Introduction to Optofluidics

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What is Optofluidics? What shall we discuss this week?

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What shall we discuss this week?

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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.

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.


**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.”


What is Optofluidics?

Light manipulates fluid and/or fluid manipulates light

Table 1 Optical devices that employ fluids

<table>
<thead>
<tr>
<th>Device or application</th>
<th>Direction of manipulation</th>
<th>Structure</th>
<th>General purpose</th>
<th>Fluidics provides</th>
<th>Refractive index important?</th>
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Table 2 Optofluidic devices and applications

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

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

Example

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

The force induced by the radiation pressure:

\[ \overrightarrow{F_r} = n_i \cos^2 \theta_i \left[ 1 + R(\theta_i, \theta_t) \right] \cdot \tan \theta_t \cdot T(\theta_i, \theta_t) \cdot \frac{P}{c} \cdot \overrightarrow{n} = A \cdot \frac{P}{c} \cdot \overrightarrow{n} \]

\( \overrightarrow{F_r} \) 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), \( \theta_i = 30^0 \)

\[ \overrightarrow{F_r} \sim -0.391 \ \frac{P}{c} \ \overrightarrow{n} \]

where: \( P \) – incident light power in watts, \( c \) – light velocity in vacuum, \( A = -0.391 \); for \( P = 1 \) W

\[ |\overrightarrow{F_r}| = 1.3 \ \text{nN} \]

Please calculate yourself to check!
Q: Is $F_r$ big enough to induce a detectable 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: $F_s \sim 2\pi r S$ maximum,
For: $r=1.2 \, \mu m$, $S=72$ $mN/m$ (surface tension of the water surface against the air at $T=25^\circ C$) $\rightarrow F_s \sim 543$ nN

Radiation pressure force: $F_r \sim 0.825 \, P/c$
considering $n_i=1 \, (air)$, $n_t=1.3 \, (\sim water)$, $\theta_i=1^0$

$F_r > F_s \rightarrow P > 198 \, W = P_0$

Pulsed laser: $P=1-4 \, kW \sim 5-20 \, P_0$

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 below 1 MW, the threshold for self-focusing

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

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.

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

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

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

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

**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.

The optofluidic microscope

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.


Optical tweezers
a technique to trap and manipulate micro-objects in fluid

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

\[ F = Q \frac{n_m W}{c} \]

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

**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**
- **Bessel**
- **Laguerre-Gaussian**

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

**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:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Force (pN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical traps</td>
<td>0.1 - 100</td>
</tr>
<tr>
<td>Electric fields (electrophoresis)</td>
<td>0-1</td>
</tr>
<tr>
<td>AFM</td>
<td>10 - 10000</td>
</tr>
<tr>
<td>Kinesin step</td>
<td>3-5</td>
</tr>
<tr>
<td>RNA polymerase stalling</td>
<td>15-30</td>
</tr>
<tr>
<td>Virus motor stalling</td>
<td>~50</td>
</tr>
<tr>
<td>DNA conformational change</td>
<td>~65</td>
</tr>
<tr>
<td>Biotin-streptavidin binding</td>
<td>300-400</td>
</tr>
</tbody>
</table>

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.

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

Radiation pressure exerted by light.
Optical trapping. Optical levitation.
Optical forces.
Comparison between various types of optical tweezers.

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 generated by motile structures of the cell in pN range.
• Drug delivery vector manipulation
Optical driven pumps and optical sensing flow measurement

Birefringent vaterite microspheres (4 µm)

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

Multiple trapping with Diffractive Optical Elements implemented on Spatial Light Modulators

Working volume:

Input Wave (Gaussian)

• 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.

• 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.
Optically driving of optically microfabricated rotors

Side view  Perspective diagram

SiO2  22 rpm/80 mW
Optical lithography + RIE


Norland resin
Two-photon lithography
20 rpm /80 mW

Optical control of electroosmotic fluid flow.

Optical control in integrated optical microfluidic devices.

Extended optical micromanipulation with test objects of special shape.

Micro and nano fabrication techniques for optofluidic devices.
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!