The Abdus Salam
International Centre for Theoretical Physics

United Nations
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International Atomic Energy Agency

2037-14

Introduction to Optofluidics

1 - 5 June 2009

What is Optofluidics? What shall we discuss this week?

D. Cojoc

TASC CNR-INFM
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What is Optofluidics ?

What shall we discuss this week?

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Optical Manipulation OM-Lab

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http://www.tasc.infm.it/research/**om**/scheda.php

TASC
CNR - INFM

Laboratorio Nazionale
Tecnologie Avanzate e nanoSCienza

Consiglio Nazionale delle Ricerche - Istituto Nazionale per la Fisica della Materia

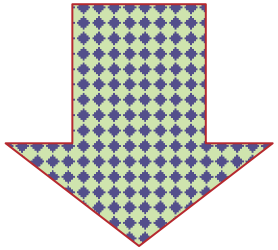
What is Optofluidics ?

Optofluidics combines **Optics** and **Micro/Nano fluidics**.

Optics: the study of light and its interactions with matter.

Fluidics: the study of materials that deform under a shear stress.

Optical (E-M) **field** interacts with the **fluid** in a **micro/nano scale** system



Light manipulates fluid and/or **fluid manipulates light**

V.R. Horowitz, D. D. Awschalom, S. Pennathur, **Optofluidics: field or technique?**
Lab Chip, **8** 1856–1863 (2008)

Optofluidic systems can be defined/described from different **points of view**:

Structure and mechanism:

(1) structured solid-liquid hybrids in which the optical properties of both media are relevant;

(2) complete fluid-based systems in which only the optical properties of the fluids are relevant;

(3) colloid-based systems in which manipulation of solid particles in liquid, or using the unique optical properties of colloidal solution, form the basis of the optofluidic devices.

D. Psaltis, S. R. Quake and C. H. Yang, **Developing optofluidic technology through the fusion of microfluidics and optics**, *Nature*, **442**, 381–386 (2006).

Function/purpose:

(1) optofluidic light sources that employ fluids as the gain medium;

(2) optical devices that employ fluids to tune or configure optical response;

(3) fluidic sensors that employ integrated photonicstructures.”

D. Sinton, R. Gordon and A. Brolo, **Nanohole arrays in metal films as optofluidic elements: progress and potential,** *Microfluidics Nanofluidics*, **4**(1) 107–116 (2008).

C.Monat, P. Domachuk and B. J. Eggleton, **Integrated optofluidics: A new river of light,** *Nat. Photonics*, **1**(2) 106–114 (2007).

Book:
Optofluidics- Fundamentals, Devices, and Applications
Ed: McGraw-Hill Sept 2009,
Authors: Y. Fainman, L. Lee, D. Psaltis, C. Yang

Review:
V.R. Horowitz, D. D. Awschalom, S. Pennathur,
Optofluidics: field or technique?
Lab on a Chip, **8** 1856–1863 (2008)

Table 1 Optical devices that employ fluids

Criteria for classification

Device or application | Direction of manipulation | Structure | General purpose | Fluidics provides | Refractive index important? | Ref.

Table 2 Optofluidic devices and applications

Criteria for classification

Device or application | Direction of manipulation | Structure | General purpose | **Optics provides** | Fluidics provides | Refractive index important? | Ref.

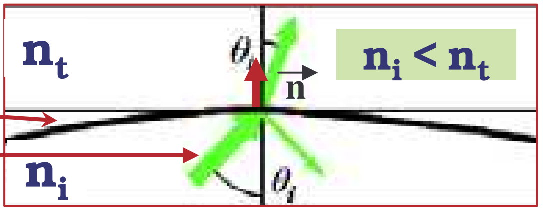
What is Optofluidics ?

Light manipulates fluid and/or **fluid manipulates light**

Light manipulates fluid

Example

Deformation of a **liquid interface** by the **radiation pressure** of a **laser wave**



J.P. Delville *et al. J. Opt. A: Pure Appl. Opt.* **11** 034015 (2009) and J.P. Delville *lecture2* today

The force induced by the radiation pressure:

$$\vec{F}_r = n_i \cos^2\theta_i \left[1 + R(\theta_i,\theta_t) - \frac{\tan\theta_i}{\tan\theta_t} T(\theta_i,\theta_t)\right]\frac{P}{c}\vec{n} = A\,\frac{P}{c}\vec{n}$$

$\vec{F}_r$ is always normal to the interface and is directed toward the dielectric medium of the lowest index of refraction (less dense medium).

Numerical example

Considering: $n_i=1.3$ (~water), $n_t=1.5$ (~ oil), $\theta_i= 30^0$ $\longrightarrow$ $\vec{F}_r \sim -0.391\, \boldsymbol{P/c}\, \vec{\mathbf{n}}$

where: **P** – incident light power in watts, **c** – light velocity in vacuum, A = - 0.391;

for **P**= 1 W $\longrightarrow$ $|\vec{F}_r|$ =**1.3 nN**

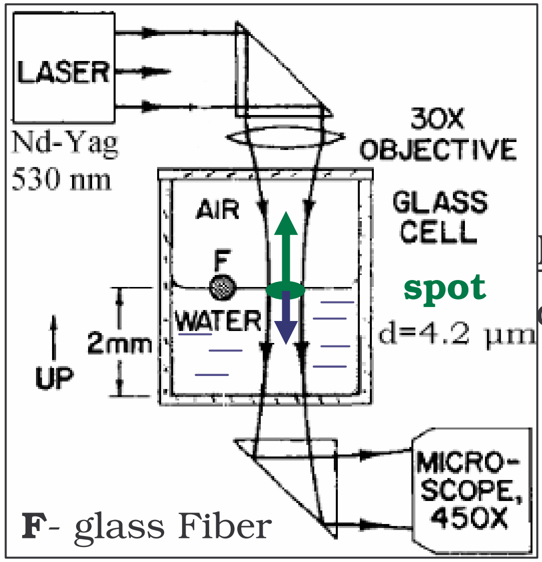
Please calculate yourself to check !

Q: Is $\mathbf{F}_r$ big enough to induce a detectabe deformation ?

To answer this question, one should consider the **surface tension** at the interface and find **laser** and **optics** to obtain adequate **P**.

Let us consider a similar experiment reported by **Ashkin** and **Dziedzic** in **1973** (*PRL*)

Abstract. The force of radiation pressure on the **free surface of a transparent liquid** dielectric has been observed using **focused pulsed laser** light. It is shown that **light** on either entering or leaving the liquid **exerts a net outward force** at the liquid surface. This **force causes strong surface lens effects,** surface scattering, and nonlinear absorption. The data relate to the understanding of the momentum of light in dielectrics.



Surface tension force: $\mathbf{F_s} \sim \mathbf{2\pi rS}$ maximum,
For: $\mathbf{r}$=1.2 μm, **S**=72 mN/m (surface tension of the water surface against the air at T= 25º C) → $\mathbf{F_s}$ ~ **543 nN**

Radiation pressure force: $\mathbf{F}_r \sim \mathbf{0.825}\ \boldsymbol{P}/\mathbf{c}$
considering n_i=1 (air), n_t=1.3 (~ water), θ_i= 1^0

$$\mathbf{F}_r > \mathbf{F_s} \rightarrow \mathbf{P} > \mathbf{198\ W} = \mathbf{P_0}$$

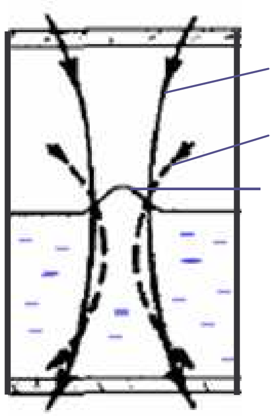
Pulsed laser: **P**= 1-4 kW ~ 5-20 $\mathbf{P_0}$

adapted from Ref: A. Ashkin A and J.M. Dziedzic,
Radiation pressure on a free liquid surface *Phys. Rev. Lett.* **30** 139-142 (1973)

Ashkin&Dziedzic reported: we have generated surface lenses free of background thermal or nonlinear index changes.

Low absorption in water at 530 nm → low thermal lens effects

40 KW peak power is well bellow 1 MW, the threshold for self-focusing



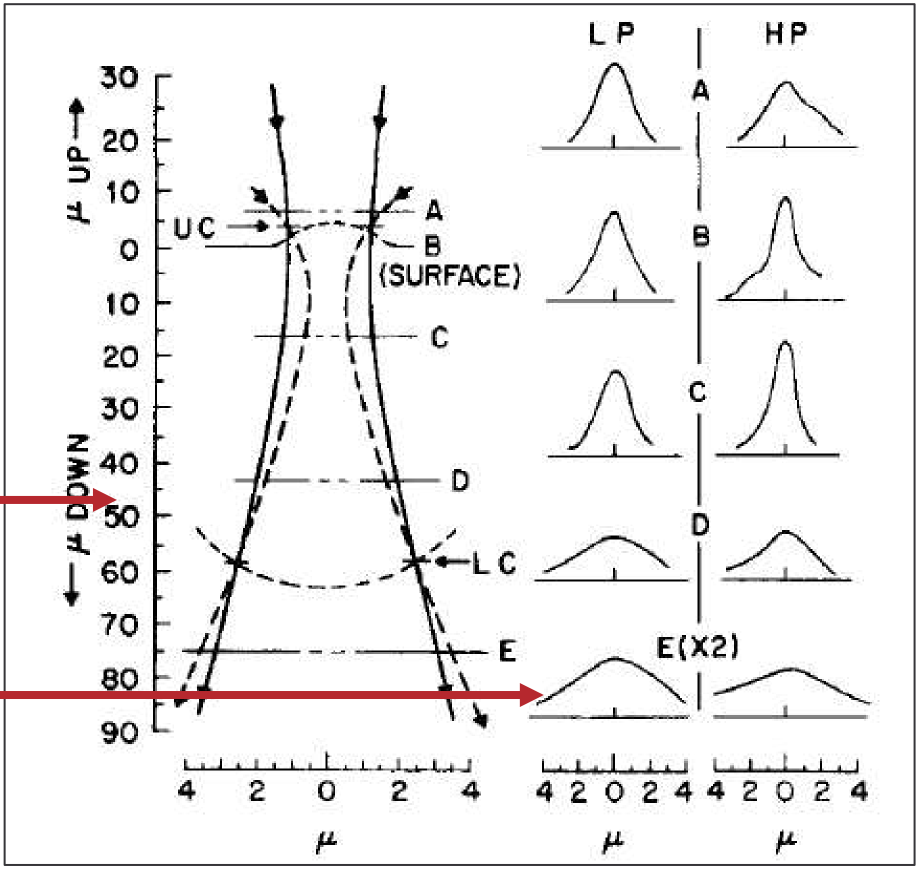
LP – Low Power

HP – High Power

Surface deformation

positive lens

f ~ 20 μm → r ~ 5 μm



Beam shapes at the half-power points, for LP (solid curve) and HP (dashed curve)

Scans of beam shapes
(i.e. power versus position)
at the planes: A, B, C, D, E

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(i.e. power versus position)
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A. Ashkin A and J.M. Dziedzic, *Phys. Rev. Lett.* **30** 139-142 (1973)

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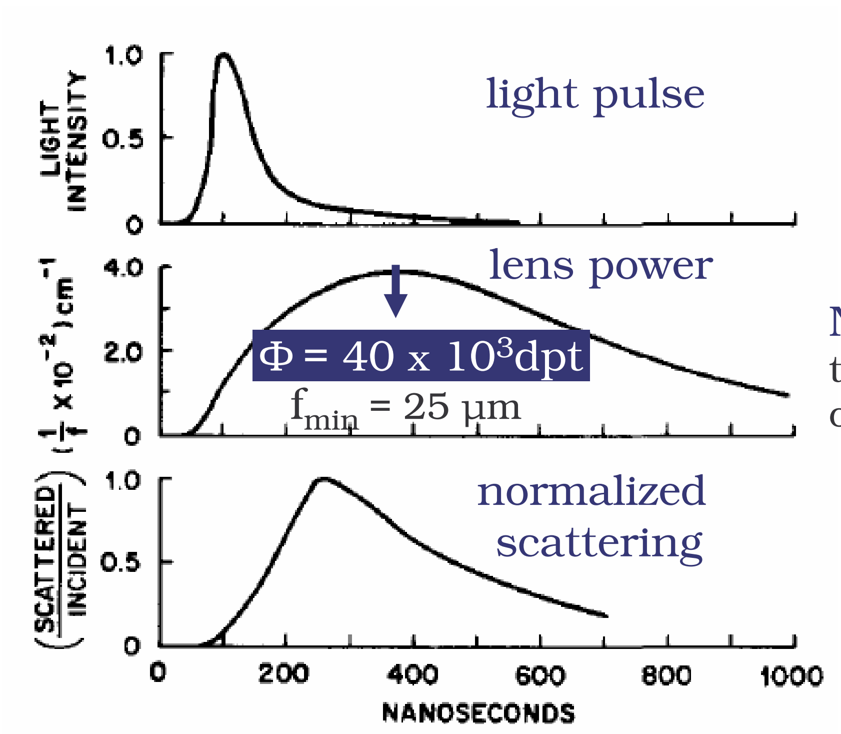
Time development of:



$\Phi = 40 \times 10^3$dpt

$f_{min} = 25\ \mu m$

Scattering time development differs from the lens development → **surface motion** → **existence of a nonlinear** optical energy loss since the kinetic energy of the moving liquid is eventually lost to heat.

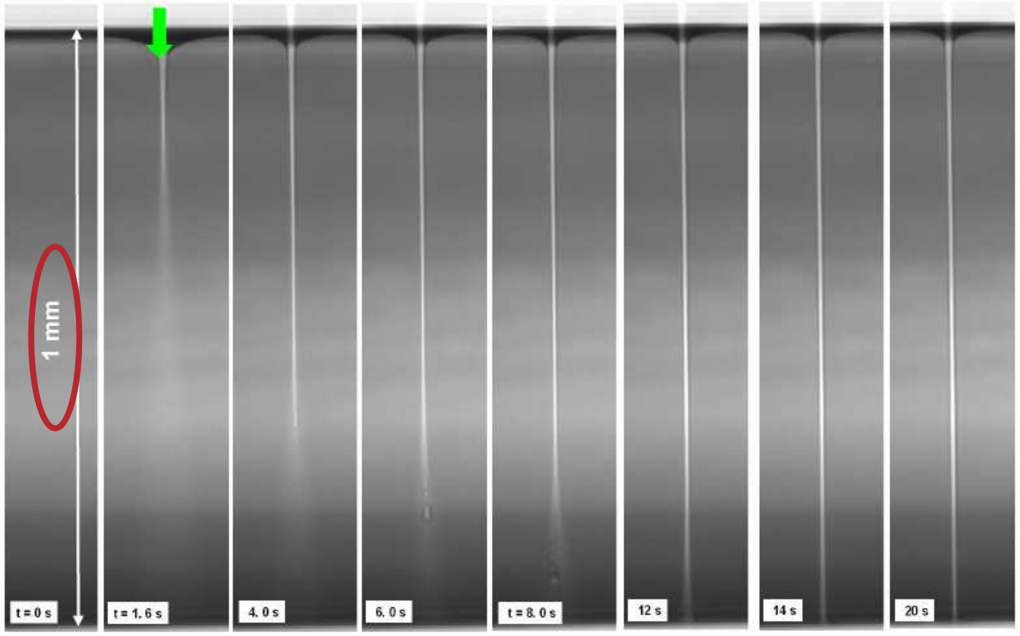
Note:
the power of a 100X microscope objective is about 500 dpt

With lower surface tension all effects should occur more strongly.
Indeed some of our strongest lenses occurred with detergent added to the water.

A. Ashkin A and J.M. Dziedzic, *Phys. Rev. Lett.* **30** 139-142 (1973)

Use near-critical micellar phases of microemulsion to reduce the surface tension to only: $\sigma \approx 10^{-7} N/m$

Note: σ (air/water) = **72** x **10^{-3}** N/m



T-T$_C$ = 4 K, ω_0 = 3.47 µm, P=0.47 W>P$_\uparrow$

Laser-sustained liquid column

Lectures

Jean-Pierre DELVILLE

University of Bordeaux,

CNRS Talence - France

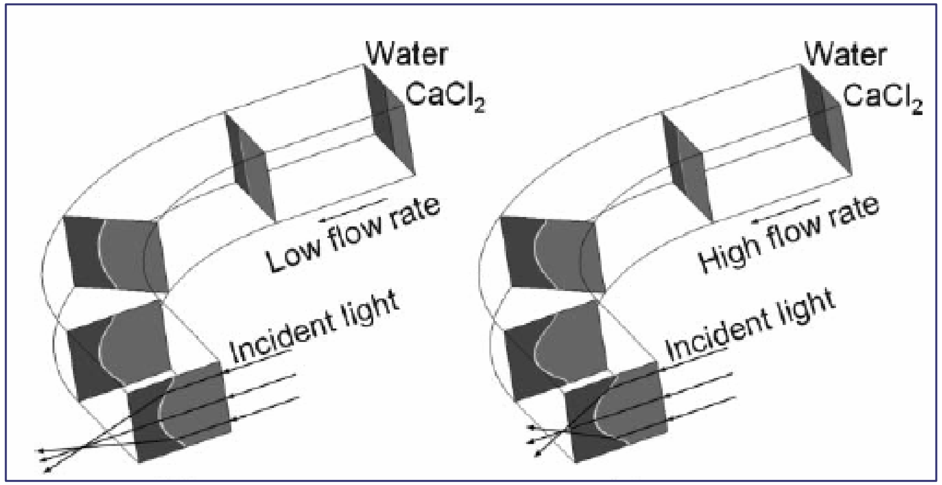
- **Optical radiation pressure effects on isotropic fluids and fluid interfaces.**
- **Optical manipulation of binary liquid mixtures.**
- **Opto-thermocapillary actuation of fluid interfaces.**

J.P. Delville, M.R. de Saint Vincent, R.D. Schroll, H. Chraibi, B. Issenmann, R. Wunenburger, D. Lasseux, W. W. Zhang and E. Brasselet, **Laser microfluidics: fluid actuation by light**, *J. Opt. A: Pure Appl. Opt.* 11 034015 (2009).

Fluid manipulates light

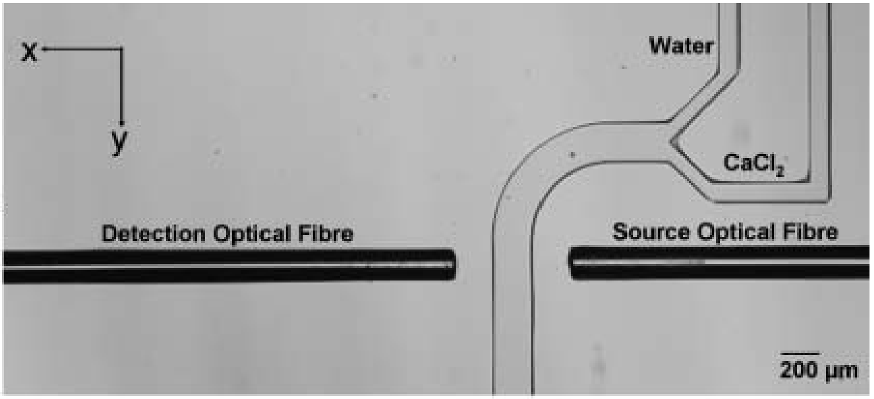
Tunable optofluidic microlens

The microlens is generated by the interface of two co-injected miscible fluids of different refractive indices (5 M CaCl2 solution, n = 1.445 and deionized water (n = 1.335).



The mechanism of the hydrodynamically tunable optofluidic cylindrical microlens.

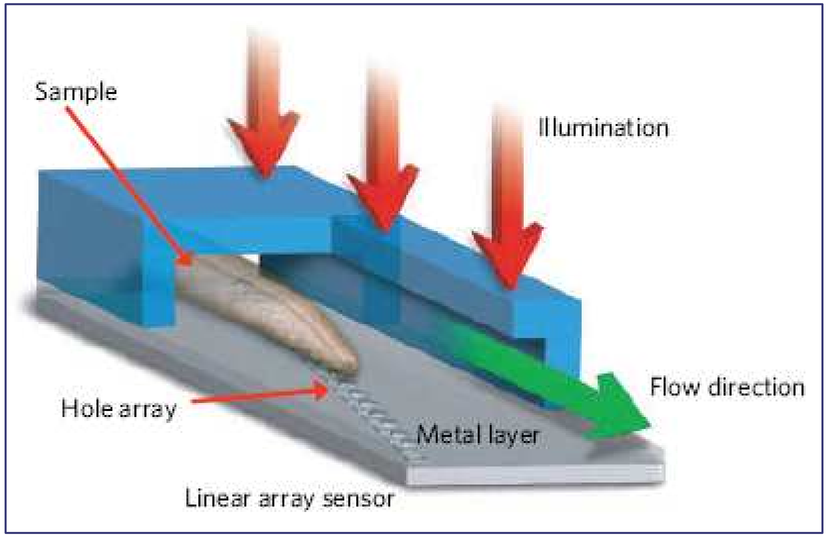
CaCl2 solution bows outward into water due to the centrifugal effect induced in the curve. Shorter focal length is obtained after flow transitions from a low flow rate to a high flow rate. (100-400 µl/min)



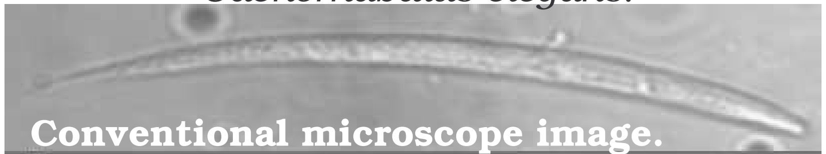
Device for the quantitative intensity analysis of the focused light.

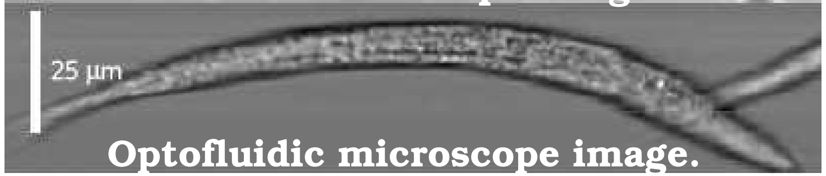
X. Mao et *al.*, **Hydrodynamically tunable optofluidic cylindrical microlens**, *Lab Chip*, **7** 1303–1308 (2007)

The optofluidic microscope



Caenorhabditis elegans.


Conventional microscope image.



Optofluidic microscope image.

Scheme of an on-chip optofluidic microscope.

The device is uniformly illuminated from the top. The target sample flows through the channel and the transmission through each hole is acquired and recorded. The composition of the transmission traces creates a transmission image of the target sample.

Lectures
Changhuei YANG
California Institute of Technology, Pasadena, USA

- **Multifunctional optofluidic microscope.**
- **Research outcomes from Caltech COI.**

X. Heng, D. Erickson, L. R. Baugh, Z. Yaqoob, P. W. Sternberg, D. Psaltis andC. H. Yang, **Optofluidic microscopy - a method for implementing a high resolution optical microscope on a chip**, *Lab Chip*, **6**(10), 1274–1276 (2006).

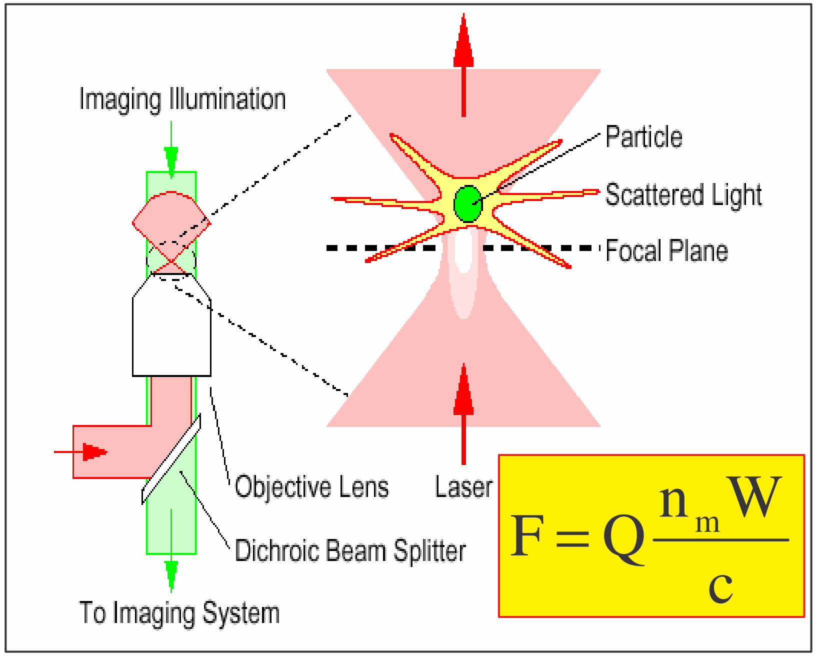
X. Cui, L. M. Lee, X. Heng, W. Zhong, P. W. Sternberg, D. Psaltis and C. H. Yang, **Lensless high-resolution on-chip optofluidic microscopes for *Caenorhabditis elegans* and cell imaging**, *Proc. Natl. Acad. Sci. U. S. A.*, **105**(31), 10670–10675 (2008).

Optical tweezers

a technique to trap and manipulat micro-objects in fluid

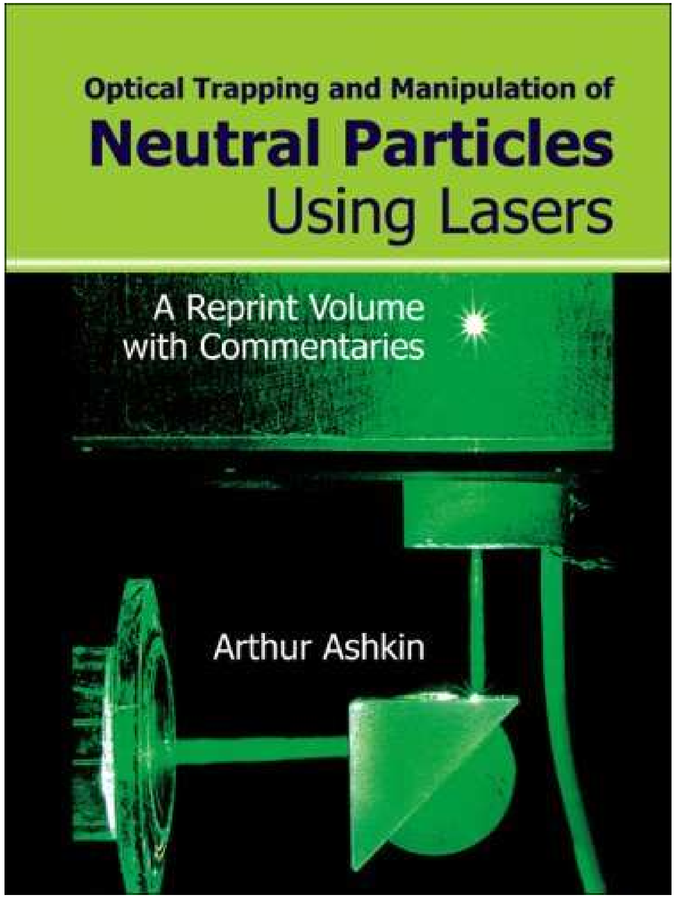
A single-beam gradient force trap is obtained by tightly focusing a cw laser beam through a high NA objective

A. Ashkin, *et al Optics Letters* **11** 288 (1986)



$$F = Q\frac{n_m W}{c}$$

F – trapping force
Q – dimensionless efficiency coefficient
W – power of the laser beam
n_m – refractive index of the medium
c – light speed



Optical Trapping and Manipulation of
Neutral Particles
Using Lasers

A Reprint Volume
with Commentaries

Arthur Ashkin

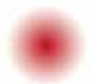
Characteristics of optical tweezers

Types of particles:

- **Material:**
  Dielectric (polystyrene, silica); Metallic (gold, silver, copper), Biological (cells, macro-molecules, intracellular structures, DNA filaments), Low index (ultrasound agent contrast)
- **Size:** 10 nm – 20 µm
- **Shape:** spherical, cylindrical, arbitrary

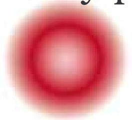
Types of laser beams:

- **Gaussian**



x-y intensity profile

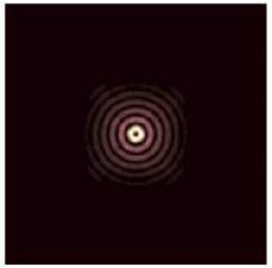
- **Laguerre-Gaussian**



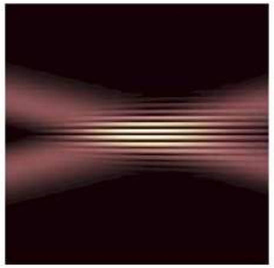
LG carries also orbital angular momentum that can be transferred to the trapped particles

- **Bessel**

x-y intensity profile



z axis propagation
non diffracted beam



Other characteristics:

- Typical stiffness: 100 pN/µm
- Typical displacements: 1-500 nm
- Typical forces: 0.1-100 pN
- Measurable displacements < 1 nm @ 1 MHz sampling rate

Comparison of OT forces with other techniques and biological processes:

Optical traps	0.1 - 100 pN
Electric fields (electrophoresis)	0-1 pN
AFM	10 - 10000 pN
Kinesin step	3-5 pN
RNA polymerase stalling	15-30 pN
Virus motor stalling	~50 pN
DNA conformational change	~65 pN
Biotin-streptavidin binding	300-400 pN

Courtesy Prof. D. Petrov, ICFO, Barcelona, Spain
http://users.icfo.es/Dmitri.Petrov/Teaching/lectures.htm

Optical forces: scattering, gradient, binding

E-M field (governed by Maxwell's equations) **exerts a force when impinging on objects.**

This force can be either computed: 1. via a direct application of the Lorentz force and bound/free current/charges within the volume of changes **2.** via the Maxwell stress tensor.

Advantage: in 2, computation efficiency since the E-M fields need to be evaluated only on a surface enclosing the object, while method 1 needs the evaluation of the fields within the whole volume.

Disadvantage: the polarizability of the object within its volume is not computed

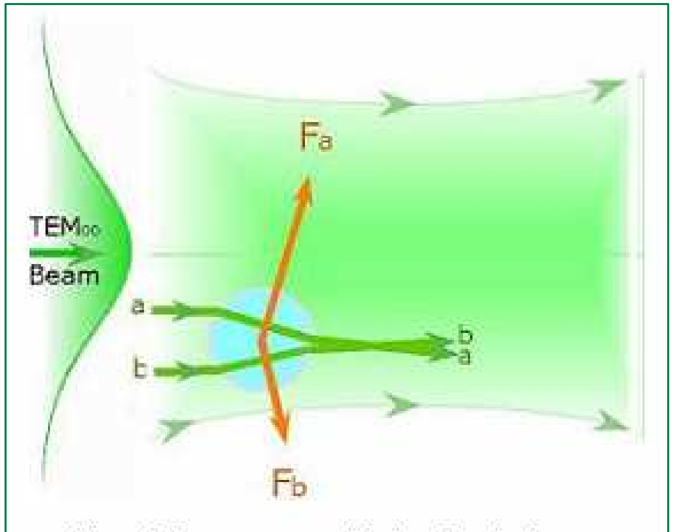


Figure 3: Forces on a particle in a Gaussian beam.
Image: J.-M. Fournier.

The **force** can be expressed as a sum of two terms:

1. the **scattering force**: a force that is parallel to the Poynting vector of the propagating wave, pushing or pulling the object in the same direction as the wave propagation.
2. the **gradient force**: a force due to the gradient of intensity of the electromagnetic radiation. Such gradient is typically obtained by laser beams or in optical lattices.

Usually there are more particles interacting with the laser beam → 3. The **binding force** represents the self-consistent interaction between the multiple particles and the incident wave

http://web.mit.edu/~ceta/obt/fund-forces.html

M. Burns, J-M. Fournier and J. Golovchenko, Optical Binding, Phys. Rev. Lett., 1989.

Radiation pressure exerted by light.

Optical trapping. Optical levitation.

Optical forces.

Comparison betweeen various types of optical tweezers.

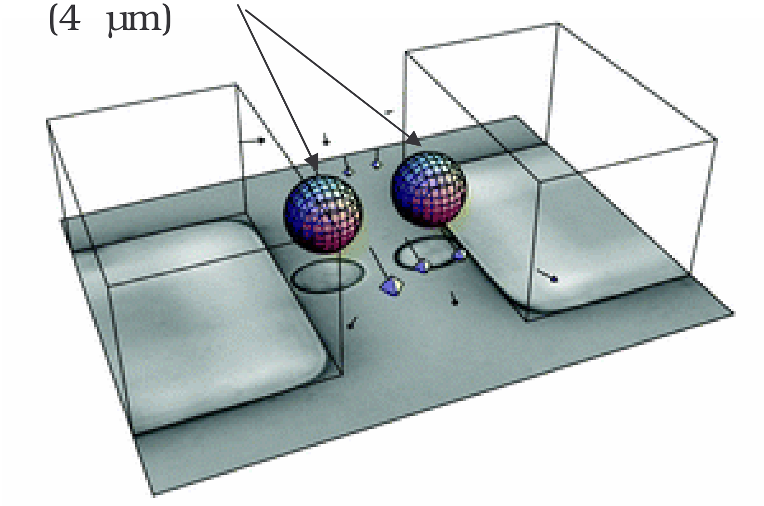
Lectures
Jean-Marc FOURNIER
EPFL - Lausanne, Switzerland

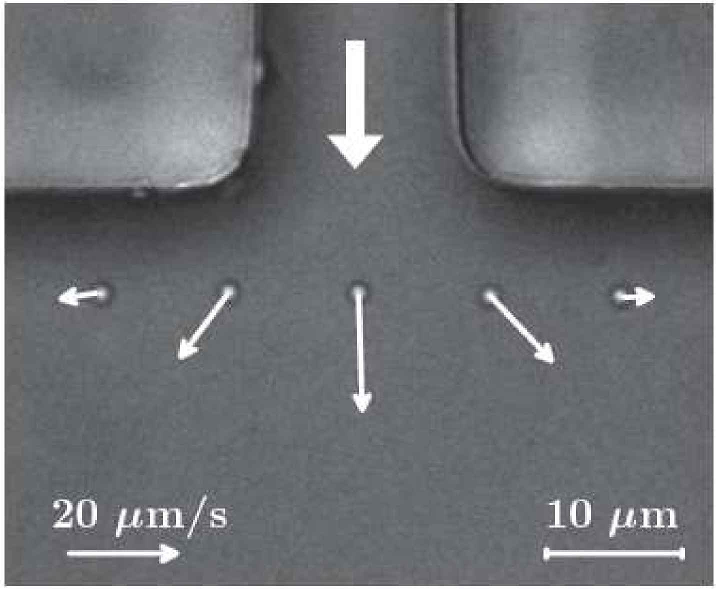
Optical manipulation of living cells in fluids.

- Select, trap, orient and move a living cell;
- cell arraying and sorting;
- apply controlled forces to cell membranes and measure mechanical properties (e.g. visco-elasticity) of the cell membranes, measure the forces generatated by motile structures of the cell in pN range.
- drug delivery vector manipulation

Lecture
Dan COJOC
Nat. Lab. TASC – Trieste, Italy

Optical driven pumps and optical sensing flow measurement





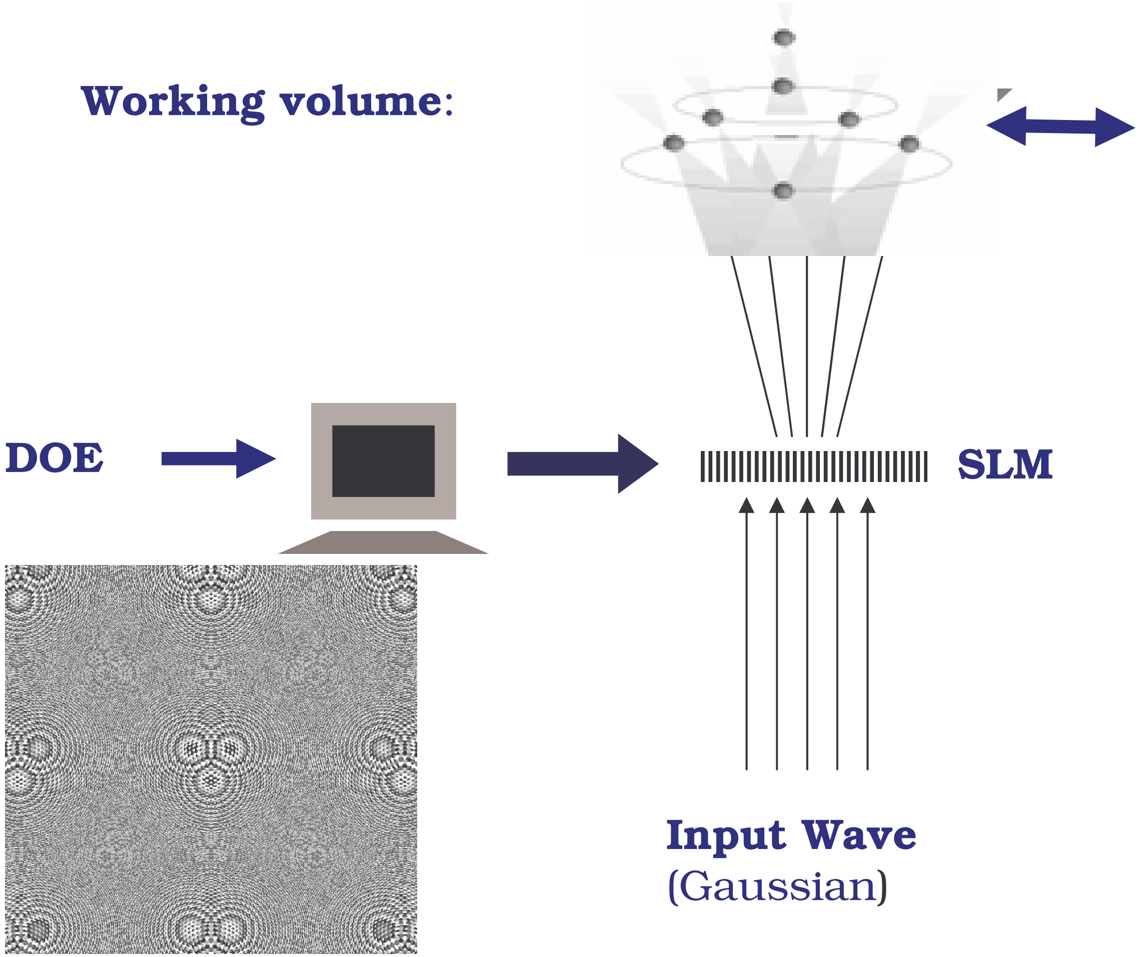
The transfer of spin angular momentum
from a circularly polarized laser
beam rotates the particles at up to 10 Hz.

Flow rates of up to 200 µm3 s–1 (200 fL s–1).

J. Leach *et al* Lab on a Chip, 2006, *6*, 735

R. Di Leonardo, PRL ***96,*** 134502 (2006)

Multiple trapping with Diffractive Optical Elements implemented on Spatial Light Modulators

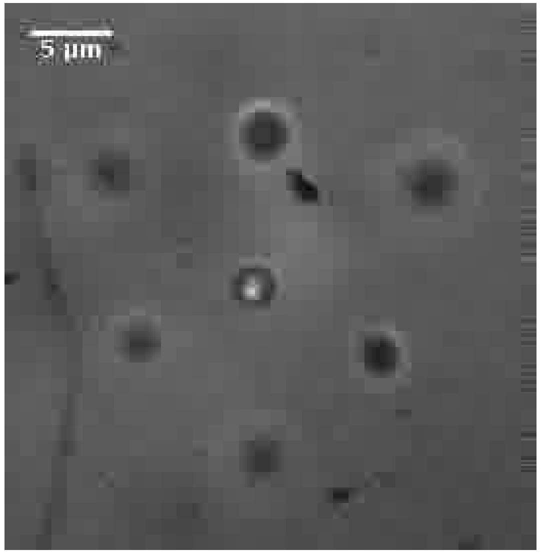


Working volume:

DOE

SLM

Input Wave
(Gaussian)



D. Cojoc *et al* Jap.J.Appl.Phys. ***43***(6), 3910 (2004)

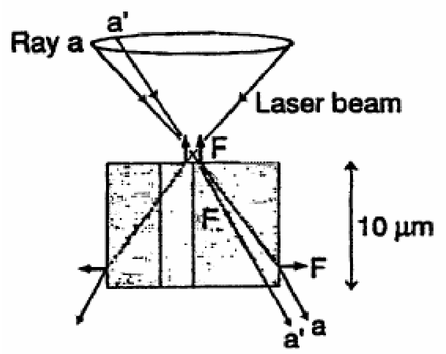
- Use of SLM for beam shaping and optical tweezers.
- Use of high-speed imaging for applications in optical tweezers.
- Applications of SLMs and high-speed imaging in optofluidics.

Lectures
Milles Padgett
University of Glasgow, UK

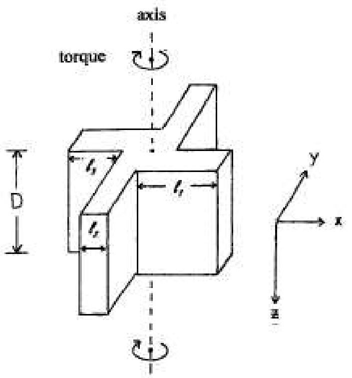
- Computer generated holograms: multipoint interactive, 3D array of traps.
- Statistical micro-hydrodynamics: fluid phenomena at the micron scale.
- Driving micro-devices with biological active fluids: new physics, new technology.

Lectures
Roberto Di LEONARDO
University La Sapienza, Rome, Italy

Optically driving of optically microfabricated rotors



Side view



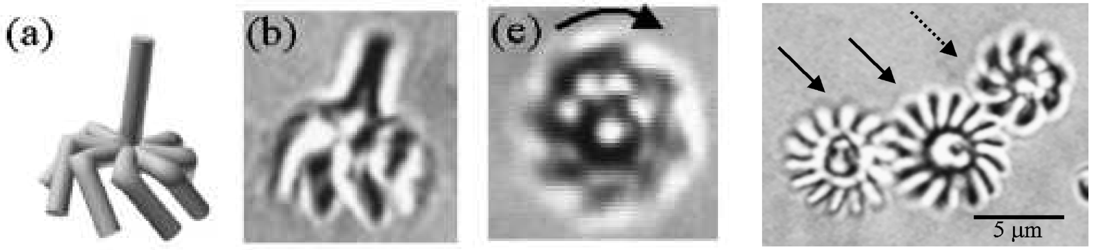
Perspective diagram

SiO2

Optical lithography
+ RIE

22 rpm/80 mW

E. Higurashi *et al*, *Appl. Phys. Lett.* **64**, 2209 (1994)



Norland resin

Two-photon lithography

20 rpm /80 mW

P. Galajda and P. Ormos, *Appl. Phys. Lett.* **78**, 249 (2001).

Optical control of electroosmotic fluid flow.

Optical control in itnegrated optical microfluidic devices.

Extended optical micromanipulation with test objects of special shape.

Lectures
Pal ORMOS
Hungarian Academy of Sciences, Szeged

Micro and nano fabrication techniques

for optofluidic devices

Lectures
Massimo TORMEN
Nat. Lab. TASC - Trieste, Italy

I wish that at the end of this week we shall know something more about Optofluidics !

Enjoy the lectures and discussions on Optofluidics !

Thank you !