Nanomaterials and their Optical Applications

Winter Semester 2012 - 2013

Lecture 10
Schedule until the end of the semester

Lecture, Mondays 16-17.30

<table>
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<th>Date</th>
<th>Topic</th>
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<tbody>
<tr>
<td>9</td>
<td>10.12.2012</td>
<td>Paper 9, Optofluidic 1</td>
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<td>14.01.2013</td>
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<td>Seminars presentations by students (2)</td>
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<td>13</td>
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Seminar, Tuesdays

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<td>6</td>
<td>08.01.2013</td>
<td>Paper 10 / Solutions HW 4 / Q's for talk</td>
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Examination: February 14th
Beutenberg campus, IAP, 14.30-16.30

Turn in HW 3 on Tuesday 17.12.2012, scan or give it to Can!
## Lecture: Nanomaterials and their optical applications

<table>
<thead>
<tr>
<th>Date</th>
<th>Room</th>
<th>Time</th>
<th>Speaker</th>
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<tr>
<td>21.01</td>
<td>IAP</td>
<td>16.00</td>
<td>Yera Ussembayev</td>
<td>Plasmonic nanoparticles for biomedicine</td>
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<td>16.30</td>
<td>Sebastian Unger</td>
<td>Nanodiamonds</td>
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<td></td>
<td>17.00</td>
<td>Zhi</td>
<td>Upconversion nanoparticles</td>
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<td>28.01</td>
<td>IAP</td>
<td>16.00</td>
<td>Pavlo Kliniev</td>
<td>Nanowires as biosensors</td>
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<td>16.30</td>
<td>Can Boran Akdal</td>
<td>SPASERs</td>
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<td></td>
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<td>17.00</td>
<td>Wondimu Alemu</td>
<td>High resolution microscopy</td>
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Map to reach the IAP seminarraum at Beutenberg Campus

Campus Beutenberg,
Institut für Angewandte Physik (IAP)
Seminarraum 1st floor
Albert-Einstein-Straße 15
07745 Jena

How to find us by Public Transport
1. to the railway stations Jena-West, Jena-Paradies or Jena-Saalbahnhof,
2. bus no. 10, 11, 12 and 13 will pass by »Campus Beutenberg
Outline: Optofluidics

• What is optofluidic?
• History of micro-nano-opto-fluidic
• Basic properties of fluids
• Nanoscale forces and scale law
• Optofluidic: fabrication
• Optofluidic: applications
Optofluidic Devices

3 categories

- Solid-liquid hybrid devices
- Complete fluid based devices
- Colloid based systems

**Fluids in solids:** optofluidic microscope, DFB laser, photonic bandgap structures

**Fluids in fluids:** liquid core / liquid cladding for waveguiding, liquid lens

**Solids in fluids:** tweezing of colloidal particles
1. **Optofluidic microscope**

- Portable imaging device without bulk optic
- High resolution and speed
- Integration friendly

**Slanted hole array**
Y: sub-wavelength resolution : 300 nm

**Main assumption:**
Micro-organism flows with constant speed, shape and orientation

1. Optofluidic microscope

Slanted hole array: fabrication by e-beam lithography

Hole size: 200 x 700 nm
Channel width: 10 x 40 µm
1. Optofluidic microscope

Point-by-point mapping: apertures in metal film map to pixels on a camera
2. Optofluidic dye lasers

**Liquid medium** : optical gain, the lasing wavelength, spatial modes and tunability

1. Advantages compared to bulk dye lasers
2. Unique optical performances not possible with solid-state lasers, like the wavelength
3. Lab-on-chip system

Single mode operation using a **Bragg grating**

The reflected wavelength ($\lambda_B$), called the Bragg wavelength, is defined by the relationship,

$$\lambda_B = 2n_e \Lambda$$

How? by creating a periodic variation in the refractive index of the fiber core, which generates a wavelength specific dielectric mirror. Used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector.
2. Optofluidic dye lasers

How to get a single mode laser?
- Confinement of the modes to get only $E_{11}$ for instance
- Free spectral range (FSR) of the cavity must be larger than the gain spectral bandwidth

$$m \lambda_m = 2n_{eff} \Lambda$$

$$\text{FSR} = \frac{\lambda_m}{m-1}, \quad (\text{or} \quad \Delta v = \frac{c}{2n_{eff} \Lambda})$$
2. Optofluidic dye lasers

Periodic structure = PDMS post (grating spaced by $\Lambda$) that reflects light with wavelength equal to $2n\Lambda/m$ = feed back for the laser operation

n beeing the refractive index of the structure
Thus tuning the frequency by changing n

How to get a single mode laser?
• Confinement of the modes to get only $E_{11}$ for instance
• Free spectral range (FSR) of the cavity must be larger than the gain spectral bandwidth
2. Optofluidic dye lasers

Liquid dye laser characteristics

Solution or organic dyes in a solvent
Rodamine 6G

4 level system
Triplet states may disturb: use short pulses and fast dye circulation

Fig. 2 Typical energy levels of a dye molecule. Each transition is labeled by its corresponding cross section or lifetime.
2. Optofluidic dye lasers

**Liquid medium**: optical gain, the lasing wavelength, spatial modes and tunability

1. Advantages compared to bulk dye lasers
2. Unique optical performances not possible with solid-state lasers, like the wavelength
3. Lab-on-chip system

2. Optofluidic dye lasers

Periodic structure (grating spaced by $\Lambda$) that reflects light with wavelength equal to $2n\Lambda/m$

$n$ being the refractive index of the structure
Thus tuning the frequency by changing $n$
Optofluidic Devices: **Fluids in fluids**

- Easy to reconfigure by changing the fluids or their flow rates
- Smooth optical interfaces between fluids without high-precision fabrication. Why?
- Easy to obtain gradient by diffusion between miscible liquids

**Design:**

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
How to provide contrast of refractive index?

1. Different liquids, $n = 1.28 - 1.75$
2. Different concentrations $n = 1.3354 - 1.4420$
3. Different temperatures: thermo-optical coefficient
   $n$ (water $10^\circ$ C) = 1.3325, $n$ (water $75^\circ$ C) = 1.3235
4. Suspension of particles: polystyrene particles in water
5. Modulation with external forces: electric field for liquid crystals

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
Switching time of liquids: not fast, second

OK for optical sensing and bioassays

Small irregularities in the walls do not propagate at the liquid interface
Switching time of liquids: not fast, second

OK for optical sensing and bioassays

Small irregularities in the walls do not propagate at the liquid interface

Match the refractive index of PDMS with the liquid to reduce scattering of light

Interface between liquids is diffuse: gradient – good for GRIN lenses

A gradient-index lens with a parabolic variation of refractive index \( n \) with radial distance \( x \). The lens focuses light in the same way as a conventional lens.

Such variations can be used to produce lenses with flat surfaces, or lenses that do not have the aberrations typical of traditional spherical lenses.
L2 Waveguides

- 2 streams of liquids of lower refractive index (cladding), water $n = 1.33$
- A stream of liquid of higher refractive index (core), calcium chloride 5M $n = 1.45$

By changing the core width: control what?

- From 100 $\mu$m down to 10 $\mu$m. How to change this width?
- 5 mm of propagation before suffering from diffusive mixing at a flow rate of 10 $\mu$l/min

Losses

- 0.1 dB/cm
- In optical fiber: 0.2 dB/km
Optofluidic Devices: Fluids in fluids

L2 Waveguides

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
L2 Waveguides: optical switch, relative rates of flow of the cladding liquids determine the path of the core liquid.
L2 Waveguides

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009

Optofluidic Devices: Fluids in fluids
L2 Waveguides: light sources
Optofluidic Devices: Fluids in fluids

L2 Waveguides

Advantages

• Dynamically reconfigurable, because of the laminar flow
• Simple fabrication, the roughness of walls does not affect the smoothness of the interfaces

Drawbacks

• Constant supply of liquids needed, 144 ml for a 24 hours use at a 100 µl/min
• Unable to guide light at Telecom wavelength (1300-1600nm)
• Speed of optical switching is 0.1 Hz much lower than 1-100 GHz

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
**L2 Lenses**

From biconvex to plano-convex by changing the relative rates of flow between the core and the cladding stream
Optofluidic Devices: Fluids in fluids

L2 Lenses

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
L2 Lenses

Focus achieved: 16 µm and diffraction limits would have been 7 µm

(a) Increasing core flow rate

(b) Increasing left cladding flow rate

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
L2 Lenses

Tang & Whitesides, Optical components based on Dynamic Liquid-Liquid Interfaces, in Optofluidics, McGraw-Hill, 2009
Optofluidic Devices: solids in fluids

Optical and fluidic applications of plasmonic nanoparticles as localized thermal heat sources

- Use different species of plasmonic nanoparticles as localized thermal sources
- Different lasers to heat different regions
- Demonstrate an optically controlled display
- Demonstrate optofluidic control with functionalized walls
Optical and fluidic applications of plasmonic nanoparticles as localized thermal heat sources
Optofluidic Devices: solids in fluids

- Glass slide
- Ag nanoparticles
- Au nanoparticles

Graph showing extinction as a function of wavelength:
- Wavelength (nm): 300, 400, 500, 600, 700, 800
- Extinction (a.u.): 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2

- 400 nm
- 532 nm

Liquid crystals
Thermal effects on liquid crystals

Nematic
General order to LC within small domains

Isotropic
Lack of any order to LC Appears dark under crossed polarizers

29 C for 6CB*

Optofluidic Devices: solids in fluids

- 532 nm & 400 nm
- 40x
- polarizer
- Filter & polarizer
- white light
- CCD
- Glass slide
- Height: 5 microns
- 4-8 mW at sample
- White light
- CCD

rachel.grange@uni-jena.de Lecture 10
Optofluidic Devices: solids in fluids

100 nm fluorescent beads

(a) Laser beam below threshold (7 mW)
(b) Laser beam below threshold (7 mW)
(c) Laser beam above threshold (10 mW)
(d) Laser beam above threshold (10 mW)
Ming Wu's group image-driven optical manipulation tool called "optoelectronic tweezers".
Using light-induced dielectrophoresis on a photoconductor, virtual electrode pattern is generated by projecting an LED light through a DMD spatial light modulator. A single LED is capable of generating more than 15,000 individually addressable traps.

**Conveyor**

**digital micromirror device**

- mirrors can be individually rotated ±10-12°, to an on or off state
- on state: light from the projector bulb is reflected into the lens making the pixel appear bright on the screen
- off state, the light is directed onto a heatsink making the pixel dark.

1. Applications in nature:
   • **Lotus effect** (one of your talk) for self-cleaning surfaces
   • Active transport in **ion channels**

2. Artificial applications
   • **Separation science**: conjugated from unconjugated
   • **Single molecule studies**: confinement of DNA, nanopore, zero-mode waveguide
   • **Information technology**: logic with acid and bases, DNA computer

Zero-Mode Waveguides for Single-Molecule Analysis at High Concentrations
Zero-Mode waveguide

optical waveguide that guides light energy into a volume that is small in all dimensions compared to the wavelength of the light.

Device = subwavelength hole in a metal film

Zero-mode waveguides have been developed for rapid parallel sensing of zeptolitres sample volumes, as applied to gene sequencing, by Pacific Biosciences (previously named Nanofluidics, Inc.)

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Zero-Mode Waveguides for Single-Molecule Analysis at High Concentrations
Zero-Mode waveguide

Volume is: attolitres or zeptolitres

(10^{-18} to 10^{-21} L)

Zero-Mode Waveguides for Single-Molecule Analysis at High Concentrations
Zero-Mode waveguide

Zero-Mode Waveguides for Single-Molecule Analysis at High Concentrations
Zero-Mode waveguide

Fig. 2. (A) Three-dimensional finite-element time-domain simulation of the intensity distribution (log scale) for a zero-mode waveguide 50 nm in diameter and 100 nm long. (B) $S(z)$ curves for different waveguide diameter, $d$. (C) $V_{\text{eff}}$ and the corresponding concentration for which there is, on average, one molecule in the volume ($\langle N \rangle = 1$).
Zero-Mode waveguide

Zero-Mode Waveguides for Single-Molecule Analysis at High Concentrations
Optofluidics for Energy Applications

(A) Photobioreactor

Energy + water + CO₂ → Photosynthesis reaction → Sugar fermentation → Fuel
Optofluidics for Energy Applications

(A) Photobioreactor

Important issues:
• Solarization dependent performance
• Shadowing of plates
• Non-uniform irradiation of species
• Might need heat sink
• Few surfaces for huge volumes
1-mm-diameter capillary-based liquid reaction chamber with nanoparticle co-catalysts generated hydrogen at 0.59 mL/min under focused green laser light. This production rate is more than 1,000 times better than the performance of a comparable bulk reactor.
(B) Photocatalytic reactor

- Light energy used to split water into hydrogen and oxygen

\[ C_2H_5OH + 3H_2O + \text{heat} \rightarrow 2CO_2 + 6H_2 \]

(B) Solar energy collection

- Liquid lenses