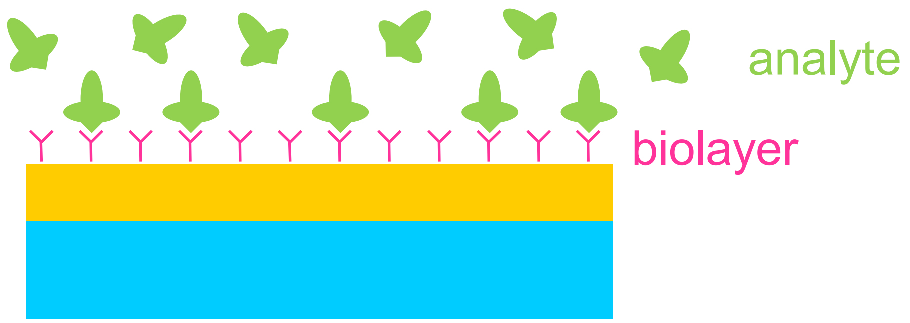
Selected Topics in Advanced Optics

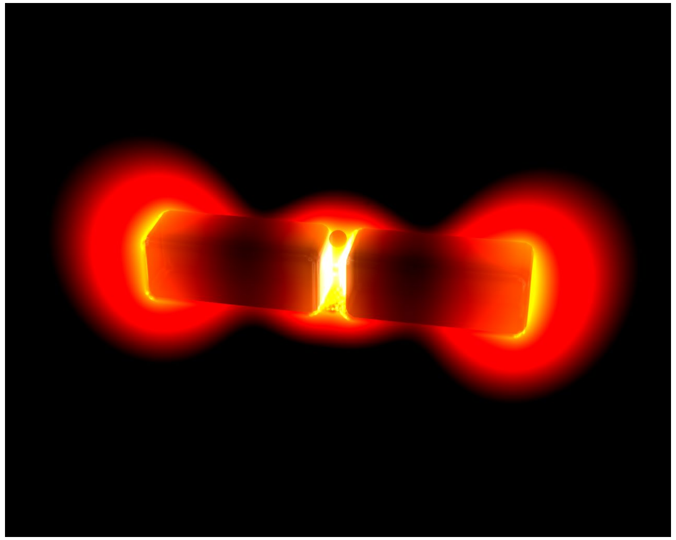
Week 7 – part 1

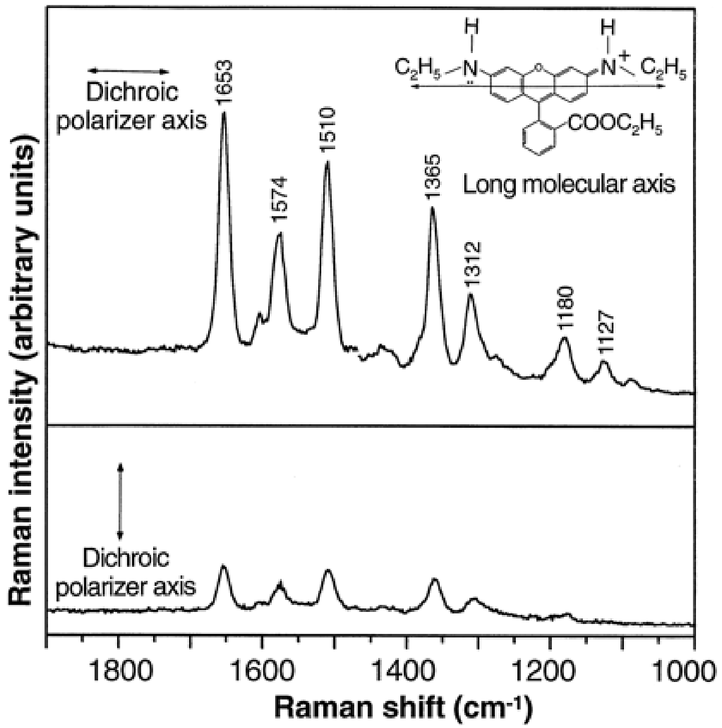
Olivier J.F. Martin
Nanophotonics and Metrology Laboratory

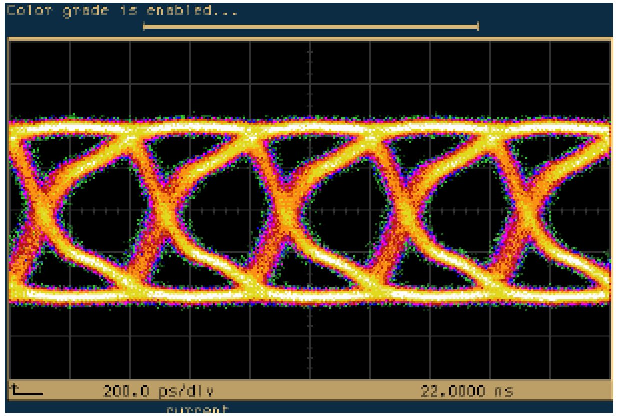
EPFL

Optics of metals and plasmonics
Part III – Applications









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Plasmonic waveguides and components

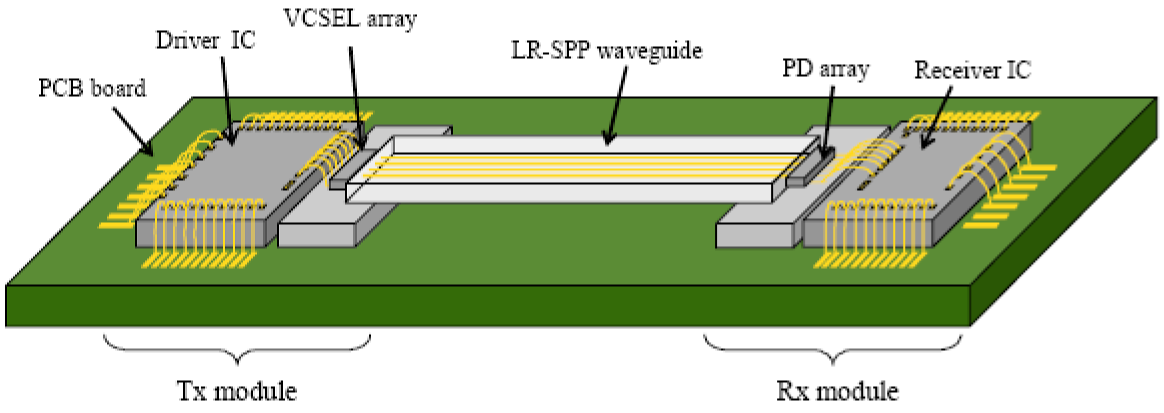
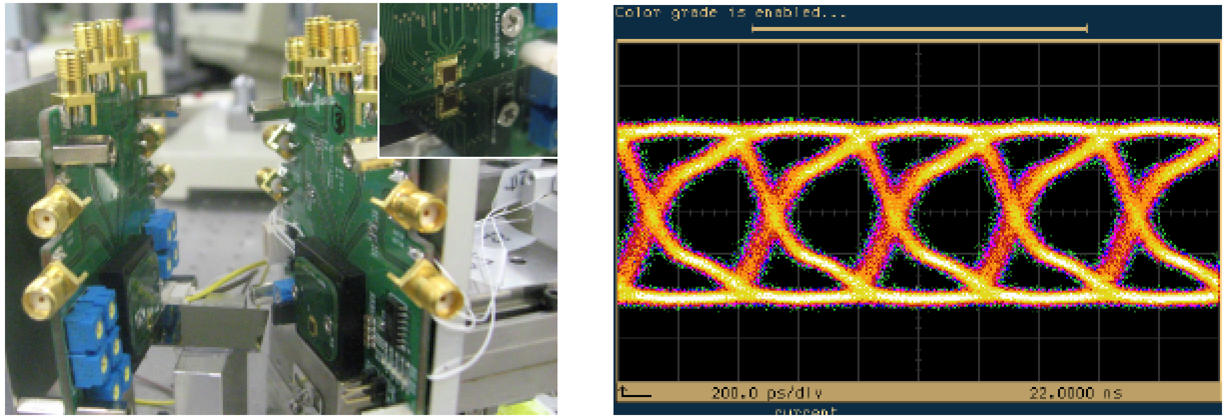


Fig. 1. Architectural view of on-board chip-to-chip optical interconnect using polymer-based Au long-range surface plasmon polariton (LR-SPP) waveguide.

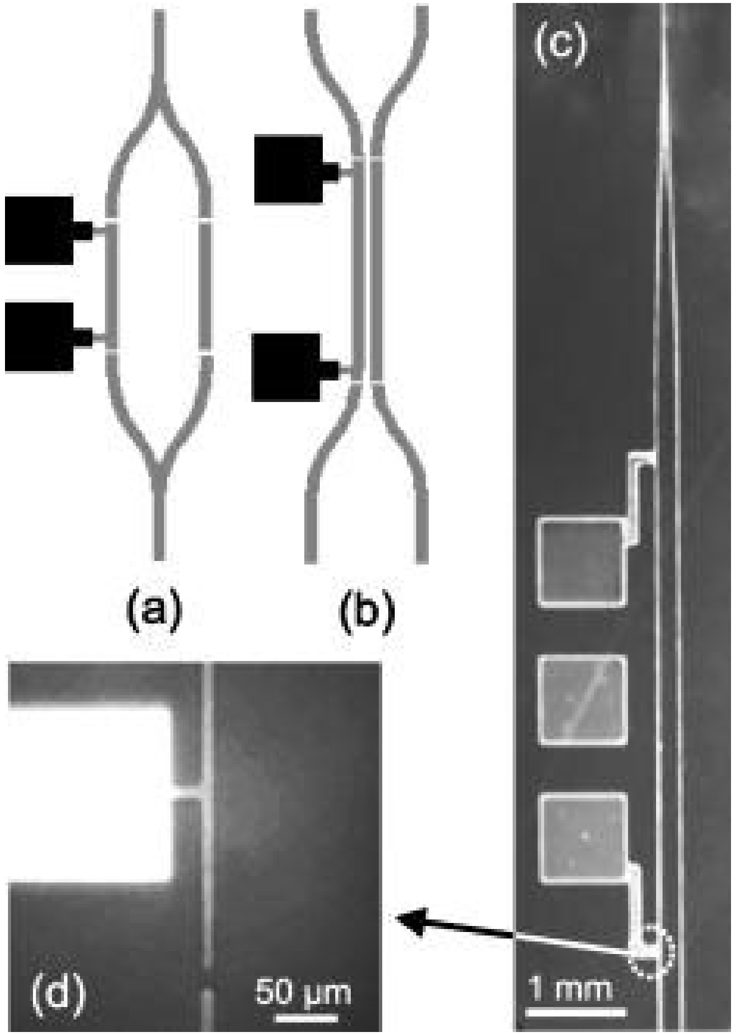


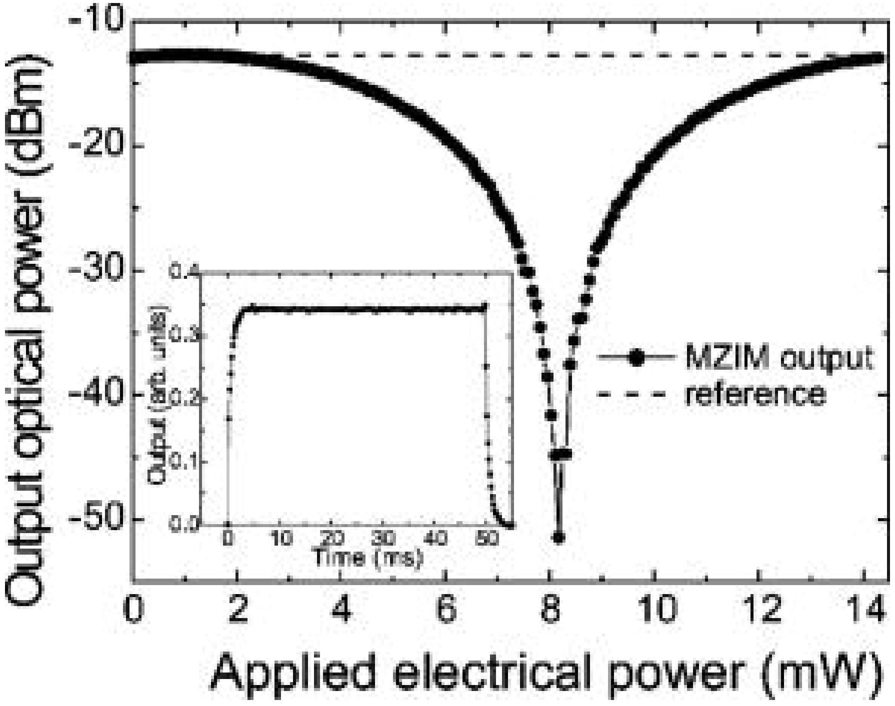
(a) (b)

Fig. 5. (a). Assembled chip-to-chip optical interconnect system using the Au LR-SPP waveguide (the inset shows the coupling between the TM-polarized VCSEL and the Au LR-SPP waveguide), and (b) measured optical eye diagram for one channel (2.5 Gbps data rate) of the four receiver channels.

J.T. Kim, Optics Express vol. 16, p. 13133 (2008)

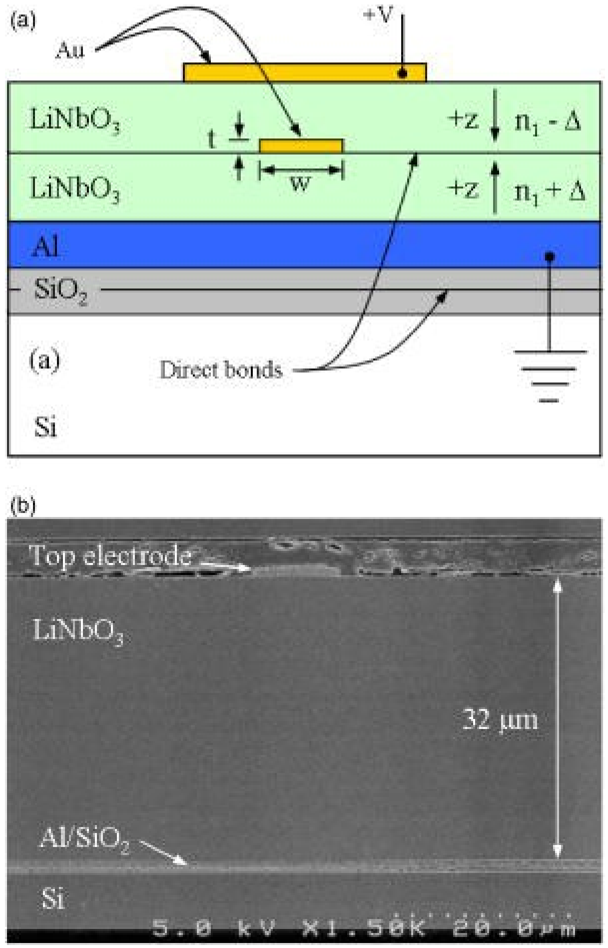
Plasmonic switch (thermo-optical Mach-Zender)

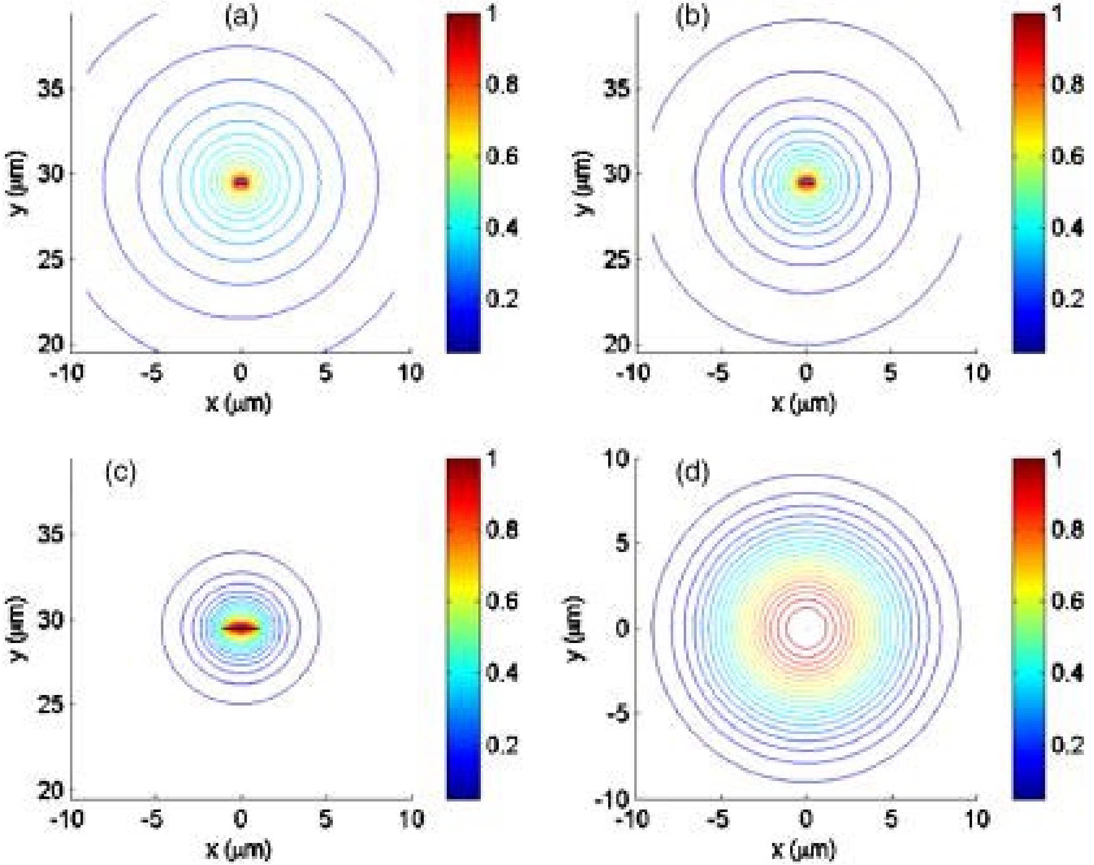




T. Nikolajsen et al., “Surface plasmon polariton based modulators and switches operating at telecom wavelengths”, Applied Physics Letters vol. 85, p. 5833 (2004).

Waveguide and modulator integration in LiNbO3





P. Berini et al., “Long-range surface plasmon-polariton waveguides and devices in lithium niobate”, *Journal of Applied Physics*, vol. 101, p. 113114 (2007).

Electro-optic modulator

- The plasmonic structure enhances the electric field to produce a strong Pockels effect

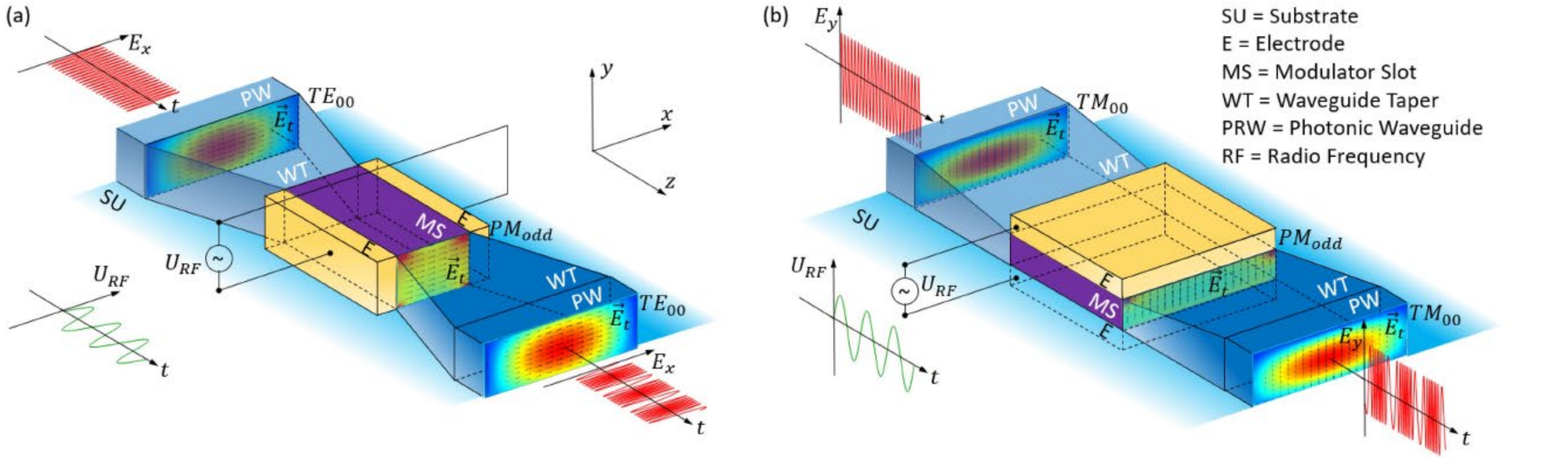


Fig. 1. (a) Horizontal- and (b) vertical-stack arrangement of an EO plasmonic modulator. An optical wave is guided in and out of the modulator by means of silicon photonic waveguides. The active area is confined to a slot within a plasmonic metal-insulator-metal (MIM) waveguide. The size of the photonic mode is adjusted to the plasmonic mode by a tapering section. At the input and output we have depicted an optical continuous wave (CW) input E_x-field component and its phase modulated output counterpart (red). The corresponding RF signal (green) used for phase modulation is also visualized. More details can be found in the text.

J. Smajic et al., “Plasmonic electro-optic modulators – A review”, *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 30, p. 3300113 (2024).

Electro-optic modulator

- Semiconductor or organic electro-optic materials can be used to modulate the optical signal above 100 GHz

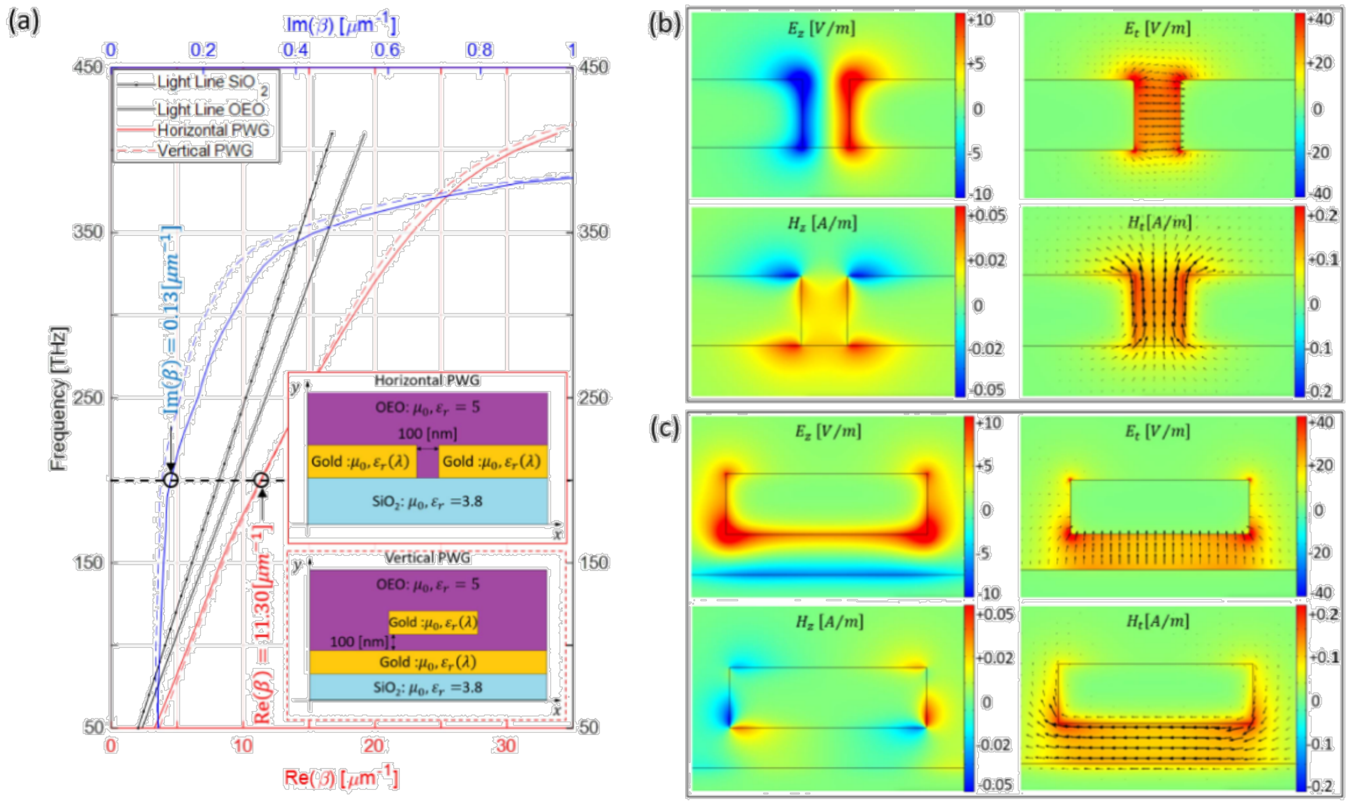


Fig. 3. Dispersion relations and field distributions of horizontal- and vertical-stack plasmonic waveguides (PWG). (a) Waveguide cross-sections and dispersion relations. Fields of guided modes of (b) horizontal and (c) vertical stack plasmonic structure for a free-space wavelength $\lambda = 1.5\ \mu m$. Here, E_z is the z-component of the electric field, $\vec{E}_t$ is the transversal electric field vector, H_z is the z-component of the magnetic field, $\vec{H}_t$ is the transversal component of the magnetic field, $\beta = Re(\beta) + jIm(\beta) = \beta_r + j\beta_i$ is the complex propagation constant of the plasmonic waveguide, and OEO represents the chosen organic electro-optical material between the golden electrodes.

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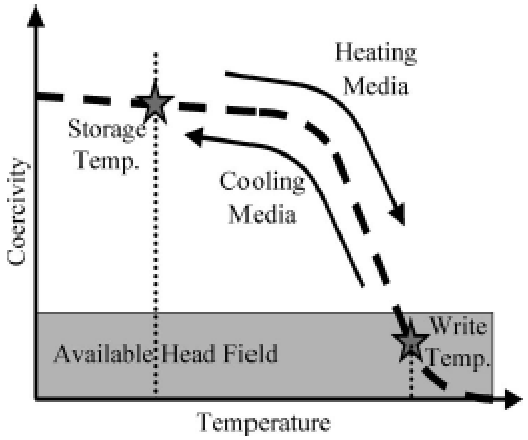
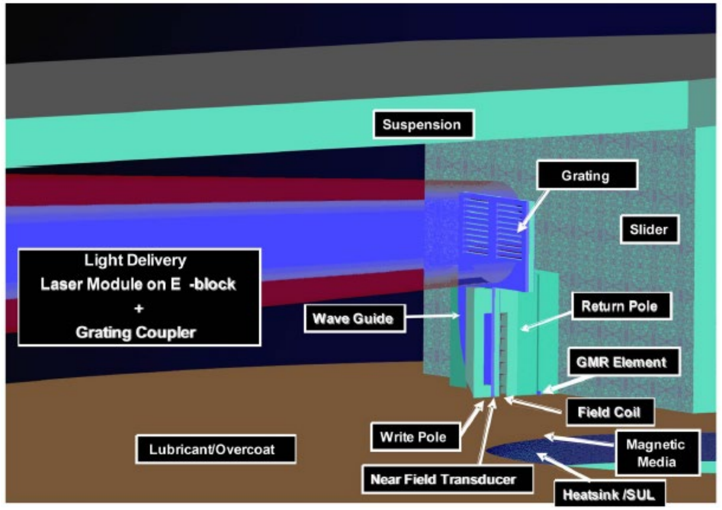
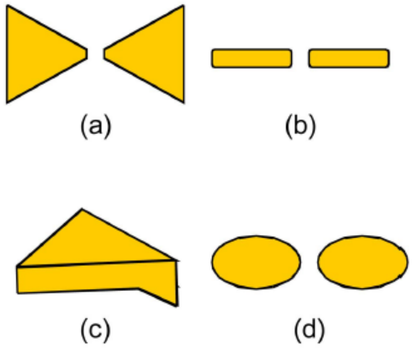
Heat-assisted magnetic recording (HAMR)

- Developed by Seagate, due to become a product soon
- Heating locally the recording medium reduces the required magnetic field for writing and increases the density 10x

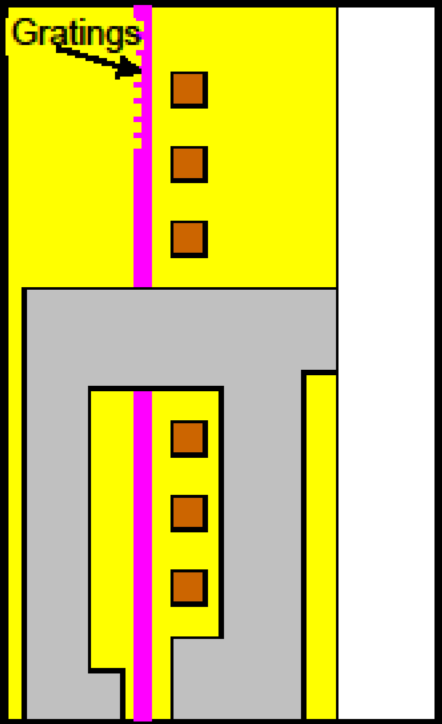


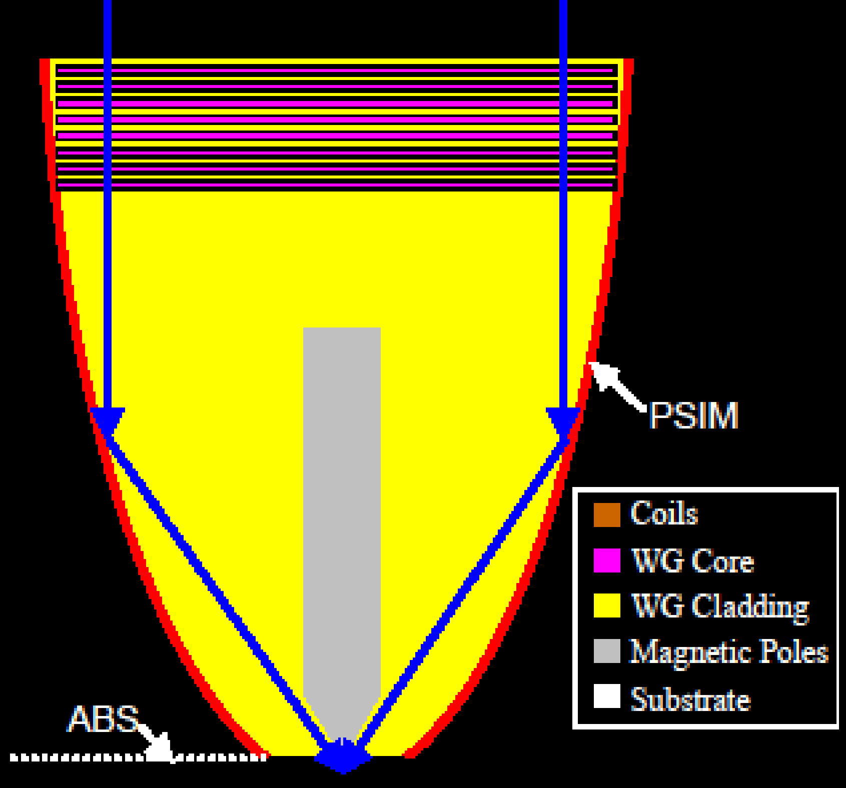


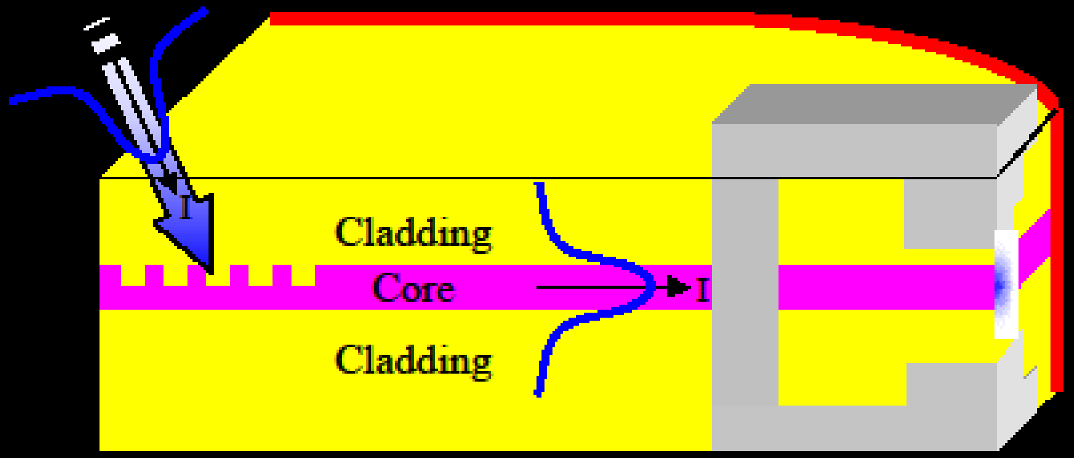


M.H. Kryder *et al.*, “Heat-assisted magnetic recording”, *Proceedings of the IEEE vol. 96, p. 2810 (2008)*.

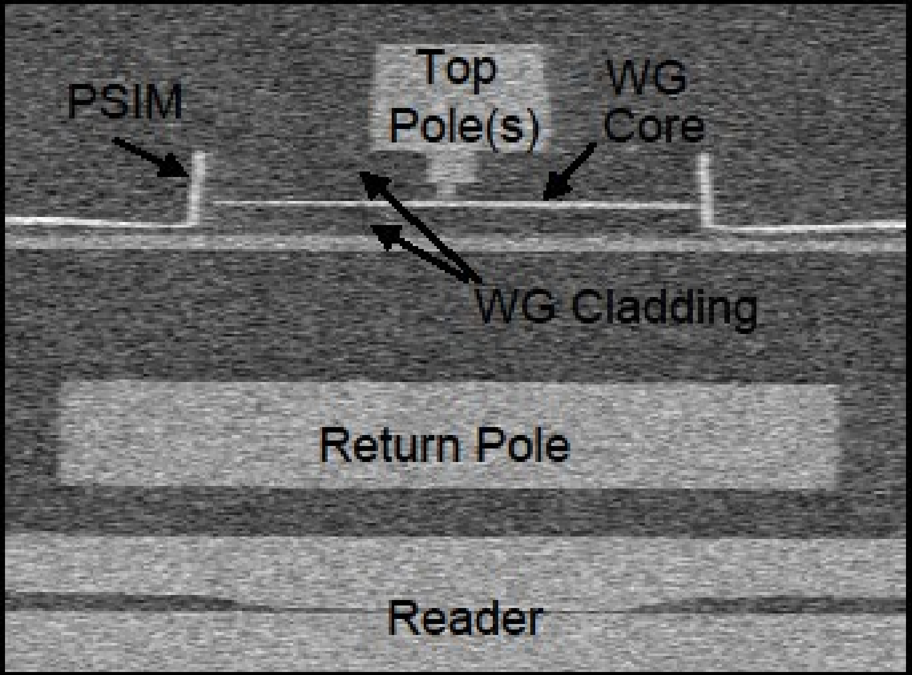
Implementation of Ring head

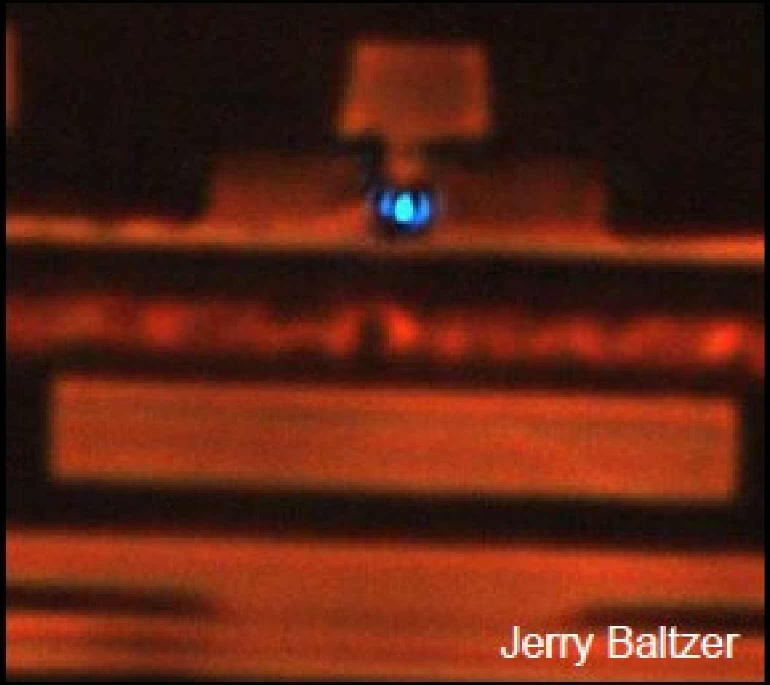






Built Integrated HAMR Head: ABS View



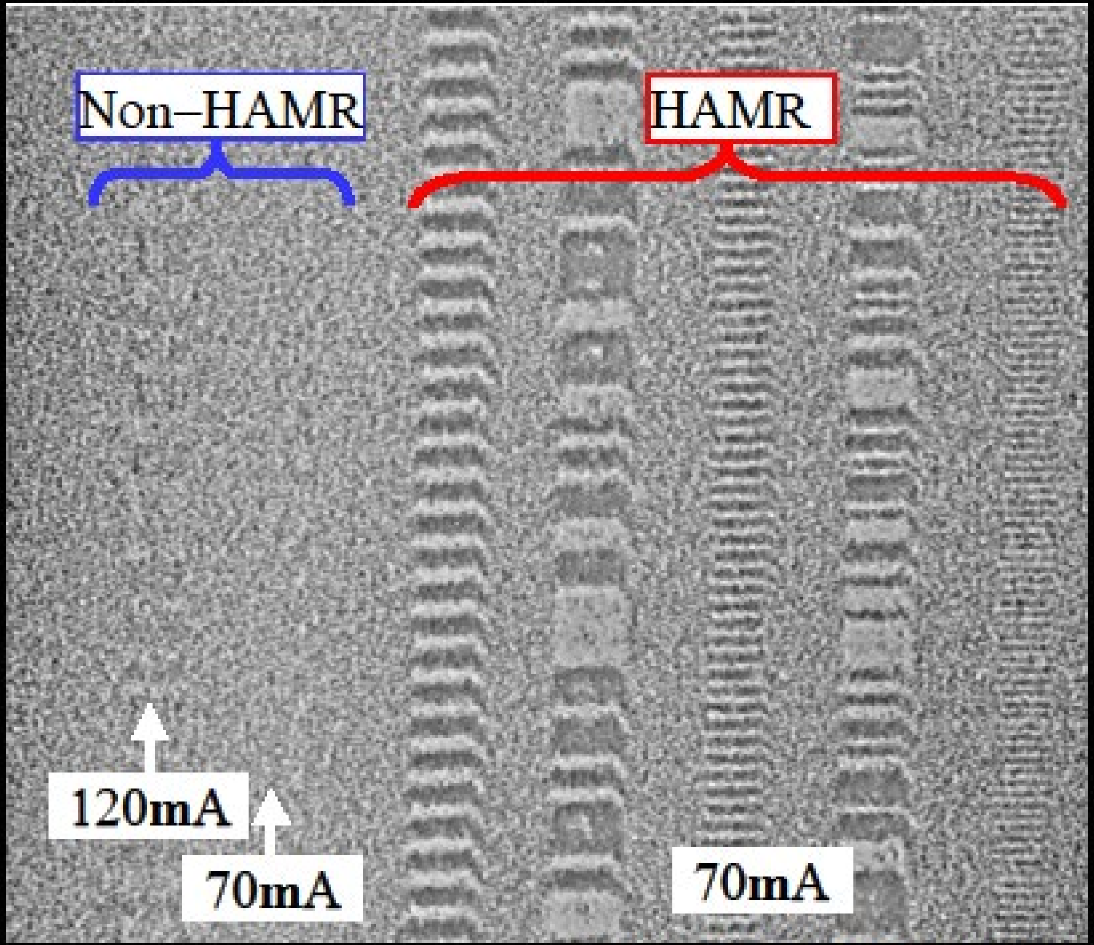


MFM of Non-HAMR & HAMR Tracks

Fully Integrated HAMR Head

HAMR Unique Media

- High Anisotropy
- Proper Heatsinking



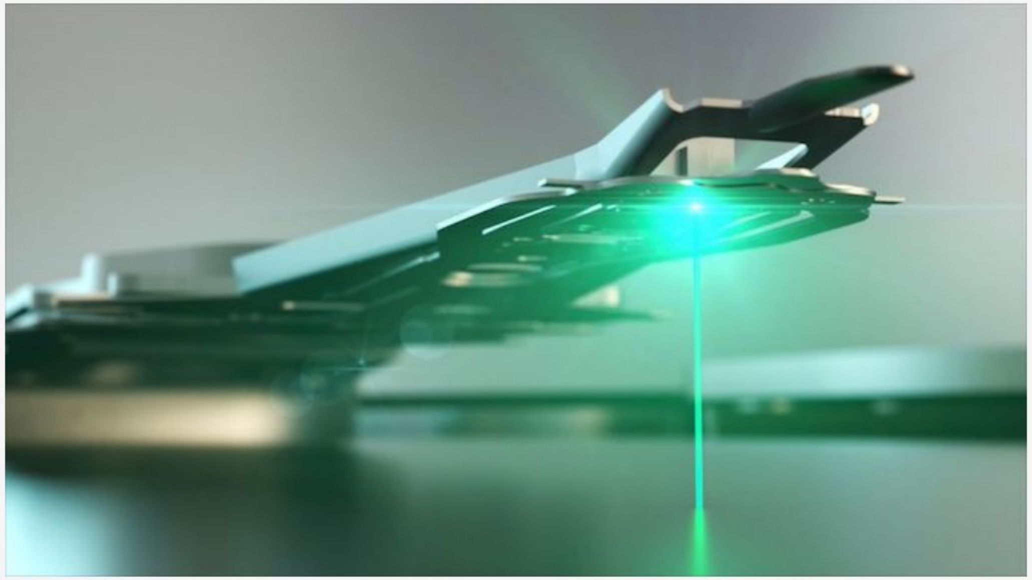
Tim Rausch, Xiaobin Zhu

Big Leap for Hard Drive Capacities: 32 TB HAMR Drives Due Soon, 40TB on Horizon

29
Comments

by Anton Shilov on June 8, 2023 8:00 AM EST

Posted in Storage Seagate HDDs SMR PMR HAMR Exos HDD CMR



Offering a brief update on the future of hard drives, Seagate has shared some fresh insights concerning launch of its next generation hard drives featuring its heat-assisted magnetic recording (HAMR) technology. The company's initial commercial HAMR hard drive is set to offer a 32 TB capacity, presumably in the third quarter of 2023, but the new recording technology will enable a relatively quick capacity increase to 40 TB. Meanwhile, high-capacity HAMR HDDs will co-exist with yet-to-be-released 24 TB and 28 TB drives.

The initial 32 TB HAMR-based HDDs from Seagate will rely on the company's 10-platter platform that is akin to that already in use by the company and which has predictable yields and which eliminates one potential point of failure. Given that the company will have to use new media and new write heads with its HAMR hard drives, it is a reasonable move to keep re-using as many proven parts as possible. That 10-platter HAMR platform will be used for 36TB, 40TB, and even higher-capacity HDDs going forward, presumably with as few changes as possible.

"When you go to HAMR, our 32TB is based on 10 disks and 20 heads," said Gianluca Romano, Seagate's chief financial officer, at the Bank of America 2023 Global Technology Conference (via SeekingAlpha). "The following product will be a 36TB and will still be based on 10 disks and 20 heads. So, all the increase is coming through areal density. The following one, 40TB, still the same 10 disks and 20 heads. Also, the 50TB, we said at our earnings release, in our lab, we are already running individual disk at 5TB."

www.anandtech.com

Compensating losses with gain

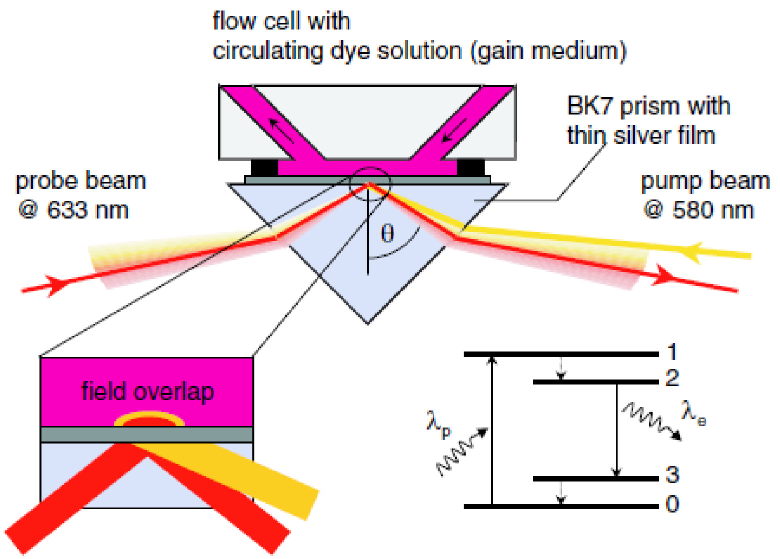


FIG. 1 (color online). Twin ATR method for SP amplification. Dye molecules, which are optically excited by the pump plasmon field, are made to coherently deliver their energy to the probe plasmon field by stimulated emission, thereby producing amplification. The signature of this process can be found in the reflected probe beam (see text). The spontaneous decay channel causes directional plasmon-coupled light emission visible as a light cone containing all colors of the dye emission spectrum. The inset shows a simplified energy level diagram of the dye molecules.

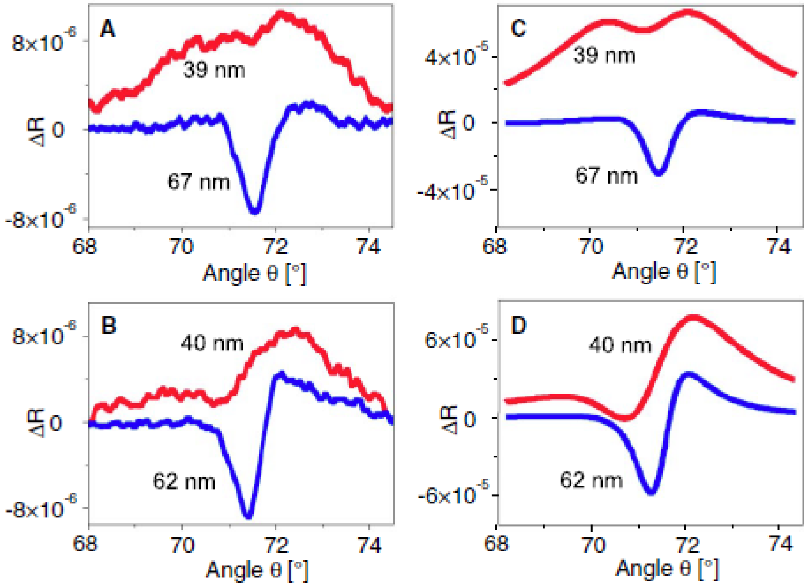
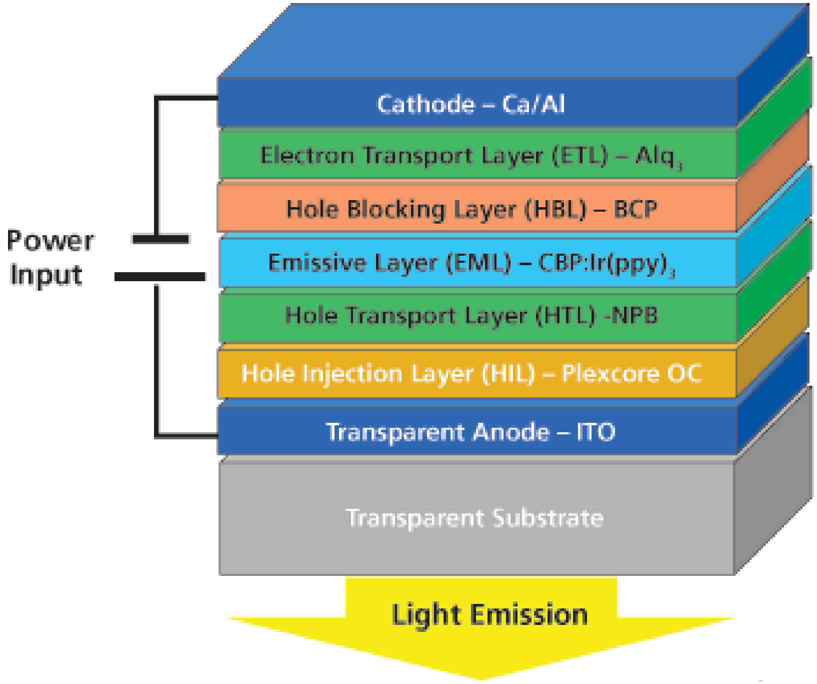


FIG. 2 (color online). Differential reflectance curves proving stimulated emission of surface plasmons for different metal film thicknesses and dyes; experiment (a), (b) and theory (c), (d). (a) and (c) refer to cresyl violet, whereas (b) and (d) depict results for rhodamine 101. The respective film thickness (measured by atomic force microscopy) is indicated for each curve. The modulation amplitude of the pump power was 10 mW root mean square (rms) for cresyl violet and 9 mW rms for rhodamine 101. The reflectance change ΔR is also given as an rms quantity. The number density of dye molecules was 7×10^{17} cm^{-3} for both dye solutions.

J. Seidel et al., “Stimulated emission of surface plasmons at the interface between a silver film and an Optically Pumped Dye Solution,” *Phys. Rev. Lett.* **94**, 177401 (2005).

Integration with organic materials

- Organic light emitting diodes always include metal layer(s)
- Often surface plasmons are excited on these metal layers and produce losses in the device
- Why not use these propagating surface plasmons for doing something useful?



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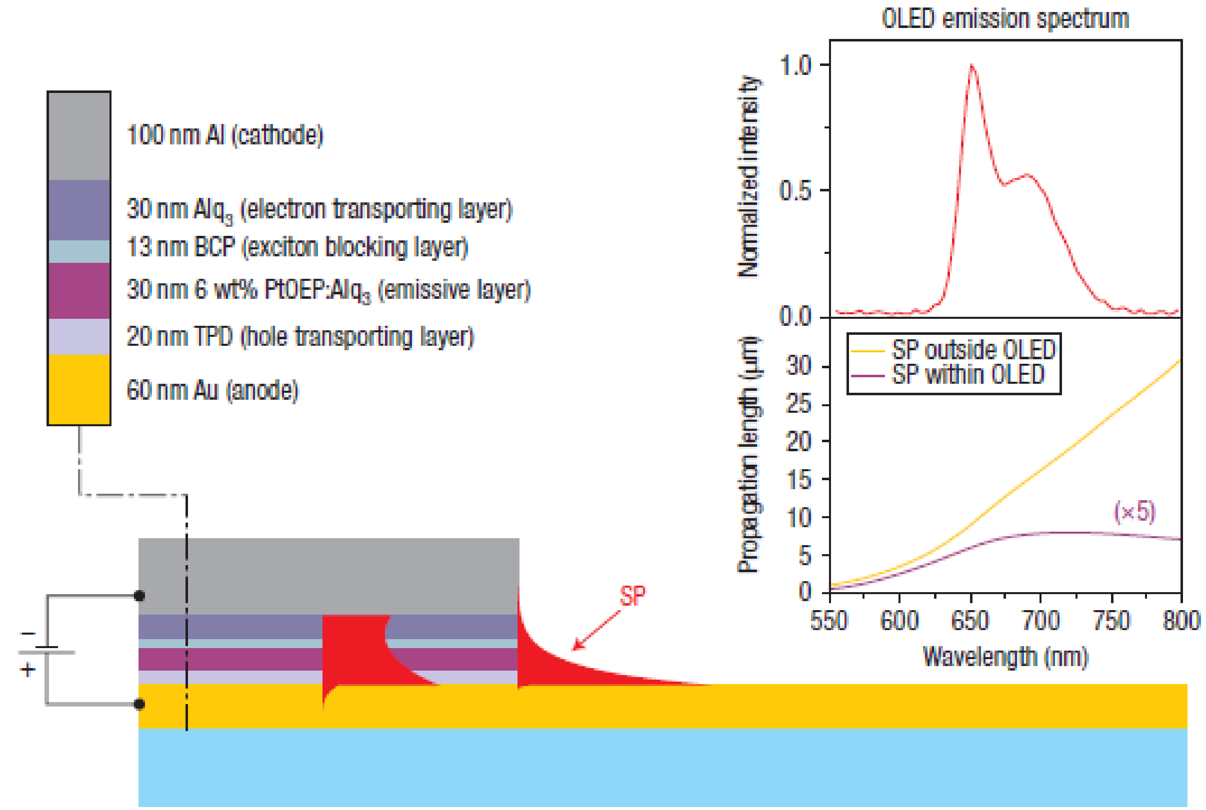
Integration with organic materials

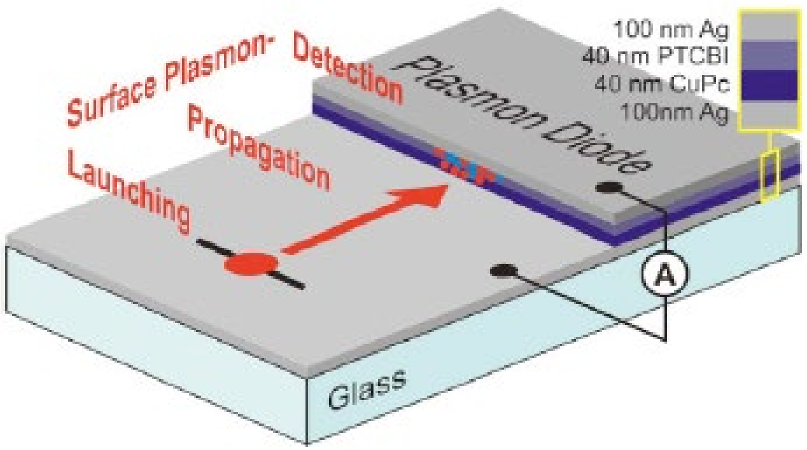
- Plasmon source (OLED)

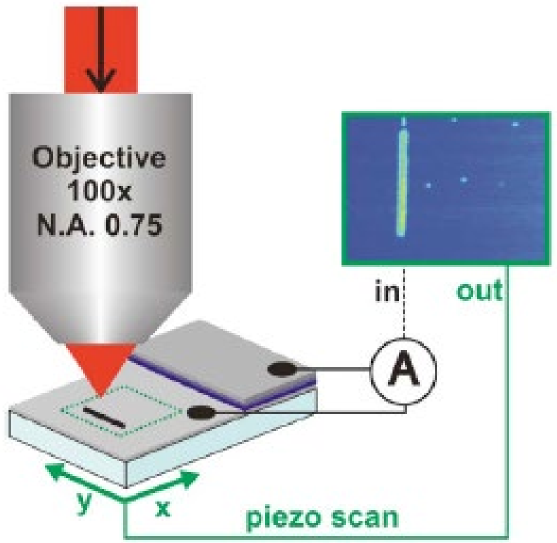


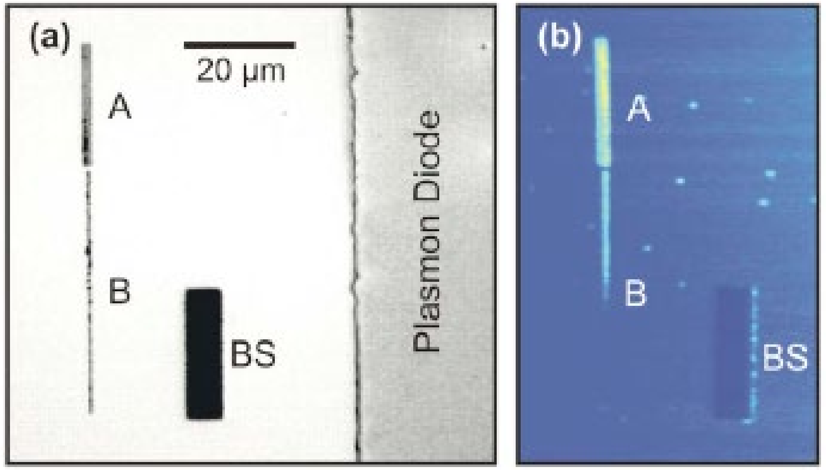
H. Ditlbacher et al., “Organic plasmon-emitting diode", Nat. Photon. vol. 2, p. 684-687 (2008).

Integration with organic materials

- Plasmon detector







H. Ditlbacher et al., “Organic diodes as monolithically integrated surface plasmon polariton detectors", Appl. Phys. Lett. vol. 89, p. 161101 (2006).

Selected Topics in Advanced Optics

Week 7 – part 2

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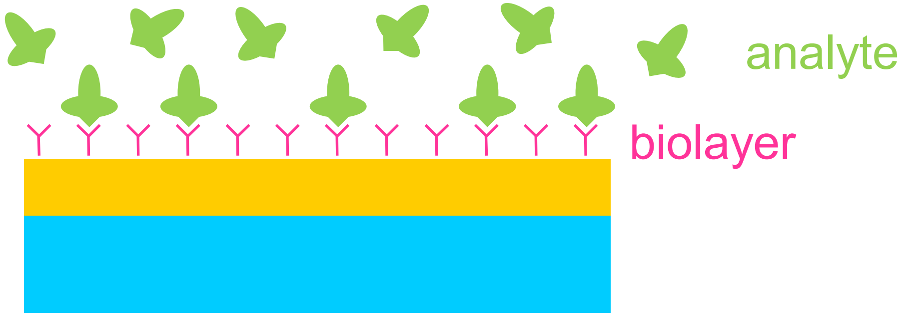
Surface plasmon sensor / Affinity sensor

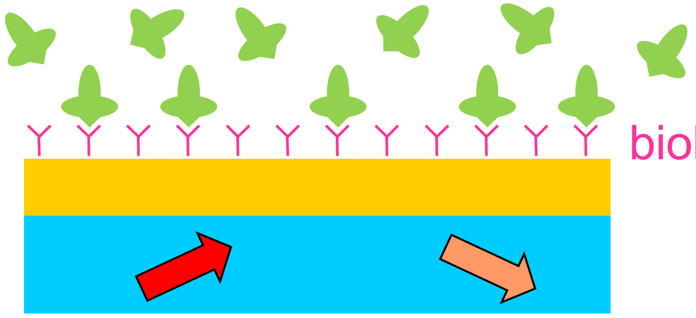
- The surface plasmon propagation is extremely sensitive to its direct environment

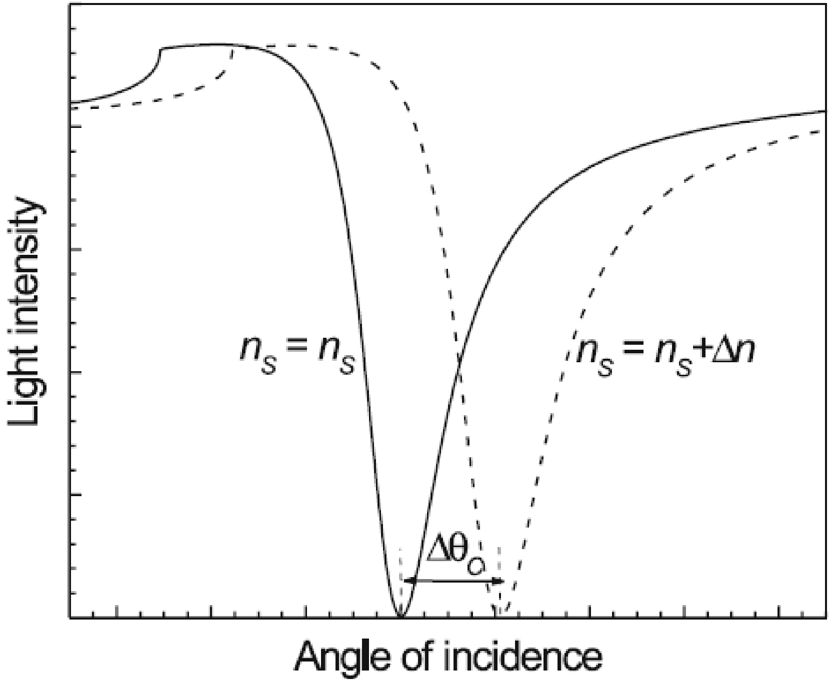


- When the analyte binds to the biolayer, the refractive index close to the metal changes and the condition for the excitation of the surface plasmon changes

Surface plasmon sensor / Affinity sensor

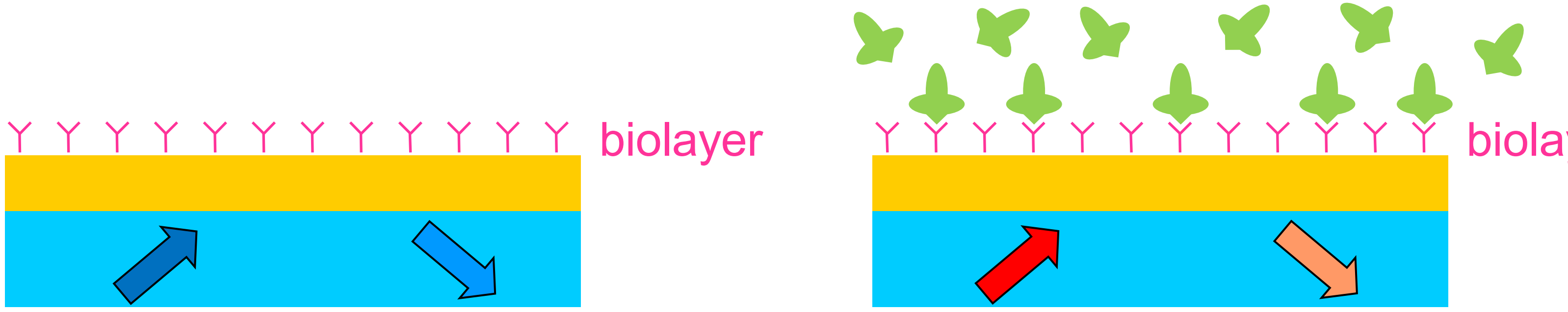
- The excitation angle for the surface plasmon can change when the analyte binds

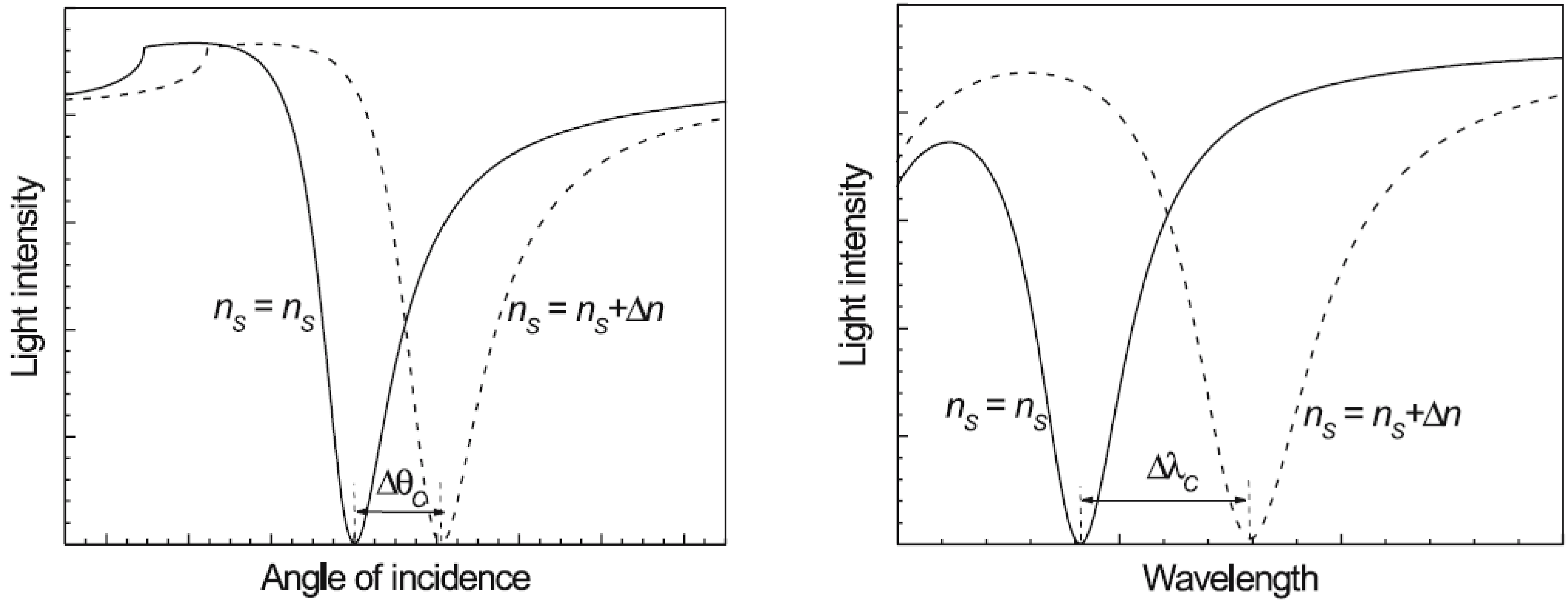




Surface plasmon sensor / Affinity sensor

- Using a broadband excitation, one can also detect the change of excitation wavelength at fixed angle of incidence

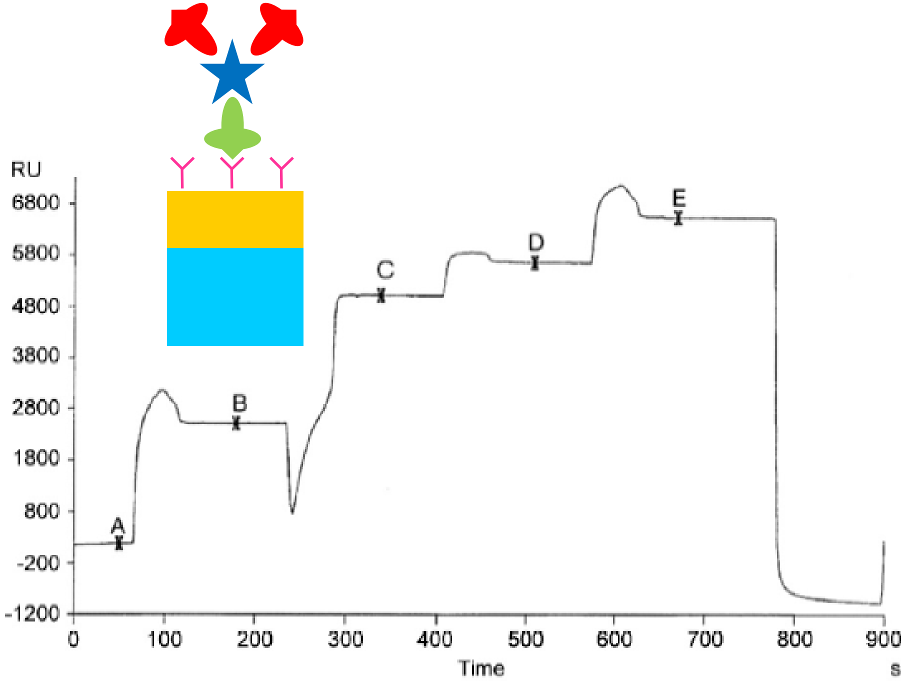




Affinity sensing

- Biacore: world leader in label free affinity sensing (€ 70 Mio sales in 2006, then sold to GE Healthcare)
- Affinity sensors also provide the dynamics of complex reactions (e.g. antibody binding)

GE Healthcare

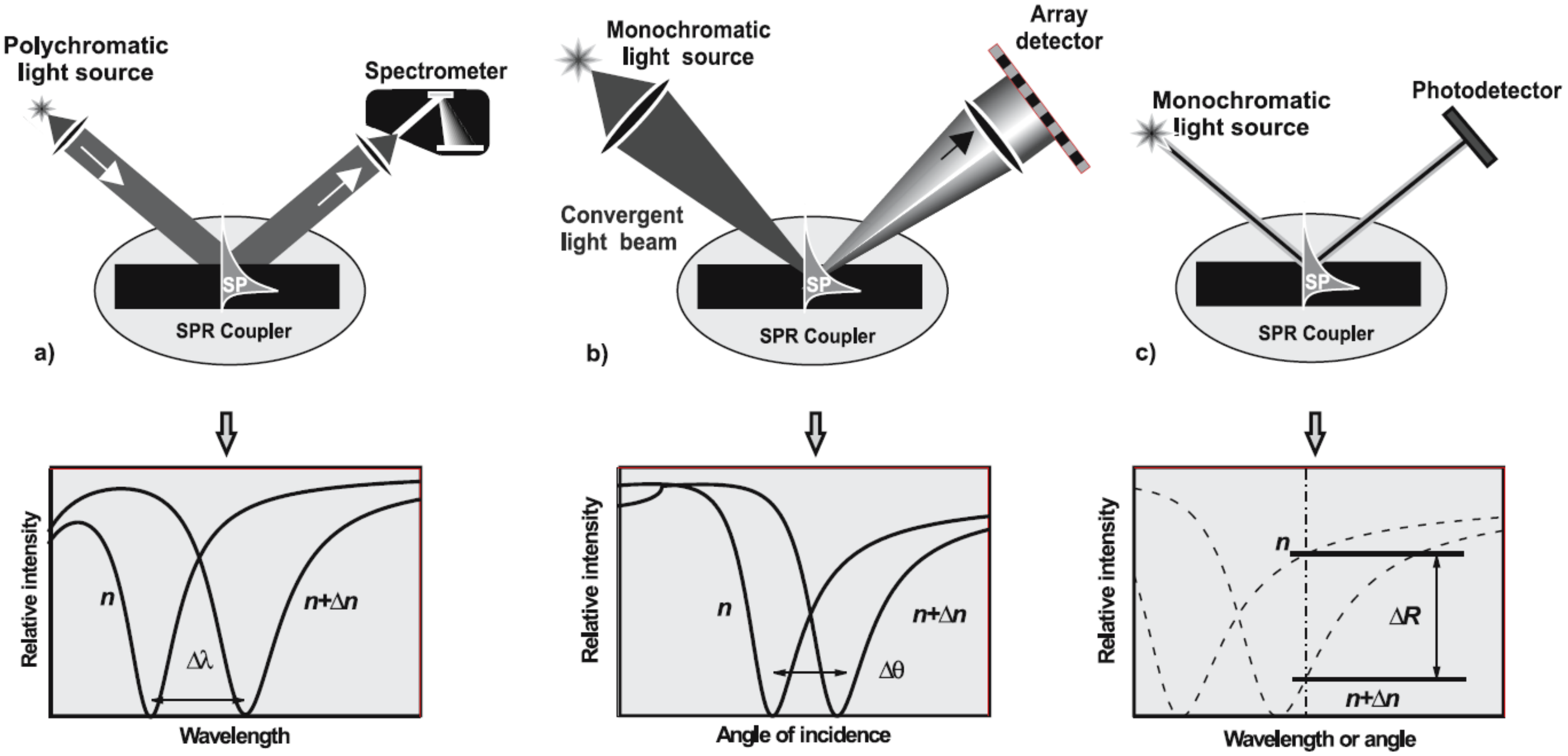


Immobilization of rabbit rabbit anti-mouse IgG1

- A: baseline
- A-B: 1st mAb against HIV1-p24
- B-C: blocking antibody
- C-D: HIV1-p24
- D-E: 2nd mAb against HIV1-p24

Surface plasmon sensor configurations

- Different detection schemes are possible: wavelength, angle of incidence or intensity



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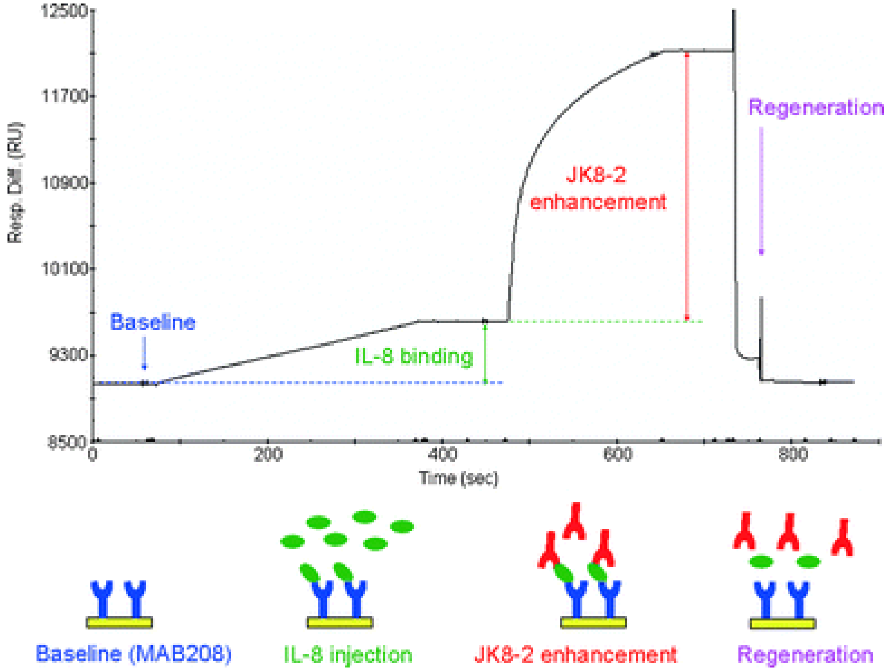
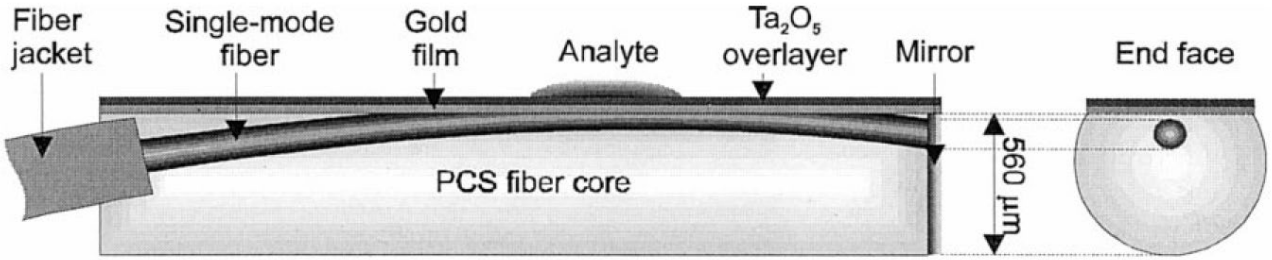
Surface plasmon sensors – Binding assay

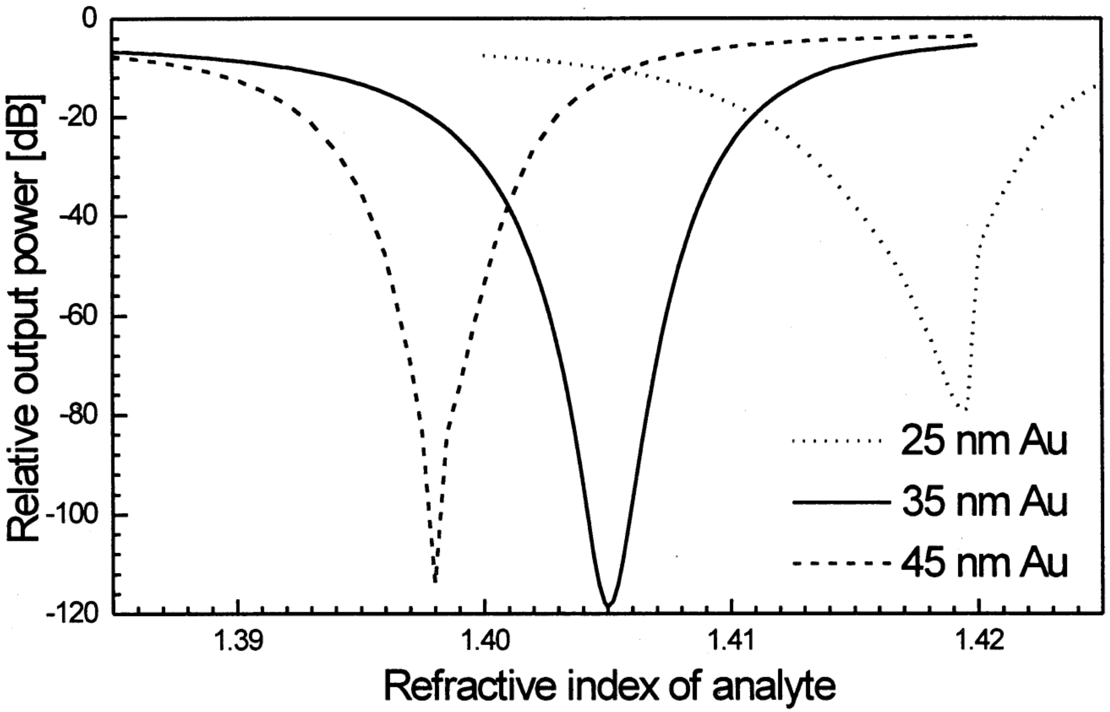
- The surface chemistry provides the selectivity
- The surface plasmon provides the sensitivity
- The resolution is given in Refractive Index Unit (RIU), typical sensitivities are $10^{-7} – 10^{-8}$ RIU (sometimes one refers to a wavelength shift of $10^4 – 10^5$ nm/RIU)
- The sensitivity depends on the plasmonic metal, the wavelength and the measurement scheme



Fiber-based surface plasmon sensor

- One can use an optical fibre to make a complete sensor





R. Slavik et al., "Miniaturization of fiber optic surface plasmon resonance sensor", *Sensors and Actuators B* vol. 51, p. 311 (1998). – Cited > 100x

Selected Topics in Advanced Optics

Week 7 – part 3

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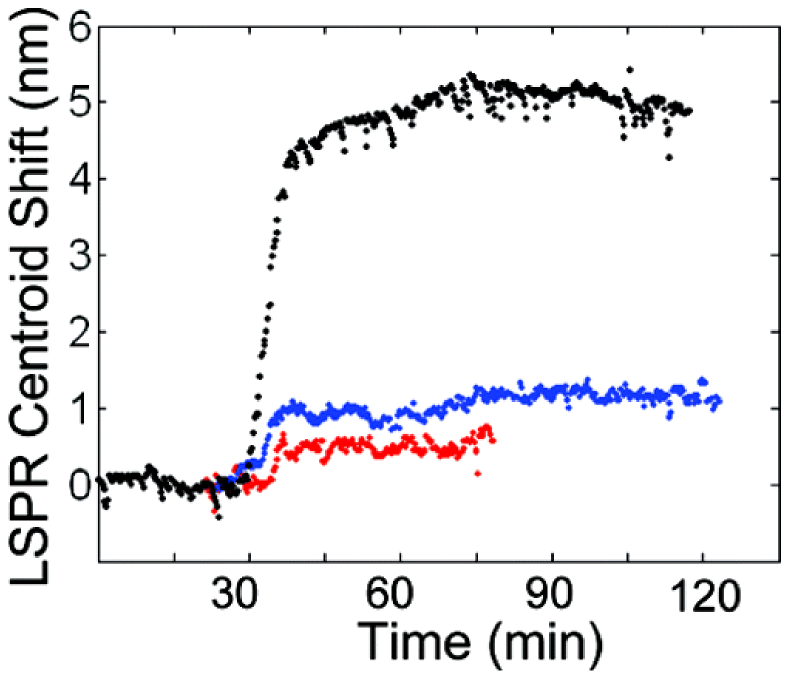
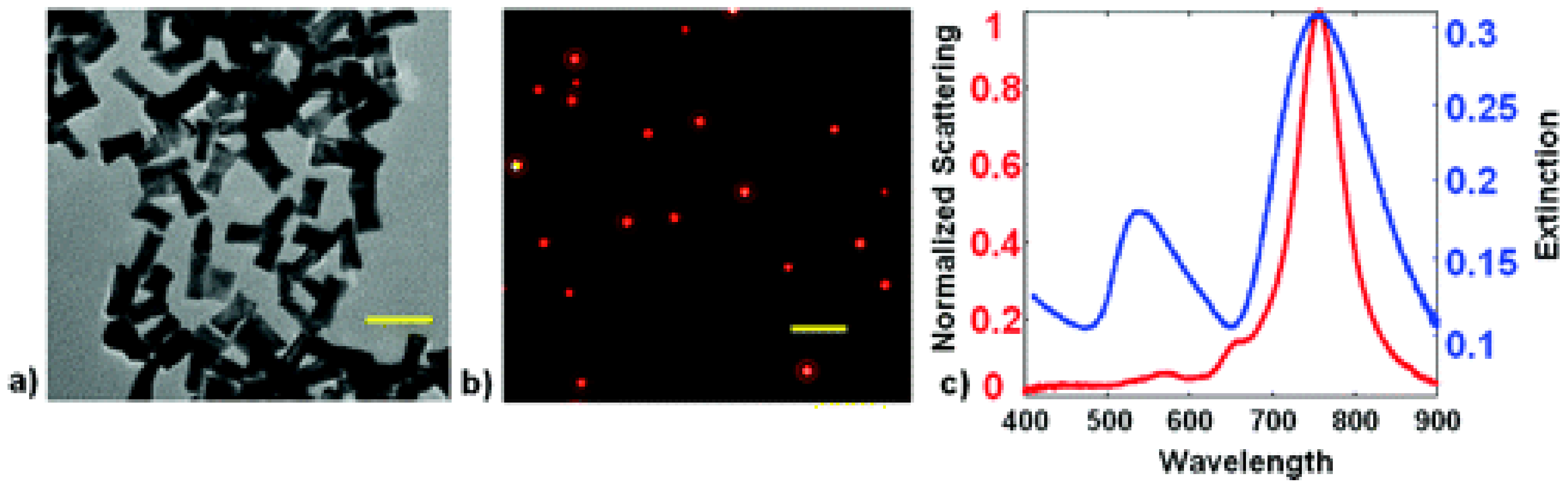
Particle-based plasmon sensor

- Localized plasmon resonances also depend on the environment and can be used for sensing
- So far, the sensitivity is about 100 less than with propagating plasmons (sensitivity: 200nm/RIU)

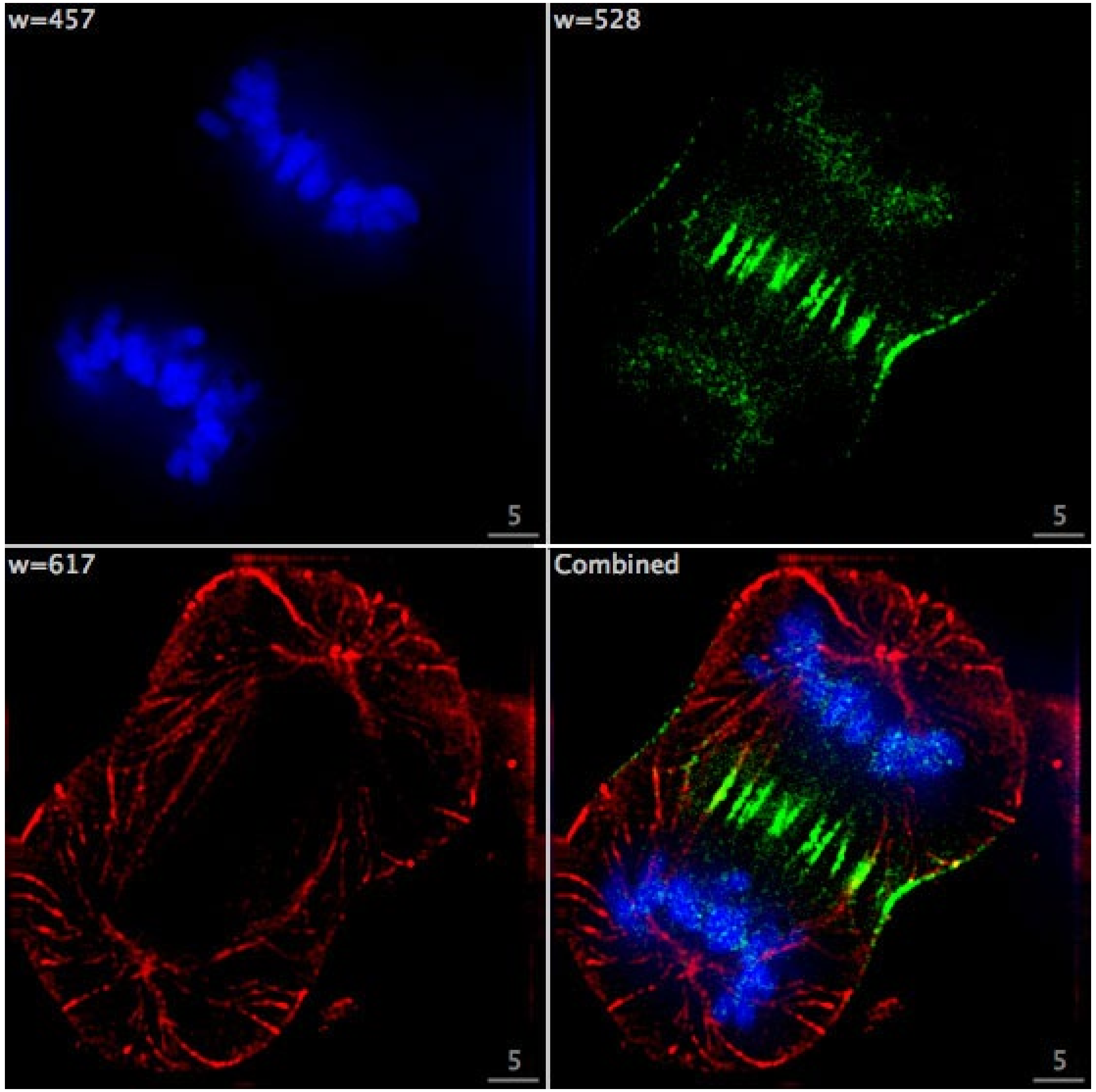




G.J. Nusz et al., “Label-Free Plasmonic Detection of Biomolecular Binding by a Single Gold Nanorod”, *Anal. Chem.* (2008)

Fluorescent biomarkers

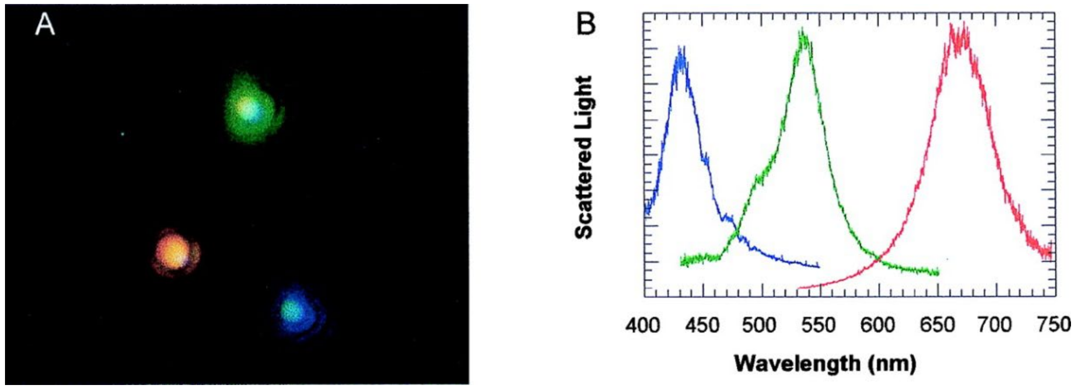
- A biomarker is « a small light bulb » (usually a fluorescent molecule) that can be attached to specific biological entities to make them visible for imaging or following some dynamics
- Unfortunately fluorescent molecules can stop emitting light (blinking, bleaching)

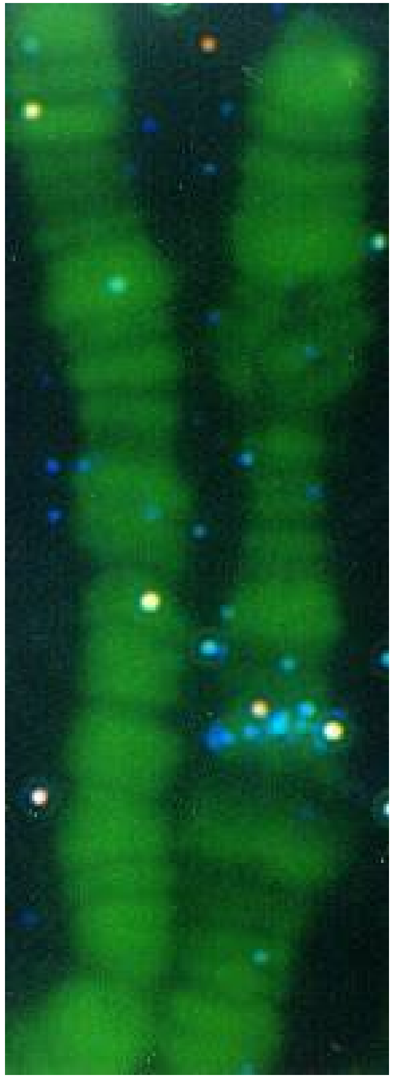


Plasmonic biomarkers

- Plasmonic nanoparticles provide very robust biomarkers
- They do not blink, they do not bleach
- They are chemically stable

3C band of the X chromosome of the Drosophile labelled with nanoparticles

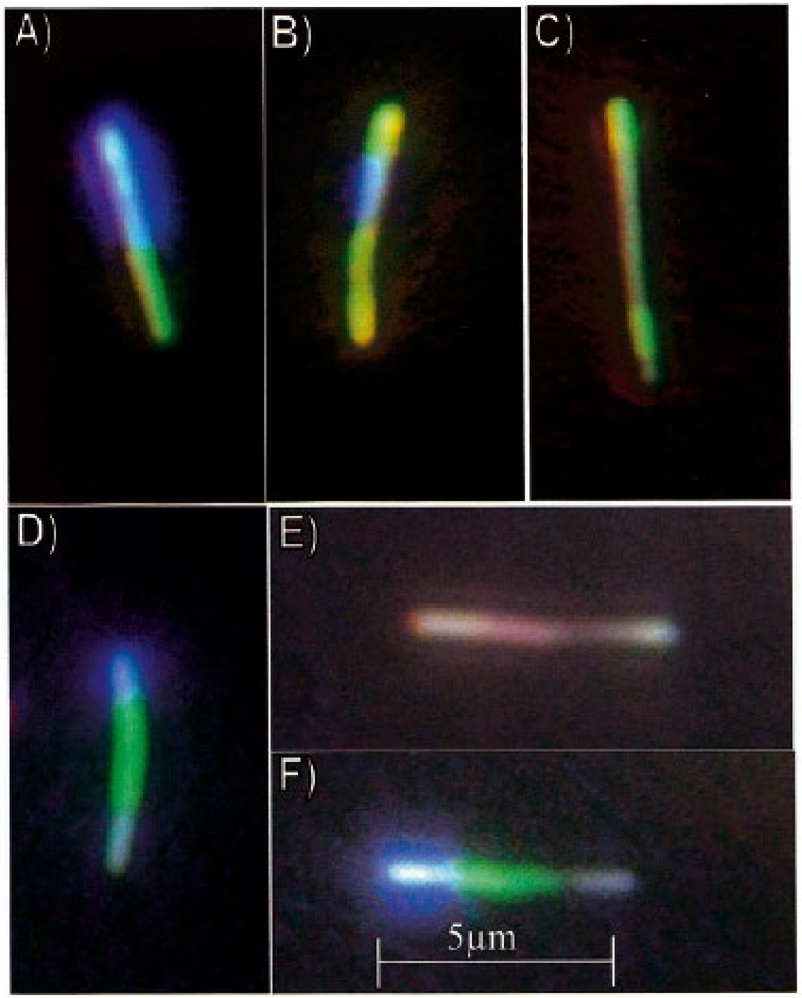




S. Schultz, Proc. Nat. Academy of Sciences vol. 97, p. 996 (2000)

Plasmonic biomarkers

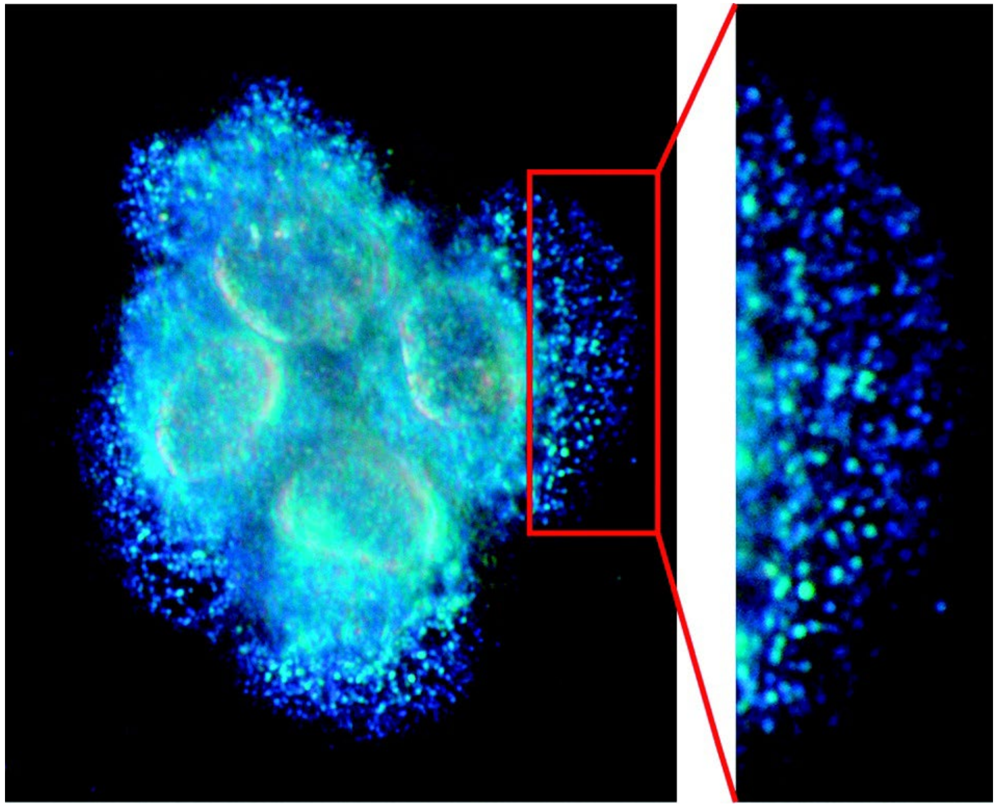
- Mixing different metals (Au, Cu, Ag, Ni) provides a very broad variety of markers (nano-codbars)



J.J. Mock, Nano Letters vol. 2, p. 465 (2002)

Plasmonic biomarkers

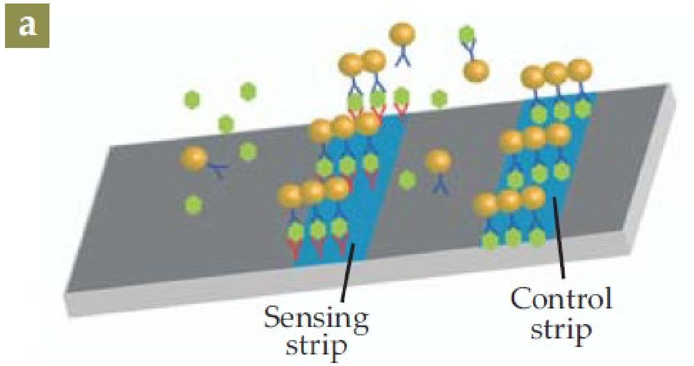
- Recently, plasmonic nanoparticles have proven a useful alternative to fluorescence for microscopy
- Visualization of individual receptors on a cell surface using Ag nanoparticles; the color shade indicates the receptor density



H. Wang, Nano Letters vol. 11, p. 498 (2011)

Lateral flow test (pregnancy, COVID)

- Human chorionic gonadotropin (hCG), a hormone found in urine when pregnant
- hCG will bind to antibodies present on the surface of the sensor
- To sense that reaction, a suspension of gold particles chemically linked to secondary antibodies is then added; when they bind to the analyte they strongly scatter light, producing a ruby red color

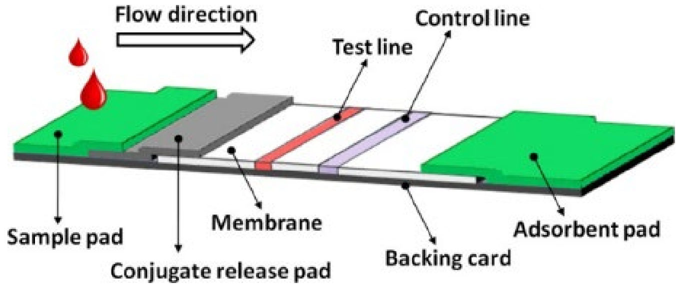


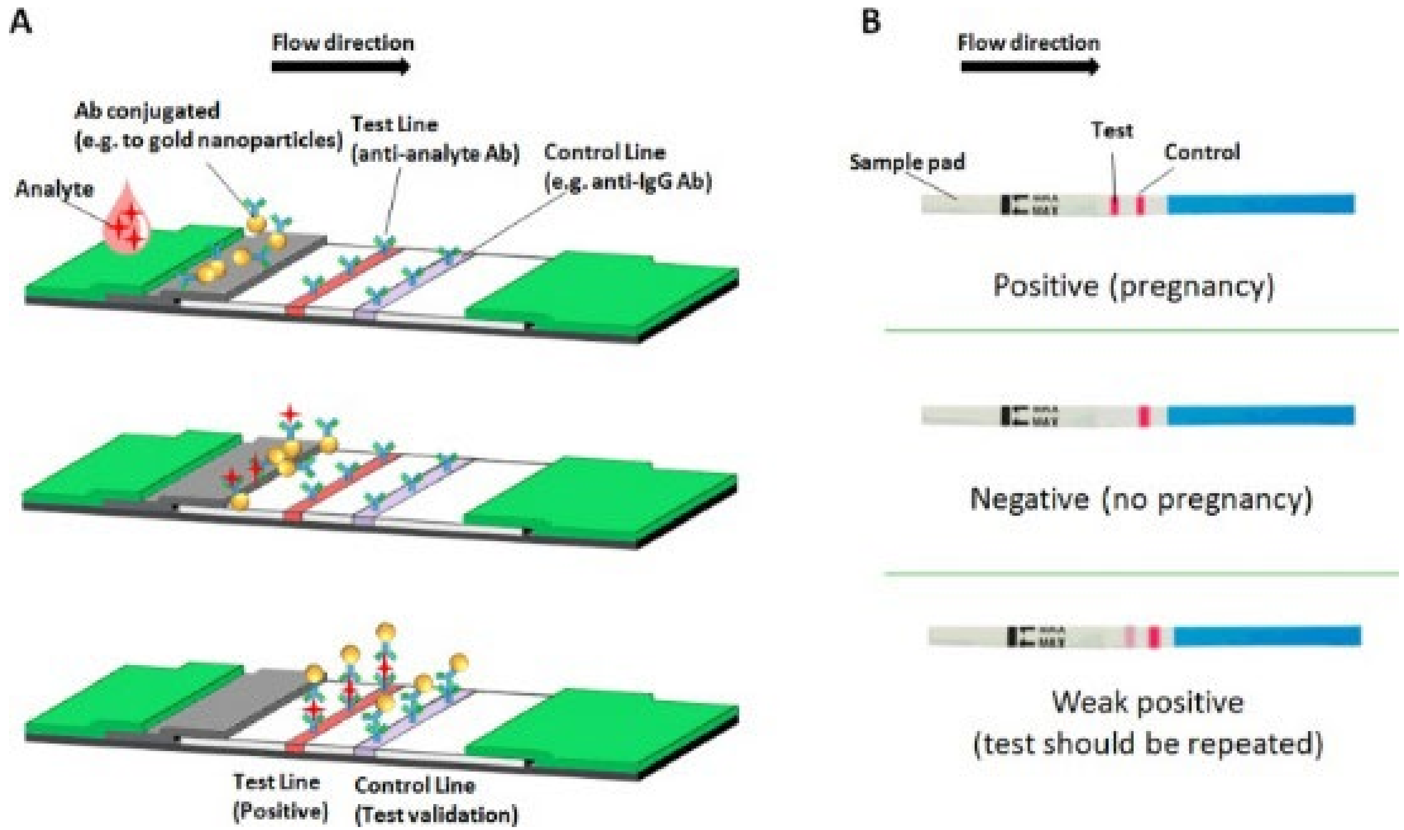
M. Stockman, Phys. Today vol. 64, p. 39 (2011)

wikimedia

Lateral flow test (pregnancy, COVID)

- The plasmonic nanoparticls are used to produce a strong optical signal





K.M. Koczula, Essays in Biochemistry vol. 60, p. 111 (2016)

Selected Topics in Advanced Optics

Week 7 – part 4

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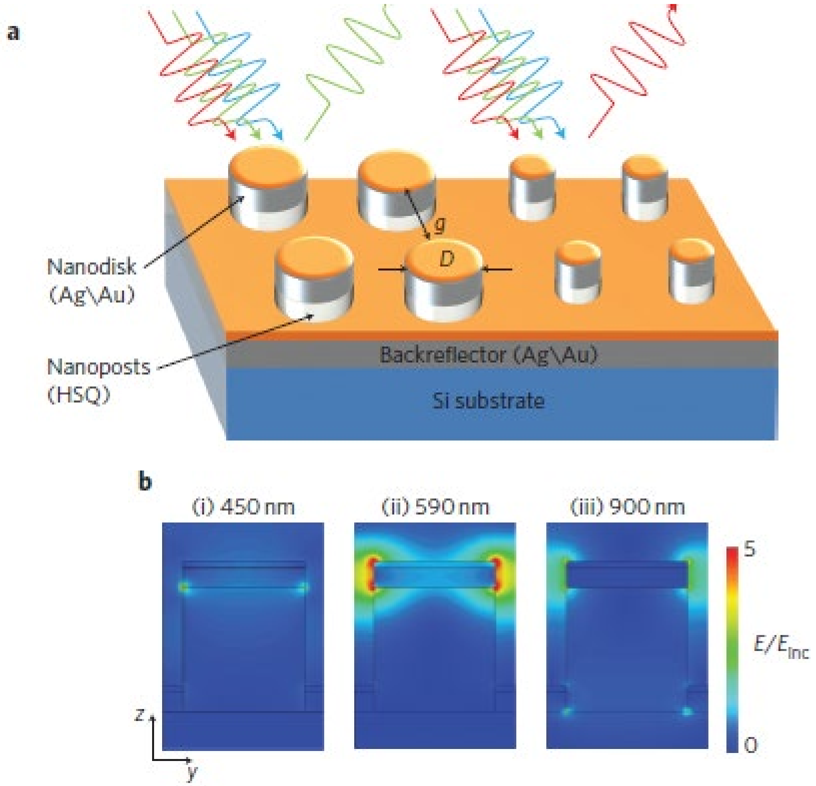
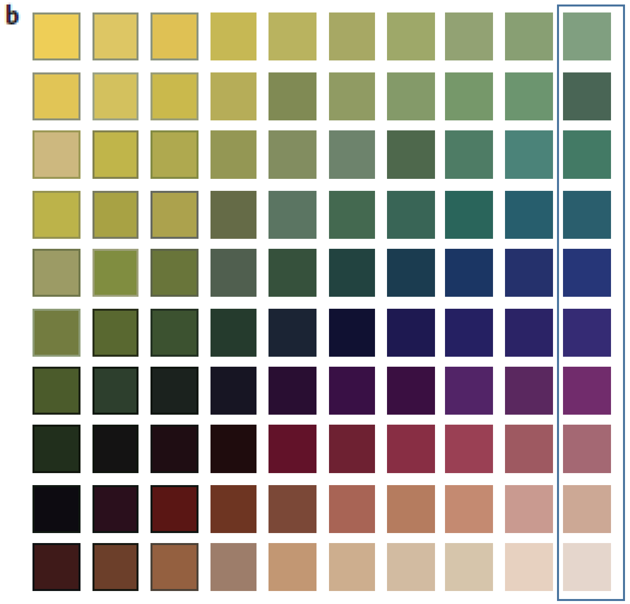
Artificial colours

- By changing the shape, size, environment of a plasmonic nanoparticle, one changes its colours
- Such artificial colours are very stable and difficult to counterfeit

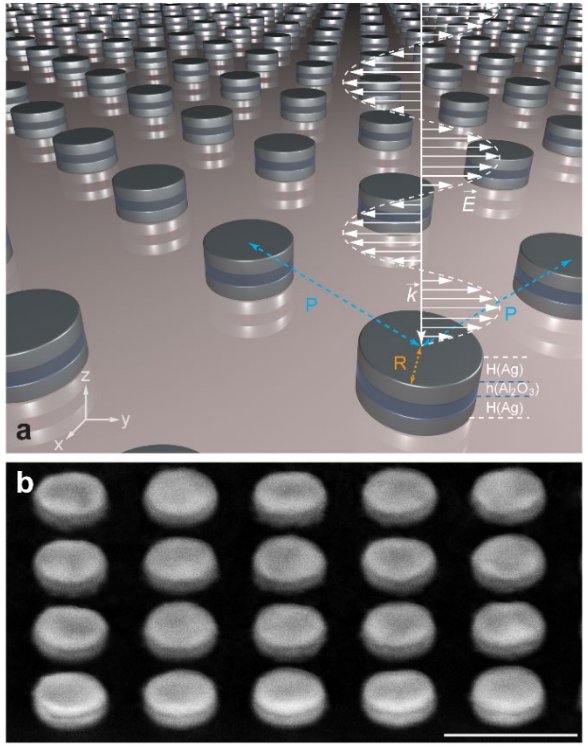


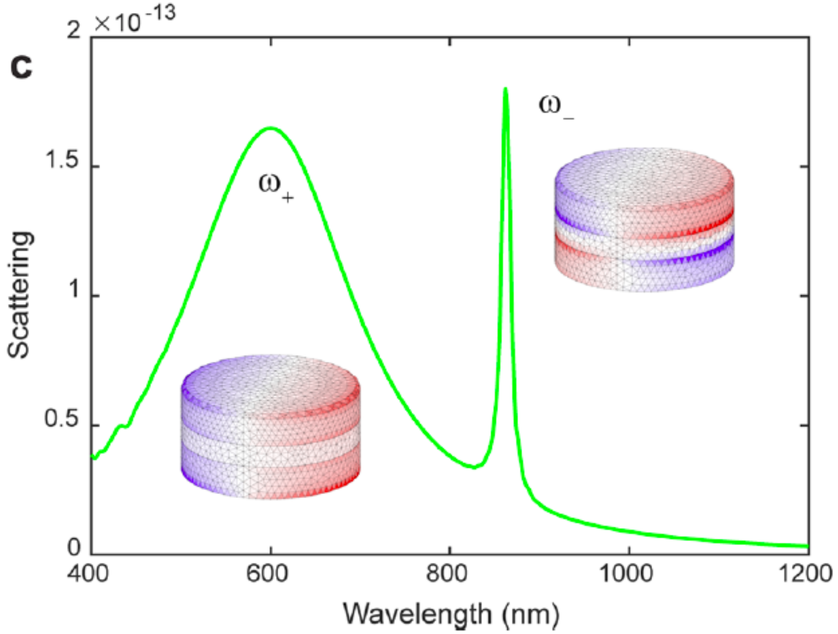


K. Kumar et al., “Printing colour at the optical diffraction limit", *Nat. Nanotech.* vol. 7, p. 557 (2012).

Artificial colours

- Exploring different materials and structures enables the production of many different colors. For example using Al:

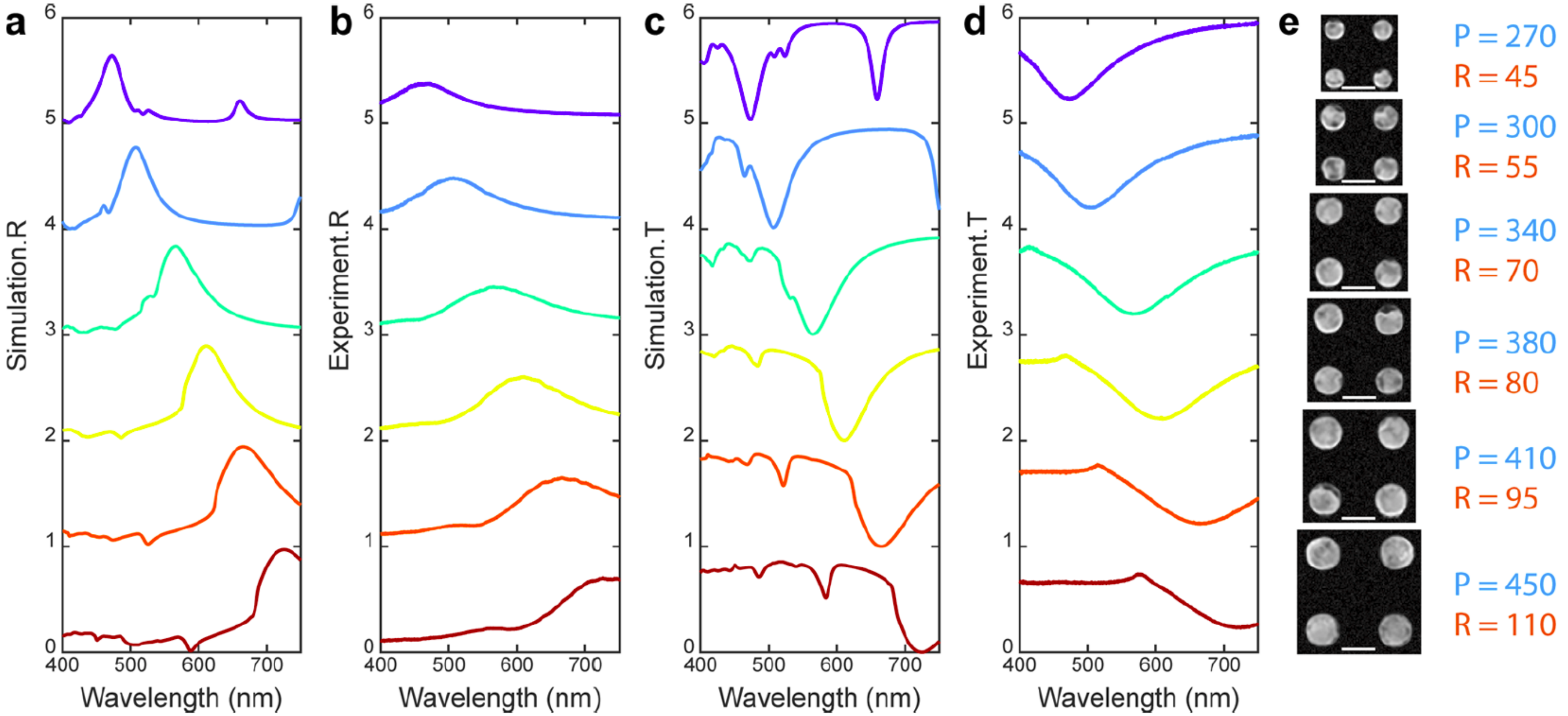




H. Wang et al., “Full color generation using silver tandem nanodisks", *ACS Nano* vol. 11, p. 4419 (2017).

Artificial colours

- The response can be controlled by the disks radius R and the period P :

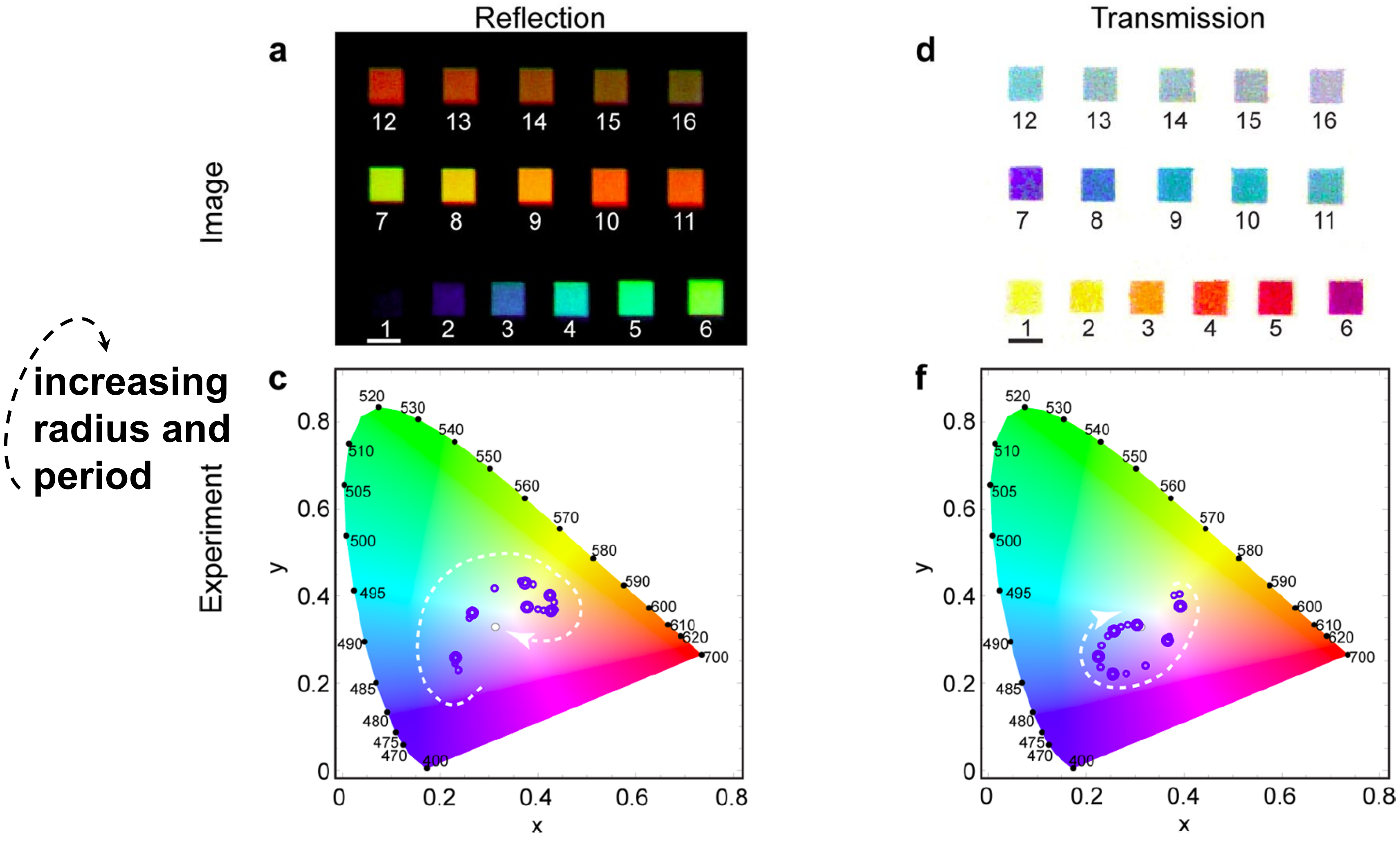


- Complementary colors in reflection (RGB) and transmission (CMY)

H. Wang et al., “Full color generation using silver tandem nanodisks", *ACS Nano* vol. 11, p. 4419 (2017).

Artificial colours

- The colors can cover most of the CIE color Gamut:



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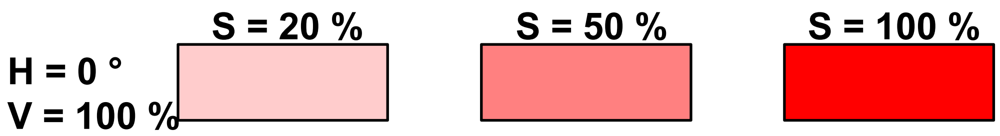
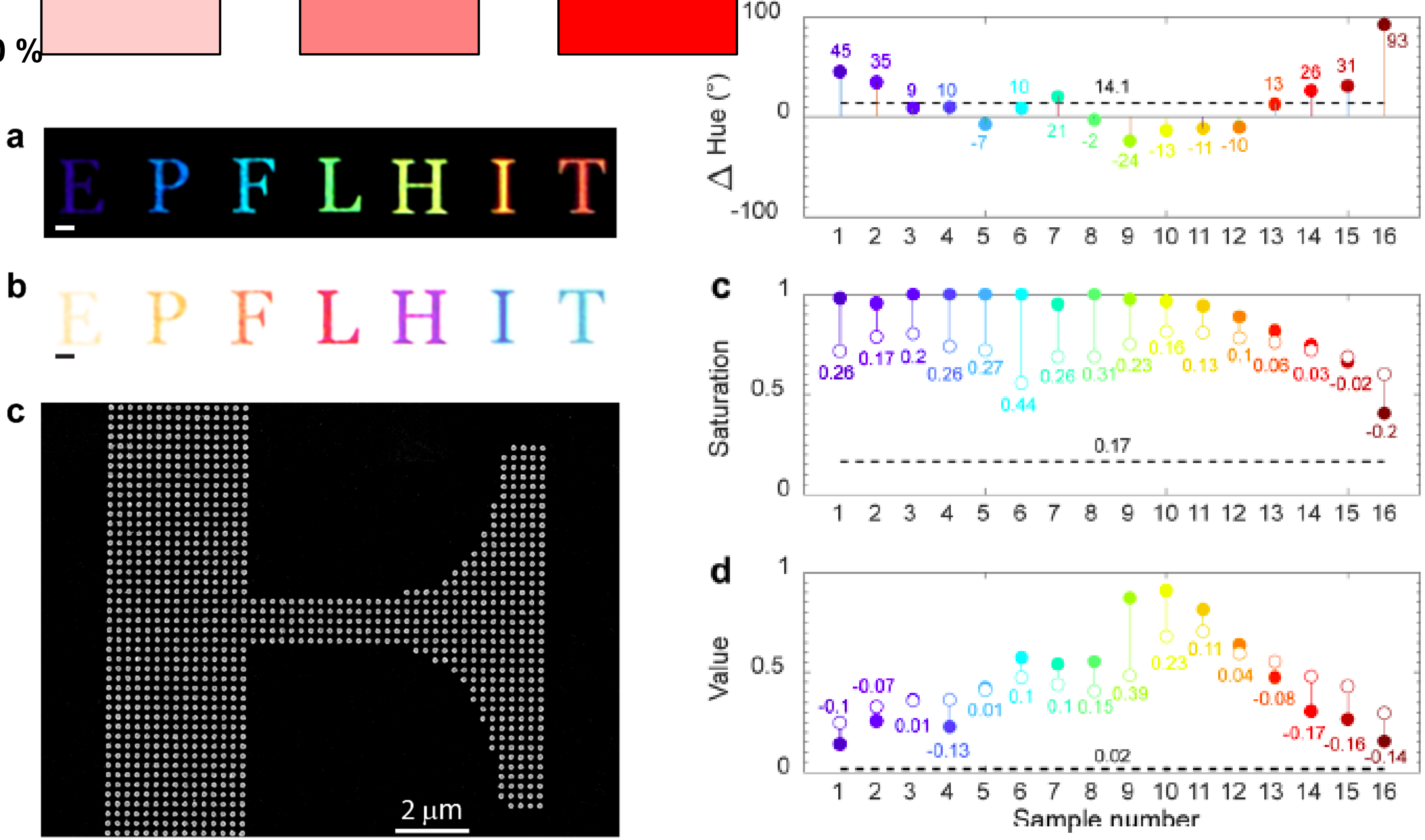
Artificial colours

- The colors can be highly saturated:





H. Wang et al., "Full color generation using silver tandem nanodisks", *ACS Nano* vol. 11, p. 4419 (2017).

Selected Topics in Advanced Optics

Week 7 – part 5

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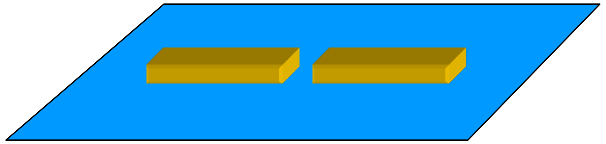
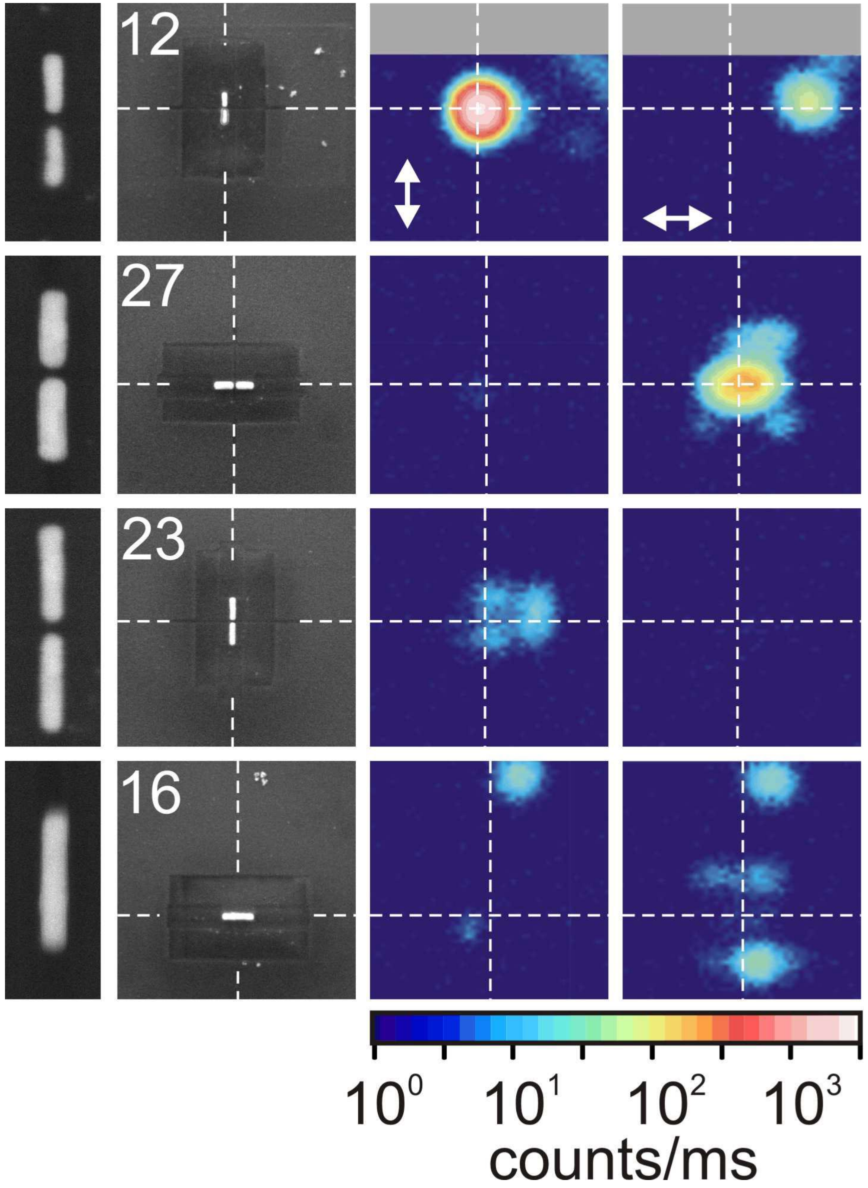
EPFL

Plasmonic dipole antennas



Focused ion beam fabrication:

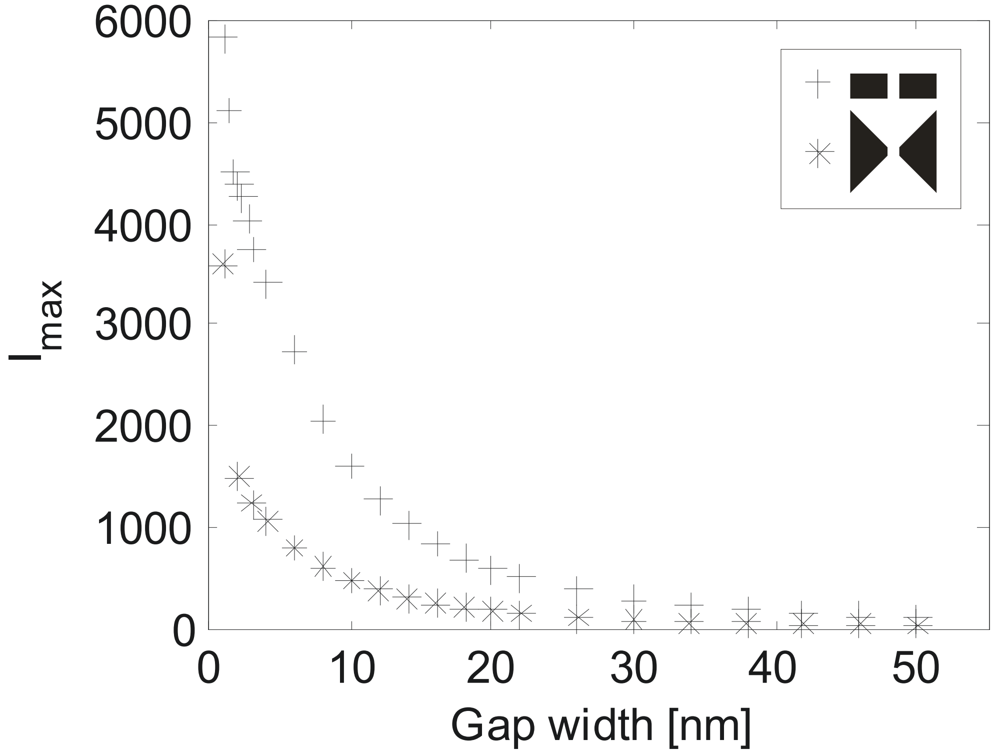
- 40nm thick gold
- Length: 190…400nm
- Width: 45nm
- Gap: 20nm
- Glass substrate

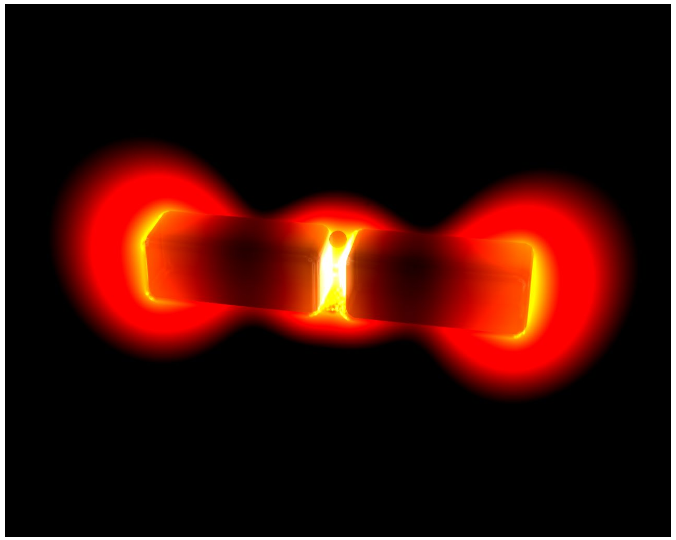


F. Mühlschlegel et al. Science vol. 308, p. 1607 (2005)

Plasmonic dipole antennas

- Plasmonic dipole antennas produce a very strong field enhancement in their gap
- The coupling between the two plasmonic nanostructures dramatically enhances the intensity in the gap
- This coupling depends on the distance between both particles

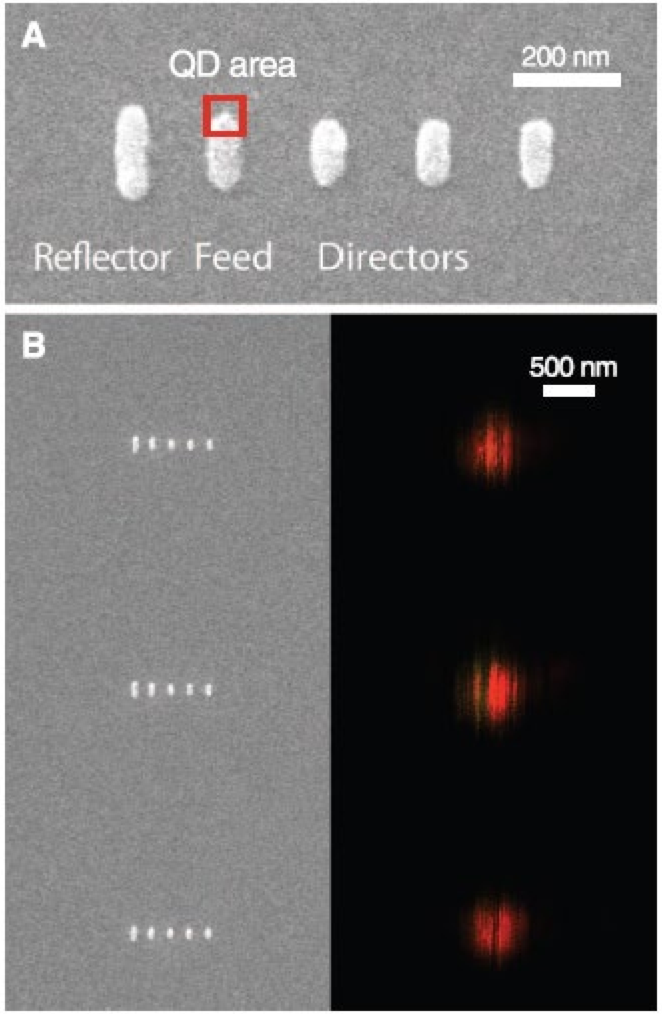


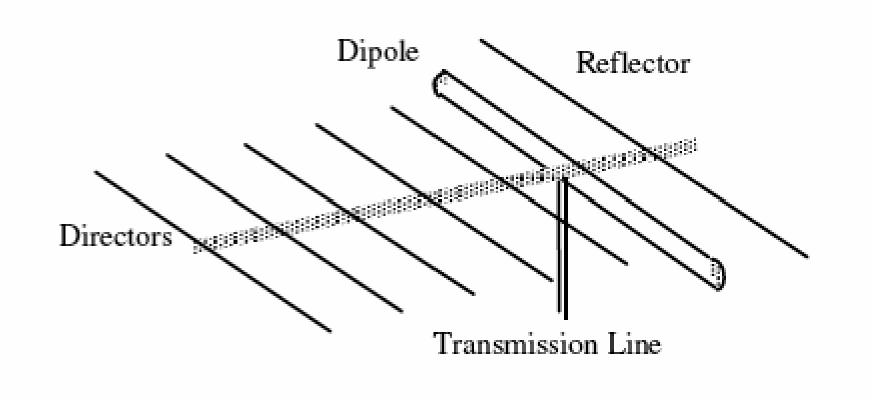


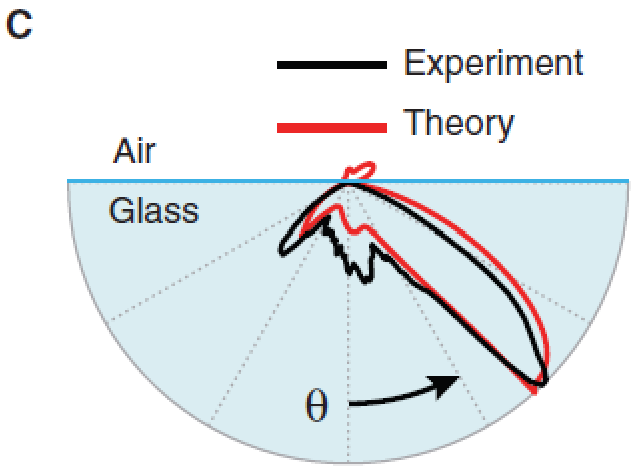
H. Fischer, Optics Express vol. 16. p. 9144 (2008)

Plasmonic antennas

- Several of the classical antenna designs have been transposed in plasmonics: e.g. Yagi-Uda antenna



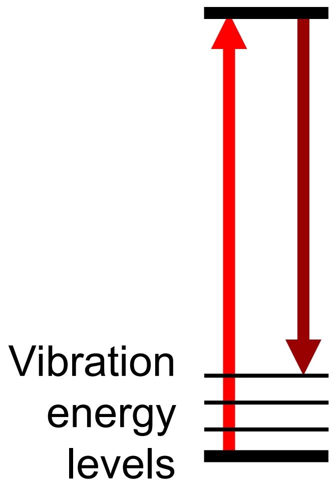


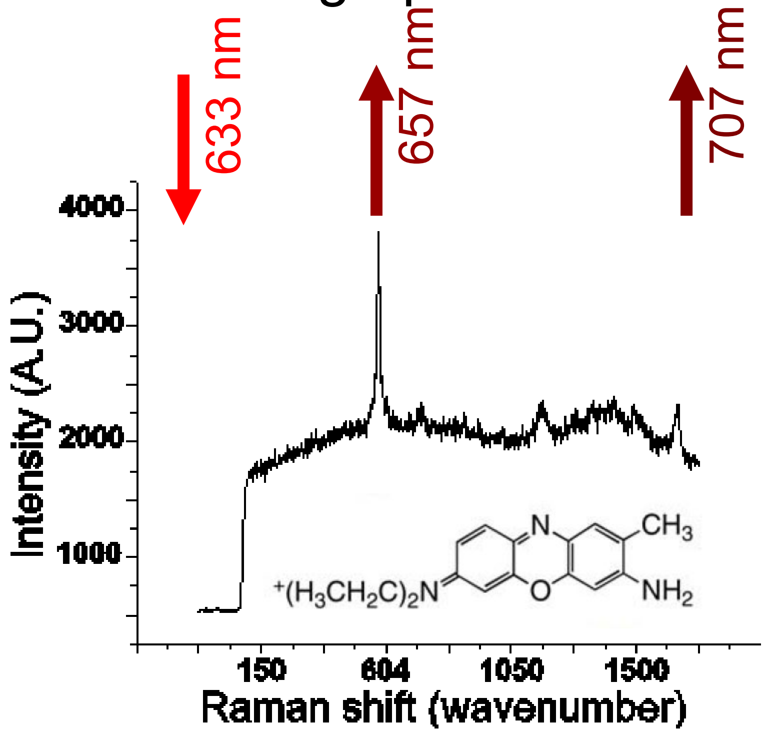


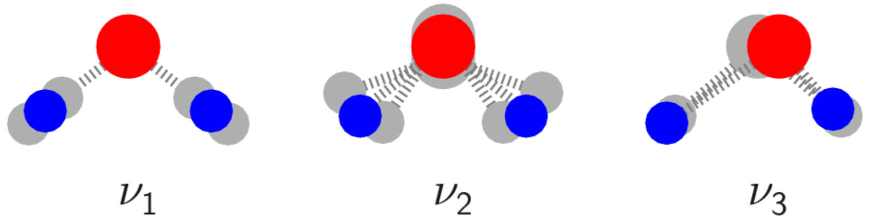
H.G. Curto et al., Science vol. 329, p. 930 (2010)

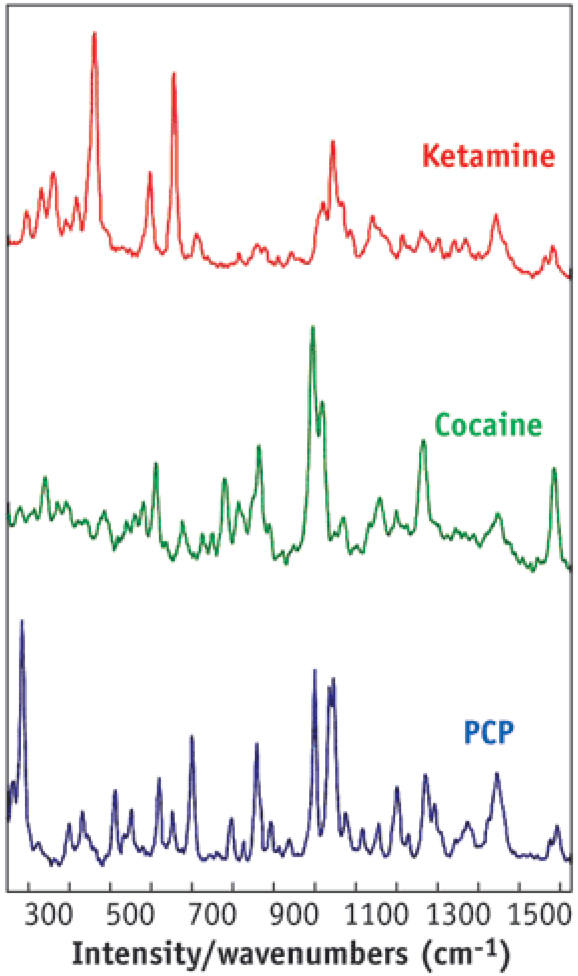
Raman spectroscopy

- Elastic and inelastic (energy not conserved) light scattering
- The energy that disappears provides information on the chemical structure (vibration modes) → molecular fingerprint



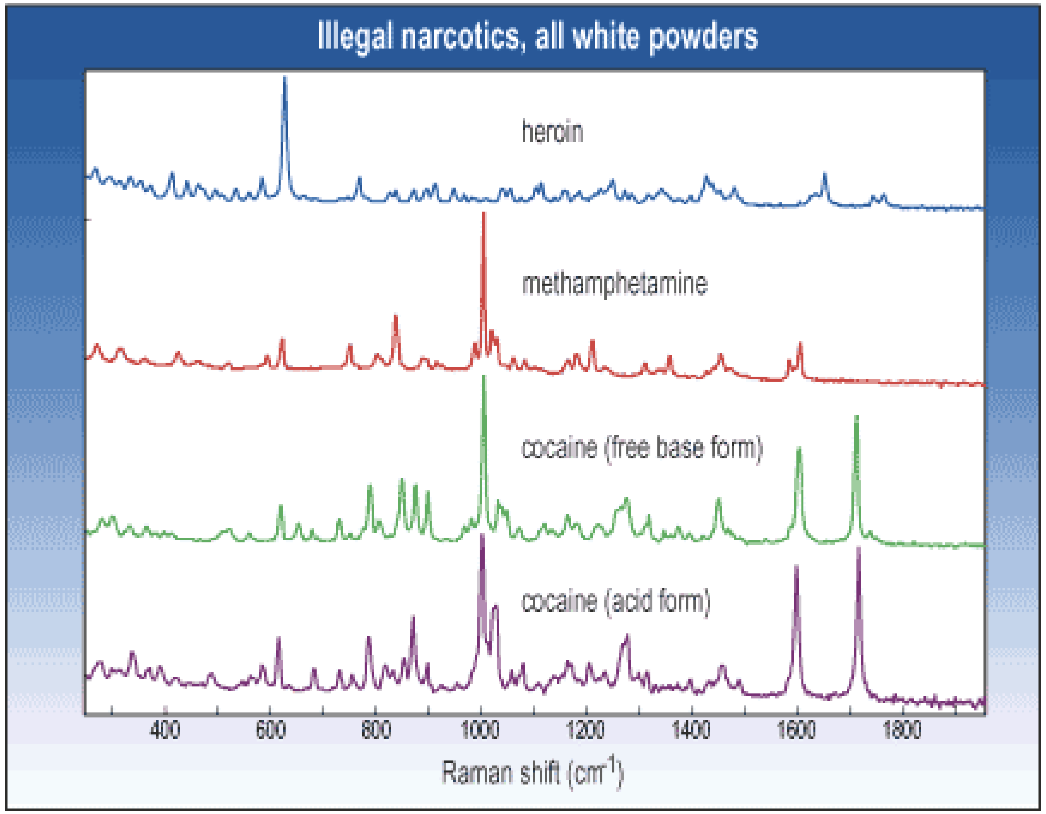






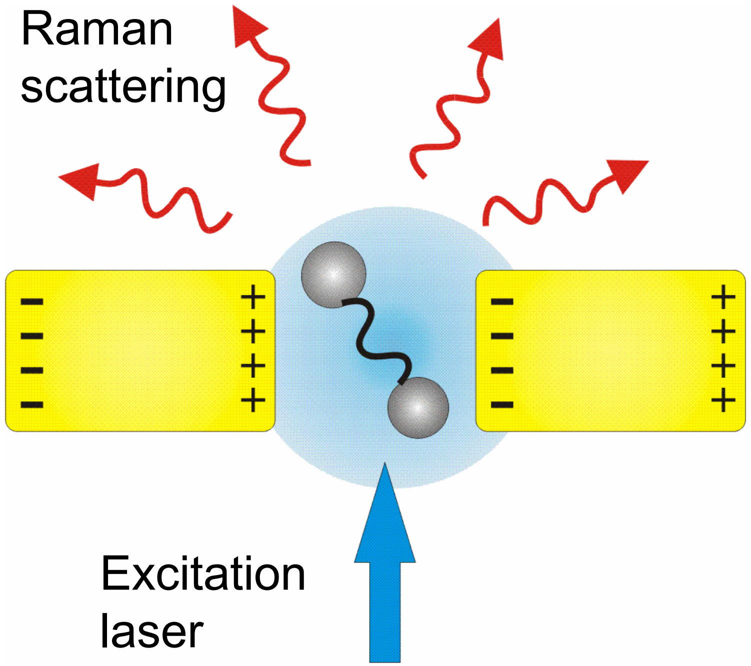
Surface enhanced Raman spectroscopy (SERS)

- Since each molecule has different chemical bonds, it exhibits a different Raman spectrum that can be used to identify the molecule (Raman fingerprint)



Surface enhanced Raman spectroscopy (SERS)

- Raman scattering is an extremely weak process $\sigma_{scat}=10^{-30}$ cm^{-2}
- It can be enhanced by polarizing the molecule: $\sigma_{scat}=10^{-15}$ cm^{-2}
- This is best achieved by putting the molecule in the vicinity of a plasmonic structure
- Both the illumination and the scattering are enhanced



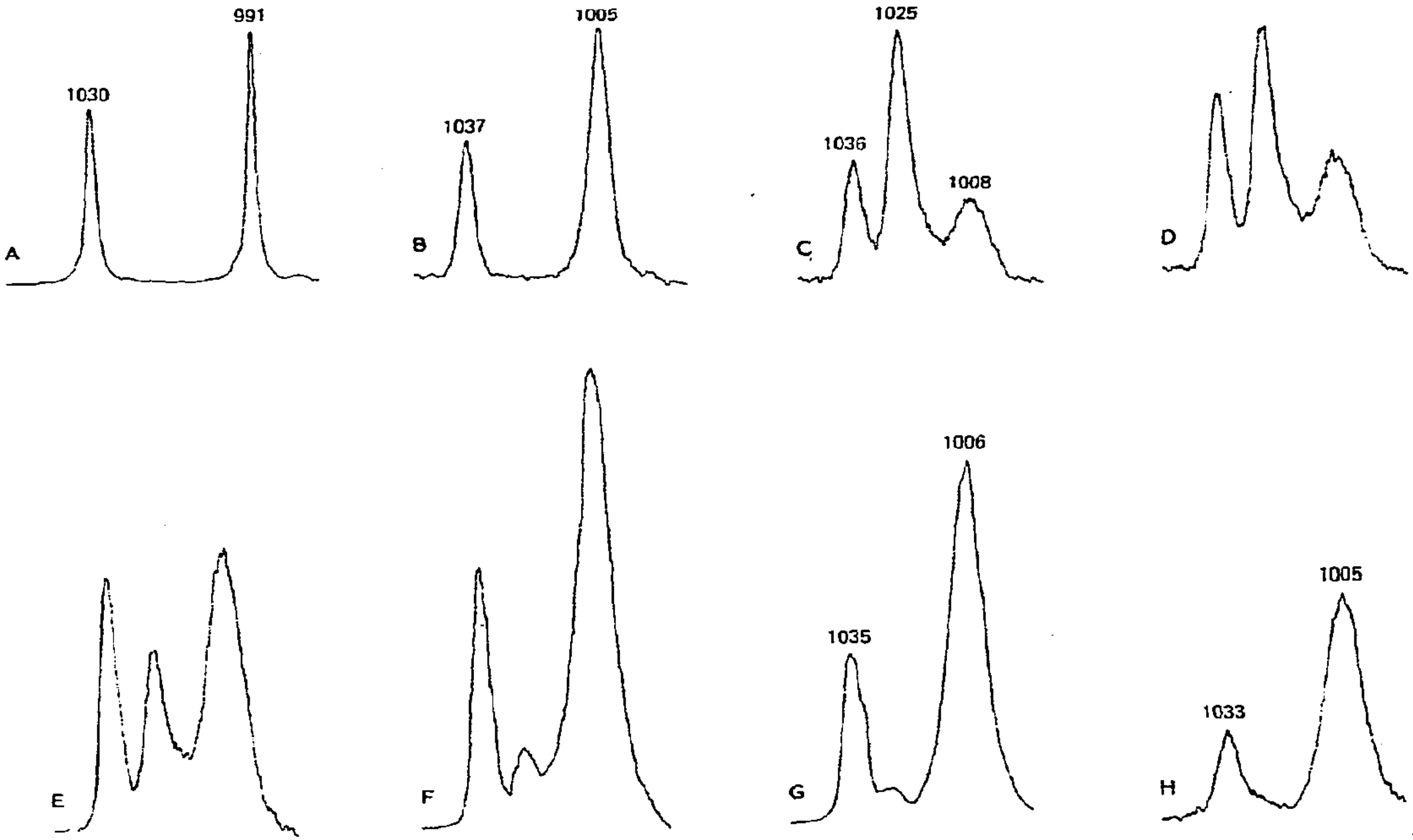
$$G(\vec{r}) = \left|\frac{E_{loc}(\vec{r},\omega_L)}{E_0(\vec{r},\omega_L)}\right|^2 \cdot \left|\frac{E_{loc}(\vec{r},\omega_R)}{E_0(\vec{r},\omega_R)}\right|^2$$

$$\Downarrow$$

$$G(\vec{r}) = \left|\frac{E_{loc}(\vec{r},\omega_L)}{E_0(\vec{r},\omega_L)}\right|^4 \simeq 10^{6\ldots16}$$

SERS – First experiment

- The very first SERS experiment occurred by accident, looking at molecules in a solution for electrolysis experiments

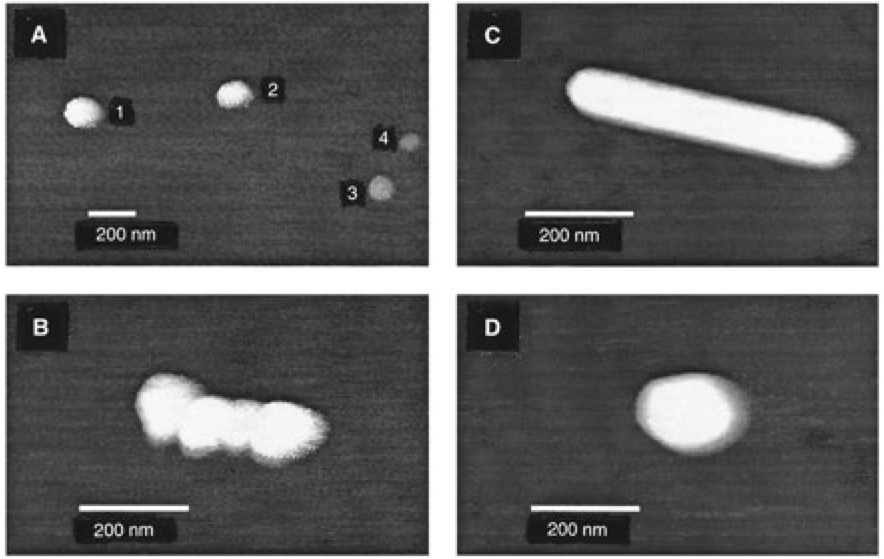


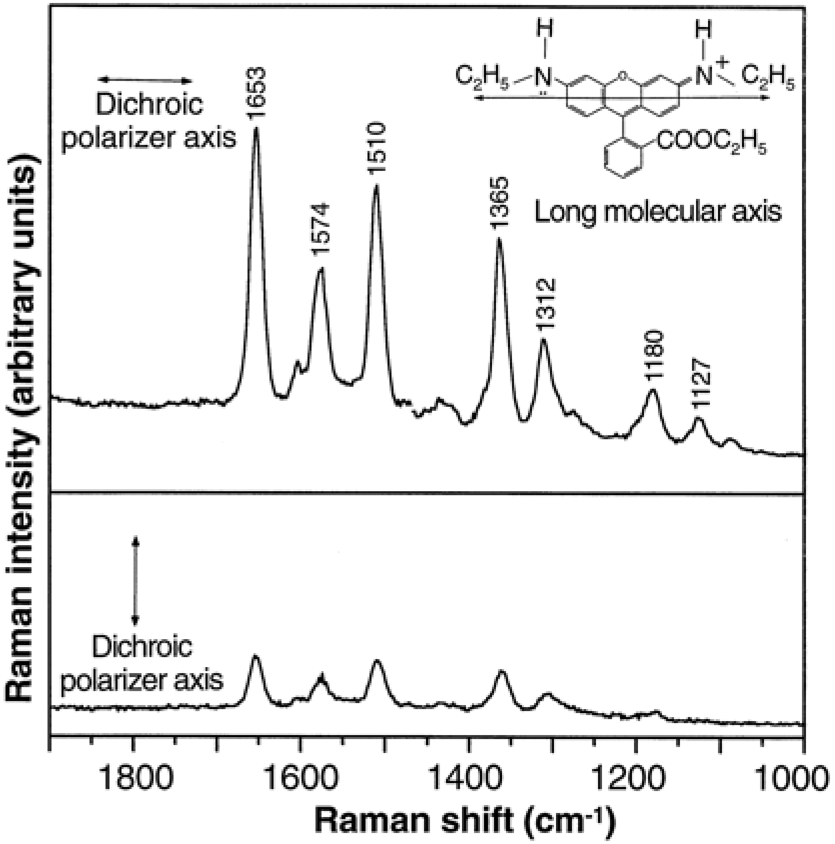
M. Fleischmann et al., "Raman spectra of pyridine adsorbed on a silver electrode", *Chem. Phys. Lett.* vol. 26, p. 163-166 (1974).

SERS – Single molecule sensitivity

- The field enhancement can be so strong that the Raman signal from one single molecule can be measured

Ag nanopaticles





S. Nie et al. "Probing Single Molecules and Single Nanoparticles by Surface-Enhanced Raman Scattering", *Science* vol. 21, p. 1102 (1997).