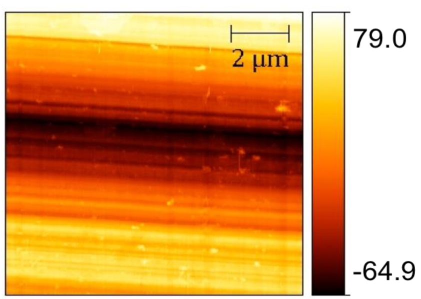
Sealing with a PDMS layer: O_2-plasma





DICING @ FEMTO-ST *prof. M. Chauvet*





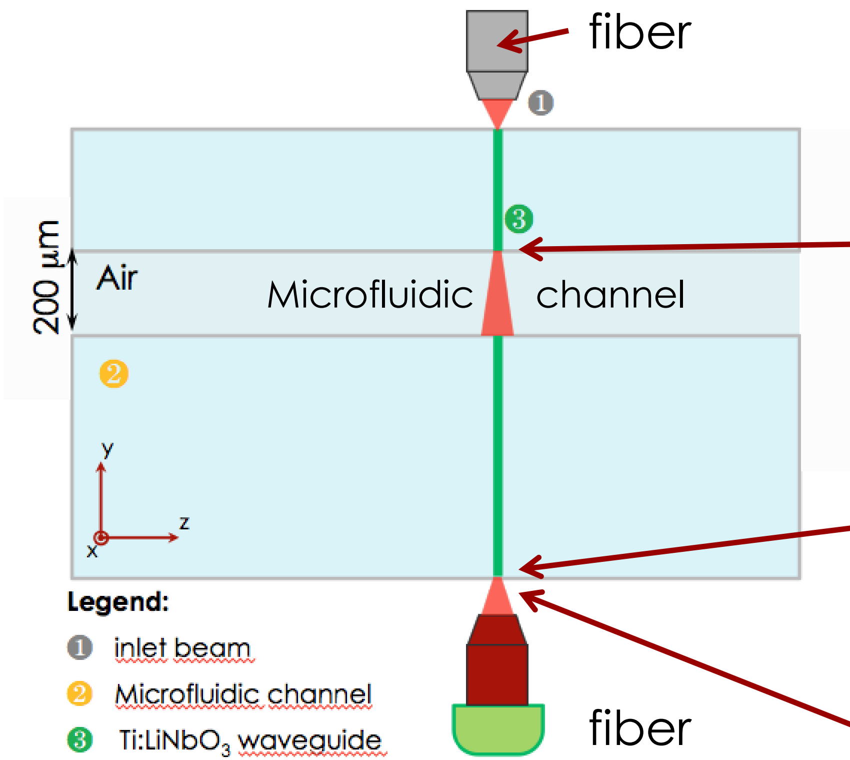
Average roughness

Bottom $R_a = (19 \pm 3)$ nm

Lateral walls $R_a = (7 \pm 1)$ nm

Optical Coupling

Integrated waveguide: Ti-indiffusion in LN

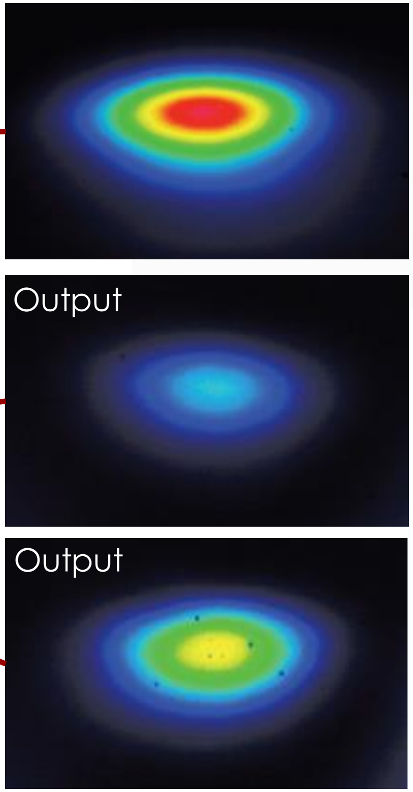


Legend:

1. inlet beam
2. Microfluidic channel
3. Ti:$LiNbO_3$ waveguide
4. CCD camera NF images

$$DT = \frac{T_L}{T_0} = \frac{2n_{LN}n_L}{n_{LN}^2 + n_L^2}\,\frac{2W_{GB}W_{gap}}{W_{GB}^2 + W_{gap}^2}\Big/ T_0$$

Near field



Input WG's exit

I/I_0 = REF 100%

Air in the channel

I/I_0 = 38%

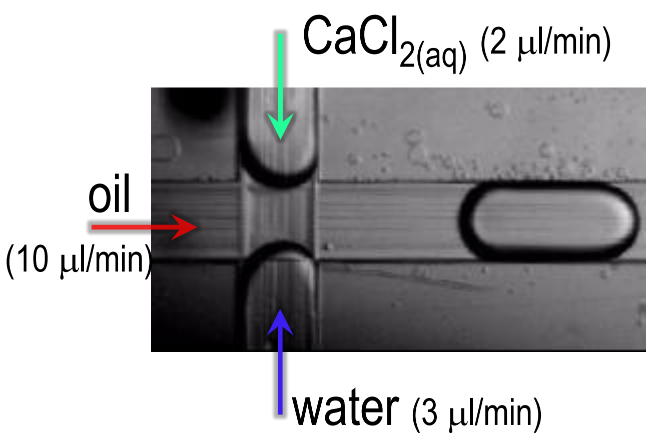
Hexadecane in the channel

I/I_0 = 76%

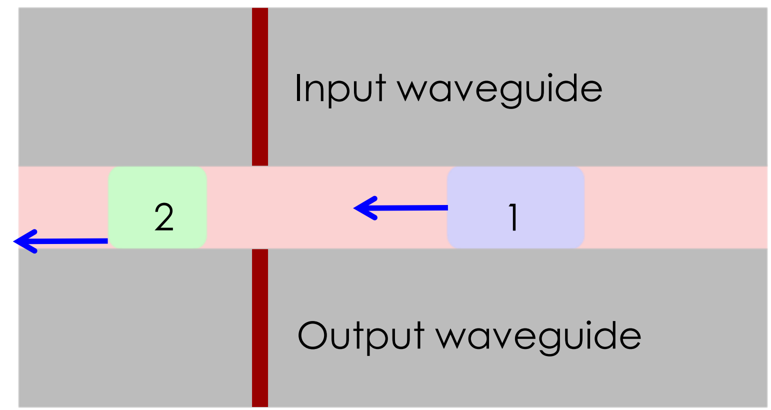
I_0 = 2.2×10^5 W/m^2

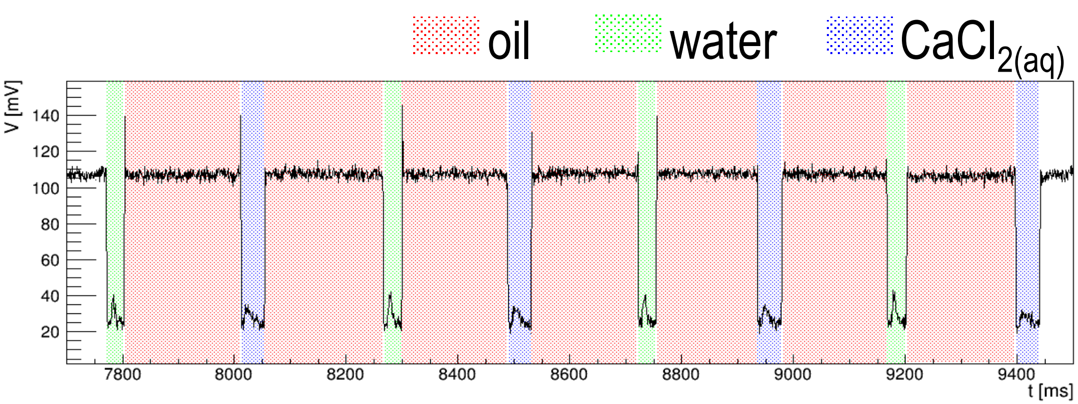
Counting

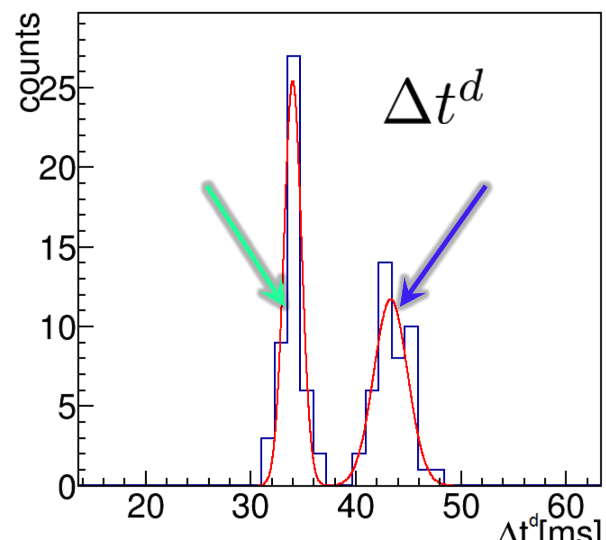
Target identification



1= reference
2=target to detect



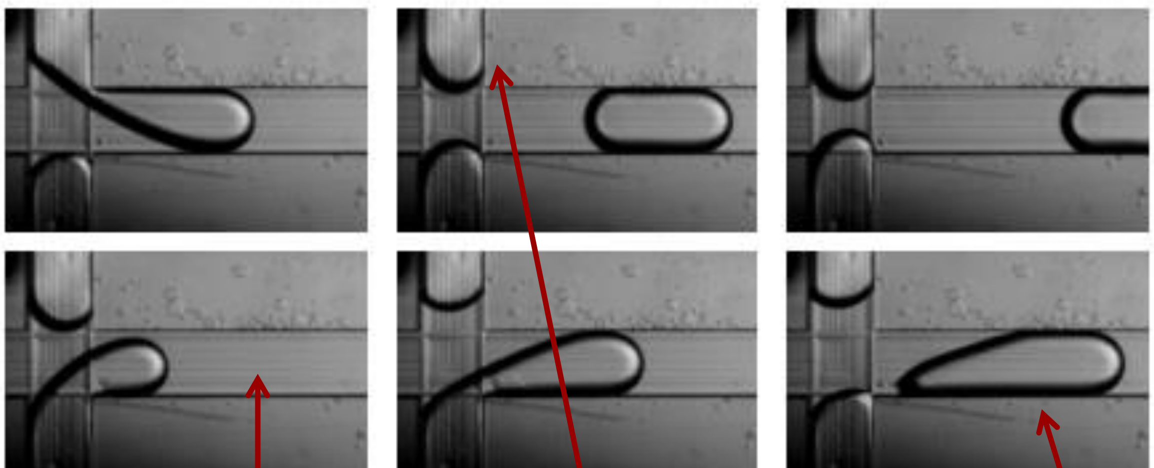


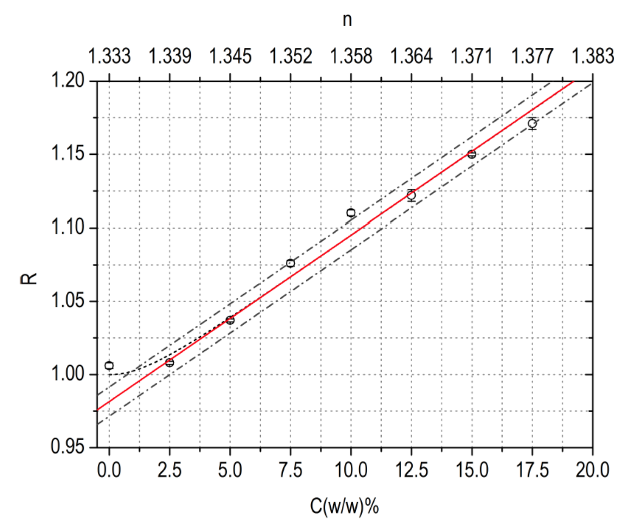


Microfluidics in $LiNbO_3$

Cross-junction

Alternating Droplets of different composition

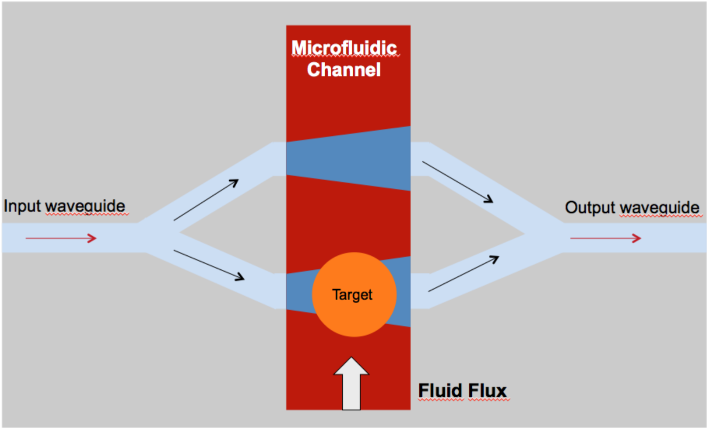




Q_C=10 μL/min $Q_D^{(w)}$=3μL/min $Q_D^{(w+CaCl2\ 5\%)}$=2μL/min

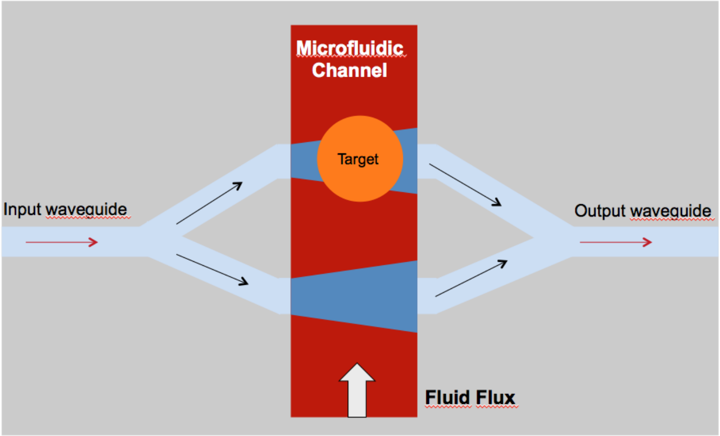
Sensing application

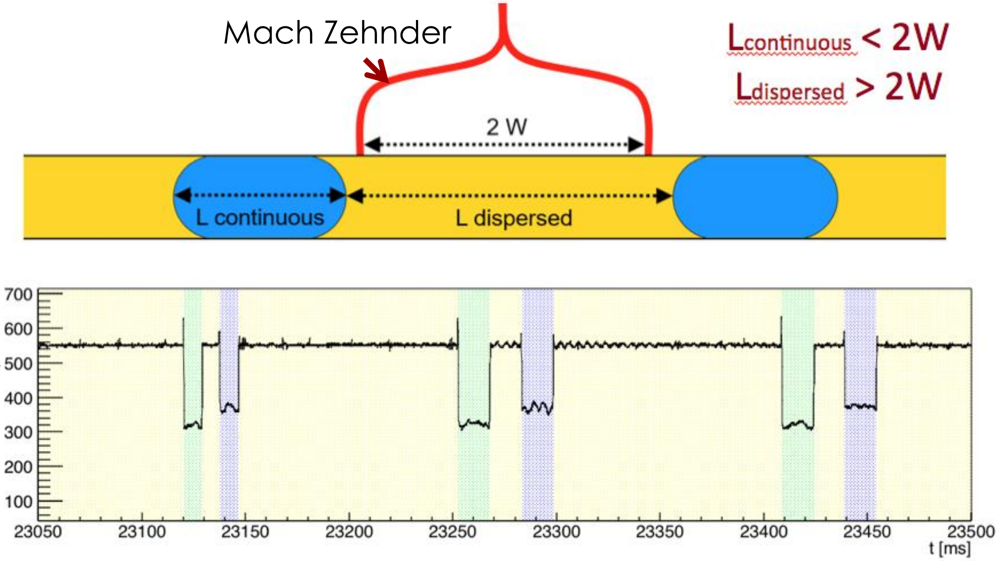
Optofluidic platform: target detection



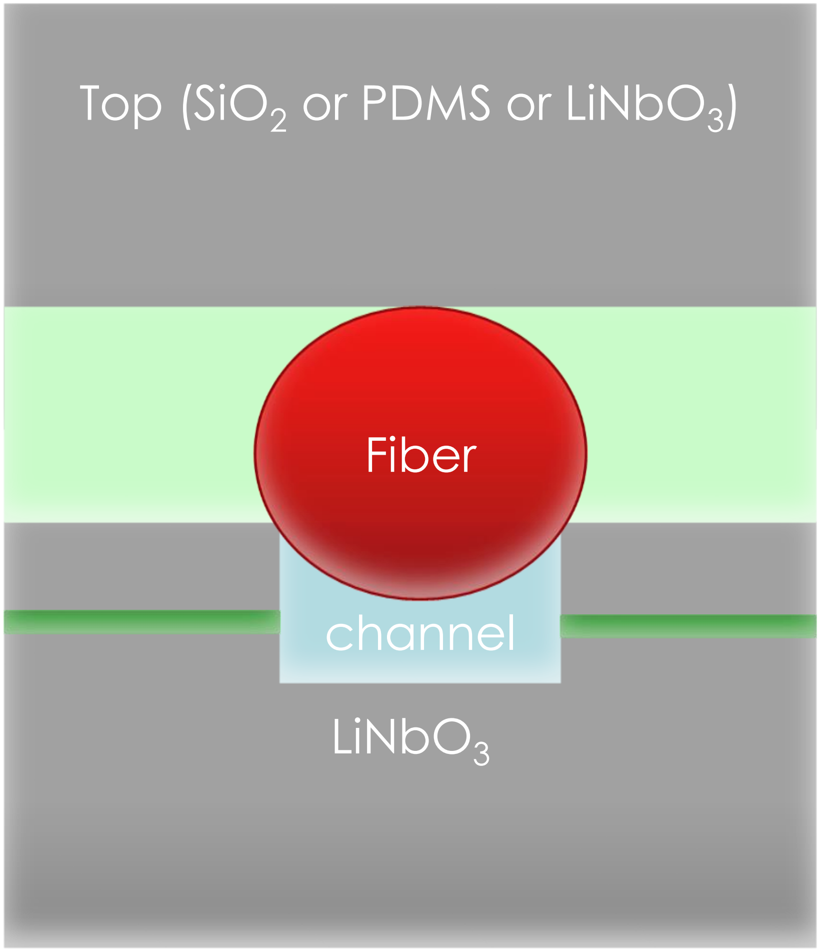
Transmitted intensity modulation

Infos on n(t)



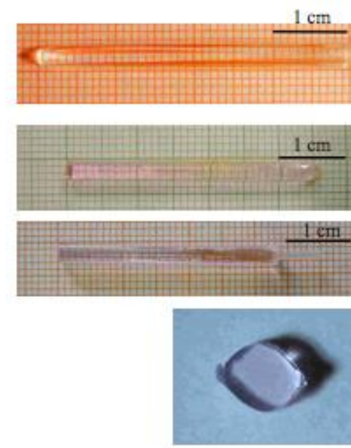


Sensing application



Evanescent field to particle driving

$LiNbO_3$ fibers growth

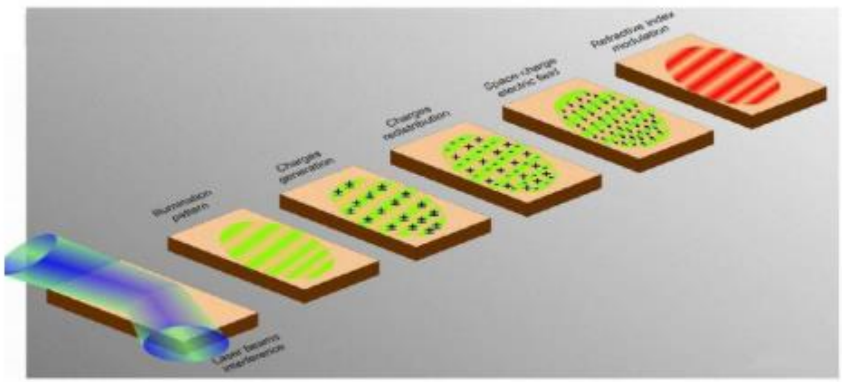


Journal of Applied Physics 104, 103114 (2008);

A. Arcangeli, M. Tonelli, A. Toncelli, C. Sada et al.

Trapping of particles

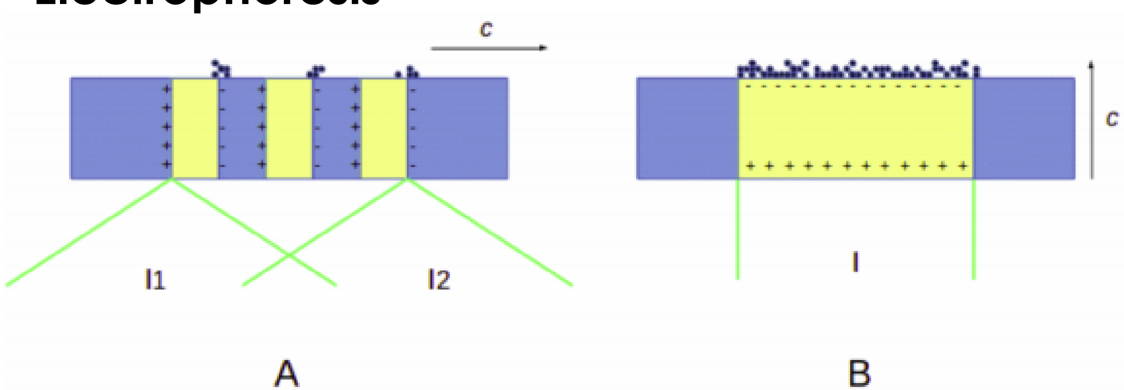
$$I(\mathbf{r}) \rightarrow N_{e,h}(\mathbf{r}) \rightarrow \mathbf{j}(\mathbf{r}) \rightarrow \rho(\mathbf{r}) \rightarrow \mathbf{E}_{sc}(\mathbf{r}) \rightarrow \Delta n(\mathbf{r})$$



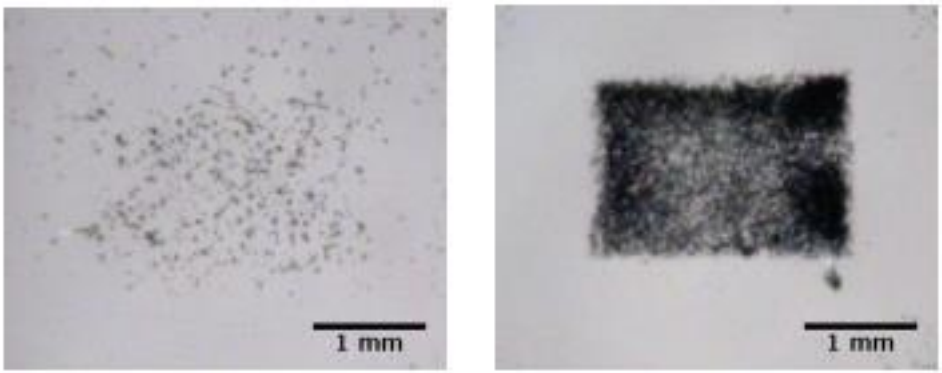
$LiNbO_3$ photorefractivity

Pattern of light modulation induces a pattern of evanescent field

Electrophoresis



Trapping of particles in fluids



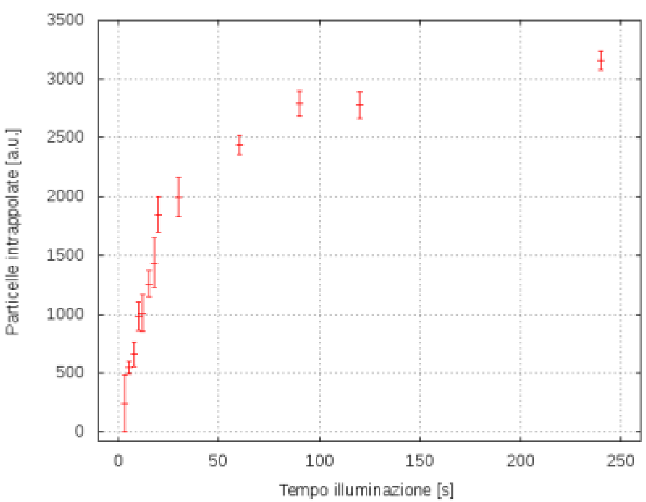
(a) Camp. 117.1, t_{ill}=40min (b) Camp. 210.6, t_{ill}=6min

Particle trapping

Electrophoresis

Integrated Round Shape Fibers To illuminate

Local definition of the Trapping region



What to do next?

Fibers to be improved focusing on the following aspects:

- Wide range of refractive index (work on new materials);
- Tailored cladding characteristics along the fiber length;
- Tailored fiber tip (new procedures for tapering, rounding,..)

AIMS

- Reduce optical losses (propagation and coupling losses)
- Improve material compatibility to simplify the integration process
- Simplify fiber processing

Conclusions

In summary:

- Thank you for your attention!

- Thank you for this opportunity to meet this community!

- I forgot.. As Editor, Welcoming you to submit papers for publication

  Optofluidics, microfluidics and nanofluidics Journal

  De Gruyter Open Ed Open Access

Optical sensing

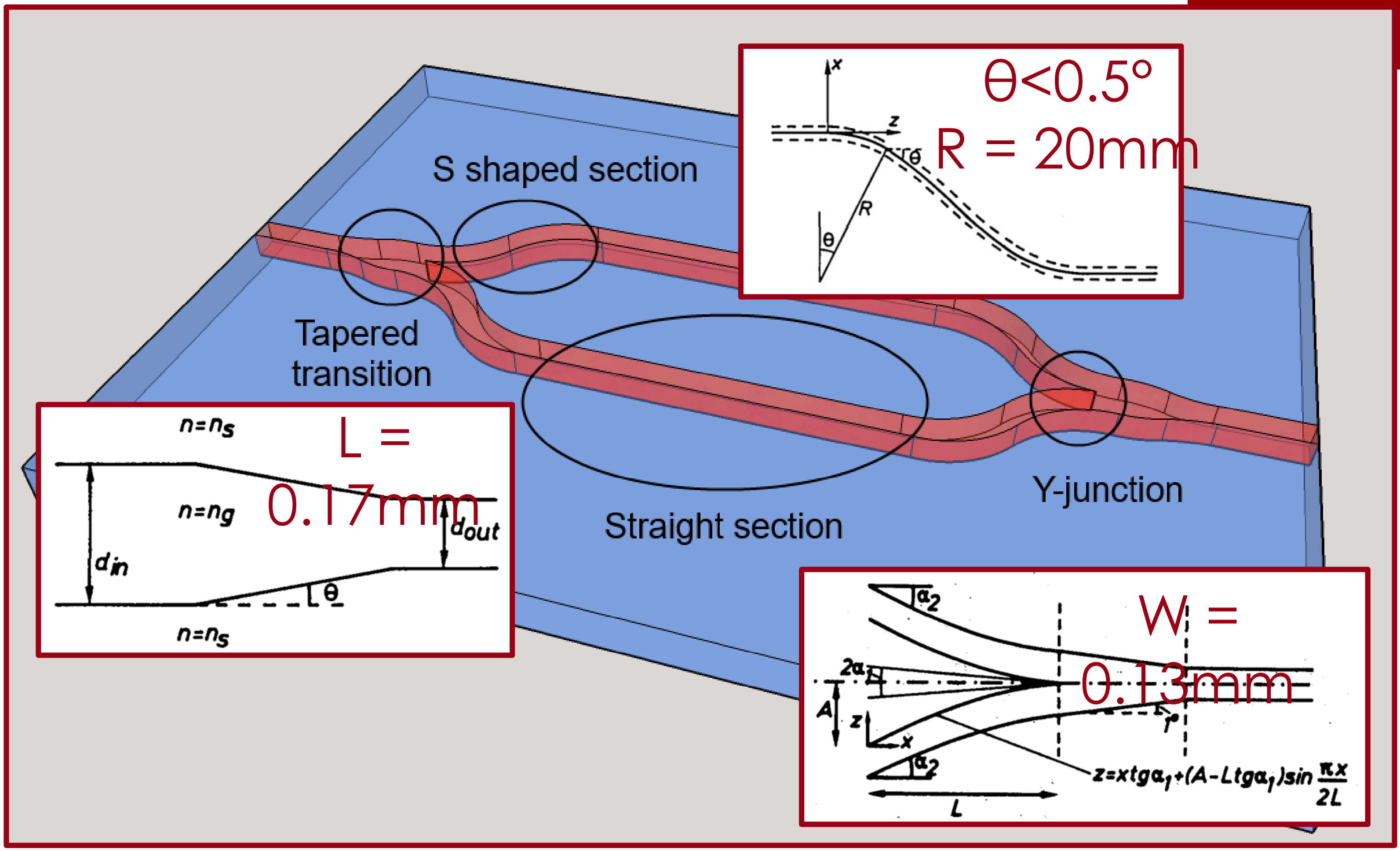
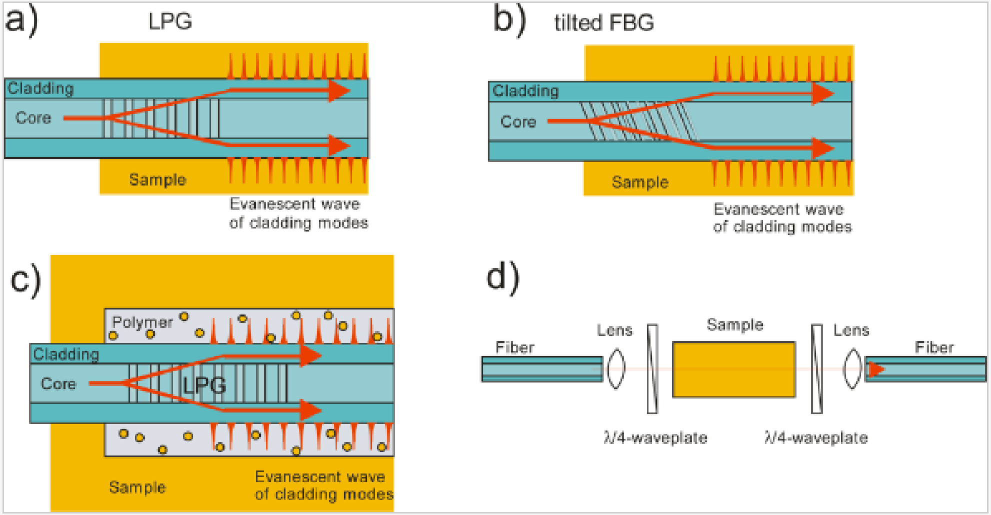
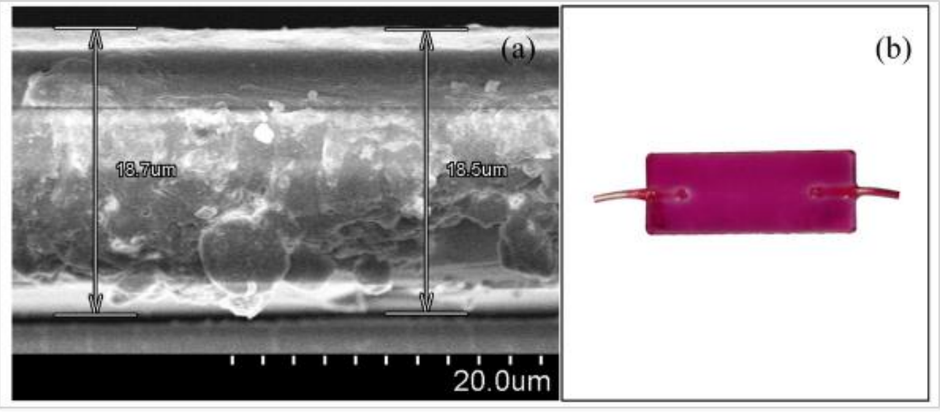


Figure 6. Different sensor elements for refractive index change measurements. Refractive index sensitive elements like **(a)** long-period gratings (LPG) or **(b)** tilted fiber Bragg gratings (FBGs) are often used. **(c)** By coating an LPG with a polymer the sensor element can be made more sensitive and more selective. **(d)** Circular birefringent samples have different refractive index for left or right circularly polarized light. In this sensor element the linear polarized light from the fiber is converted to circular polarized light by a quarter waveplate before being transmitted through the sample. A second quarter waveplate restores the linear polarization before coupling the light back into the cavity fiber.

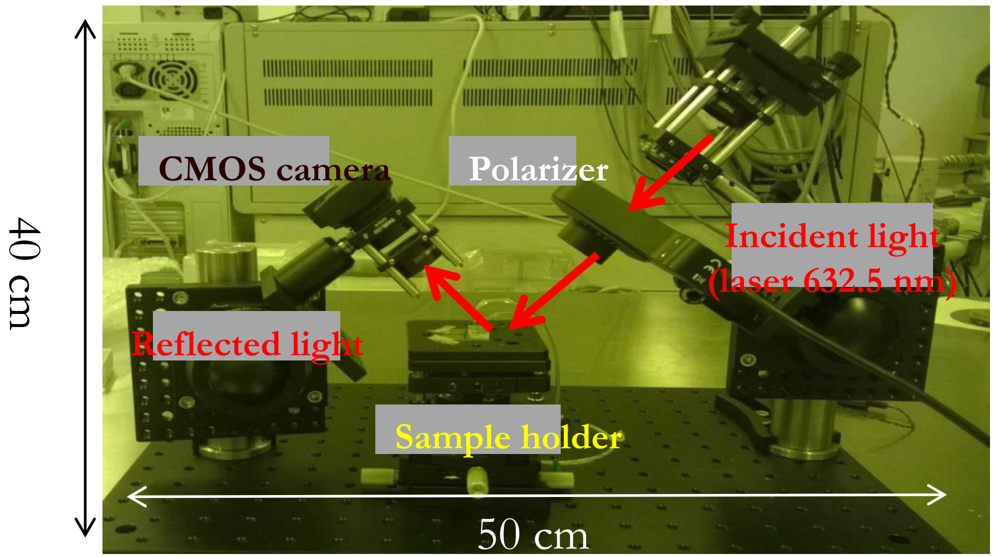


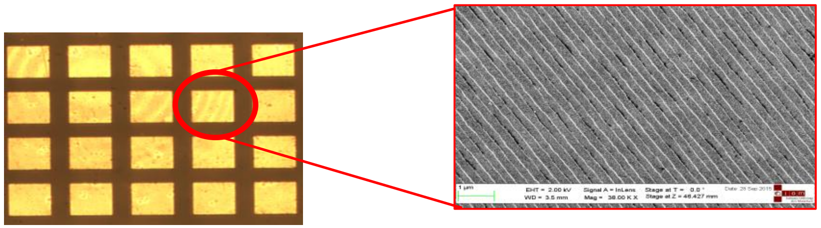
solvatochromism

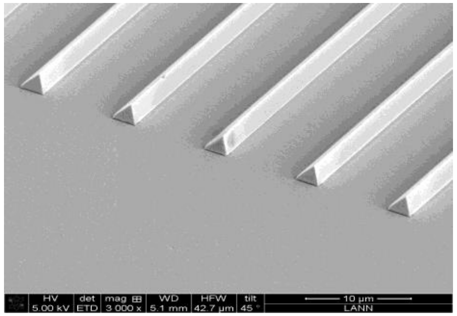
Figure 2. VOC sensitive sensing membrane: (**a**) SEM image of the thickness of the VOC sensing membrane and (**b**) photograph of the fabricated side-polished fiber-optic device after incorporation of the Nile Red-containing sensing membrane.

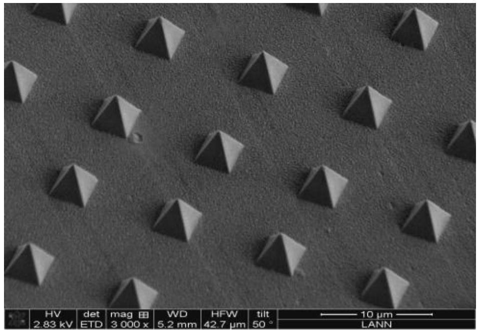


Nile Red dye, N,N-dimethylacetamide (DMAC, 99%), and PVP were used to prepare the sensing solution


CMOS camera
Polarizer
Incident light
(laser 632.5 nm)
Reflected light
Sample holder
50 cm
40 cm

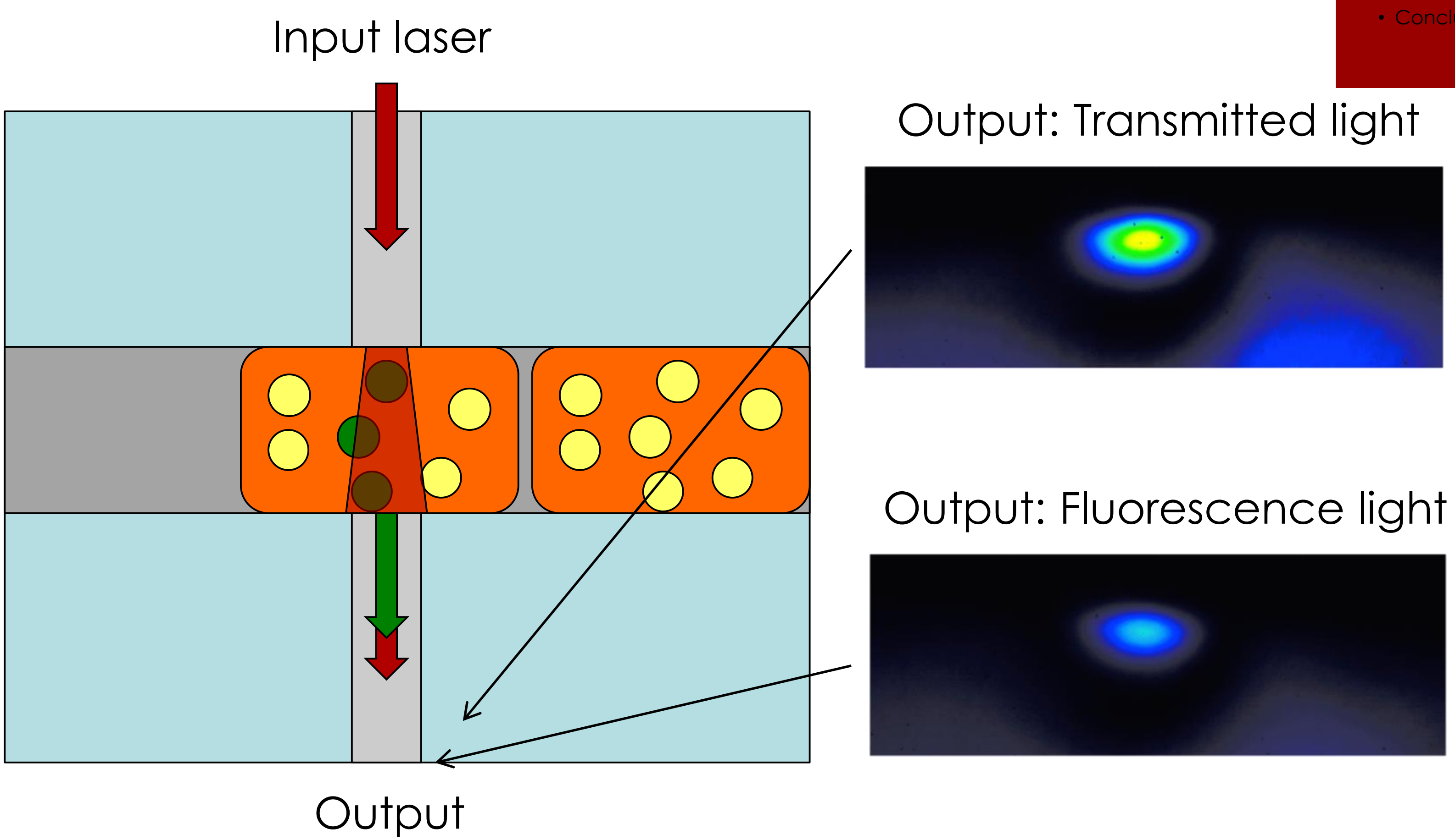






Spectral analysis

First Tests on fluorescence detection



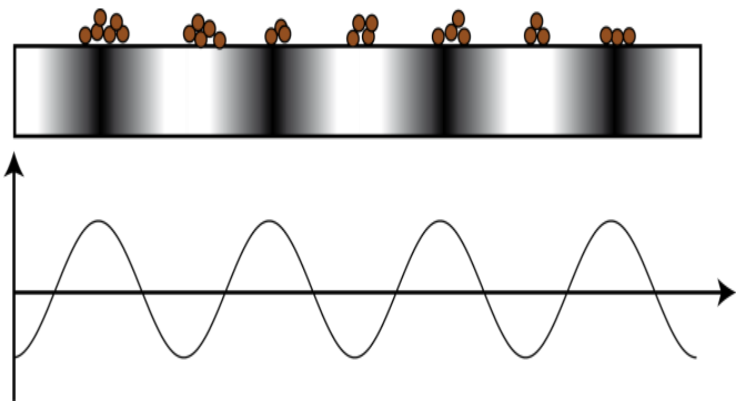
Input He –Ne laser intensity coupled into the waveguide: 2.2 x 10^5 W/m^2

Test made with: Rhodamine 6G and Cy5 in water

Particles trapping

Collaboration with Prof. Denz's research group @ Münster (Michael Esseling)

Non homogeneous illumination → Space charge field modulation → Dielettrophoresis force



$$F_{DEP} = 2\pi r^3 \varepsilon_m \mathrm{Re}\left[\frac{\varepsilon_p(\nu) - \varepsilon_m(\nu)}{\varepsilon_p(\nu) + 2\varepsilon_m(\nu)}\right]\nabla E^2$$

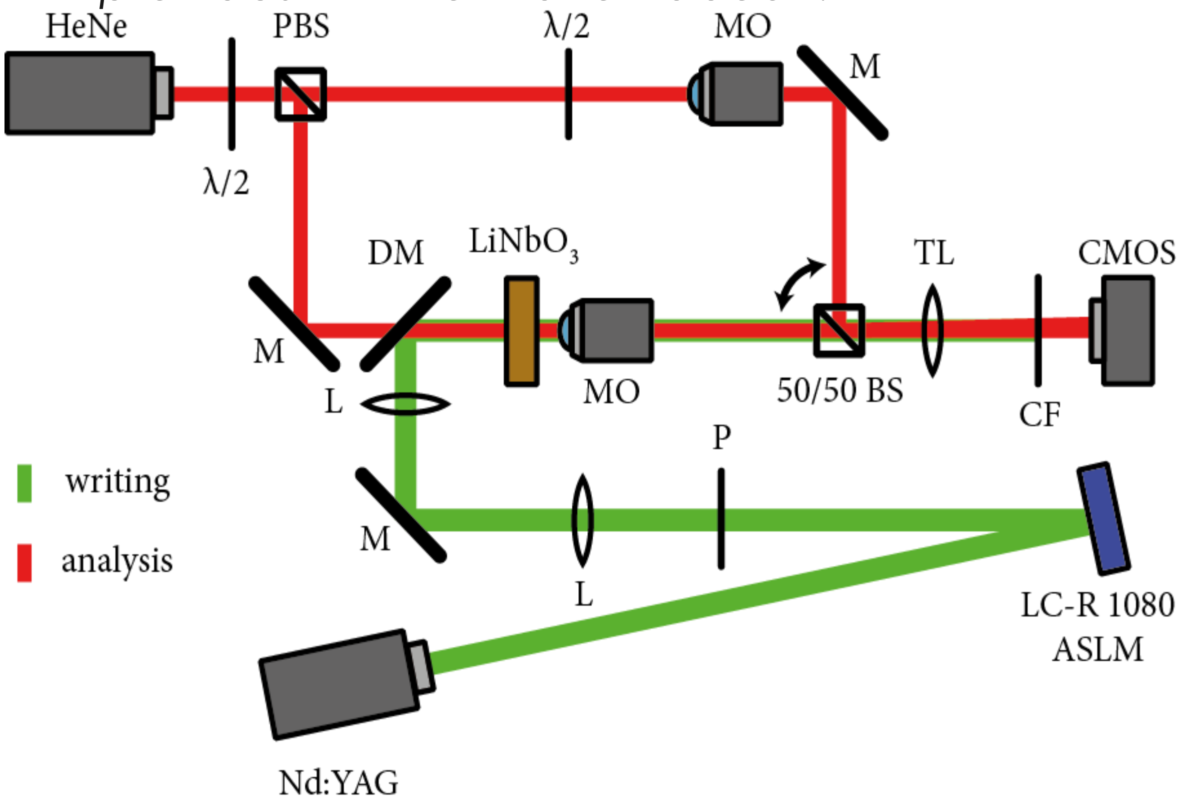
$LiNbO_3$ crystals possess unique properties for particles trapping

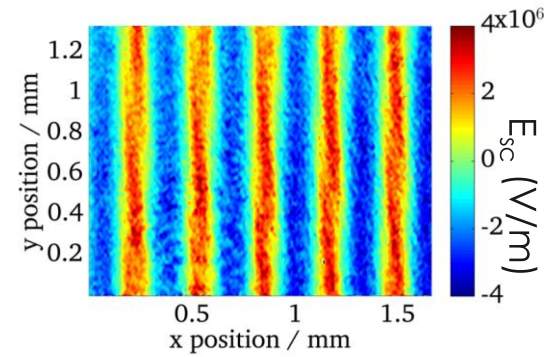
- high internal fields up to kV/mm
- low light intensity (good for living cell)
- easy reconfiguration (uniform white light)

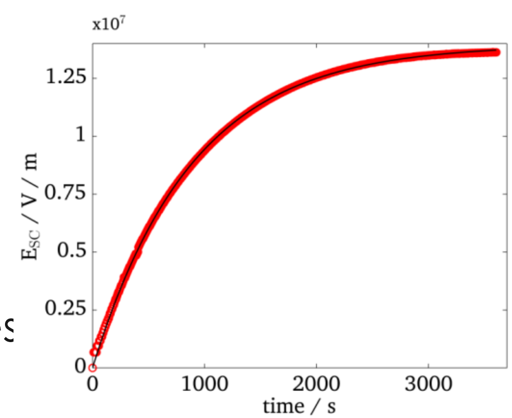
Digital holographic microscopy (DHM)

provides 2D information about :

- the magnitude of E_{SC}
- temporal evolution of E_{SC}
- internal structure of E_{SC}







- Fe-doped Lithium Niobate (enhancement of PR properties
- Reduced $Fe:LiNbO_3$ samples (to speed up PR response)

Particles trapping

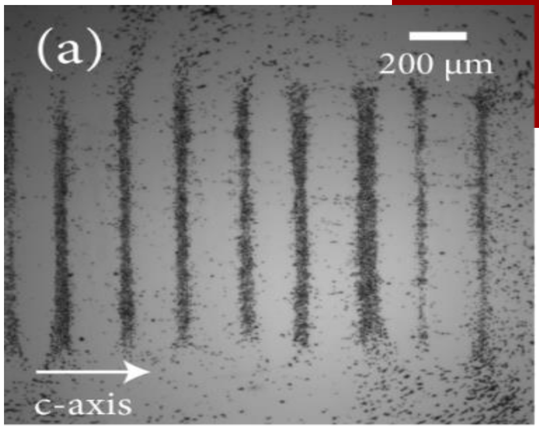
y-cut Fe:LN samples ⟶ light patterns with k-vector along c-axis of $LiNbO_3$

↓

anisotropy of the bulk photovoltaic effect

⬇

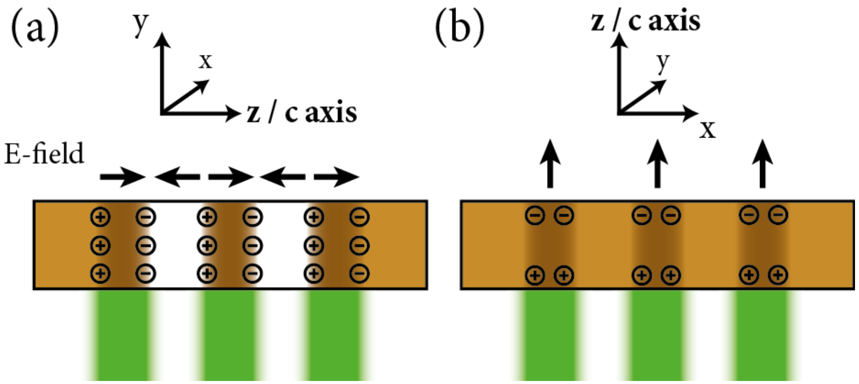
no arbitrary 2D patterns



z-cut Fe:LN samples ⟶ charges also accumulate on ±z faces

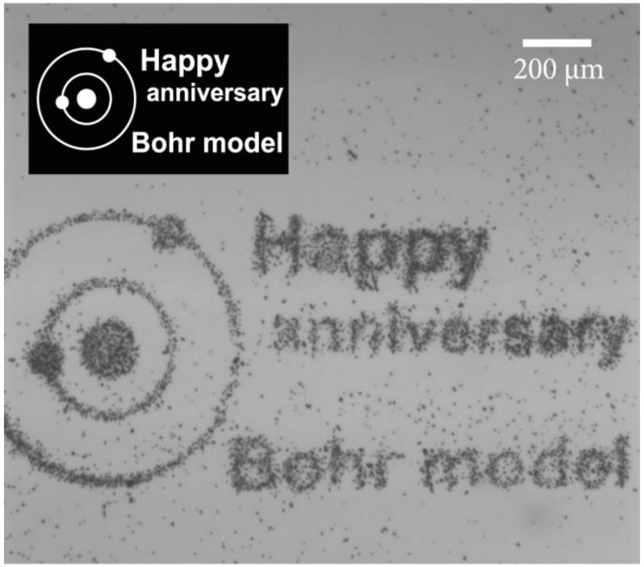
↓

- electrophoretic attraction to accumulated charges on +/- c face
- negligible dielectrophoresis perpendicular to c-axis



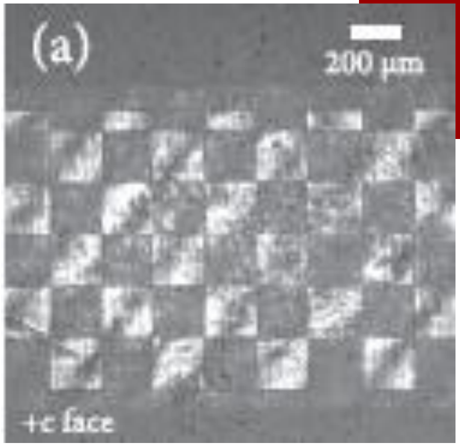
z-cut Fe:LN samples

✓ Arbitrary 2D patterns (particles trapping)



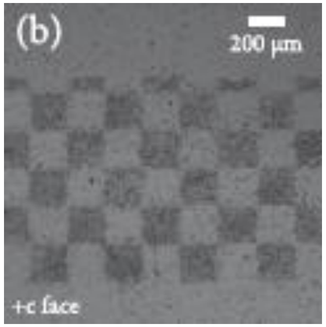
✓ charge sensor

Light pattern on ± c faces

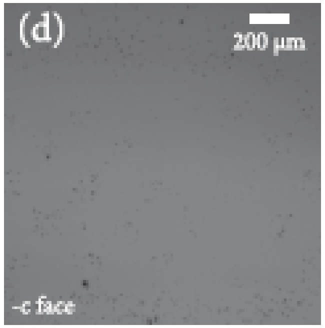


Positive particles are:

trapped



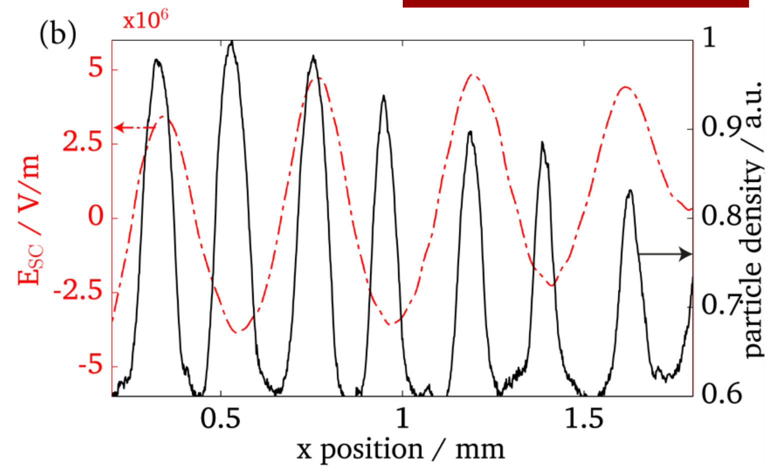
repulsed



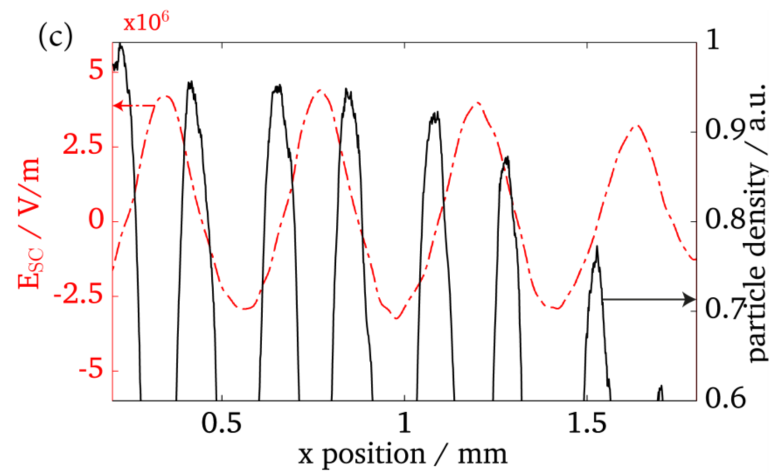
→ *next step: integration of particle sorting device*

- glassy carbon (GC) spheres (2 -12 μm) in tetradecane: **uncharged, manipulated by DEP**
- GC in Novec 7500/7300: **charged, influenced by electrophoresis (EP)**
- charge state determined by phase shift between electric field and trapped particles (y-cut geometry)
  - DEP attracts GC towards high field intensity
  - EP attracts to regions of high charge density

-> in NOVEC 7500, both charge states exist (!)



tetradecane



NOVEC 7500

Optical sensing

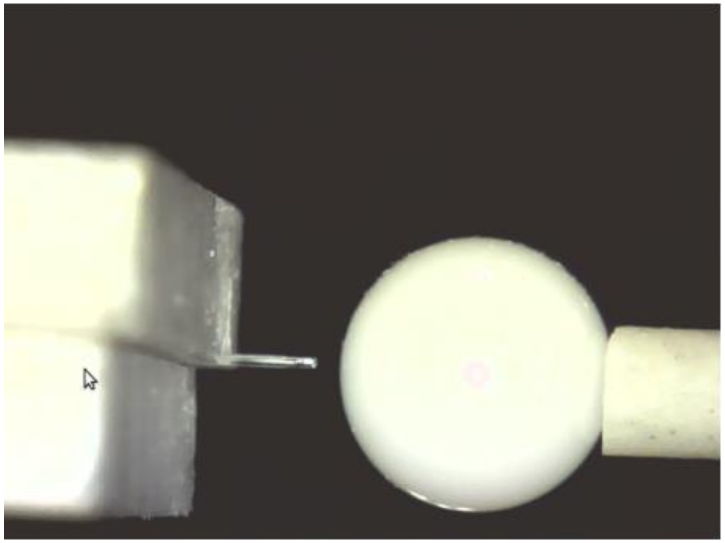
Optical sensing

Optical sensing

Optical sensing

Growth and characterization of Er-doped single crystal lithium niobate fibers

Optical sensing



fiber to a sphere at high temperature (1200 – 1600∘C)

Produce really concave spherical tips with a larger useful diameter (and so more stable cavities)

Optical sensing

Life time 2.3 ms

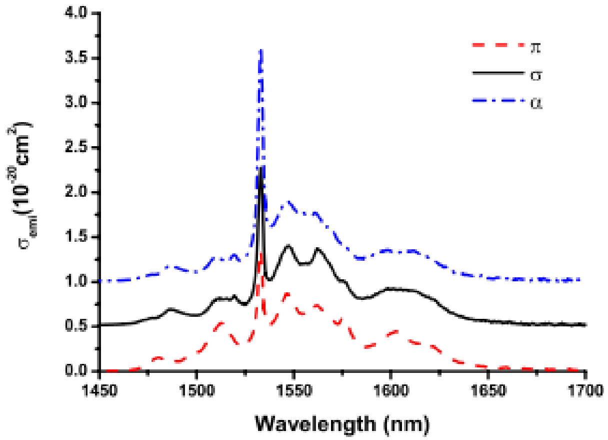
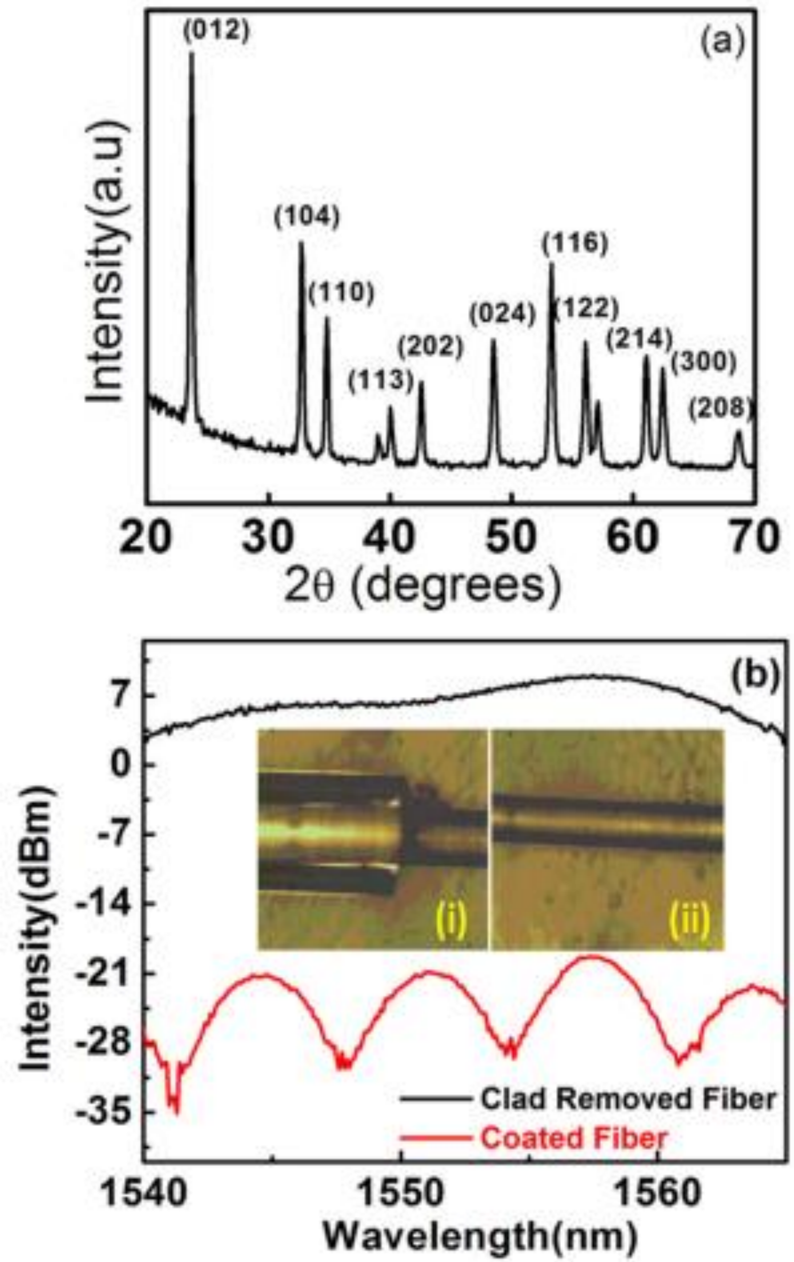


FIG. 8. (Color online) Polarized emission cross section of the $^4I_{13/2}$ level.


(a)
Intensity(a.u)
(012)
(104)
(110)
(113)
(202)
(024)
(116)
(122)
(214)
(300)
(208)
20
30
40
50
60
70
2θ (degrees)
(b)
Intensity(dBm)
7
0
-7
-14
-21
-28
-35
(i)
(ii)
Clad Removed Fiber
Coated Fiber
1540
1550
1560
Wavelength(nm)

Volatile organic compounds (VOCs) are common air pollutants

VOCs can contain:
C, O, F, Cl, Br, S N

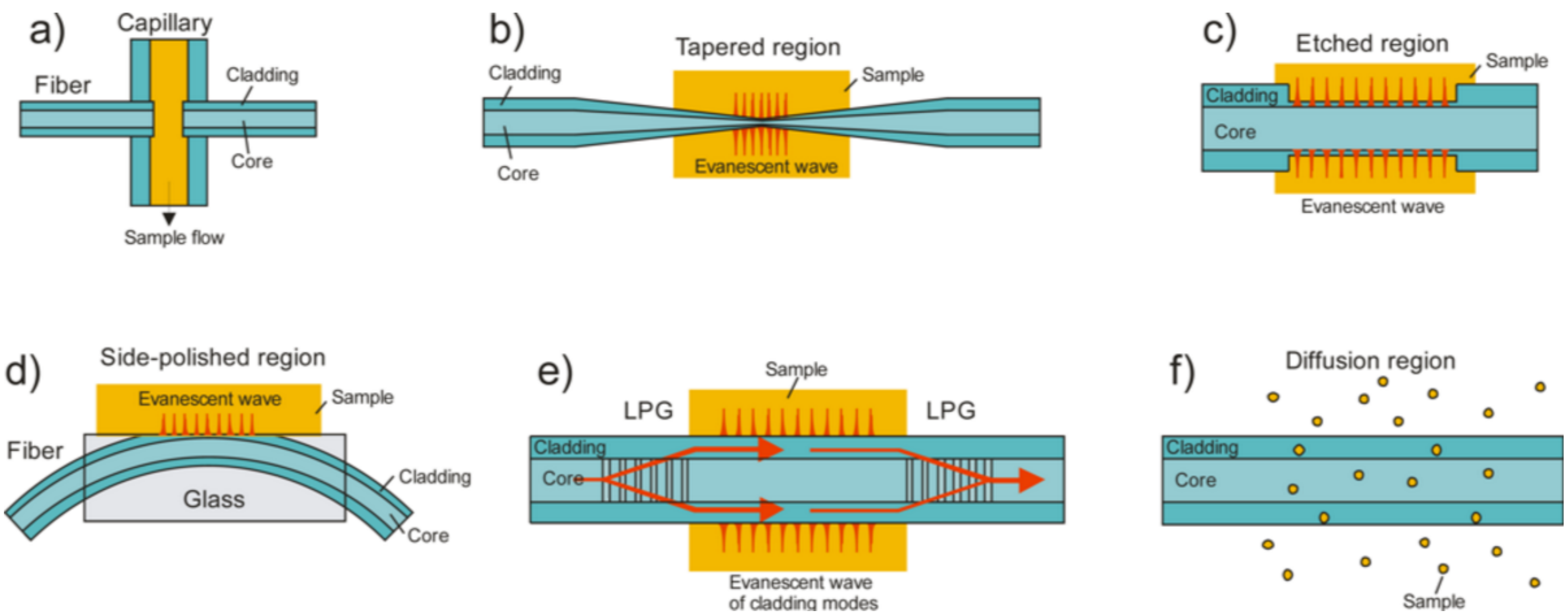
VOCs can:
evaporate easily at room temperature;
Give strong health risks

Several types of sensors were developed

surface acoustic wave sensors
polymer composite sensors
carbon nanotubes
CMOS
capacitive sensors

Fiber optics sensors

EF: fibers for sensing



Sensors 2010, 10(3), 1716-1742

Helen Waechter, Jessica Litman, Adrienne H. Cheung, Jack A. Barnes and Hans-Peter Loock