EE 6301

Smart Biosensors and Systems for Healthcare Technology

EE6301 Week 3-
Optical Biosensor (2)

Structure and applications of photonic biosensing

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2025

CONTENT

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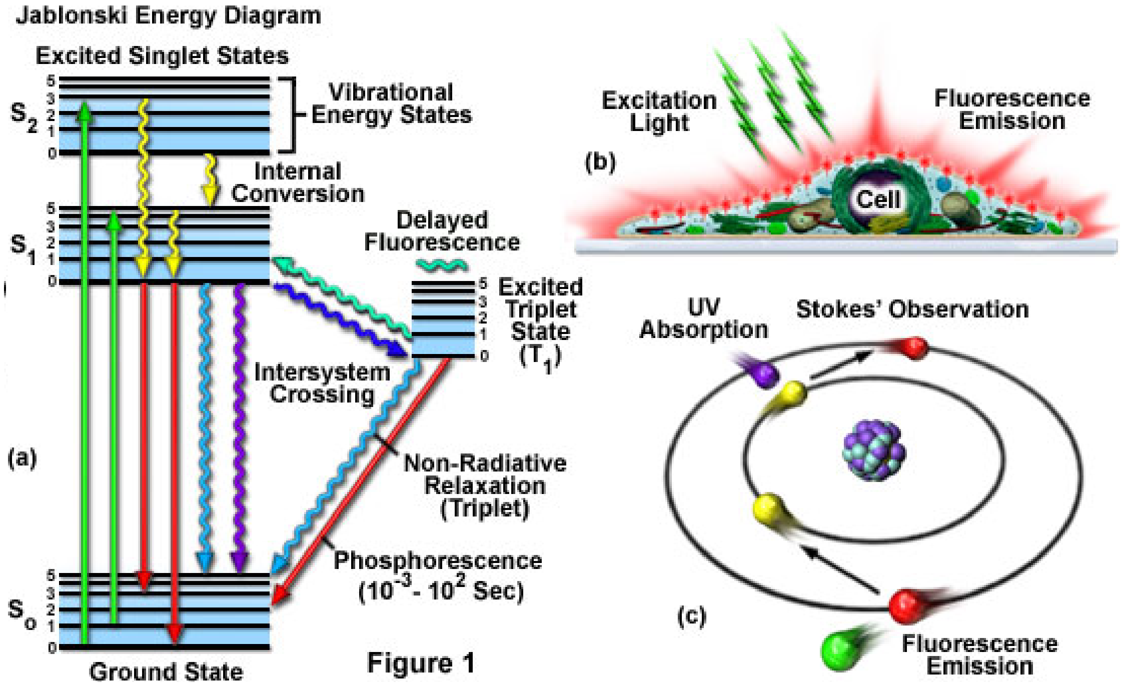
PART ONE

Fluorescence Biosensors

Fluorescence Biosensors- Labeled Sensors



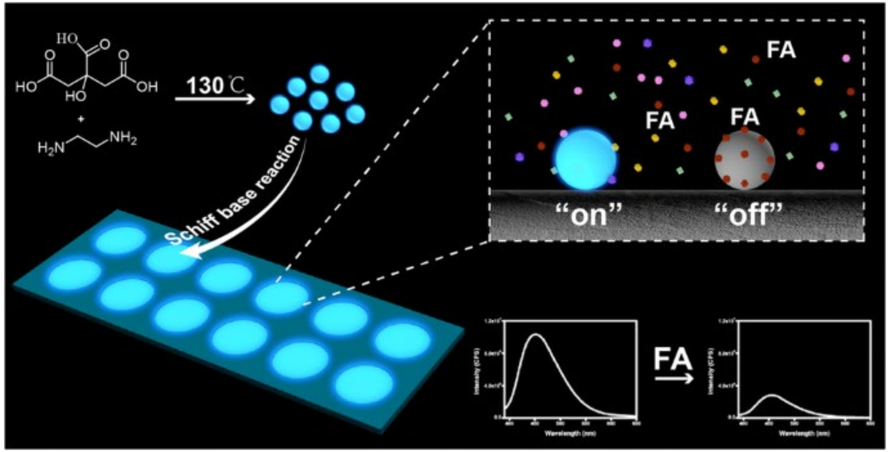
The fluorescence emission process can be summarized as:

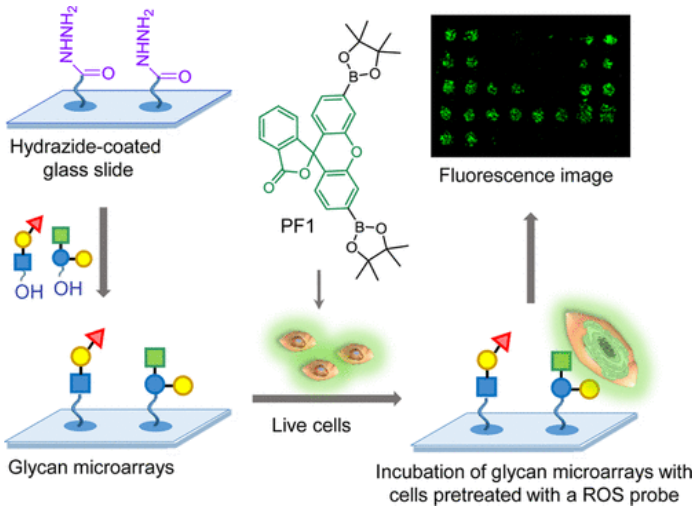
Step 1. Excitation of a fluorophore through the absorption of light energy.

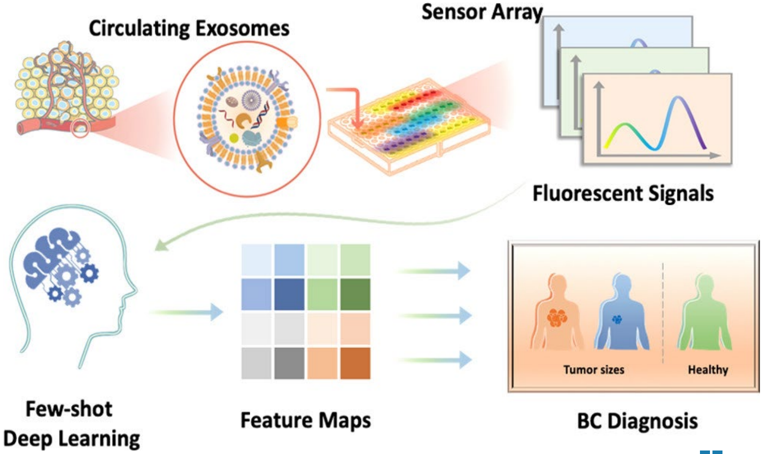
Step 2. A transient excited lifetime with some loss of energy.

Step 3. Return of the fluorophore to its ground state, accompanied by the emission of light.

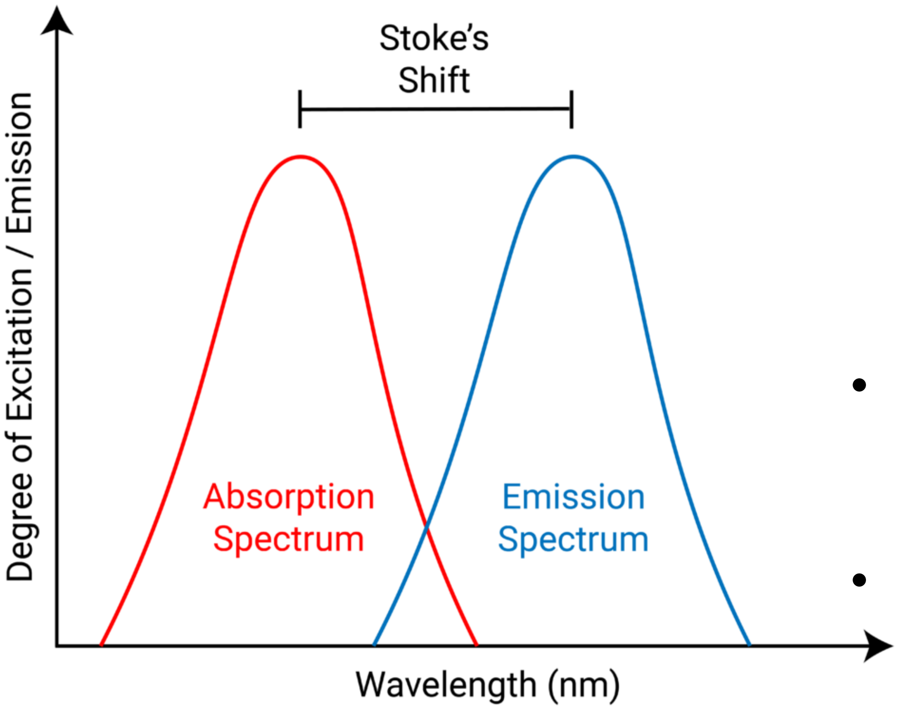
Applications





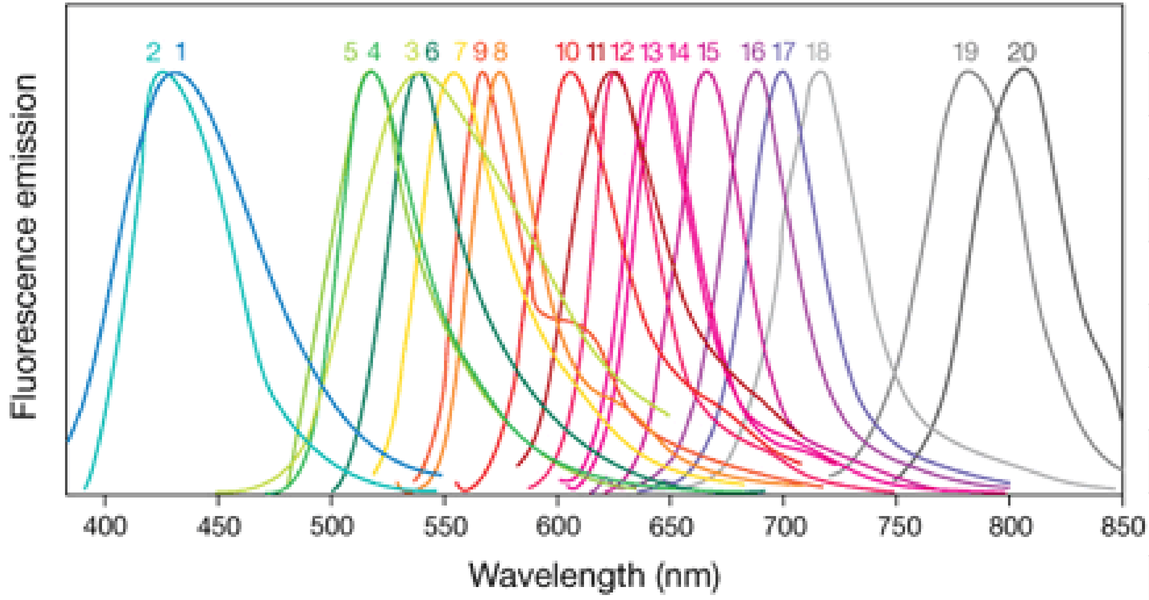


Fluorescence dyes



- Synthetic organic dyes
  - Fluorescein; fluorescein isothiocyanate (FITC); rhodamine
  - Small molecular weight; easier for bioconguation to macromolecules such as antibodies without interfering biological function
- Biological fluorophores
  - Green fluorescent protein (GFP); Nobel prize 2008
- Quantum dots
  - Nanoscale-sized (2-50nm) semiconductors
  - Fluorescence emission wavelength is size dependent

Fluorescence dyes



Alexa Fluor® Dye *	Quantum yield (QY)†	Lifetime (τ (ns))‡
Alexa Fluor® 488	0.92	4.1 §
Alexa Fluor® 532	0.61	2.5
Alexa Fluor® 546	0.79	4.1
Alexa Fluor® 555	0.10	0.3
Alexa Fluor® 568	0.69	3.6 §
Alexa Fluor® 594	0.66	3.9 §
Alexa Fluor® 647	0.33	1.0
Alexa Fluor® 660	0.37	1.2 **
Alexa Fluor® 680	0.36	1.2
Alexa Fluor® 700	0.25	1.0
Alexa Fluor® 750	0.12	1.0

Quantum Yield and Lifetime

- The fluorescence quantum yield Φ is the fraction of excited molecules that return to the ground state S_0 with emission of fluorescence photons

$$\Phi = k_r/(k_r+k_{nr}) = k_r\tau_s$$

τ_s: the lifetime of S_1 state.

k_r is called rate constant

- Fluorescence intensity is defined as the amount of photons emitted per unit time and per unit volume of solution

- Brightness
  - Brightness= **ε x Φ**
  - **molar extinction coefficient (ε)** is defined as the quantity of light that can be absorbed by a fluor at a given wavelength
  - **quantum yield (Φ)** is calculated as the number of photons that are emitted by the fluor divided by the number of photons that are absorbed.

Example

Accurate values of fluorescence rate constants (k) can be obtained with experimental values of fluorescence quantum yields and fluorescence lifetimes. Provide the k. value for a fluorophore with fluorescence quantum yield 0.46 and fluorescence lifetime = 8.4 ns.

Answer. K = Fluorescence Quantum Yield/ Fluroscence Lifetime

K = 0.46/8.4

K = 0.055 ns-1

Example

The fluorescence quantum yield of green fluorescent protien CGFP) is 0.79. Determine the fluorescence rate constant (in s^{-1}) if the fluorescence emission decayed with a lifetime measured to be 25 hours

1

The objective is to calculate the fluorescence rate constant (in s^{-1}) to the following data.

Ans

Given that,

Fluorescence Quantam yield is given as:

As $\phi = K_f \tau$

where,

ϕ = Fluorescene Quantam yield = 0.79

K_f = Fluorescene rate constant.

τ = Lifetime = 25 hrs = $(25 \times 3600)s$

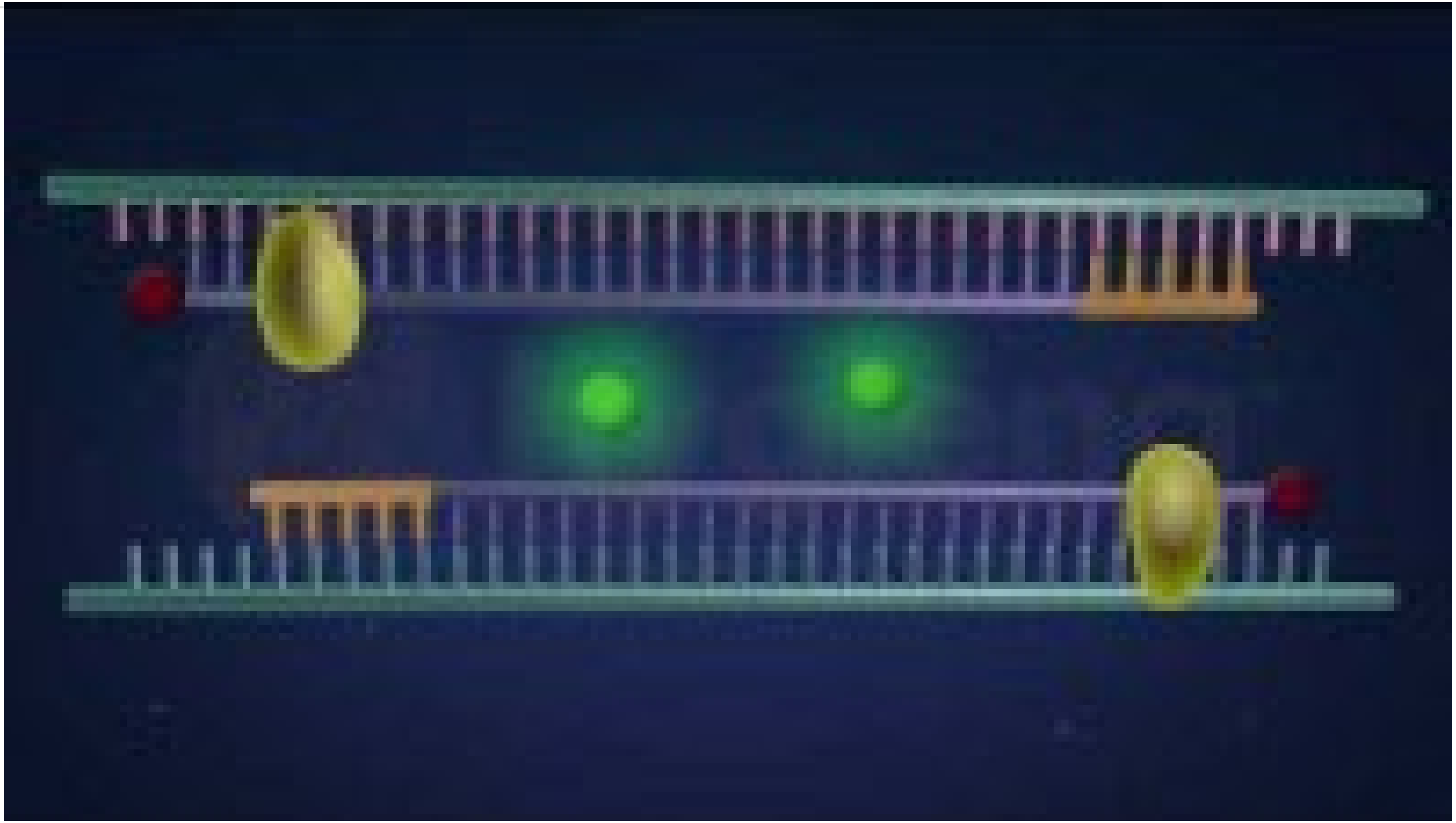
$$\phi = K_f \tau$$

$$0.79 = K_f \times (25 \times 3600)s$$

$$K_f = \frac{0.79}{(25 \times 3600)s}$$

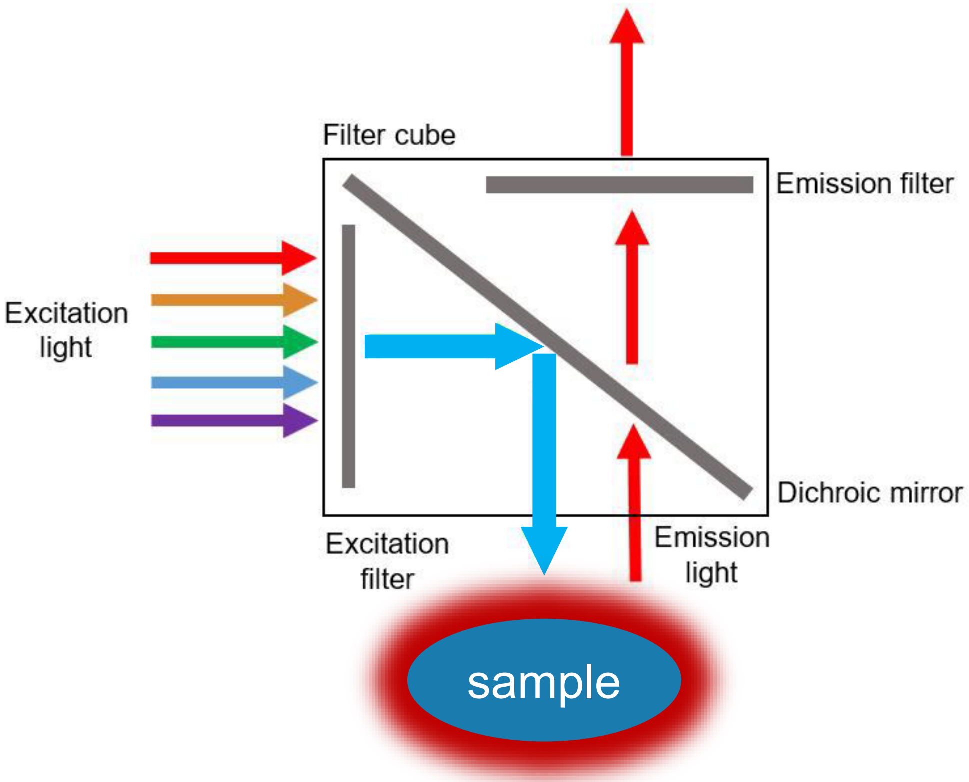
$$K_f = 8.78 \times 10^{-6} s^{-1}$$

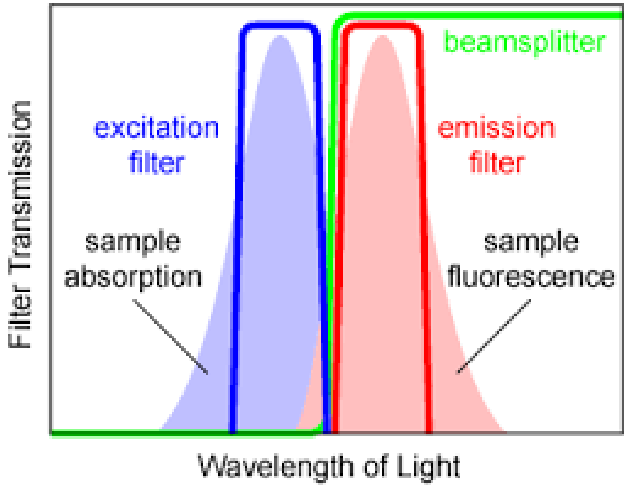
$\therefore$ Fluorescene rate constant = $\boxed{8.78 \times 10^{-6} s^{-1}}$



https://www.youtube.com/watch?v=JeL77b1UyfU

Selecting Filters





Selecting Filters

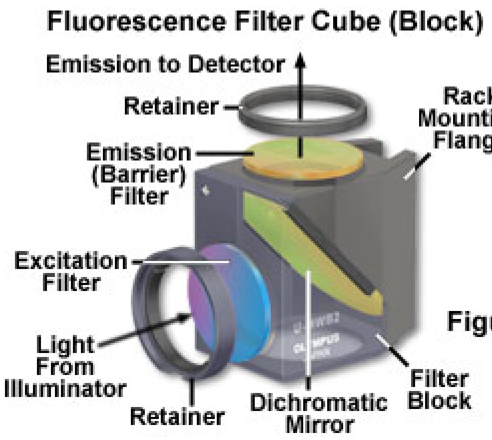
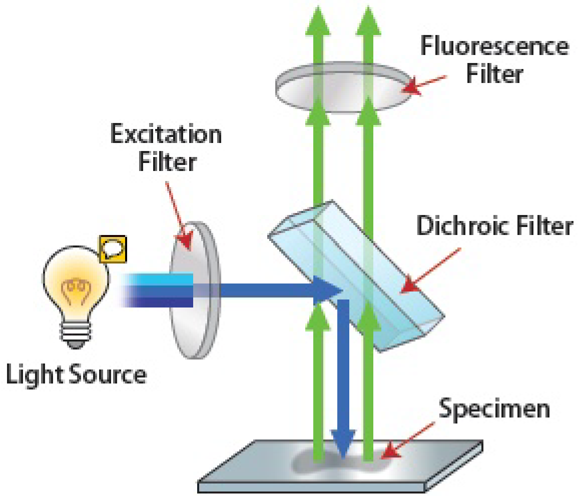


Figure 1



https://www.microscopyu.com/tutorials/spectralprofiles

Example

b) What is fluorescence? Why the absorption and emission wavelengths are different?

c) The normalized absorption and emission spectra of DPM in methanol and dioxane are presented below. Select a solvent and identify the absorption and emission spectrum Justify your answer.

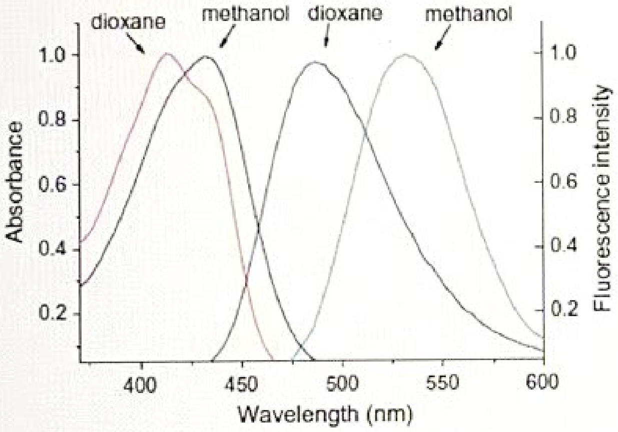
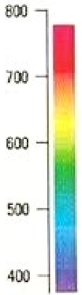


Fig. 1. Normalized absorption and fluorescence spectra of DPM.

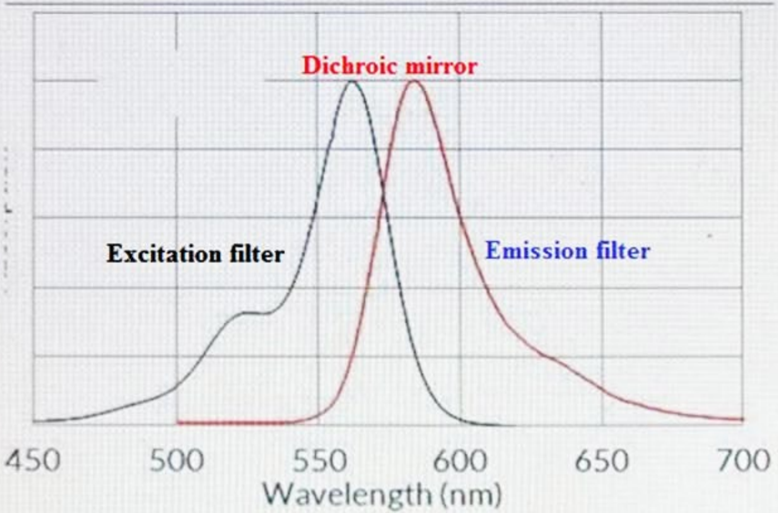


Wavelength [nm]	Absorbed color	Complementary color
650-780	red	blue-green
595-650	orange	greenish blue
560-595	yellow-green	purple
500-560	green	red-purple
490-500	bluish green	red
480-490	greenish blue	orange
435-480	blue	yellow
380-435	violet	yellow-green

d) What is the color emitted by DPM in methanol and dioxane?

Example

The fluorescence spectrum of a fluorescent molecule is shown below.



Build the best filter set for detecting this fluorophore with an epifluorescence microscope. List the wavelengths/wavelength ranges.

A. Excitation Filter Range **Ans.** **460 nm to 560 nm**

B. Dichroic Mirror wavelength **Ans.** **560 nm to 590 nm**

C. Emission Filter Range **Ans.** **590 nm to 700 nm**

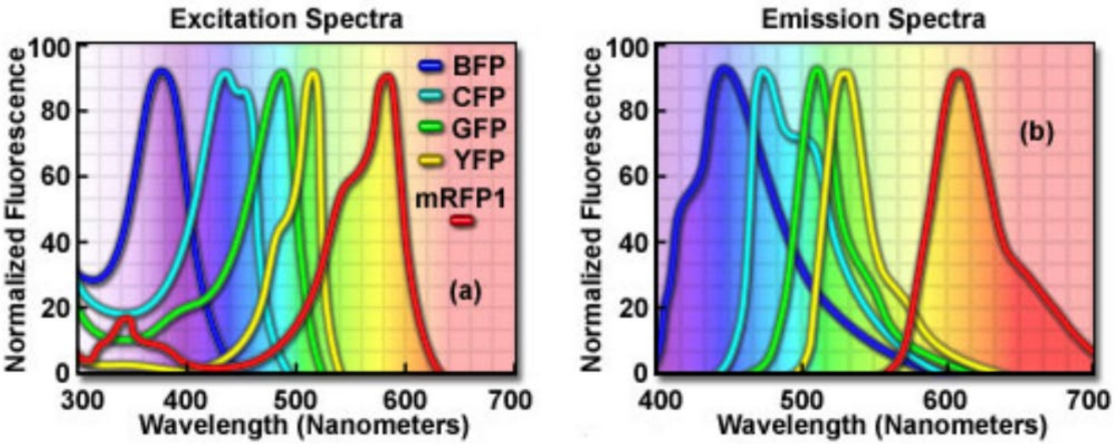
Example

Selecting filters for fluorescence microscopy

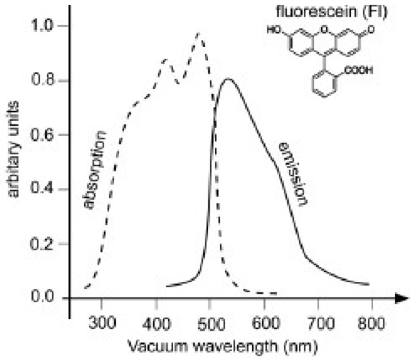
In a fluorescence microscope, the fluorescence filter set containing three essential filters (excitation filter, dichromatic mirror, and emission filter) are positioned in the optical path between the epi - illuminator and the objective.

- A 100 W mercury lamp is used as the light source. Pick the optimal combinations of filters to observe fluorescence from the dyes Green Fluorescent Protein (GFP) and Red Fluorescent Protein (mRFP1).

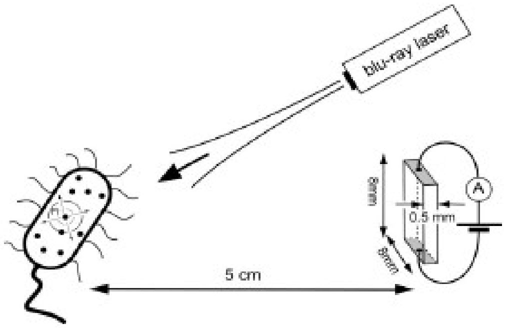
The absorption and emission spectra for the dyes:



Example



The photo-absorption and fluorescence emission spectra of fluorescein is shown above, where the probability of a molecule emitting a photon upon absorbing one is 88%. A bacterial cell containing approximately 1 million randomly oriented fluorescein molecules is tracked by illuminating it with a 10nW beam of 410 nm violet light from a blu-ray laser diode, where these molecules completely absorb the light beam. The fluorescence light emitted from the cell is detected with a photoconductivity detector, placed at a distance of 5 cm away from the cell. This detector consists of an 8-by-8 mm square section of silicon wafer facing towards the cell. The wafer has a thickness 0.5 mm and its electrodes along opposite sides are connected in series with a zero-resistance ammeter and a 1.5V battery as shown.



Determine the number of photons per second incident on the bacterium.

[4 marks]

Solution

$$E = h\nu = \frac{hc}{\lambda}$$

$$E(eV) \approx \frac{1240 eV \cdot nm}{\lambda(nm)}$$

E = Energy of a single photon

$h = 6.626\times10^{-34}$ J$\cdot$s (Planck's constant)

ν = frequency (Hz)

λ = wavelength (m)

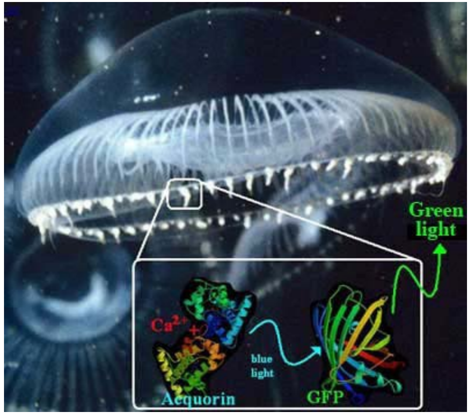
$c = 2.998\times10^{8}$ m/s (speed of light)

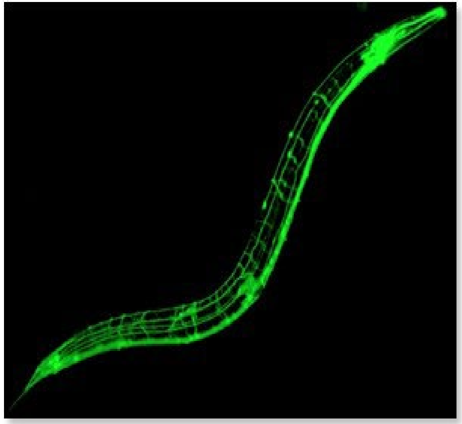
Number of photons incident per second on the bacterium is total energy incident per second divided by energy of single photon.
For the photon, E=1.24 eV nm/ λ nm

so, E_p= 1.24/(0.410) eV
=> E_p= 3.024**x**(1.6**x**10^{-19}) Joules
=> E_p= 4.84**x**10^{-19} Joules
therefore, number of photons incident per second (say N) = 10*10^{-9} (joules per second) /4.84*10^{-19} (joules)
or N= 2.066**x**10^{10}

Fluorescence Proteins

- Osamu Shimomura of Princeton University first realize that this fluorophore in jelleyfish was actually a *protein*
- 4-(*p*-hydroxybenzylidene)-5-imidazolidinone moiety covalently linked within the polypeptide chain (Shimomura 1979)





- Prasher (1992) got primary sequence of the 238 amino acids of *Aequorea* green fluorescent protein
- expression of the gene in *Escherichia coli* resulted in green fluorescent bacteria (Inouye and Tsuji 1994)
- Nobel prize 2008

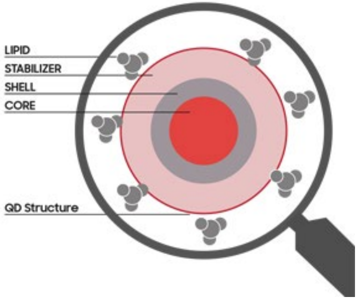
Fluorescence Proteins

Table 1 | Properties of the best FP variants[a,b]

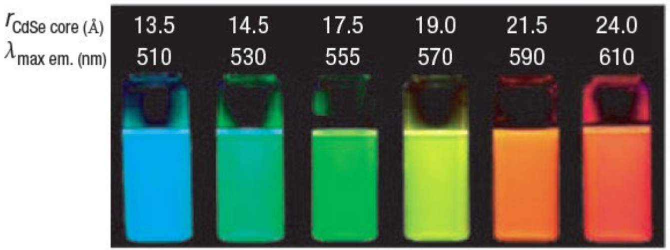
Class	Protein	Source laboratory (references)	Excitation[c] (nm)	Emission[d] (nm)	Brightness[e]	Photostability[f]	pKa	Oligomerization
Far-red	mPlum[g]	Tsien (5)	590	649	4.1	53	<4.5	Monomer
Red	mCherry[g]	Tsien (4)	587	610	16	96	<4.5	Monomer
	tdTomato[g]	Tsien (4)	554	581	95	98	4.7	Tandem dimer
	mStrawberry[g]	Tsien (4)	574	596	26	15	<4.5	Monomer
	J-Red[h]	Evrogen	584	610	8.8*	13	5.0	Dimer
	DsRed-monomer[h]	Clontech	556	586	3.5	16	4.5	Monomer
Orange	mOrange[g]	Tsien (4)	548	562	49	9.0	6.5	Monomer
	mKO	MBL Intl. (10)	548	559	31*	122	5.0	Monomer
Yellow-green	mCitrine[i]	Tsien (16,23)	516	529	59	49	5.7	Monomer
	Venus	Miyawaki (1)	515	528	53*	15	6.0	Weak dimer[j]
	YPet[g]	Daugherty (2)	517	530	80*	49	5.6	Weak dimer[j]
	EYFP	Invitrogen (18)	514	527	51	60	6.9	Weak dimer[j]
Green	Emerald[g]	Invitrogen (18)	487	509	39	0.69[k]	6.0	Weak dimer[j]
	EGFP	Clontech[l]	488	507	34	174	6.0	Weak dimer[j]
Cyan	CyPet	Daugherty (2)	435	477	18*	59	5.0	Weak dimer[j]
	mCFPm[m]	Tsien (23)	433	475	13	64	4.7	Monomer
	Cerulean[g]	Piston (3)	433	475	27*	36	4.7	Weak dimer[j]
UV-excitable green	T-Sapphire[g]	Griesbeck (6)	399	511	26*	25	4.9	Weak dimer[j]

Quantum Dots

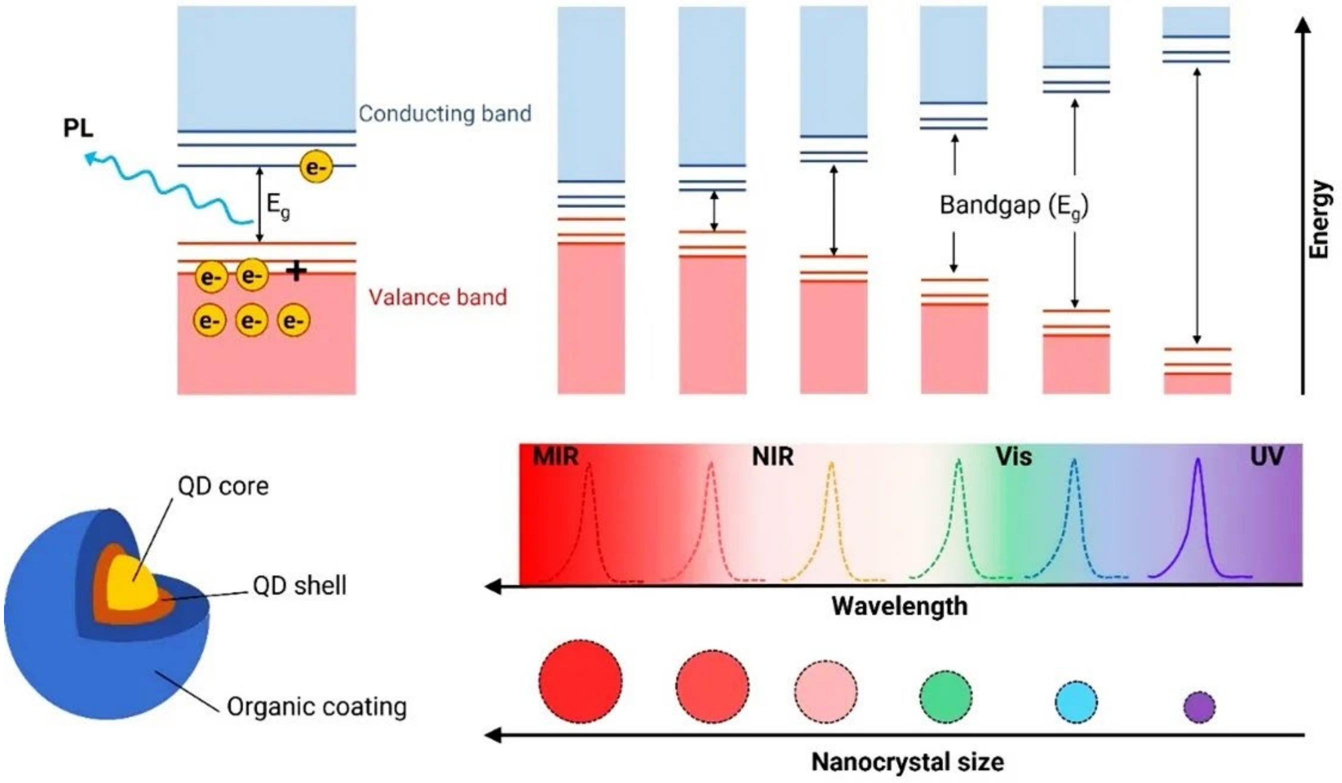
A quantum dot is a nanocrystal-sized semiconductor with quantum-mechanical properties. These tiny crystals, ranging from 2 to 10 nanometers in size, absorb light and then emit it at a specific color determined by their size.

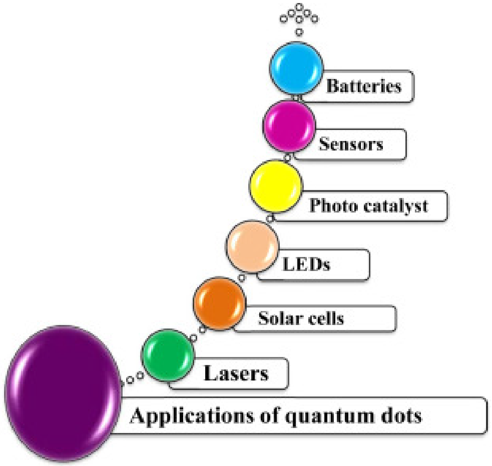


Band-gap energy and color are dependent on the size of the crystal



Quantum Dots

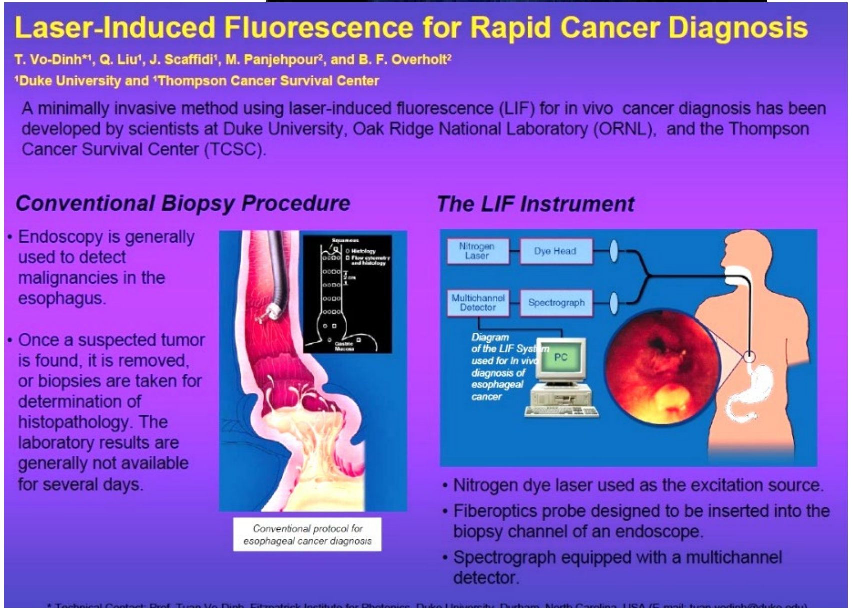




Comparison

	Fluorophore	Quantum dots	Consequences
Quantum yield	~ 10 – 50%	> 50%	Larger fluorescence signal and lower detection limit
Chemical/Photostability	Bad	Good	Larger signal, more accurate and reproducible measurement
Multi-color detection	Possible, multiple types of dyes.	Yes, same type of QDs with different sizes.	Higher multiple analyte detection capability
Number of color channels	Low	High	Higher multiple analyte detection capability
Excitation light	Multiple sources are required for different dyes	Single source above QD band gap	Simplifying sensor devices and lowering the cost

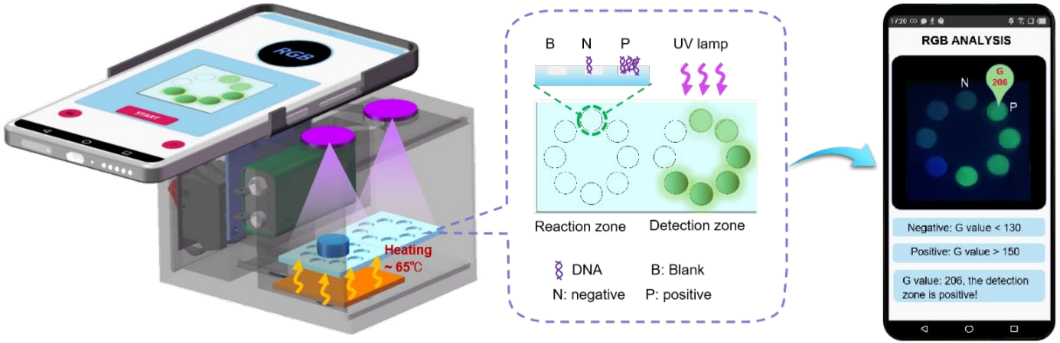
Imaging and Diagnosis



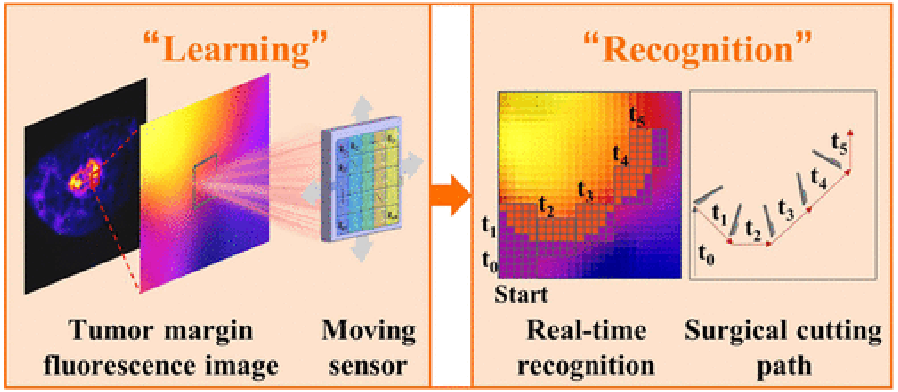
https://youtu.be/uVFEgbsFyYs

https://www.youtube.com/watch?v=mLa_gy1SyZA

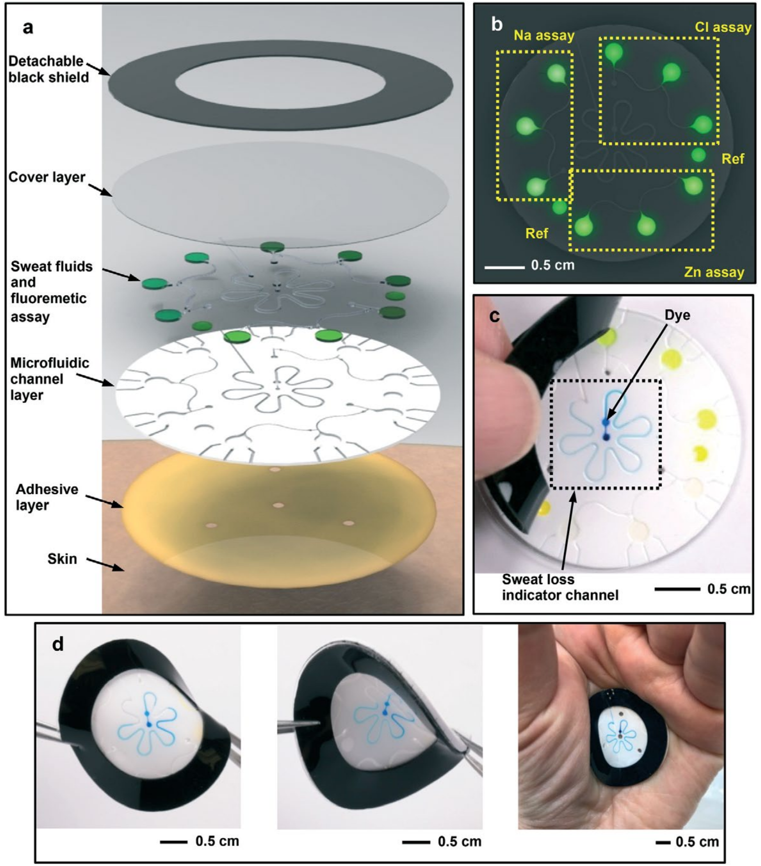
Imaging and Diagnosis



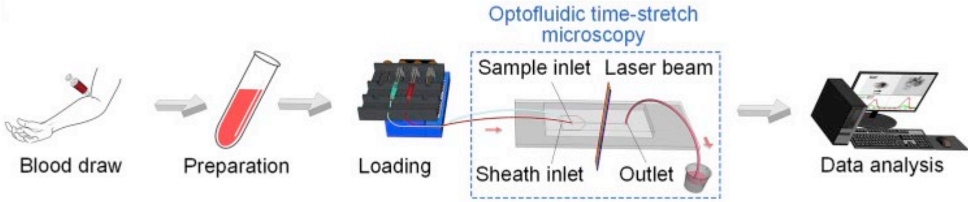
https://link.springer.com/article/10.1007/s00604-022-05419-x#Sec16

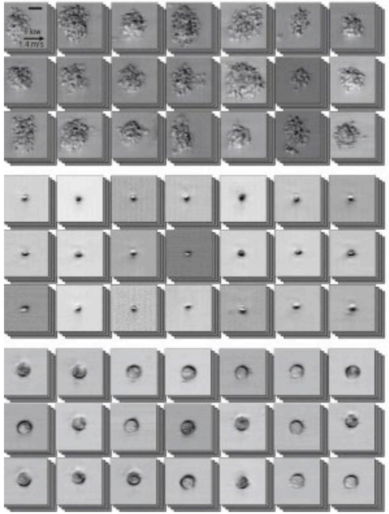


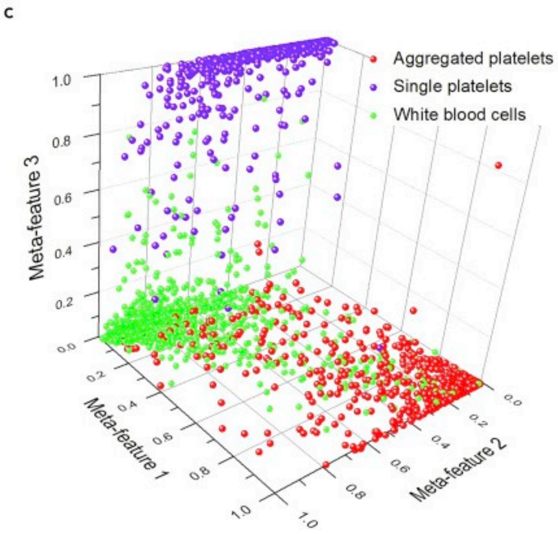
Ultrafast Intelligent Sensor for Integrated Biological Fluorescence Imaging and Recognition

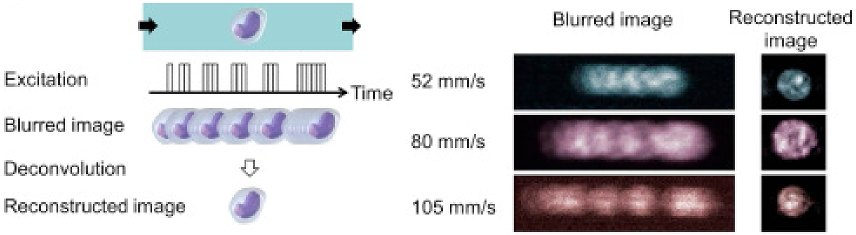


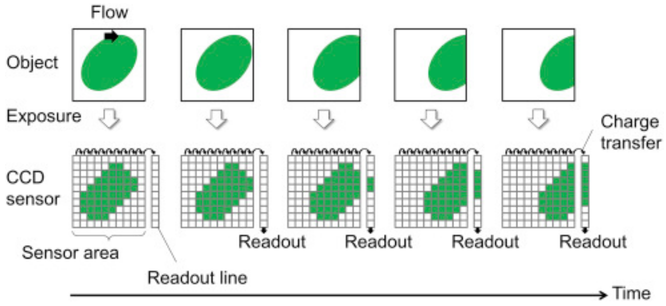
Imaging and Diagnosis

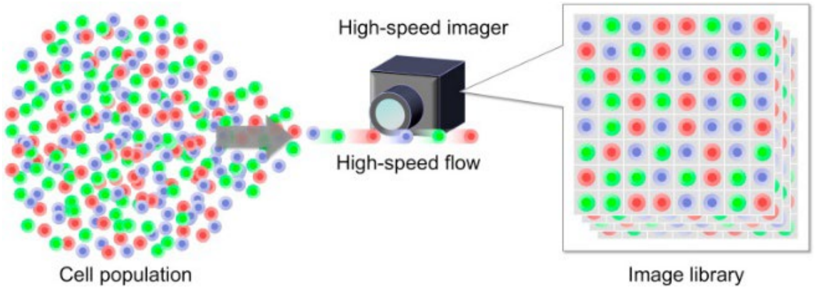






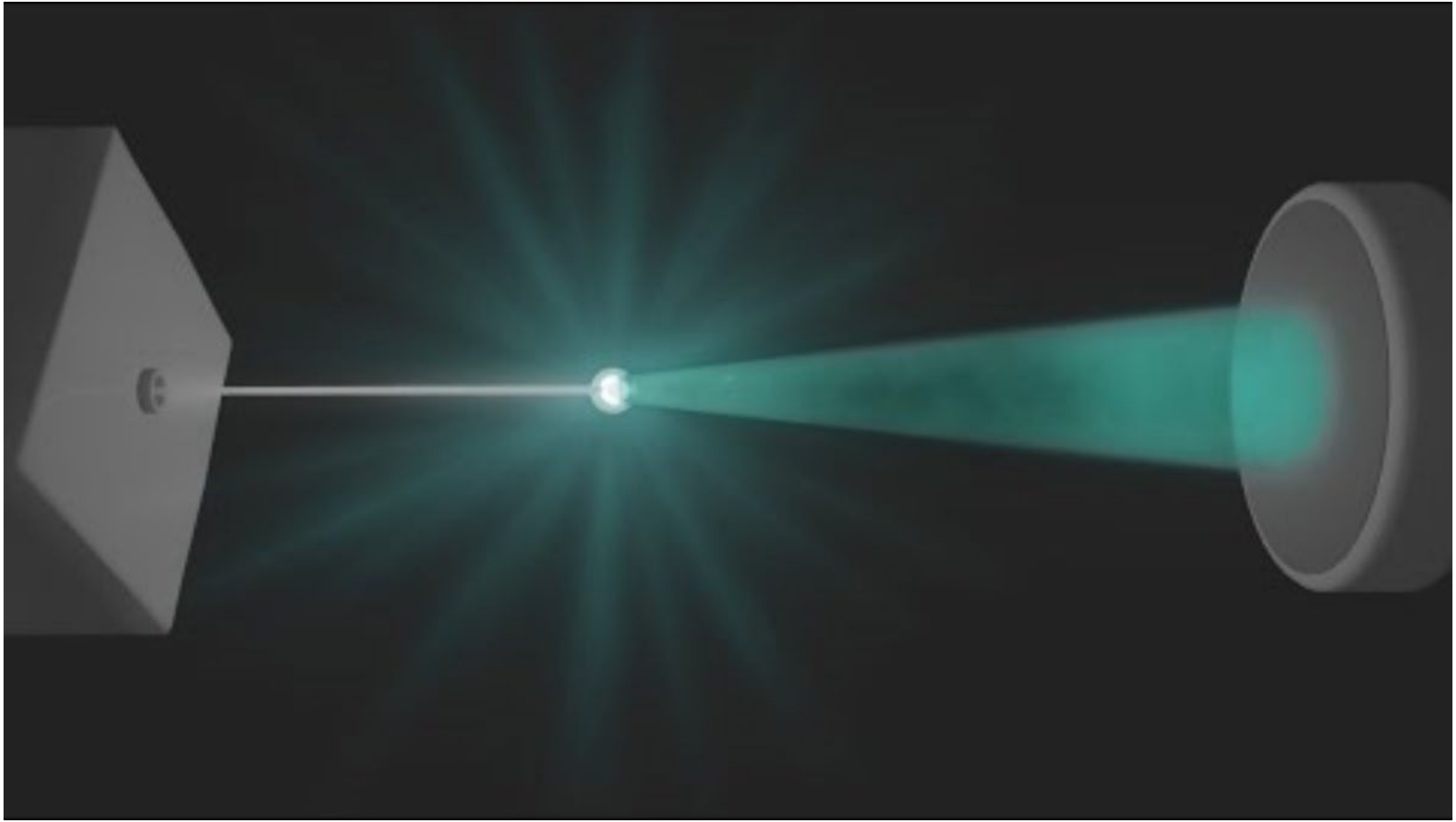






https://www.youtube.com/watch?v=gZrETCxzGyk

Application – flow cytometry



https://www.youtube.com/watch?v=EQXPJ7eeesQ

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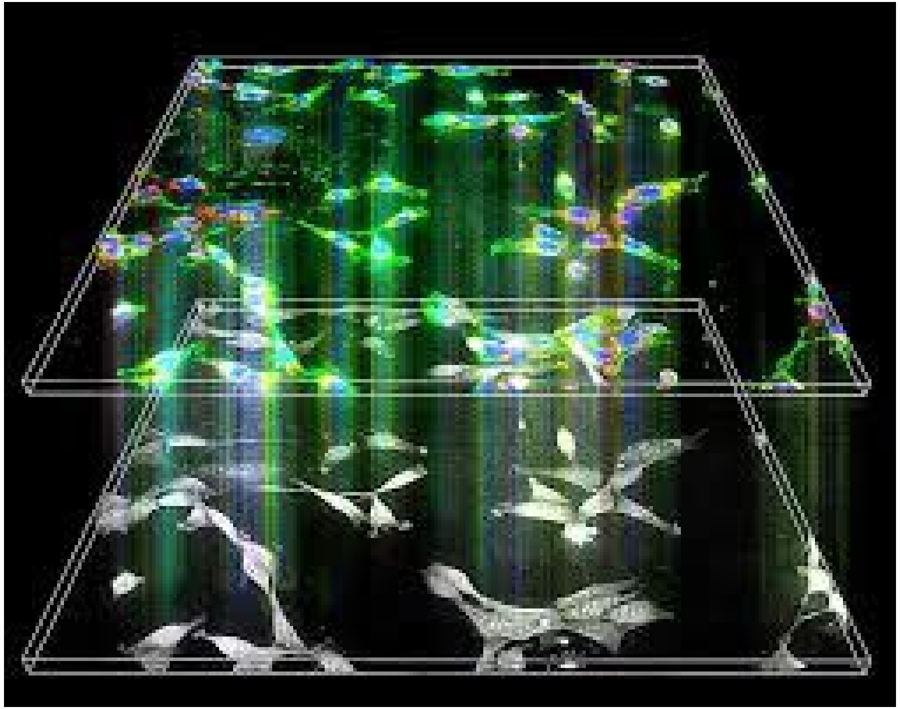
PART TWO

Label Free Biosensors – Fiber

What is Label Free ? Why?



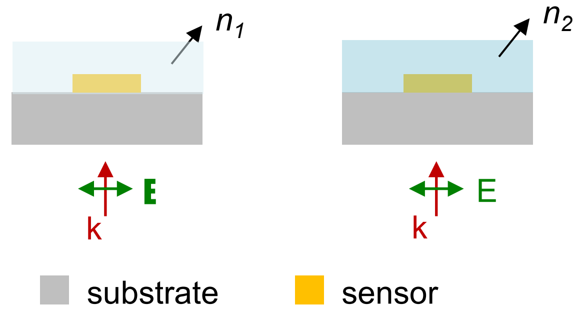
How does machine learning play an important role?

https://www.youtube.com/watch?v=jLd2I2adQtw

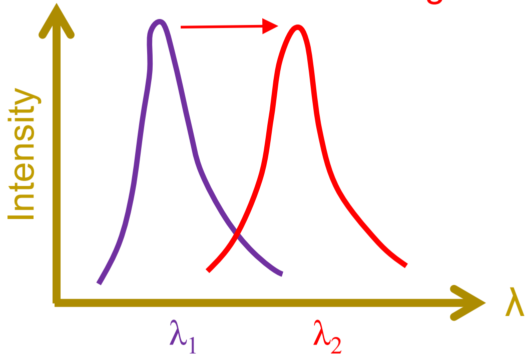
https://www.olympus-lifescience.com/de/resources/white-papers/label-free_segmentation/

Label-Free Sensor Working Principle

Spectral shift during change of environment



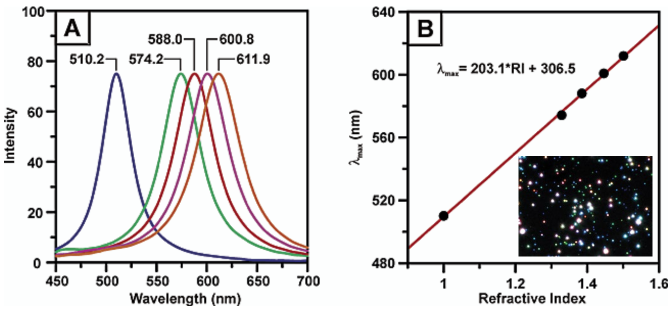
Refractive index change



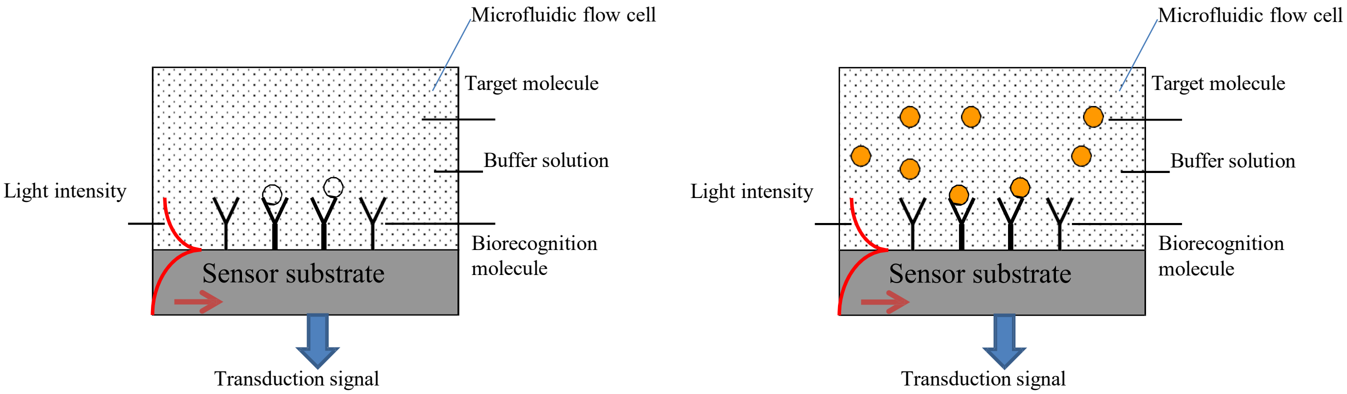
Sensitivity S_λ

$$S_\lambda = \frac{\Delta\lambda_{res}}{\Delta n} = \frac{\lambda_2 - \lambda_1}{n_2 - n_1}$$

Unit: nm/RIU, RIU = refractive index unit



Label-Free Biosensors



- Analyte has different RI than that of environment (such as water, buffer, air)
- Sensing signal: RI change before and after a binding event at sensor surface

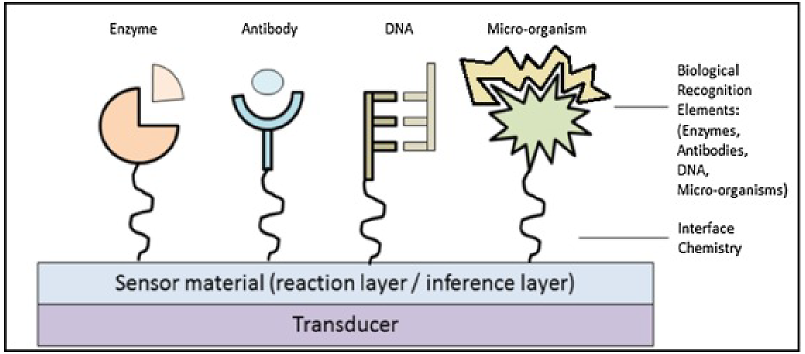
Label-Free Biosensors

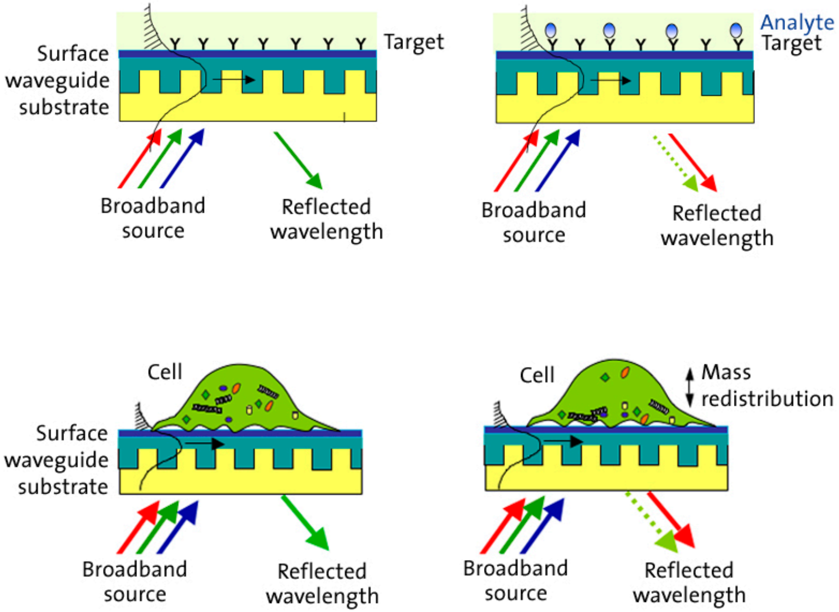
- **Measure refractive index change**
  - Absorption and Raman do not require sample labeling, but require sample excitation

- **Advantages**
  - No labeling involved
  - Direct sample measurement with minimal treatment or modification
  - No sample excitation
  - Low sample volumes needed
  - Potential rapid detection

- **Current optical label-free sensor platforms**
  - Fiber and waveguide
  - Optical microcavity (Fabry-Perot cavity, ring resonator)
  - Surface plasmon resonance (SPR) (metal film and nanoparticle)
  - Interferometer (Young interferometer, Mach-Zehnder interferometer)
  - Photonic crystals (photonic crystal fiber, photonic crystals on a wafer)

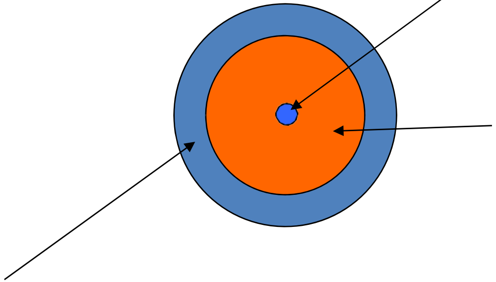
Label-Free Biosensors



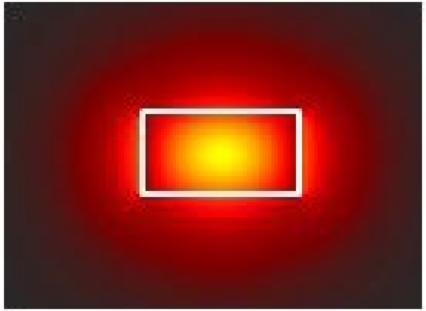


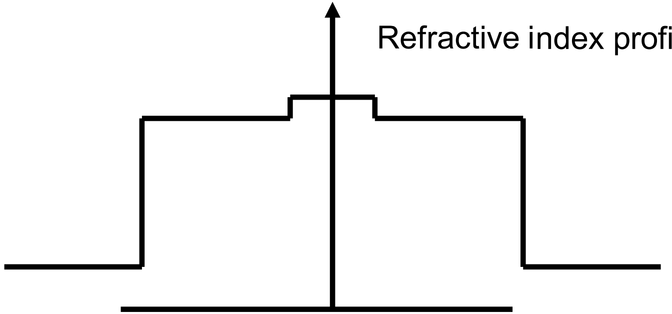
Optical Fiber

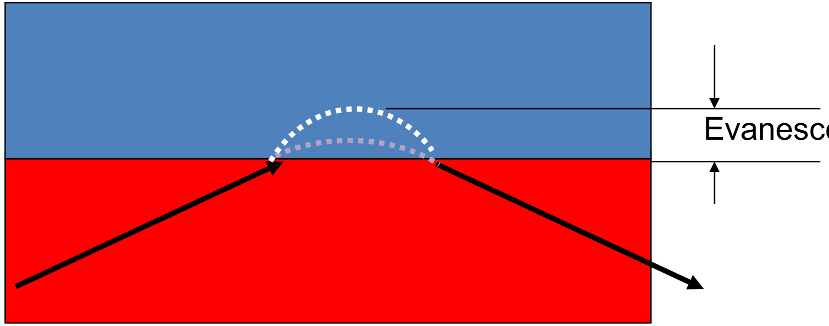
Step-index fiber



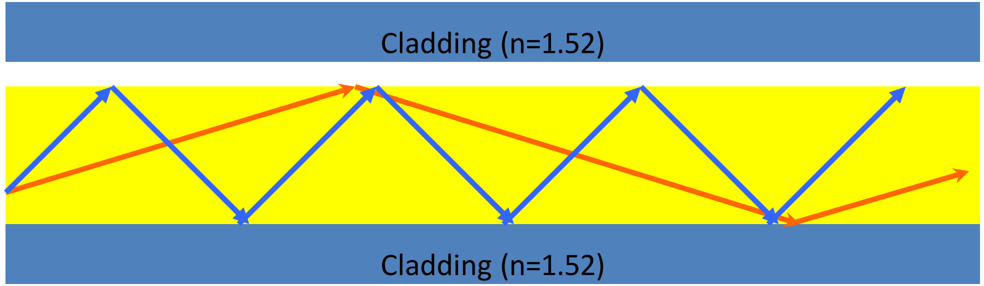
Fiber material: doped glass/ polymer

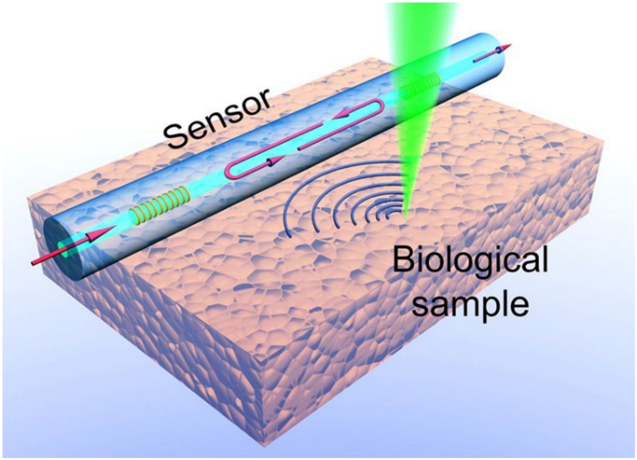






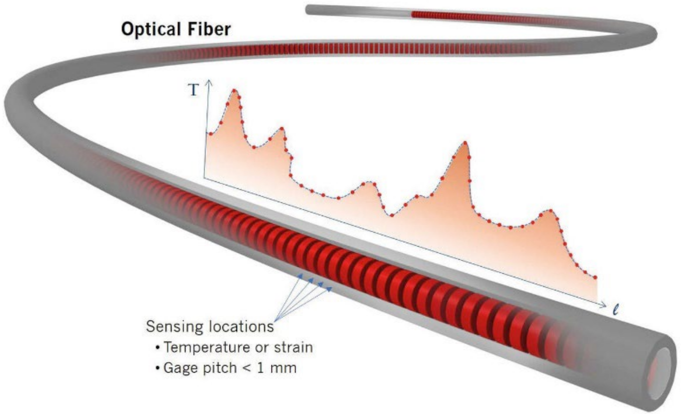
Optical Fiber



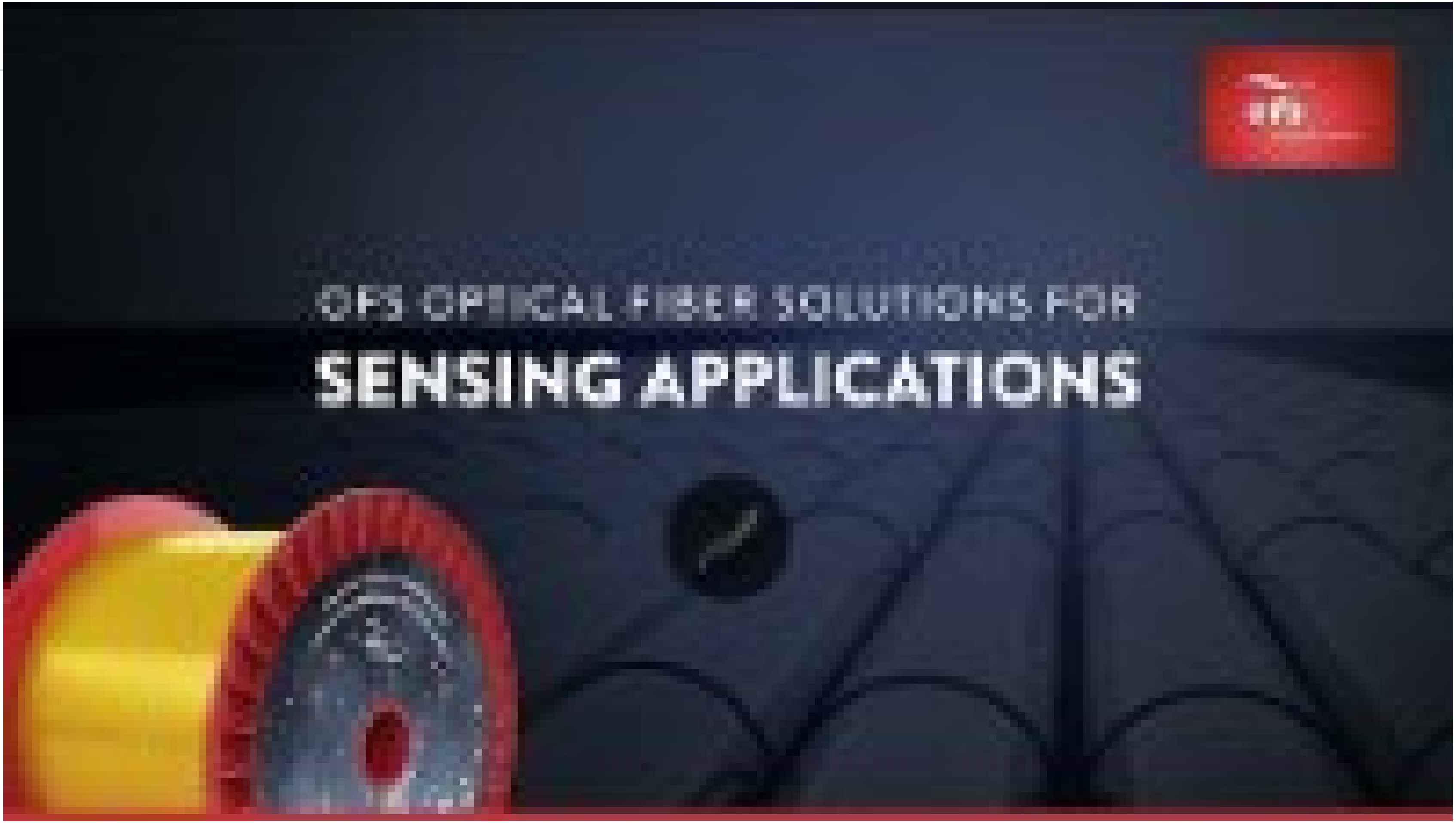


Single mode: only one mode (or incident angle) exists

Multi-mode: many modes (or incident angles) can be present simultaneously

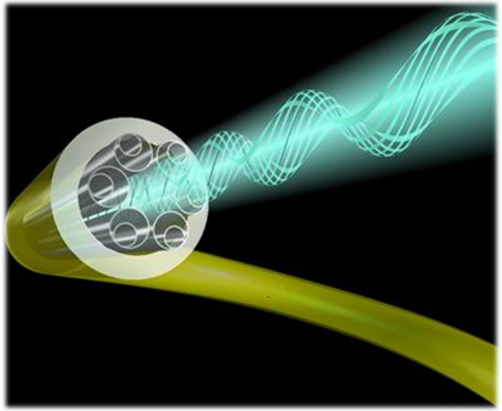


Higher light collection efficiency, but higher dispersion



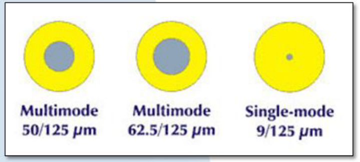
https://www.youtube.com/watch?v=PzsLwhi0vbs

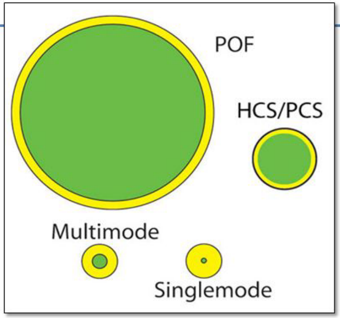
Multi-Mode vs. Single-mode

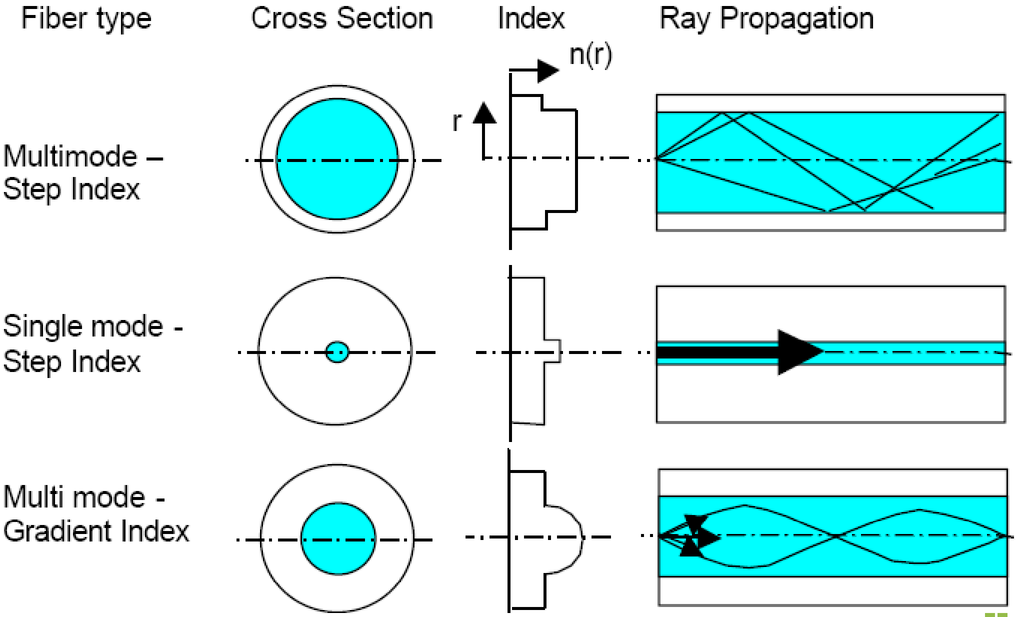


Fiber Sizes and Types

Fiber comes in two types, singlemode and multimode. Except for fibers used in specialty applications, singlemode fiber can be considered as one size and type. If you deal with long haul telecom or submarine cables, you may have to work with specialty singlemode fibers. (HSC/PSC- plastic or hard clad silica, plastic cladding on a glass core)

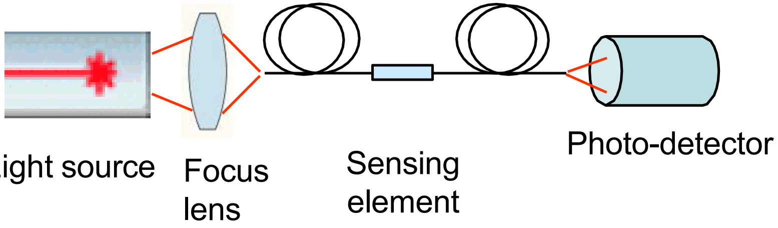




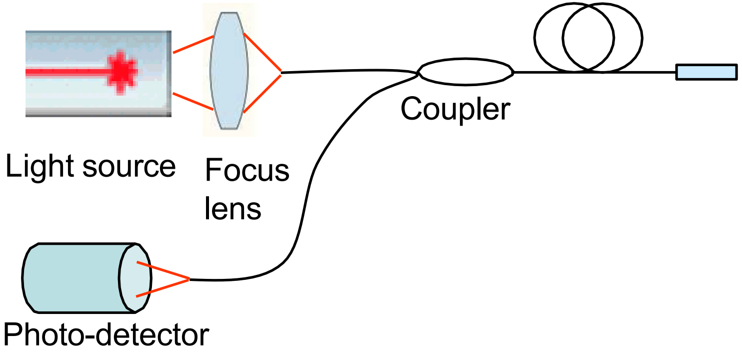


Typical Optical Fiber Sensing Mechanism

Transmission Measurement



Reflection Measurement



Fiber Optics Biosensor

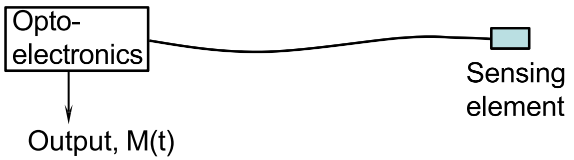
Advantages:

- Many choices commercially available: single-mode fibers, multi- mode fibers, fiber bundles, single-core fiber, dual core fiber
- Inexpensive
- Glass: Easy surface functionalization
- Compatible with catheters or endoscopes for *in vivo* biosensing
  - Hot topic: minimally invasive optical fiber based biosensing and imaging devices to measure in vivo blood flow, glucose, optical coherence tomography
- Sensing and light delivery in one device
- Compact size
- Multi-functional
- Remote accessible

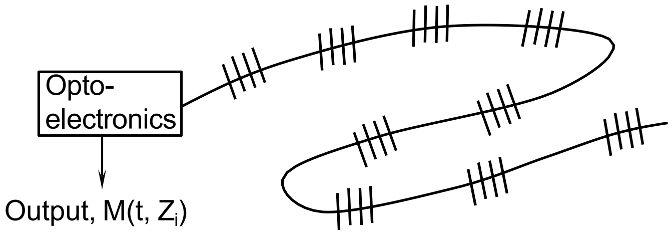
Bottom Line for sensing: You have to have access to the evanescent field

Different Types

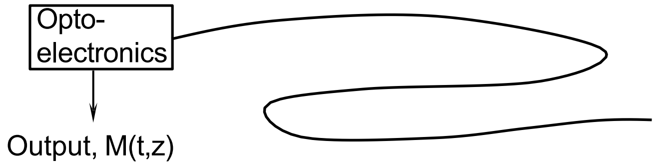
Point sensor:
detect measurand variation only in the vicinity of the sensor



Multiplexed sensor:
Multiple localized sensors are placed at intervals along the fiber length.

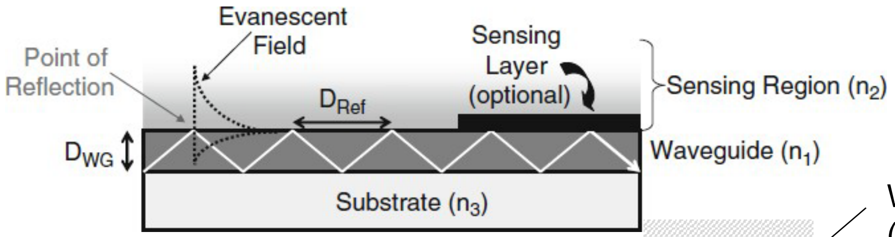


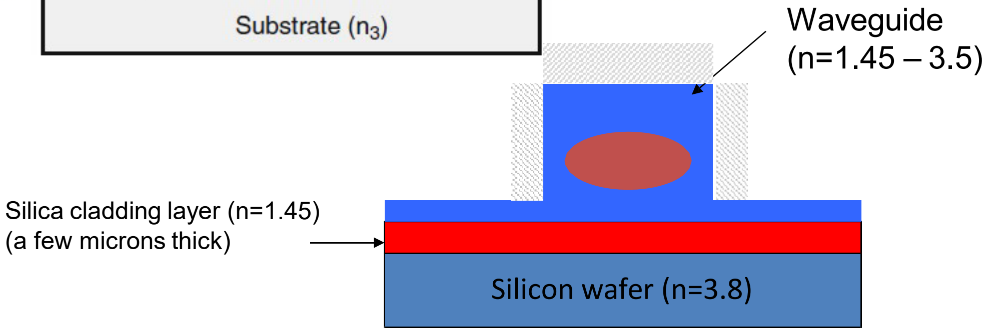
Distributed sensor:
Sensing is distributed along the length of the fiber

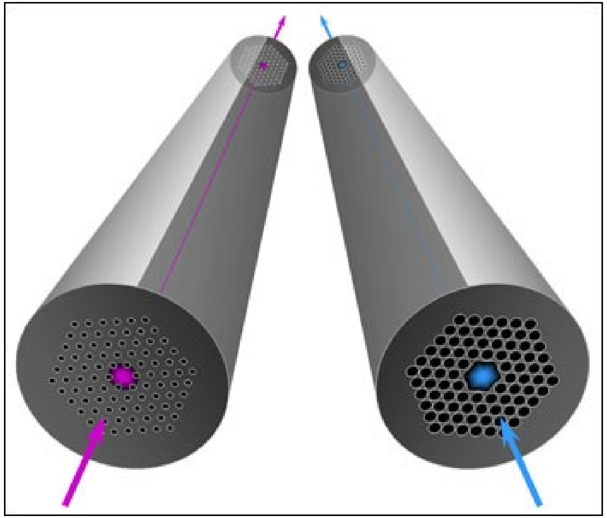


Optical waveguides

- Solid-state waveguide (TIR; index guiding)
- Liquid-core waveguide (index guiding & interference)





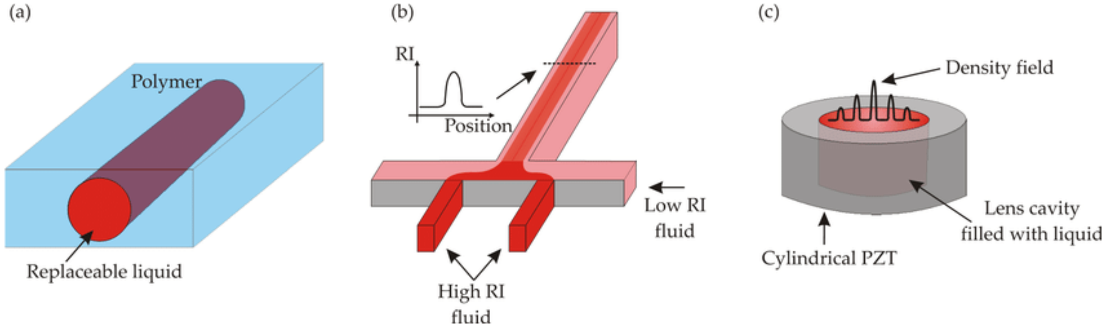


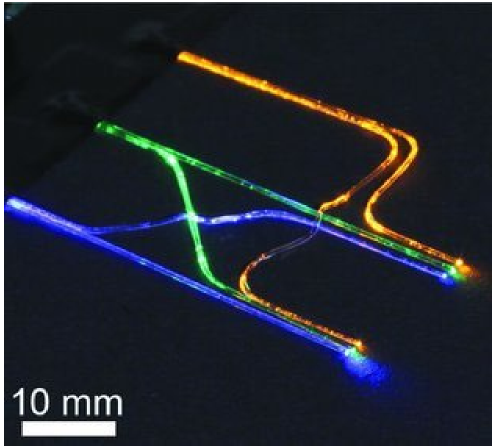
Liquid Core waveguides

- Motivation: enhance light-analyte interaction
- How to achieve index guiding in fluidic channel?
  - Use a solid cladding material with a RI below 1.33

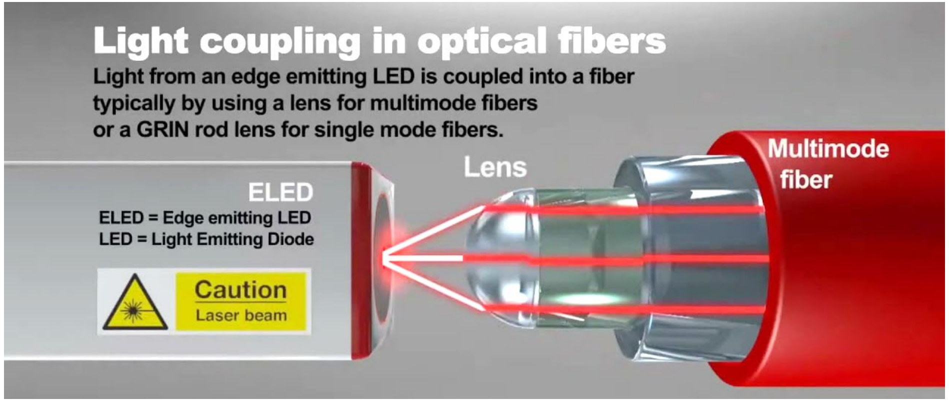
    Fluorinated polymers, Teflon AF (RI=1.29)
  - Nanoporous cladding waveguide (1.15<RI<1.37)
  - Liquid-liquid waveguide

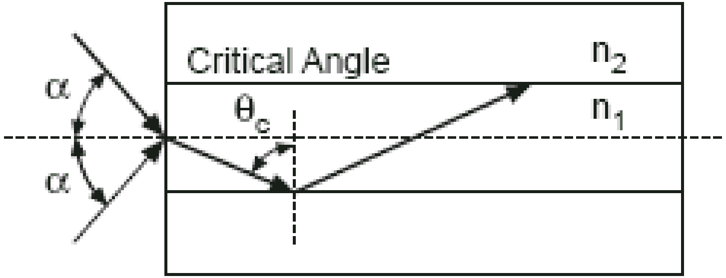
    control over the fluidic properties allows modification of the optical performance
  - Slot waveguide (nanofluidics)





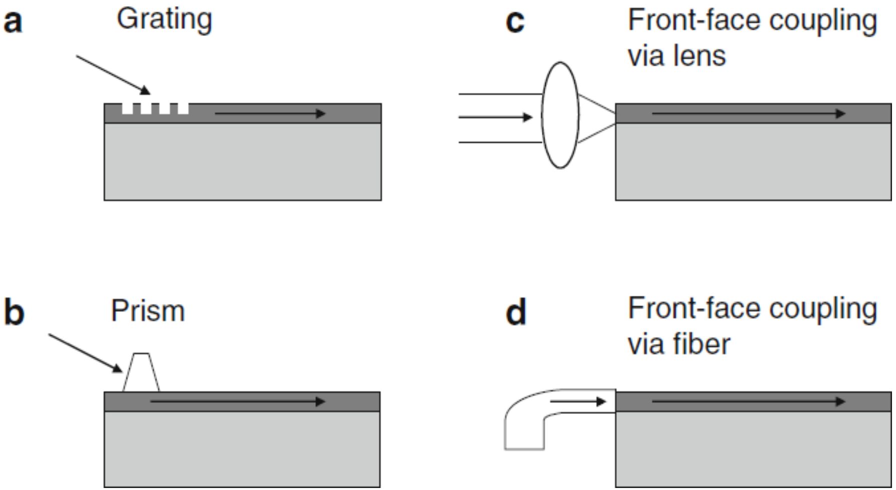
Light Coupling into Sensor



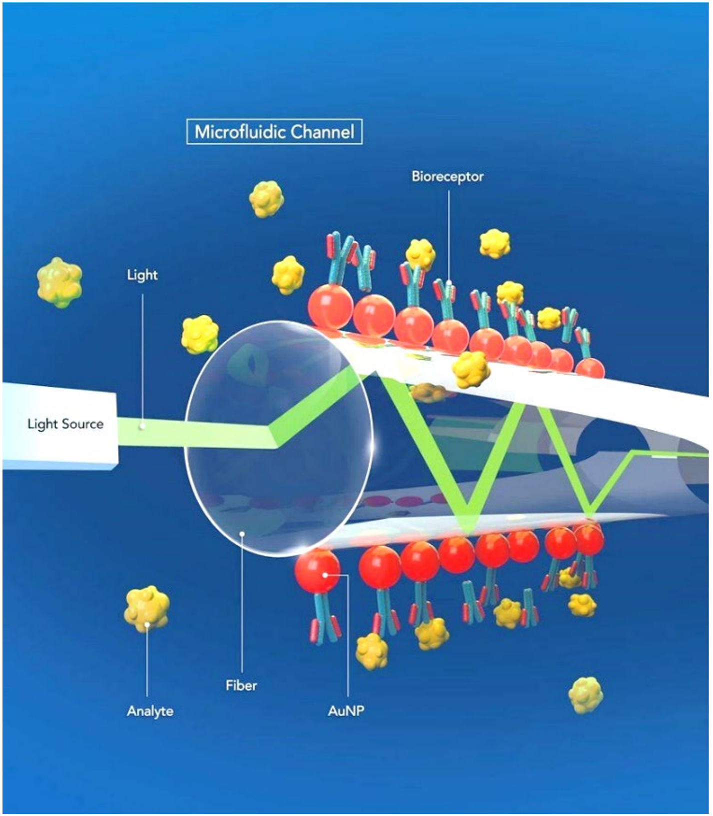


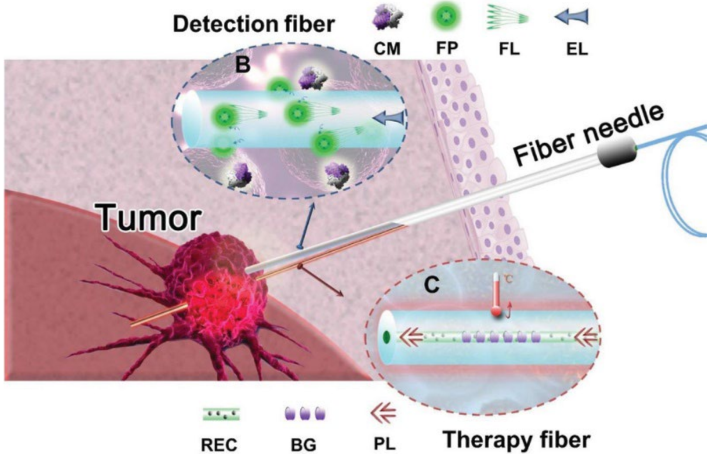
$$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

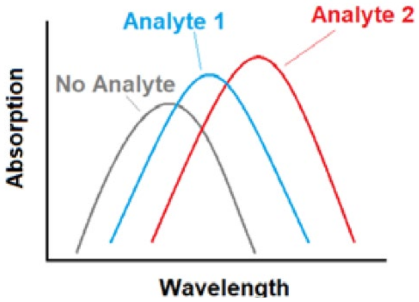
Full Acceptance Angle = 2α

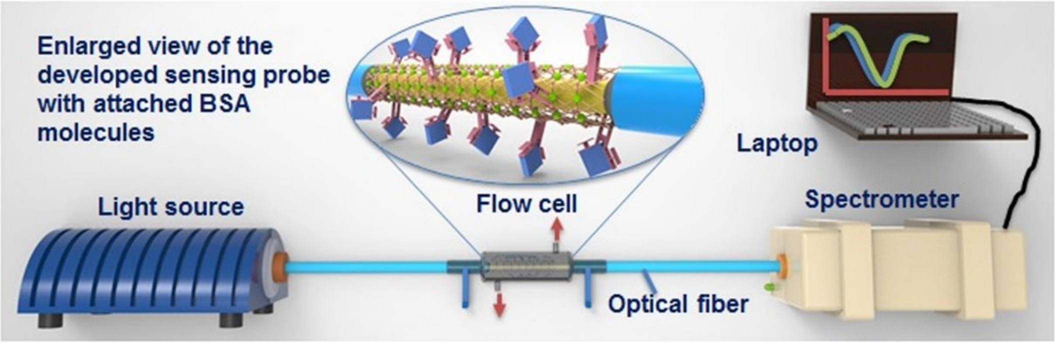


Optical fiber biosensing at surface

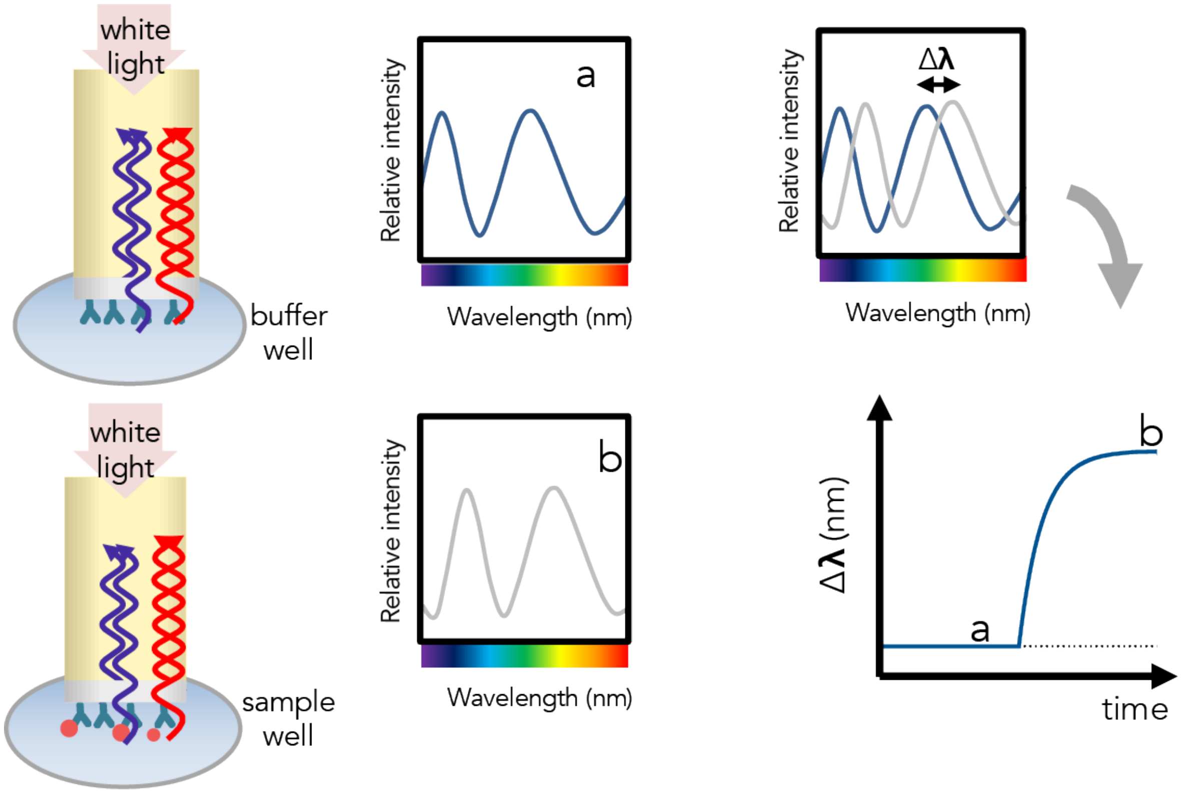


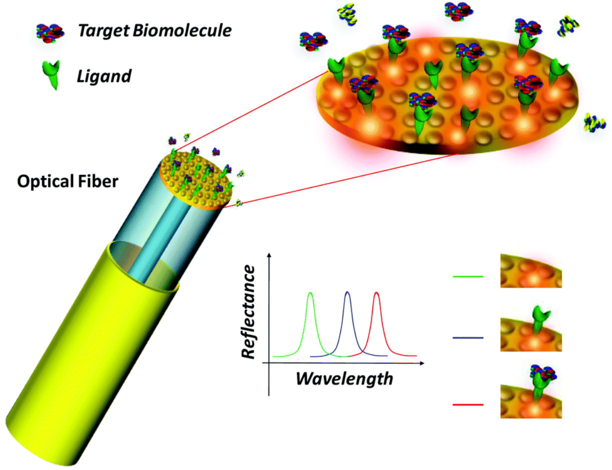






Optical fiber biosensing at tip

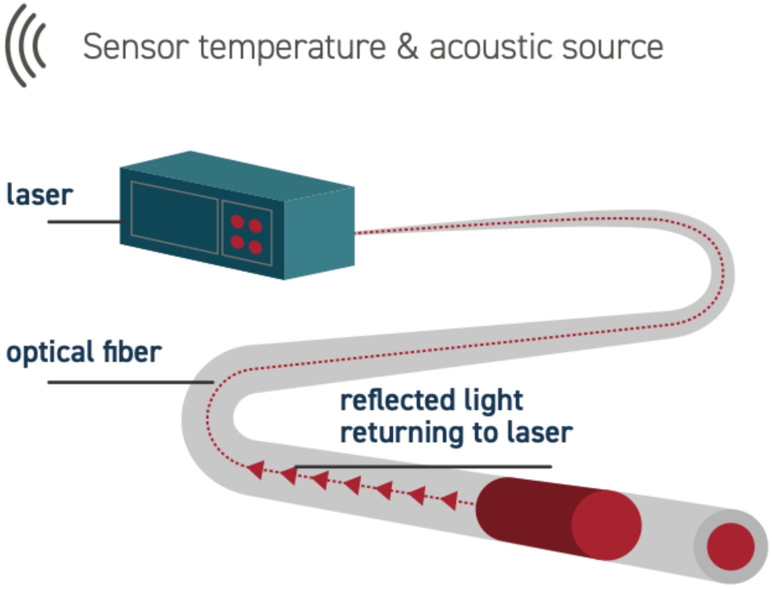




Distributed Fiber Sensors

- Distributed optical fiber sensors provide a method to measure the physical field of the surrounding environment through the distribution of different parameters, such as temperature, strain, vibration, magnetic and gas sensing, etc. across the sensing fiber.

- Unlike traditional sensors that rely on discrete sensors measuring at pre-determined points, distributed sensing **utilizes the optical fibre**. The optical fiber is the sensing element. These systems allow acoustic signals to be detected over large distances and in harsh environments.

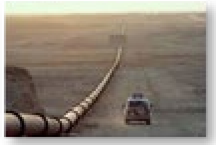


Distributed Fiber Sensors

Oil & Gas

- Fatigue monitoring
- Leaks and flow lines blockage
- Reservoir monitoring
- Thermal oil recovery

Pipeline



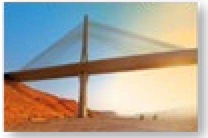
- Leak detection
- Ground movement monitoring

Electric Utilities

- Hot spot detection and localization
- Ampacity (Real Time Thermal rating..)
- Smart Grid

SHM

(Structural Health Monitoring)

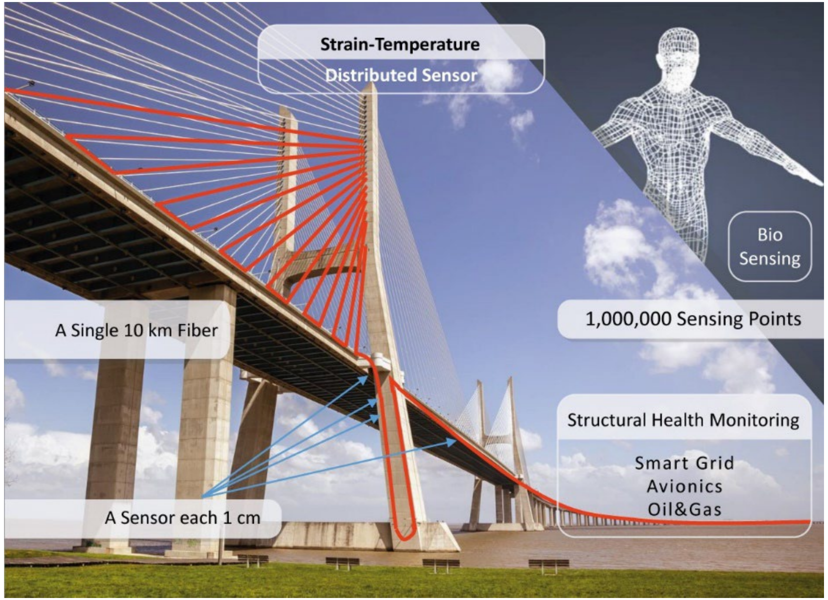


- Crack detection
- Infrastructure management & design
- Dam, dike
- Seismic areas

Telecom Cables

- Buried fiber optic cables monitoring
- Aerial cable monitoring
- Overstressed fiber identification
- Fiber aging

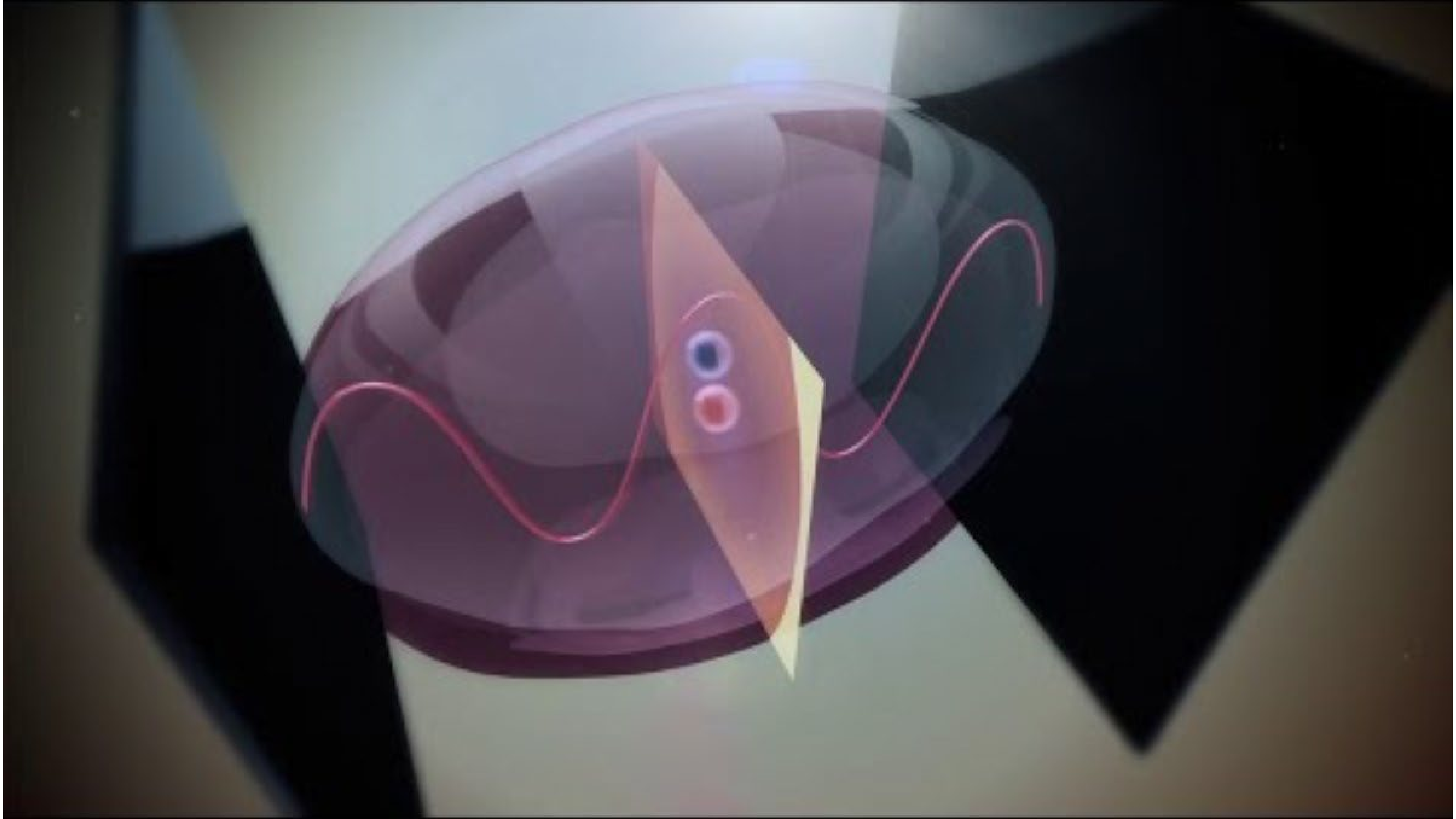
Structured Health Monitoring



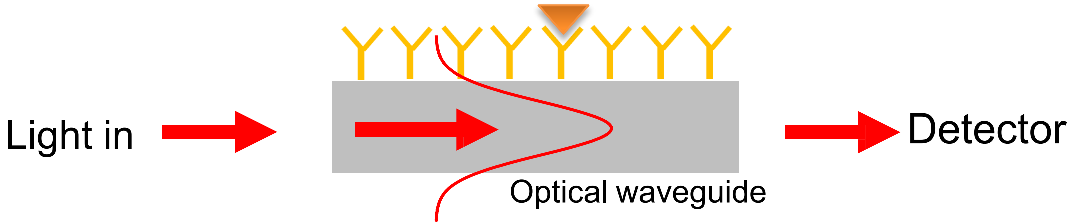
3

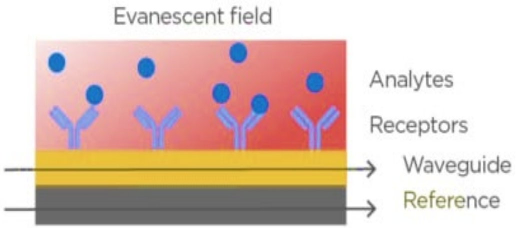
PART THREE

Resonator Biosensors



Conventional Optical Biosensor

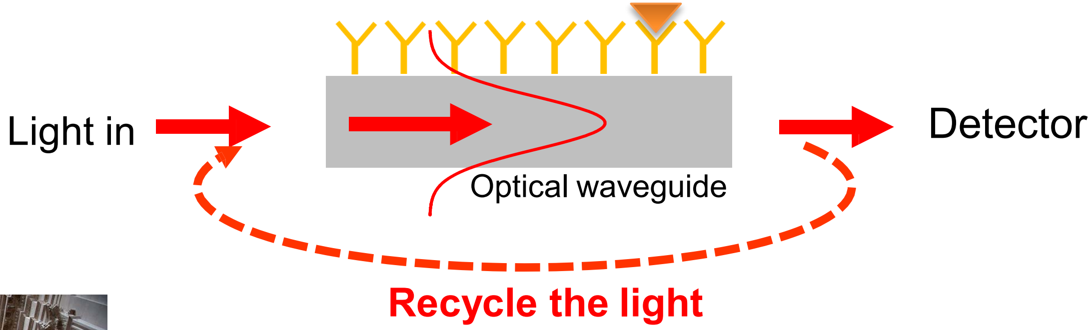




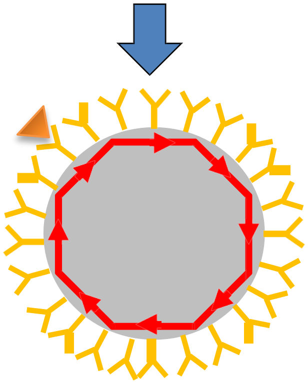
Challenges: Weak signals !

- light passes the waveguide only once
- device size is large
- large surface is needed, large sample quantity

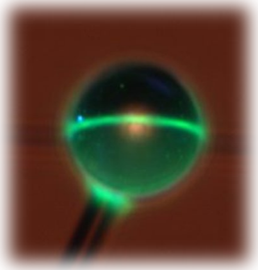
How to Amplify Light- Matter Interactions?



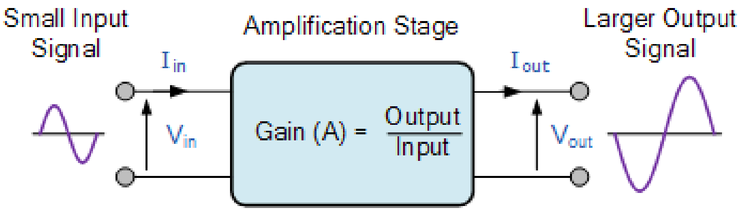
Lord Rayleigh descripted the phenomena
St Paul's Cathedral in London

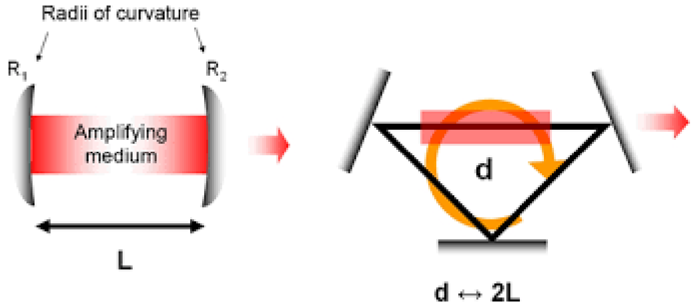


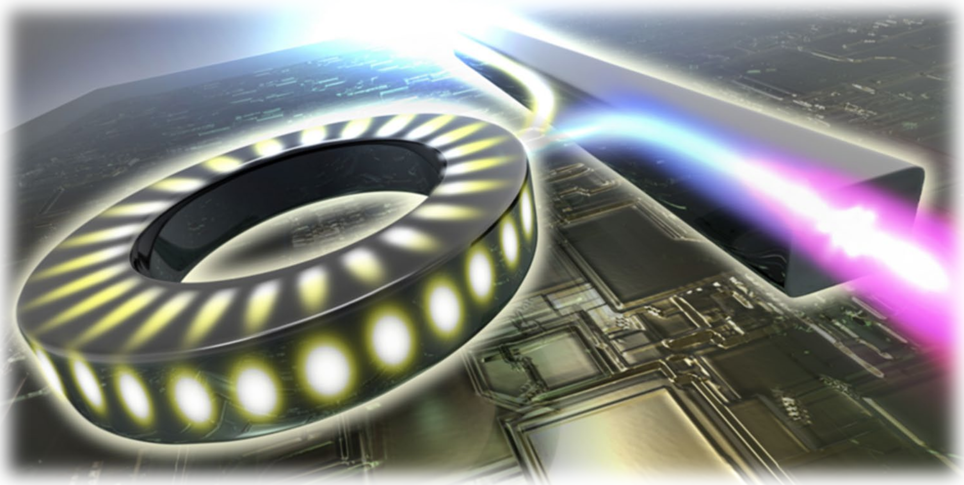
Whispering Gallery Mode (WGM)



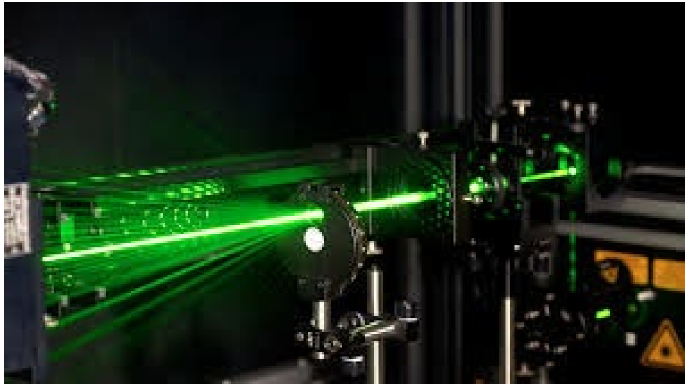
Electrical Amplifier to Optical Amplifier

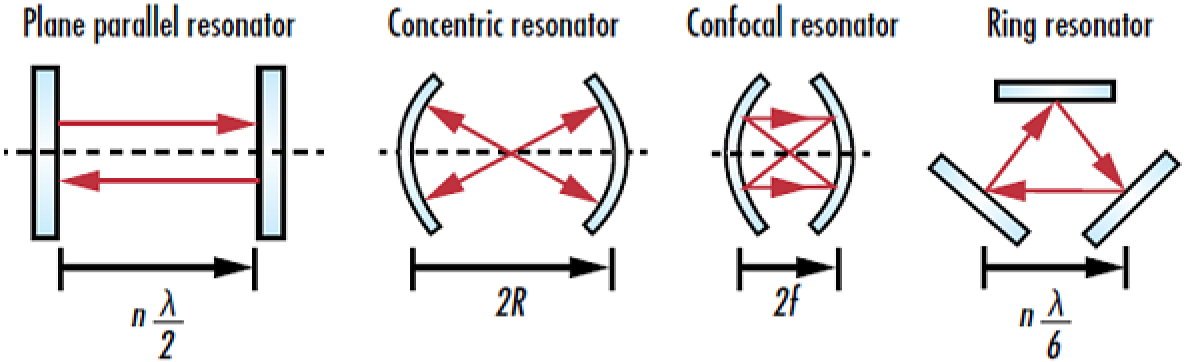






Resonators

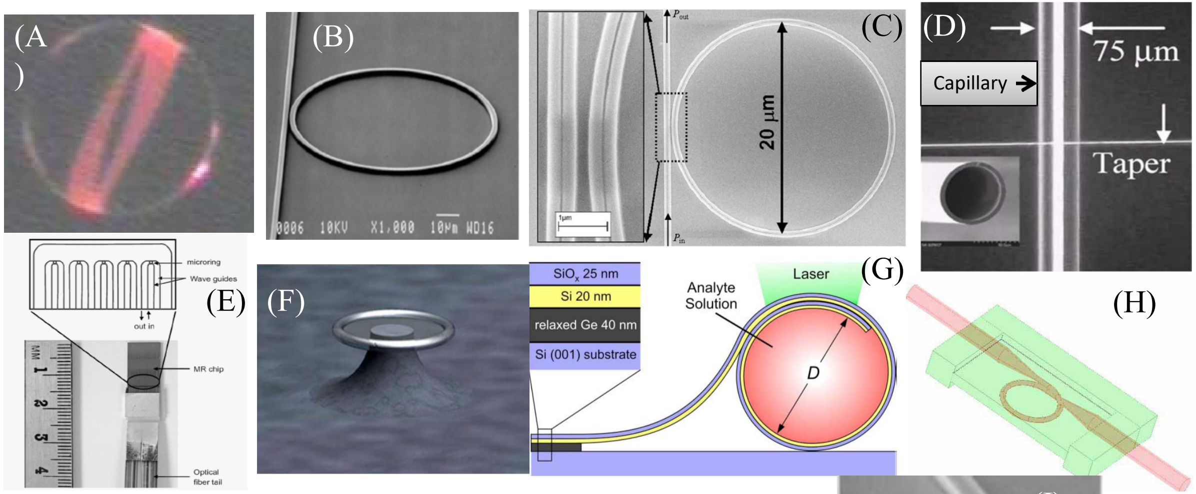


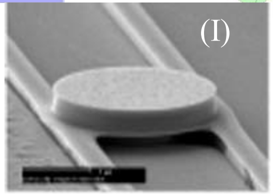


Plane parallel resonator
Concentric resonator
Confocal resonator
Ring resonator
$n\frac{\lambda}{2}$
2R
2f
$n\frac{\lambda}{6}$

Optical Resonators

- Optical resonator
  - Microstructures made by dielectric material (e.g., silica, polymer)
  - Various geometries: sphere, planar ring, planar disk, and microtoroid

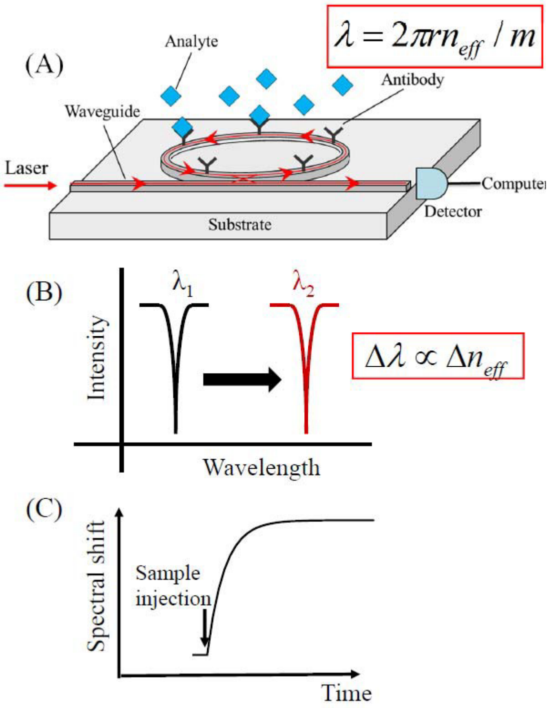


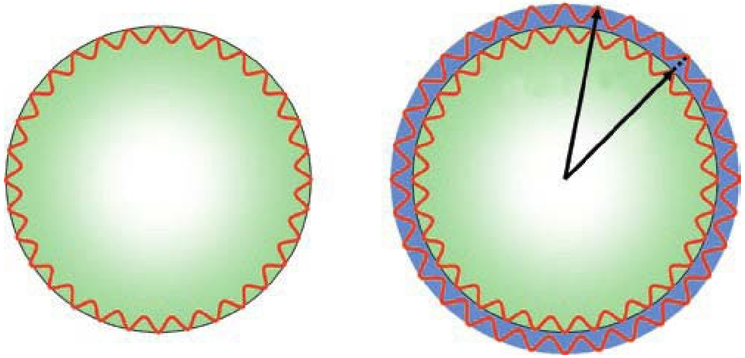


Size in diameter: 20-200 μm

Sun, et al., Anal. Bioanal. Chem. 399, 205–211 (2011).
Vollmer et al., Nature Methods 5, 591 (2008)

Sensing Principle



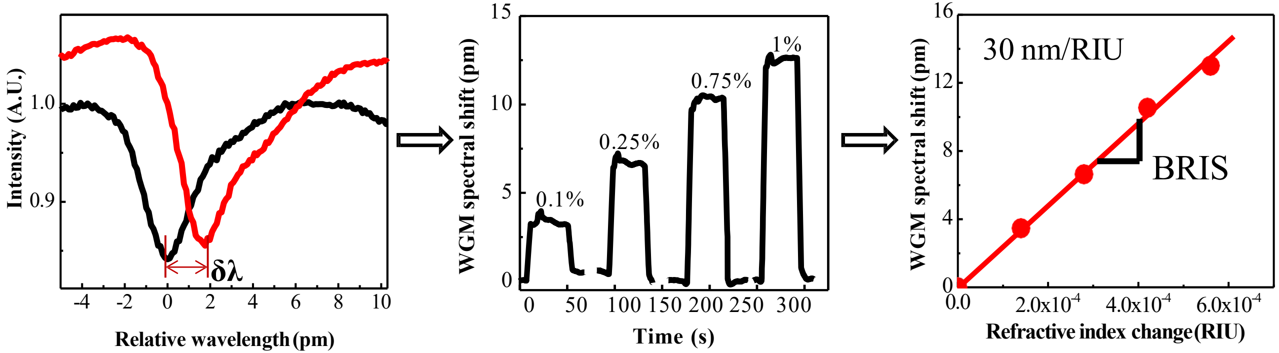


Resonance wavelength change due to changes in radius ΔR or refractive index Δn:

$$\Delta\lambda r / \lambda r = \Delta R/R + \Delta n/n$$

Measuring Bulk Solution

- Characterize the bulk refractive index sensitivity (BRIS).
  - Ethanol/water solution with known refractive index
  - Measure the WGM spectral shift for a known refractive index change



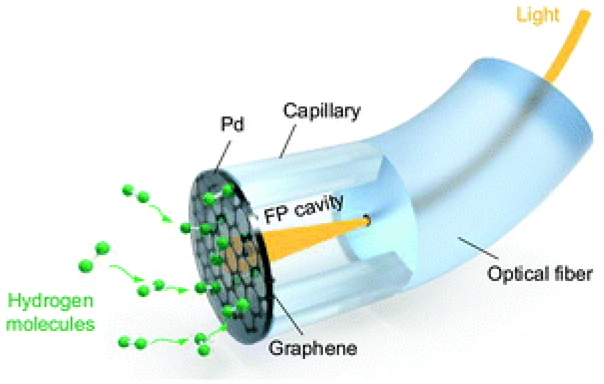
Resonant wavelength:

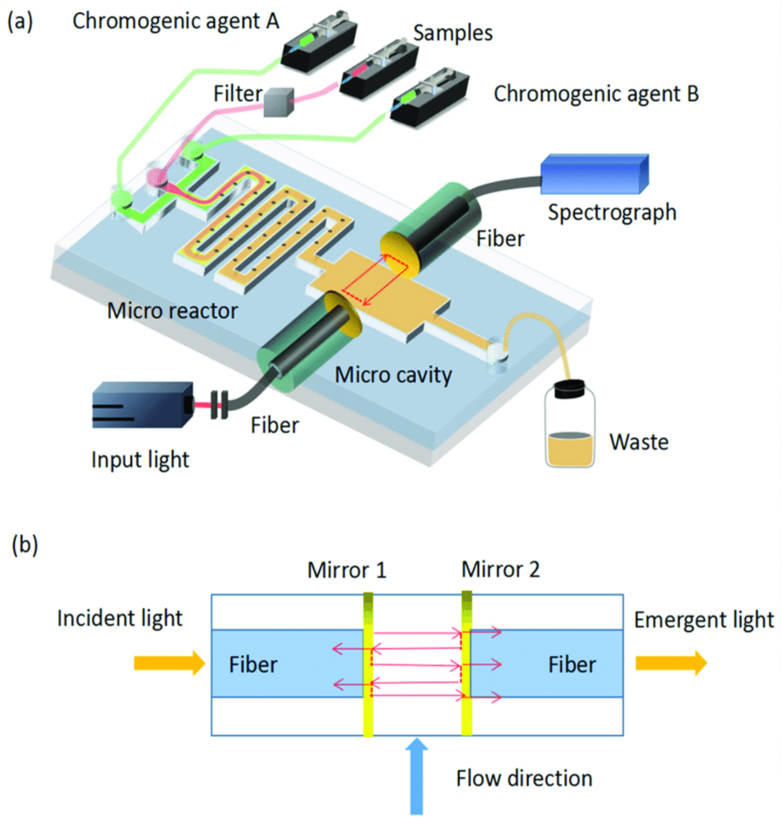
$$\lambda = 2\pi r n_{eff} / m$$

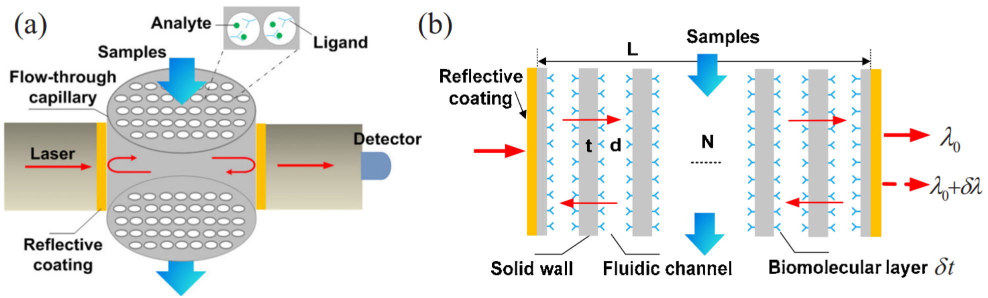
Remember this method characterizes the sensing device response to the RI change in bulk solution

Universal, not dependent upon samples

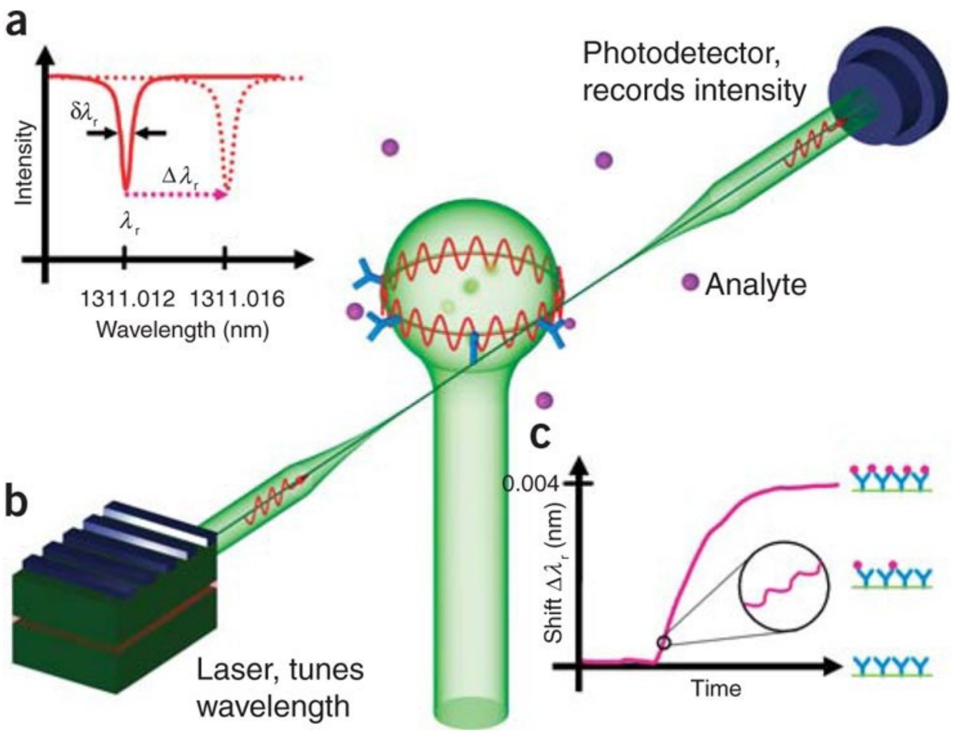
Fabry-Perot Sensors

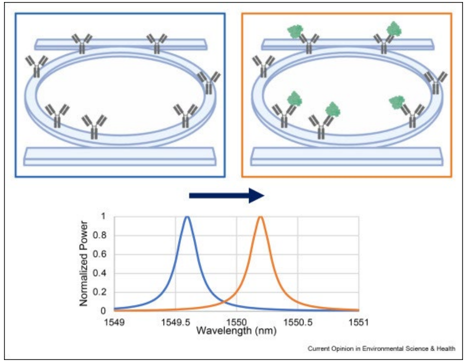


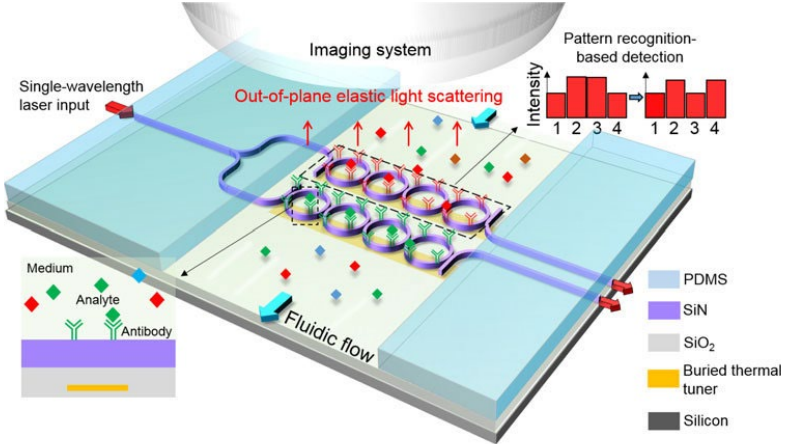




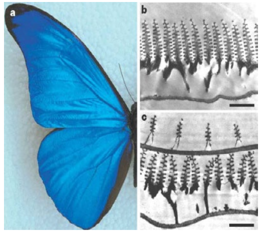
Whispering Gallery Mode Sensors

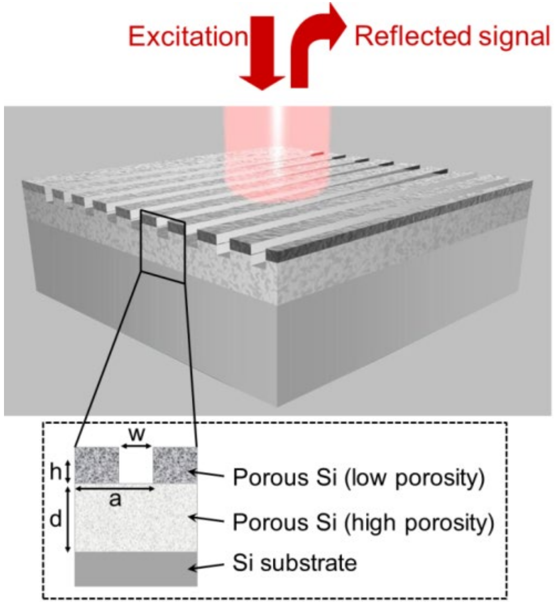


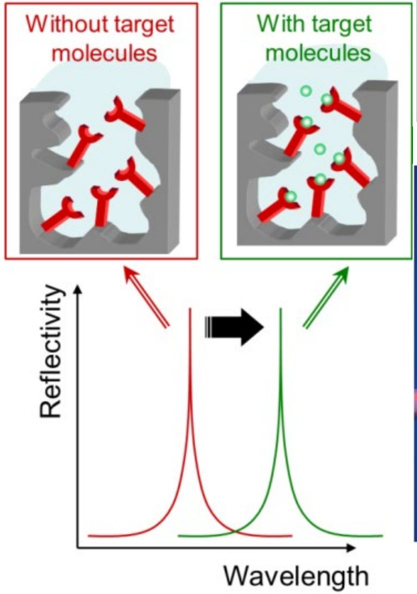


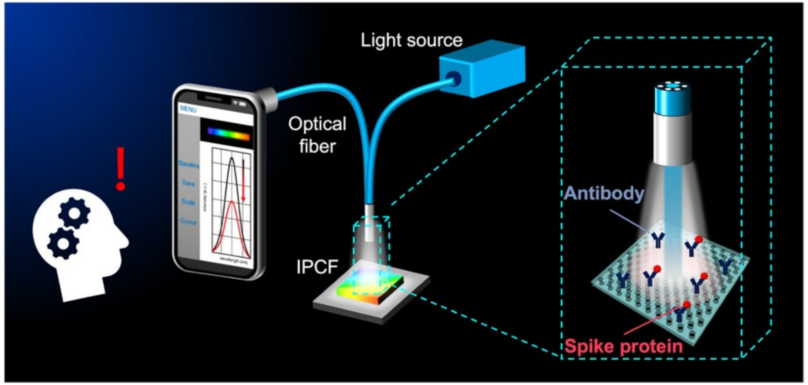


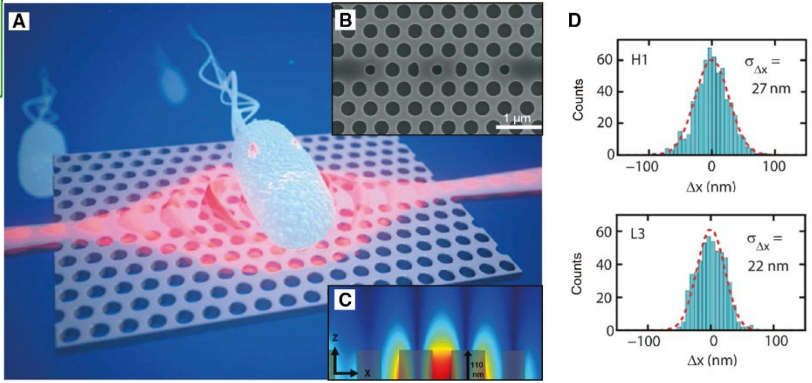
Photonic Crystal Sensors











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PART FOUR

Surface Plasmon Biosensor

Light Under Nanoscale

- In the past, devices were slow and bulky.
- Semiconductor industry managed to scaling electronic devices to nanoscale dimensions.

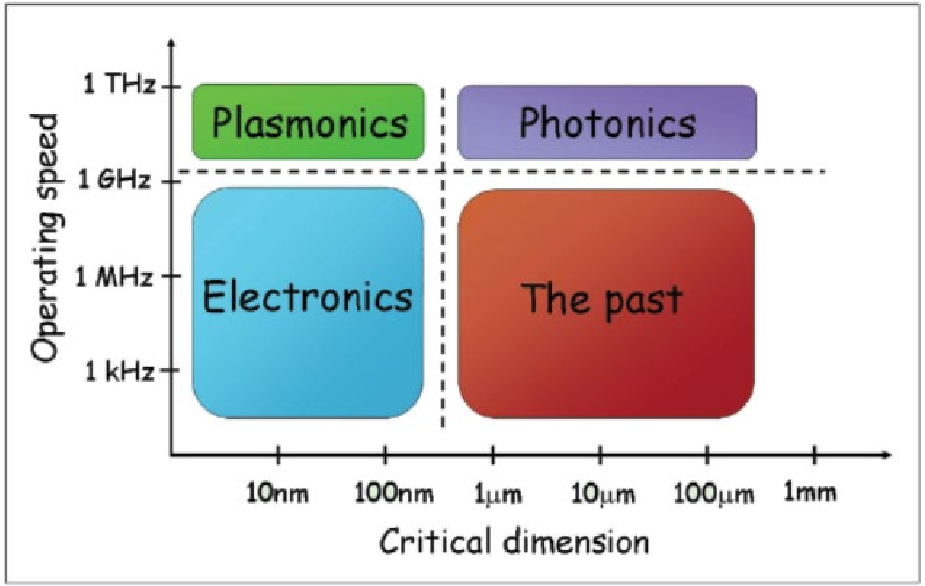
  ✗ Time delay issue (operating above ~10 GHz)

- Photonic devices has high data carrying capacity.

  ✗ Limited by the laws of diffraction
  - (λ/2, wavelength of light ~micron).

- Plasmonics, a new technology promises to bring the revolution by putting together the best of electronics and photonics.

  ✓ The size of electronics
  ✓ The speed of photonics

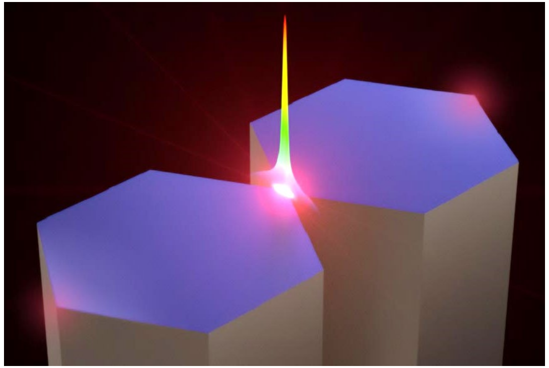


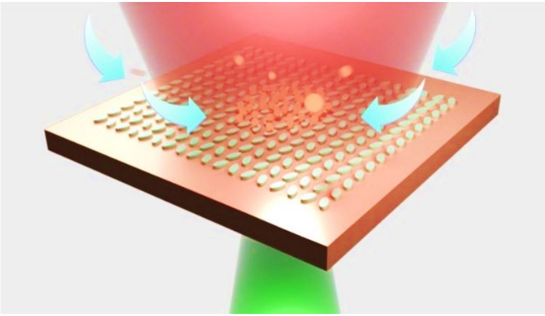
Operating speeds and critical dimensions of various technologies.

Light Under Nanoscale

Technological applications

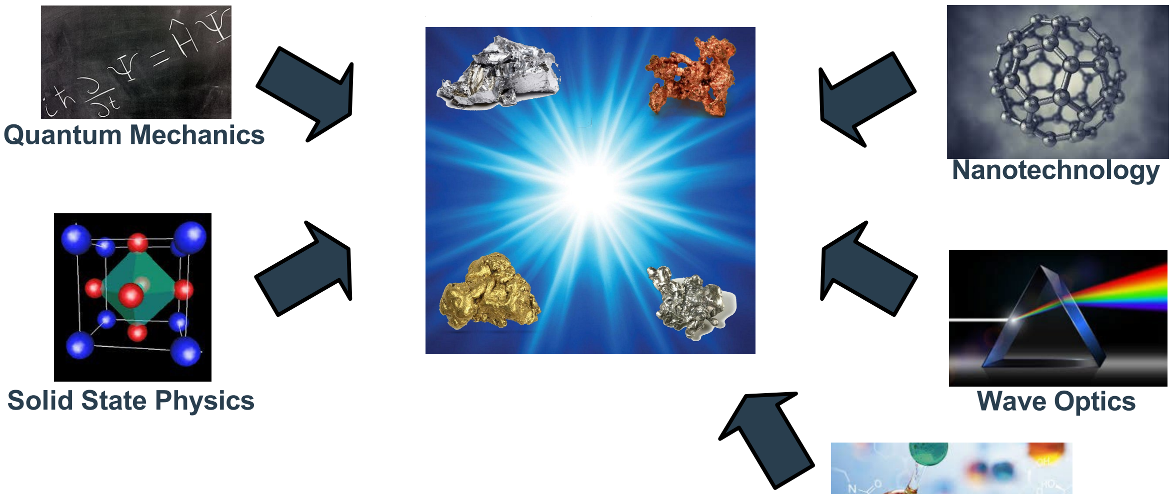
- Sub-diffraction limited optics,
- Bio- and chemical sensing, Surface-enhanced spectroscopies,
- Solar energy harvesting (photovoltaic),
- Medicine (therapy, drug delivery, imaging),
- Waveguiding, Optoelectronics, Integrated circuitry,
- Catalysis and Sustainability,
- Novel optical media (transparency, (an)isotropic, chiral, nonlinear, NRI, …)

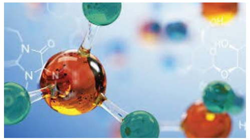




Plasmonics

Plasmonics = field dealing with the resonant interaction of light with conduction electrons in metals.

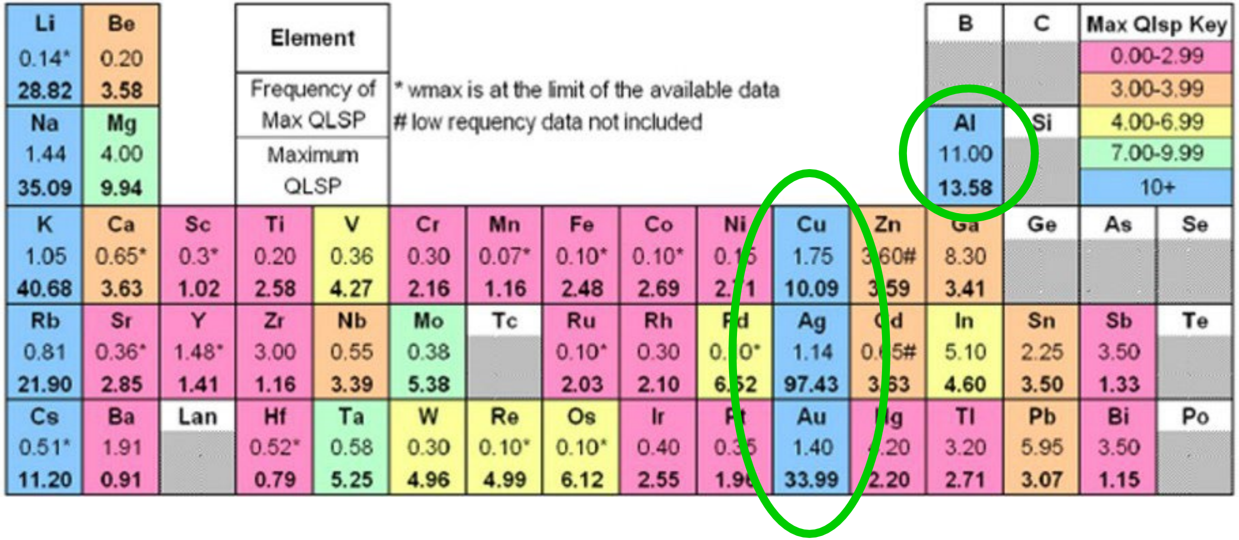




The resonance occurs when light frequencies corresponding to the natural frequency of collective and coherent electron oscillations is incident on the metal.

Plasmonic Materials

"Best" plasmonic materials = Noble metal



Li 0.14* 28.82	Be 0.20 3.58		Element Frequency of Max QLSP Maximum QLSP									B	C	Max Qlsp Key	
Na 1.44 35.09	Mg 4.00 9.94											Al 11.00 13.58	Si		
K 1.05 40.68	Ca 0.65* 3.63	Sc 0.3* 1.02	Ti 0.20 2.58	V 0.36 4.27	Cr 0.30 2.16	Mn 0.07* 1.16	Fe 0.10* 2.48	Co 0.10* 2.69	Ni 0.1[illegible]5 2.[illegible]1	Cu 1.75 10.09	Zn 3[illegible]60# 3[illegible]59	Ga 8.30 3.41	Ge	As	Se
Rb 0.81 21.90	Sr 0.36* 2.85	Y 1.48* 1.41	Zr 3.00 1.16	Nb 0.55 3.39	Mo 0.38 5.38	Tc	Ru 0.10* 2.03	Rh 0.30 2.10	Pd 0.[illegible]0* 6.[illegible]2	Ag 1.14 97.43	Cd 0.[illegible]5# 3[illegible]63	In 5.10 4.60	Sn 2.25 3.50	Sb 3.50 1.33	Te
Cs 0.51* 11.20	Ba 1.91 0.91	Lan	Hf 0.52* 0.79	Ta 0.58 5.25	W 0.30 4.96	Re 0.10* 4.99	Os 0.10* 6.12	Ir 0.40 2.55	Pt 0.3[illegible]5 1.9[illegible]	Au 1.40 33.99	Hg [illegible].20 2.20	Tl 3.20 2.71	Pb 5.95 3.07	Bi 3.50 1.15	Po

* wmax is at the limit of the available data
# low requency data not included

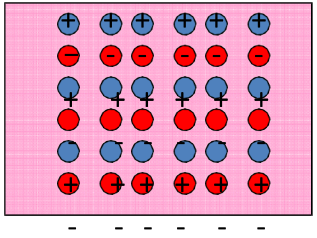
Max Qlsp Key
0.00-2.99
3.00-3.99
4.00-6.99
7.00-9.99
10+

West *et al.*, *Laser Photonics Rev.* **2010**, *4*, 795

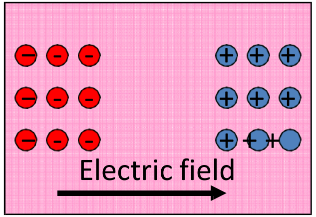
Plasmon

- What is "Bulk Plasmon" or "Plasmon"

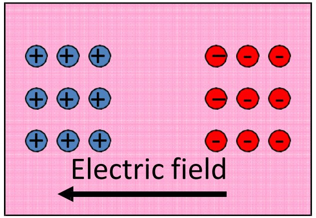
In metals such as gold or silver



Initially no net charge (positively charged ions and negatively charged electrons are well mixed)

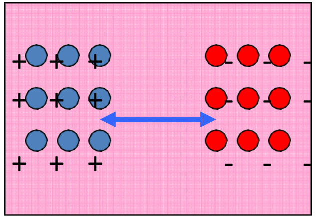


Under external electric field



Surface Plasmon

When electric field is removed, electrons move back and forth at the plasma frequency in metal, relative to the fixed positively charged ions



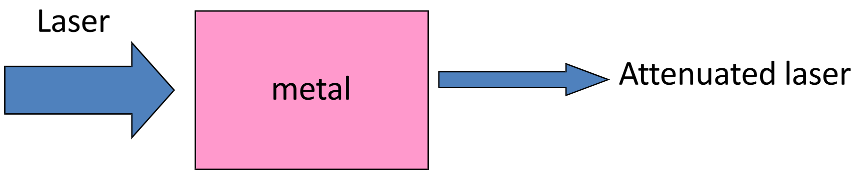
The collective motion of electrons in metal relative to ion background is called "plasmon"

Absorption of the light: how can it happen?

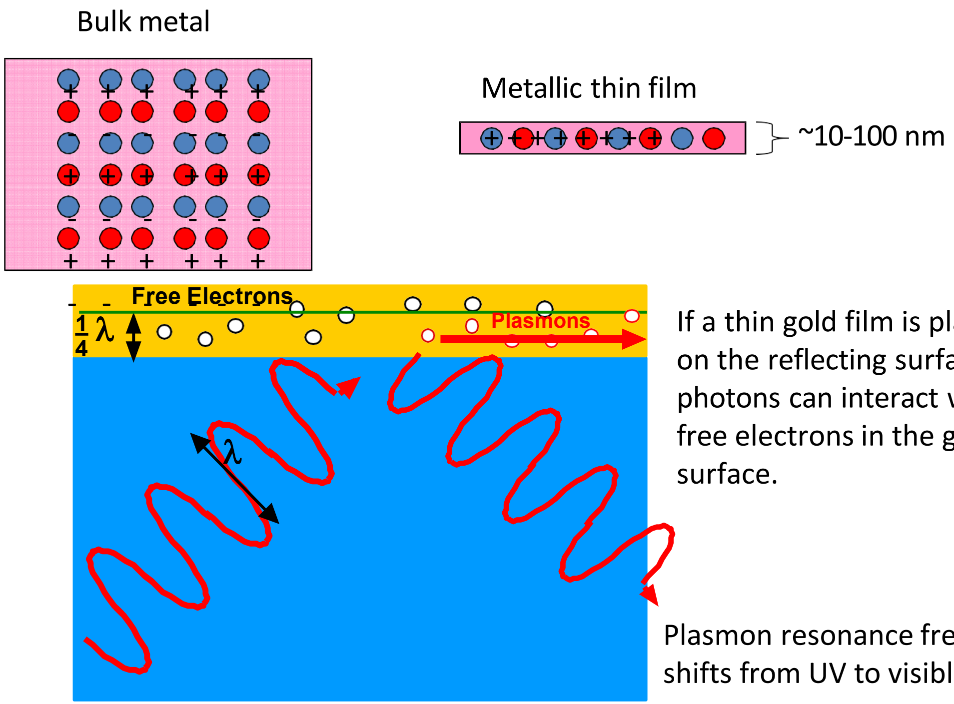
Electrons motion → current

All metal has a finite resistance

} Light becomes Joule heat and is dissipated



Surface Plasmon Resonance



If a thin gold film is placed on the reflecting surface, the photons can interact with free electrons in the gold surface.

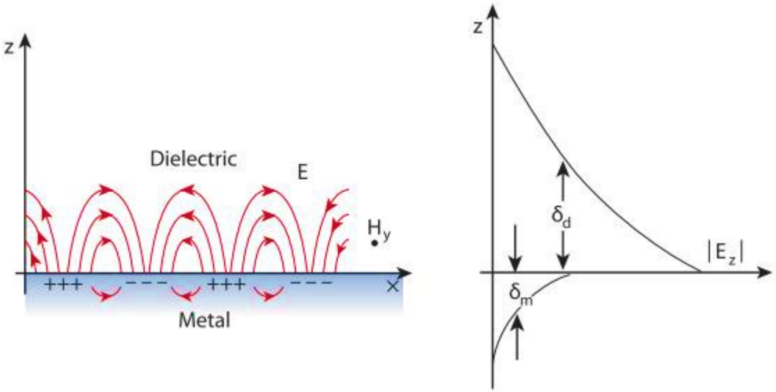
Plasmon resonance frequency shifts from UV to visible light

Under the right conditions, this causes the photons to be converted into **propagating surface plasmons (PSPs)** and the light is no longer reflected.

Surface Plasmon Resonance

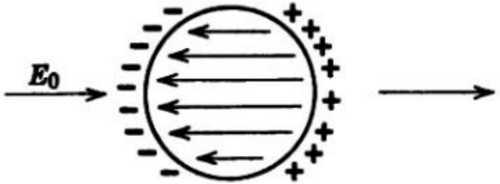
- **Plasmon polaritons** are electromagnetic excitations propagating at the interface between a dielectric and a conductor, evanescently confined in the perpendicular direction.
- These electromagnetic surface waves arise via the **coupling** of the electromagnetic fields to oscillations of the conductor's electron plasma.

Surface plasmon polaritons:



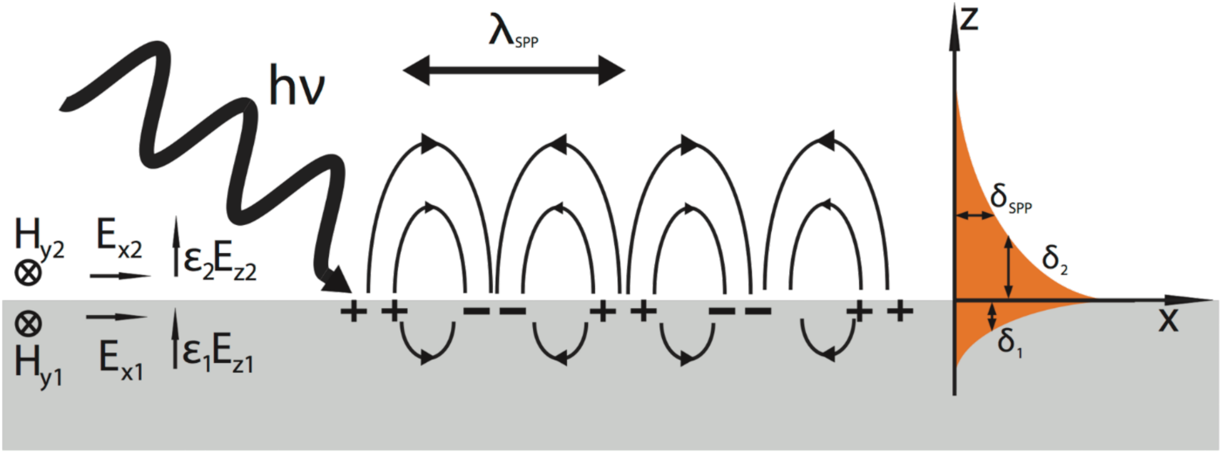
Coherent charge oscillations supported at the interface between conductor and insulator

Localized surface plasmons:



Coherent charge oscillations at the particle surface

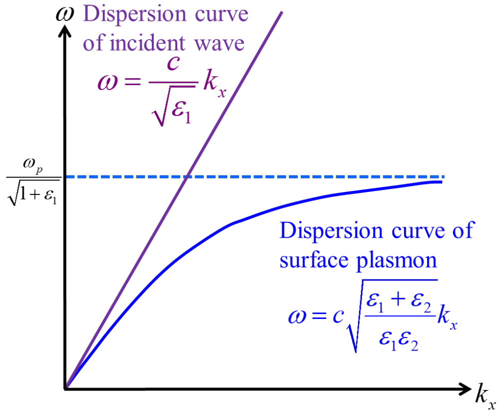
Surface Plasmon Polaritons



Schematic representation of an electron density wave propagating along a metal–dielectric interface.

The SPPs can only be excited for the case of TM illumination

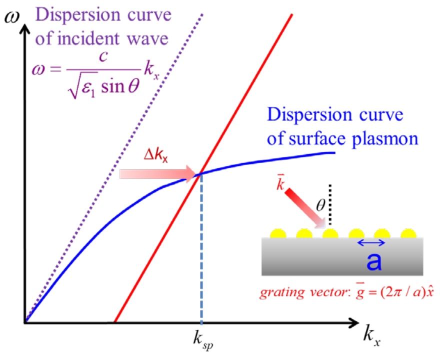
Dispersion and Excitation of SPP



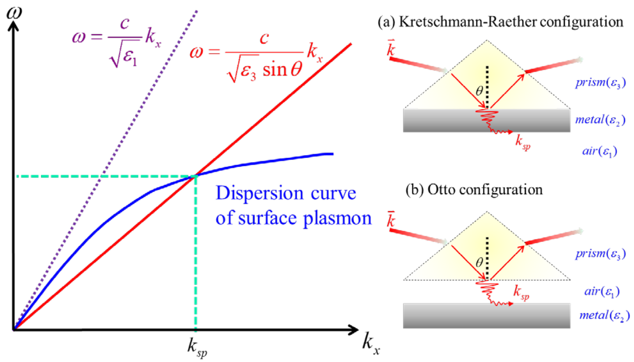
$$k_{sp} = k_0\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} > \frac{\omega}{c}\sqrt{\varepsilon_1}$$

It is impossible to excite the SPP when electromagnetic wave is illuminated directly onto a flat metal.

Grating coupling

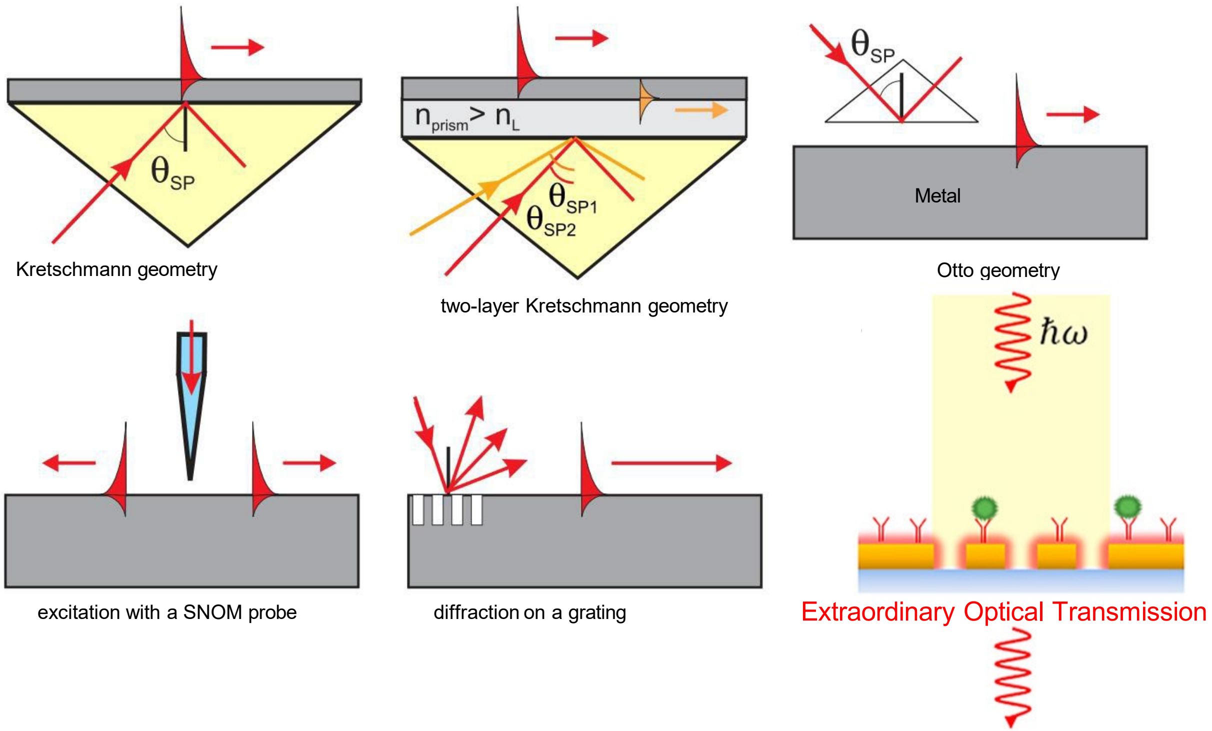


Prism coupling

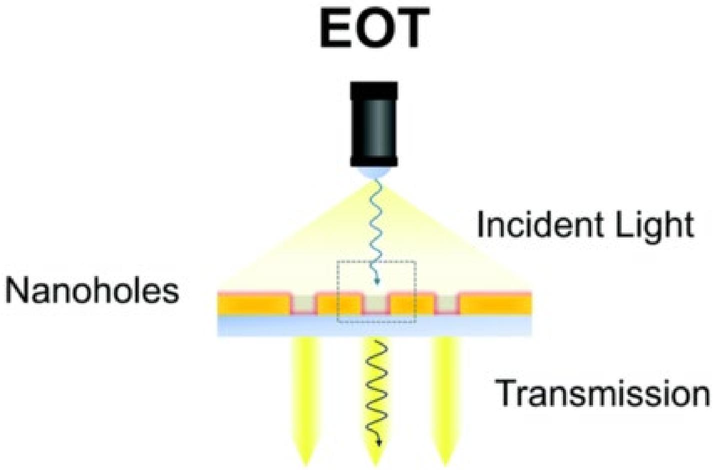


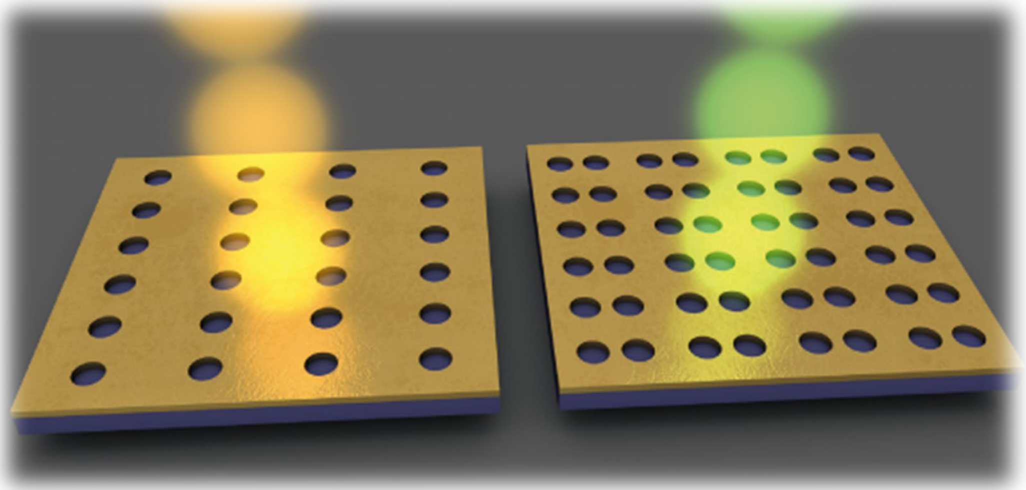
Excitation Methods

- Optical prism
- **Coupling gratings**
- **Extraordinary Optical Transmission (EOT)**
- Optical fiber/ cantilever tip
- High energy electron beam
- Highly focused optical beams

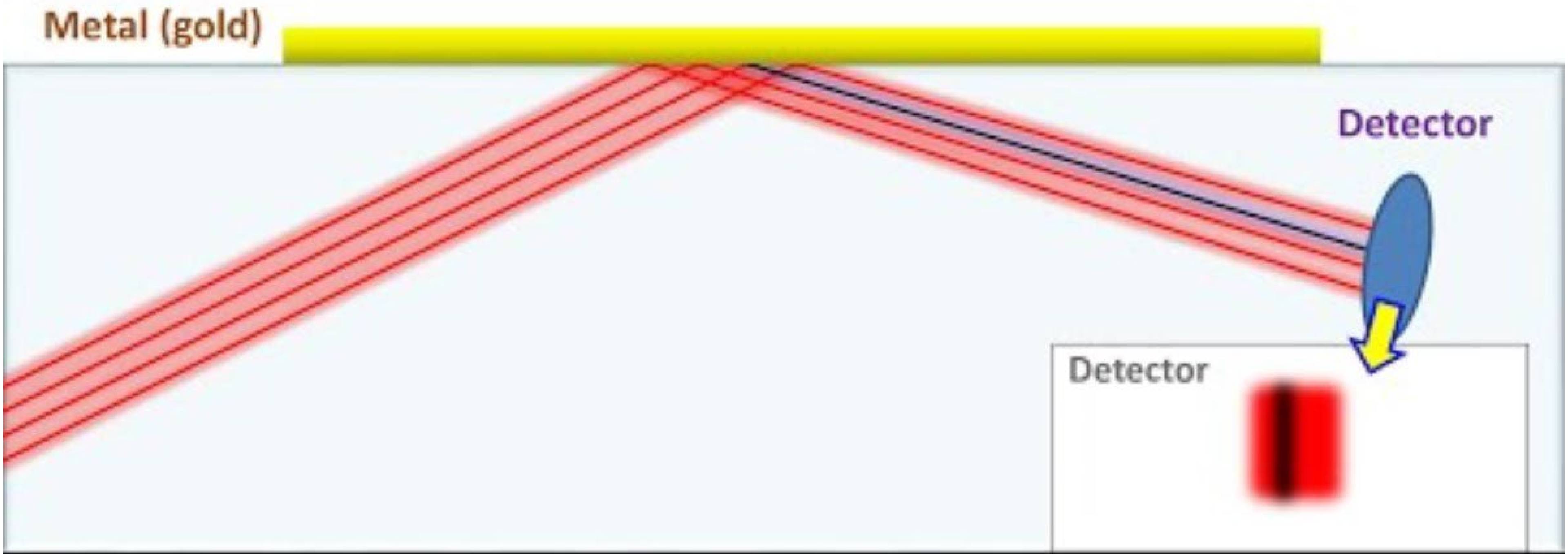


Extraordinary Optical Transmission

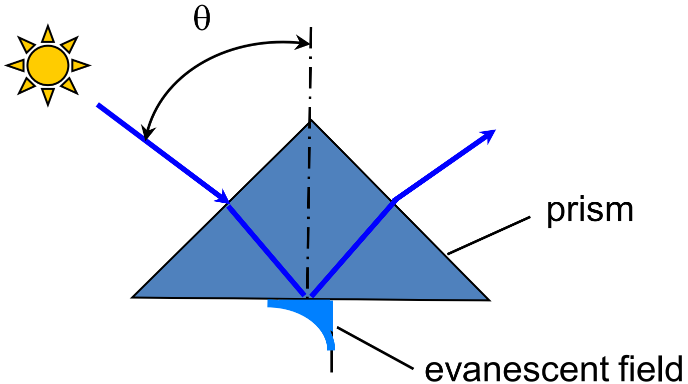


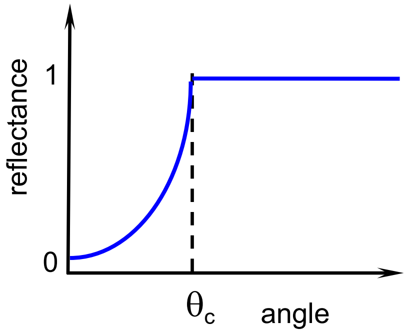


Surface Plasmon Resonance



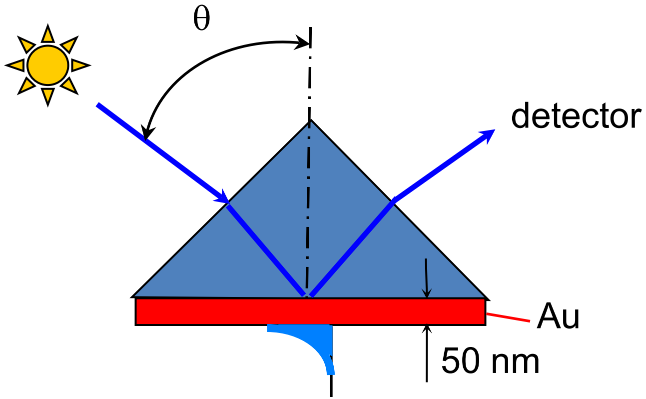
Building a SPR Device



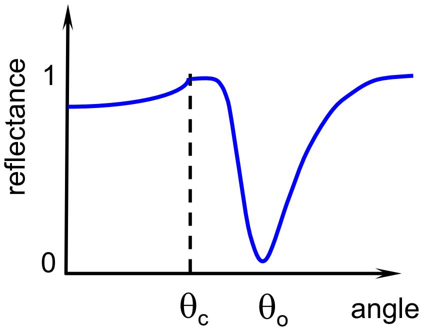


evanescent wave: - nearfield standing wave,
- extends about 1/2 λ,
- decays exponentially with the distance

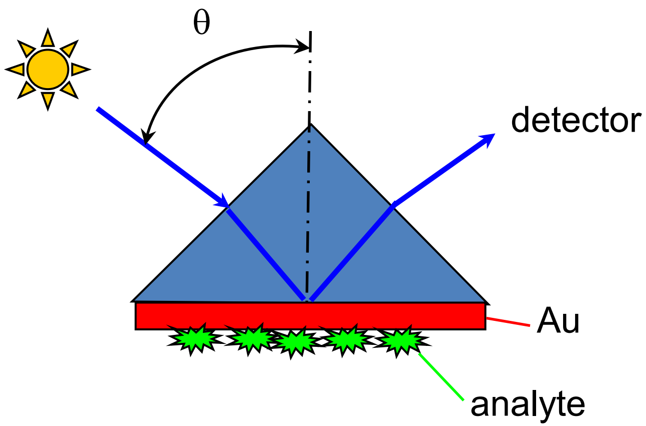
Building a SPR Device

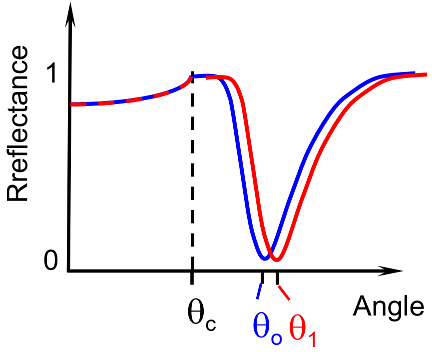


(Kretschmann)



Building a SPR Device

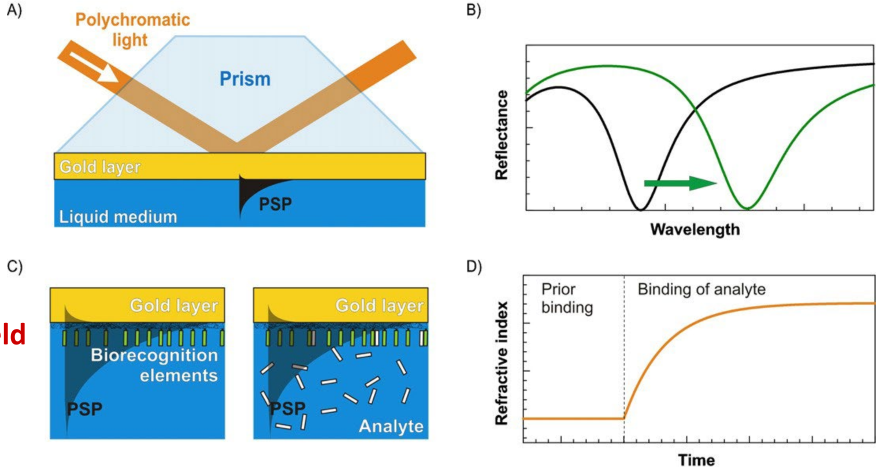




Fixed wavelength light is directed at the sensor surface and binding events are detected as changes in the particular angle where SPR creates extinction of light.

Building a SPR Device

Evanescent field



Propagation constant

$$\beta = \frac{\omega}{c}\sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}}$$

Dielectric medium ∆RI in the evanescent wave produces a change in the propagation constant

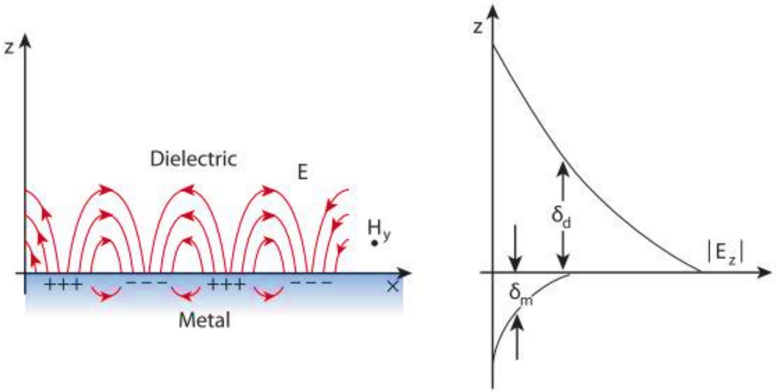
change in the propagation constant alters coupling condition between light and PSP

Change in **incident angle**, **Wavelength**, **intensity**, and **phase**

Surface Plasmon Resonance

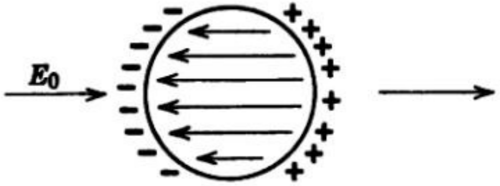
- **Plasmon polaritons** are electromagnetic excitations propagating at the interface between a dielectric and a conductor, evanescently confined in the perpendicular direction.
- These electromagnetic surface waves arise via the **coupling** of the <u>electromagnetic fields</u> to <u>oscillations of the conductor's electron plasma.</u>

Surface plasmon polaritons:



Coherent charge oscillations supported at the interface between conductor and insulator

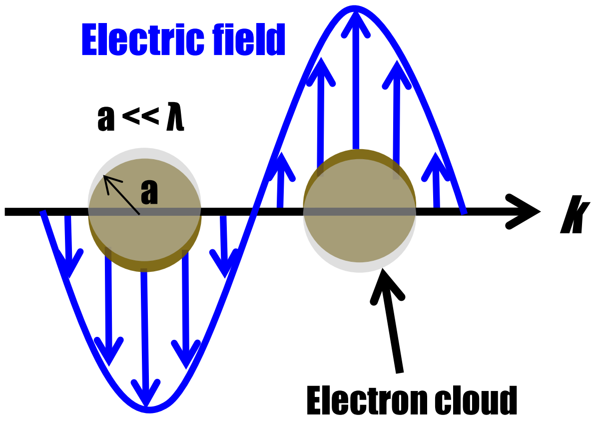
Localized surface plasmons:



Coherent charge oscillations at the particle surface

Localized Surface Plasmons

Confine surface plasmon polaritons in a nanoparticle of size comparable to or smaller than the wavelength of light

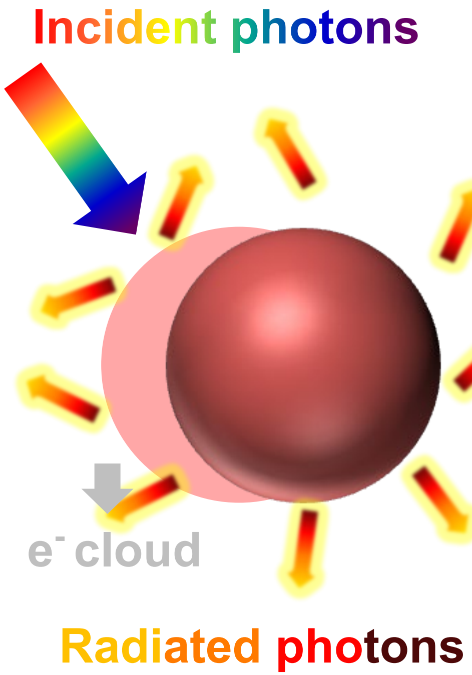


Two important effects:

1. The electromagnetic field around the nanoparticle are greatly enhanced.
2. The particle's optical absorption has a maximum at the plasmon resonant frequency.

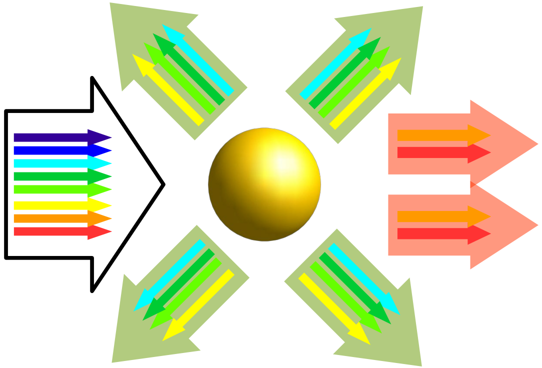
Localized Surface Plasmons

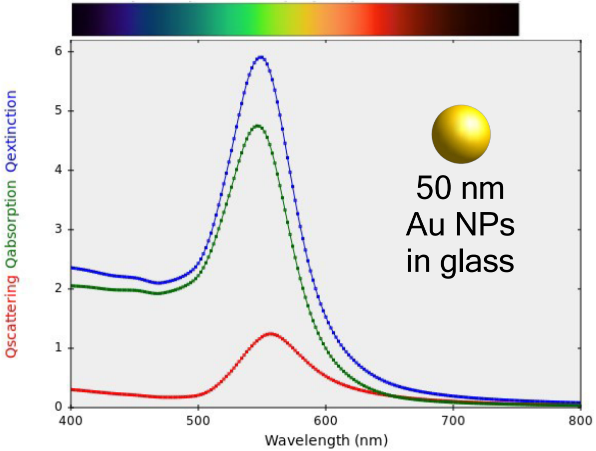
Confine surface plasmon polaritons in a nanoparticle of size comparable to or smaller than the wavelength of light



- Unlike the propagating surface plasmon polaritons, localized surface plasmons are bounded to a nanometer sized metal particle.
- **Localized surface plasmon resonance (LSPR)** can be excited in almost any illumination condition with a matching resonance frequency.

Famous Example – Lycurgus Cup





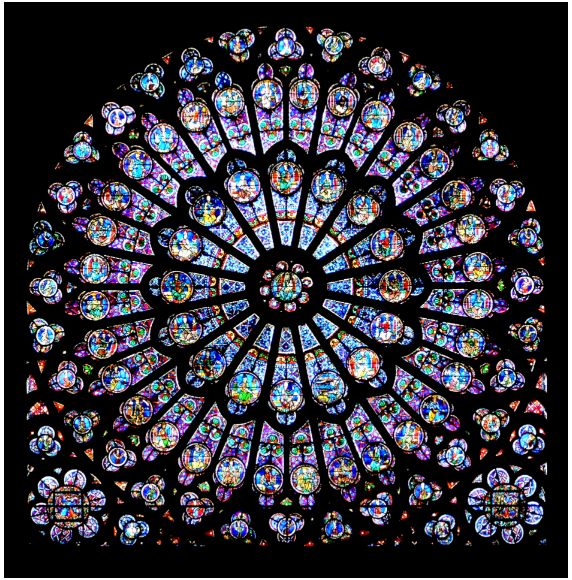
Au NP in glass has scattering & absorption.

Transmission: the absorption component allows only the large wavelengths (>600 nm) to be transmitted ▶ red

Reflection: the scattering component dominates, allowing the NP resonant wavelength to be observed ▶ green

Plasmonics - History

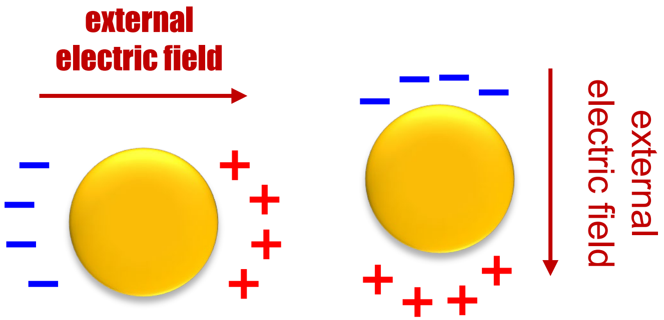
- Centuries ago, people started using metamaterials deliberately in art pieces without a full understanding of the physics behind the results they achieved.



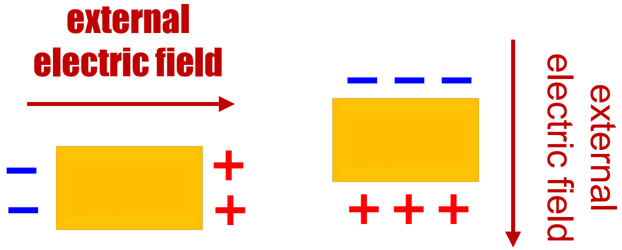
One of the many stained-glass windows at Canterbury Cathedral

The Lycurgus Cup, a 4th-century Roman glass cage cup made from ruby glass with gold nanoparticles embedded

Plasmon Resonances in Non-spherical Particles

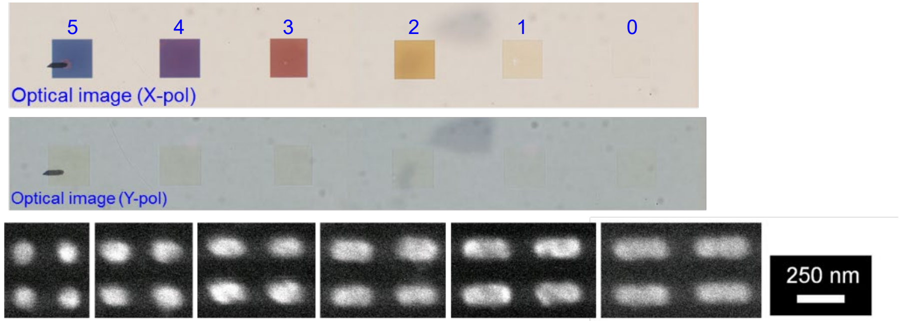


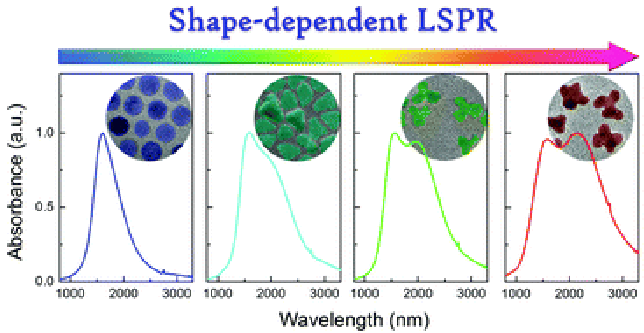
when $\omega = \omega_0\ (\omega_1 = \omega_2)$



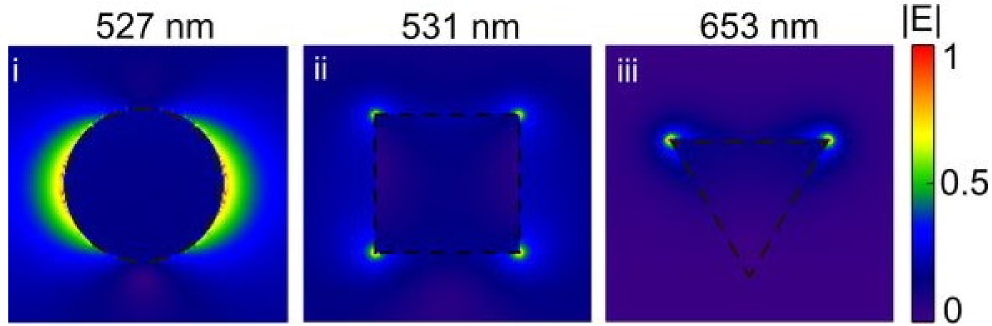
when $\omega = \omega_0\ (\omega_1 < \omega_2)$

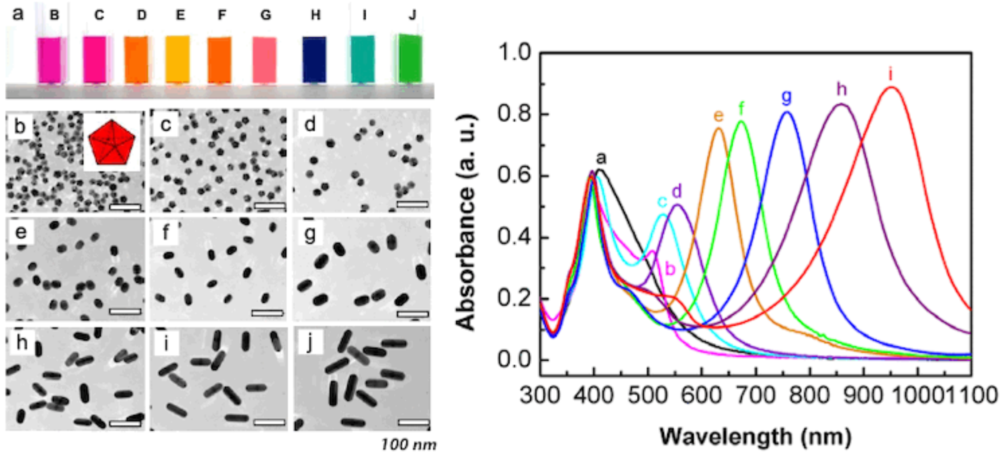
- Polarization- and shape-dependent optical properties





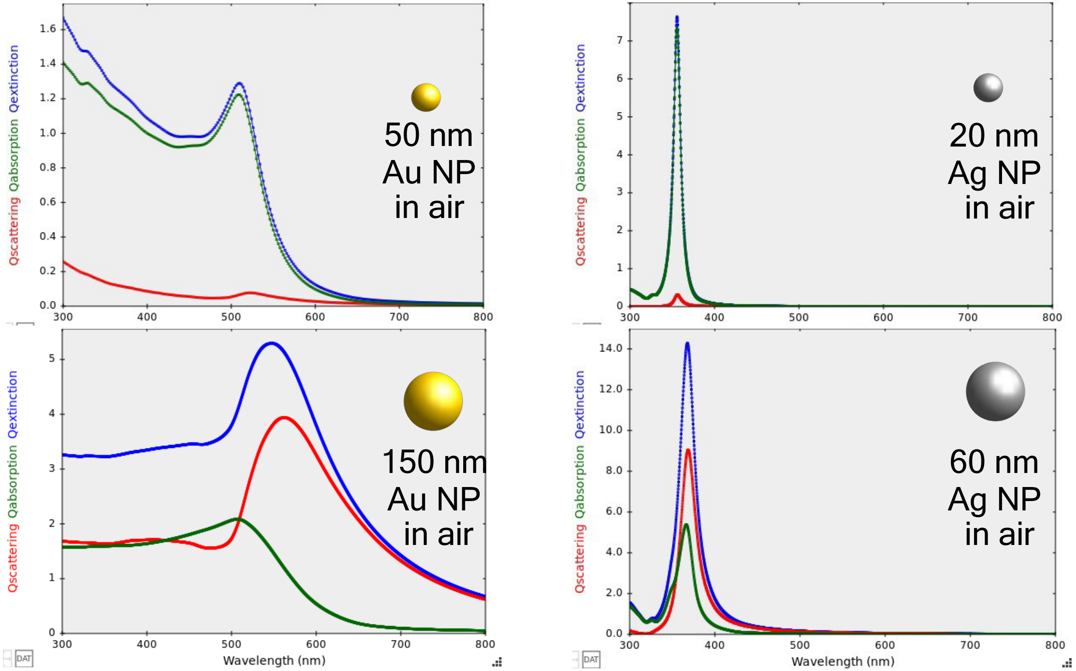
Plasmon Resonances in Non-spherical Particles





- Localized surface plasmon resonance (LSPR) on plasmonic nanoparticles.
- Finite difference time domain (FDTD) calculation of the on-resonance (wavelength labeled on the top of each figure) normalized electric field (|E|) distribution of (i) a nanosphere, (ii) a nanocube, and (iii) a nanotriangle, demonstrating the highly localized enhancement especially at the sharp tips and rapid attenuation with the distance.

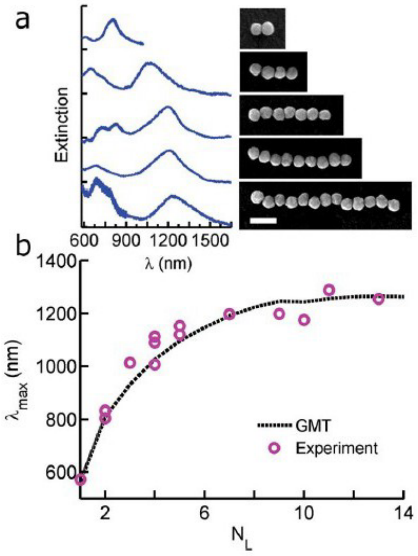
Plasmon Resonances with Different Sizes



The transition between the two regimes is characterized by a distinct color change

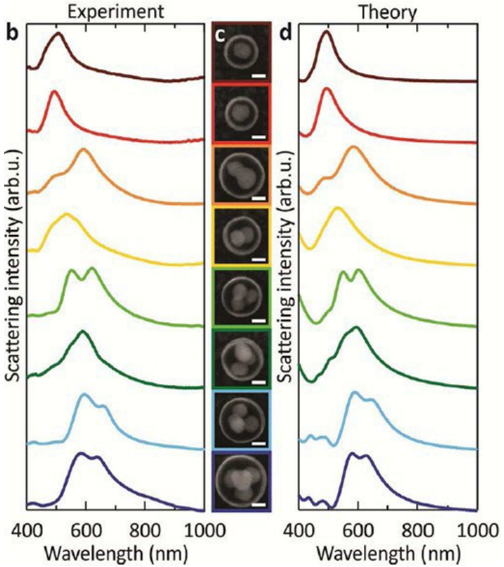
Plasmon Interactions

NP chains



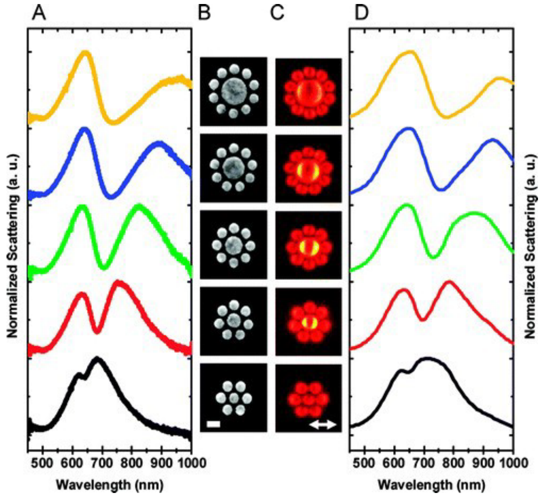
Slaughter *et al.*,
Nanoscale **2014**, *6*, 11451

NP clusters



Urban *et al.*,
Nano Lett. **2013**, *13*, 4399

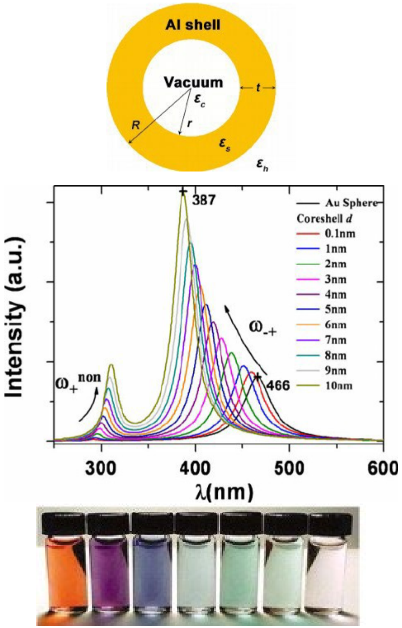
NP oligomers



Lassiter *et al.*,
Nano Lett. **2012**, *12*, 1058

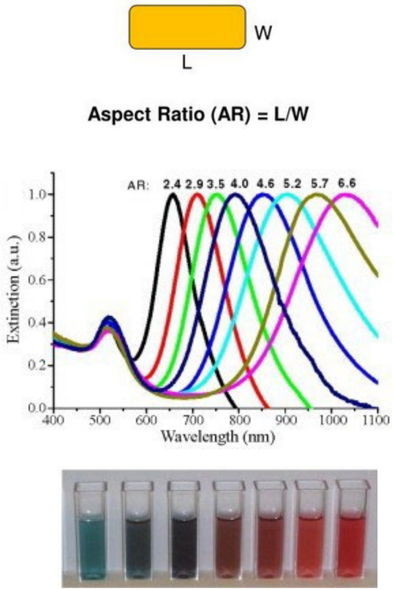
Spectral Tunability of the LSPR

Nanoshell



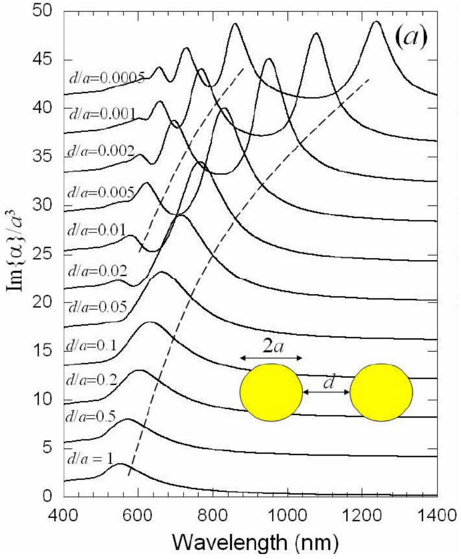
Chen *et al.*, *Plasmonics* **2012**, *7*, 509

Nanorod



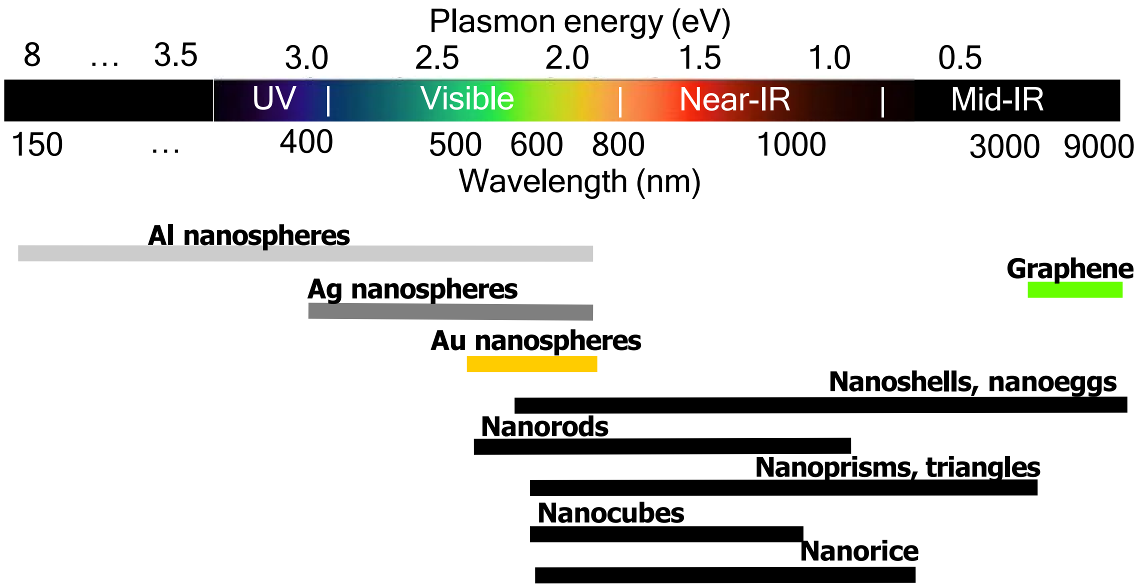
El–Sayed *et al.*, *J. Adv. Res.* **2010**, *1*, 13

Dimer



Romero *et al.*, *Opt. Express* **2006**, *14*, 9988

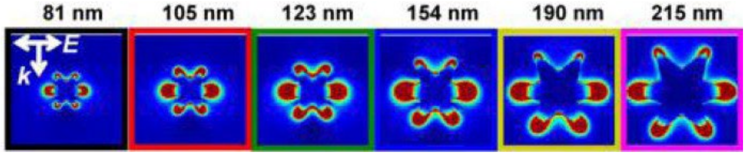
Spectral Tunability of LSPR



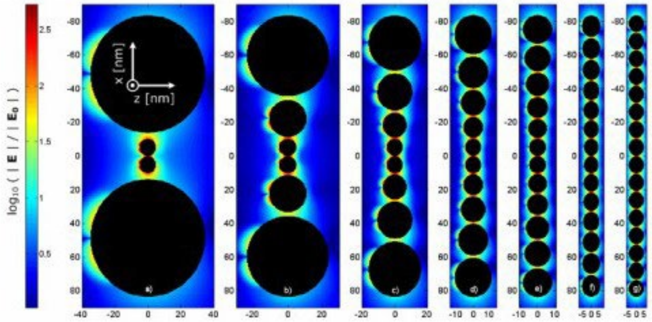
Near-Field Enhancement

The NP size, shape, and arrangement strongly influence local electric field distribution and intensity near the NP surfaces.

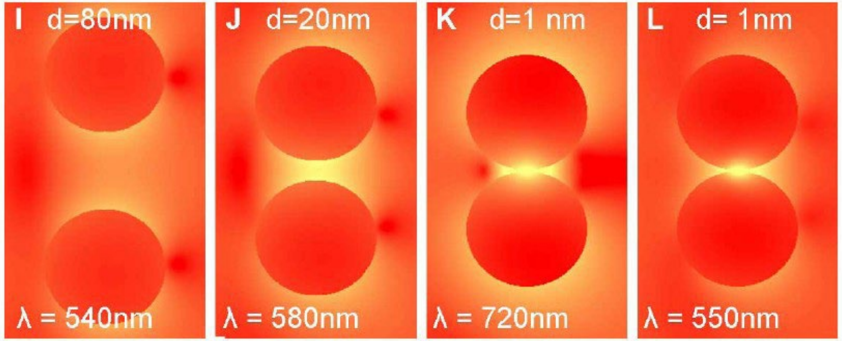
▶ **Localization & Enhancement**

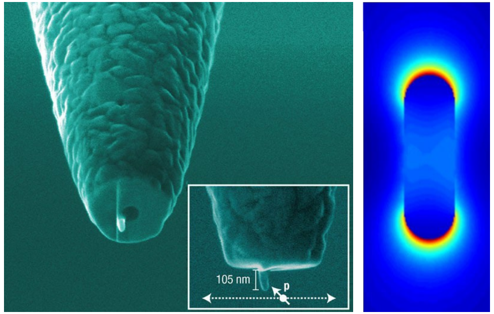


Zhang *et al.*, *ACS Appl. Mater. Interfaces* **2014**, *6*, 17255



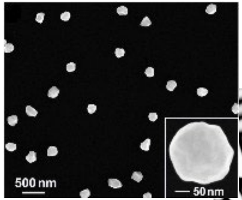
Chien *et al.*, *Opt. Express* **2008**, *16*, 1820





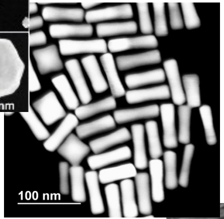
Playing with Shapes – Bottom-Up Approach

Spheres



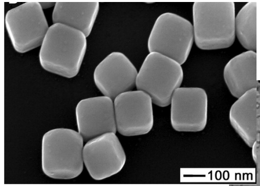
Zhang *et al*,
JPC Lett. 2014, *5*, 370

Rods



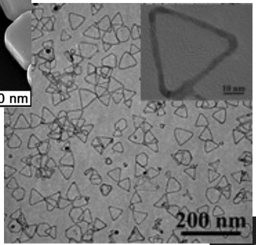
Martinsson *et al*,
Small **2016**, 12, 1613

Cubes



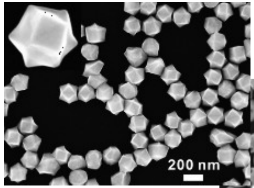
Martinsson *et al*,
Small **12**, 1613 (2016)

Triangular Frames



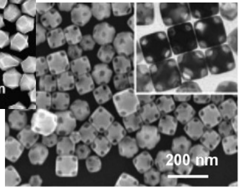
Shahjamali *et al*,
Small **9**, 2880 (2013)

Trisoctahedra



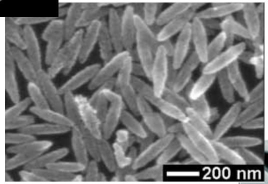
Zhang *et al*,
ACS Applied Materials Interfaces **6**, 17255 (2014)

NanoCages



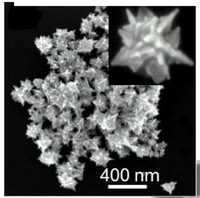
Sun *et al.*
J. Am. Chem. Soc. **126** (2004)

NanoRice



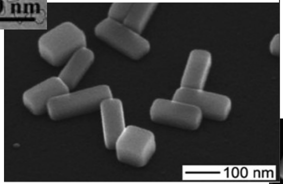
Halas *et al.* Rice University

Stars



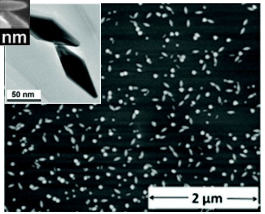
Das *et al*,
Nanotechnology **2014**, *24*, 405704

Cuboids/Bars



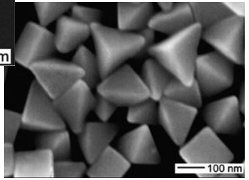
Im *et al.*
Angew. Chem. Int. Ed. **2005**, *44*

Bipyramids



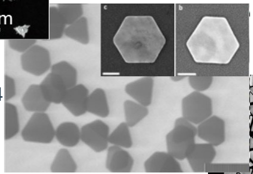
Lee *et al*,
Chem. Commun. **2015**, *51*, 15494

Pyramids



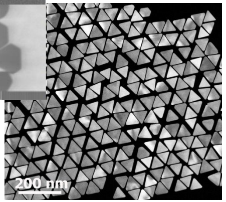
Lofton *et al.*
Adv. Func. Mater. **2005**

Platelets



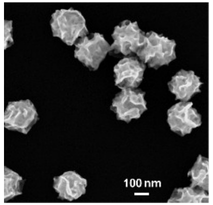
McEachran *et al*,
Chem. Commun., **2008**, 573

Prisms



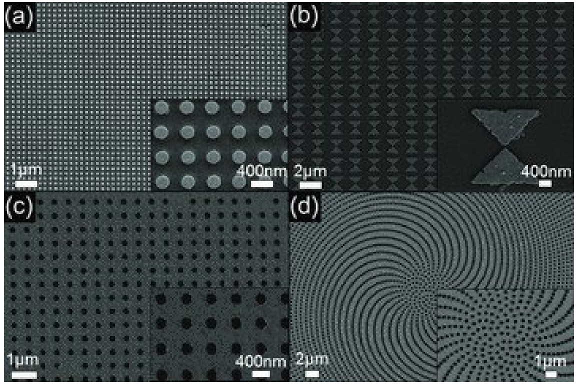
Martinsson *et al*,
Small **12**, 1613 (2016)

Porous NPs

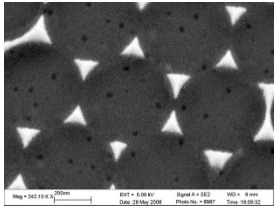


Zhang *et al*,
JPC Lett. **2014**, *5*, 370

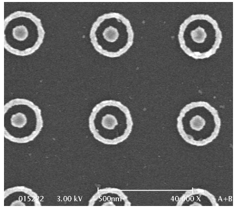
Playing with Shapes – Top-Down Approach



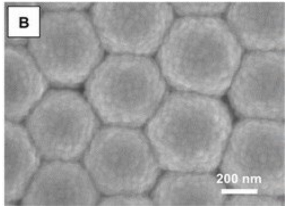
Lin *et al*, *Adv. Mater.* **2012**, *24*



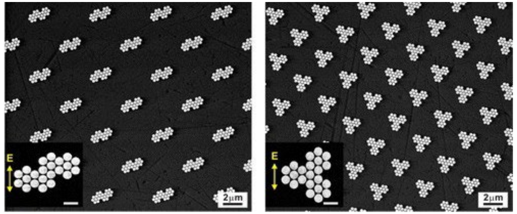
Zhou *et al*,
Int. J. Nanomedicine **2011**



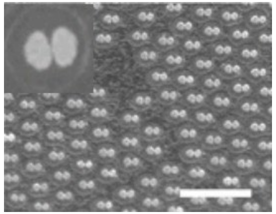
Large *et al*,
Opt. Express **2011**, *19*, 5587



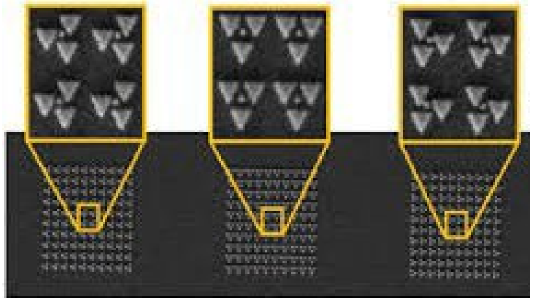
Massango *et al*,
Nano Lett. **2016**, *16*, 4251



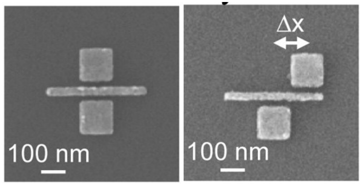
Liu *et al*, *ACS Nano* **2012**, *6*, 5482



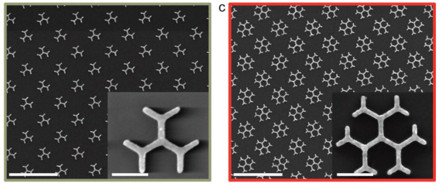
Zhang *et al*,
ACS Nano **2015**, *9*, 9331



Kolkowski *et al*, *ACS Photonics* **2015**

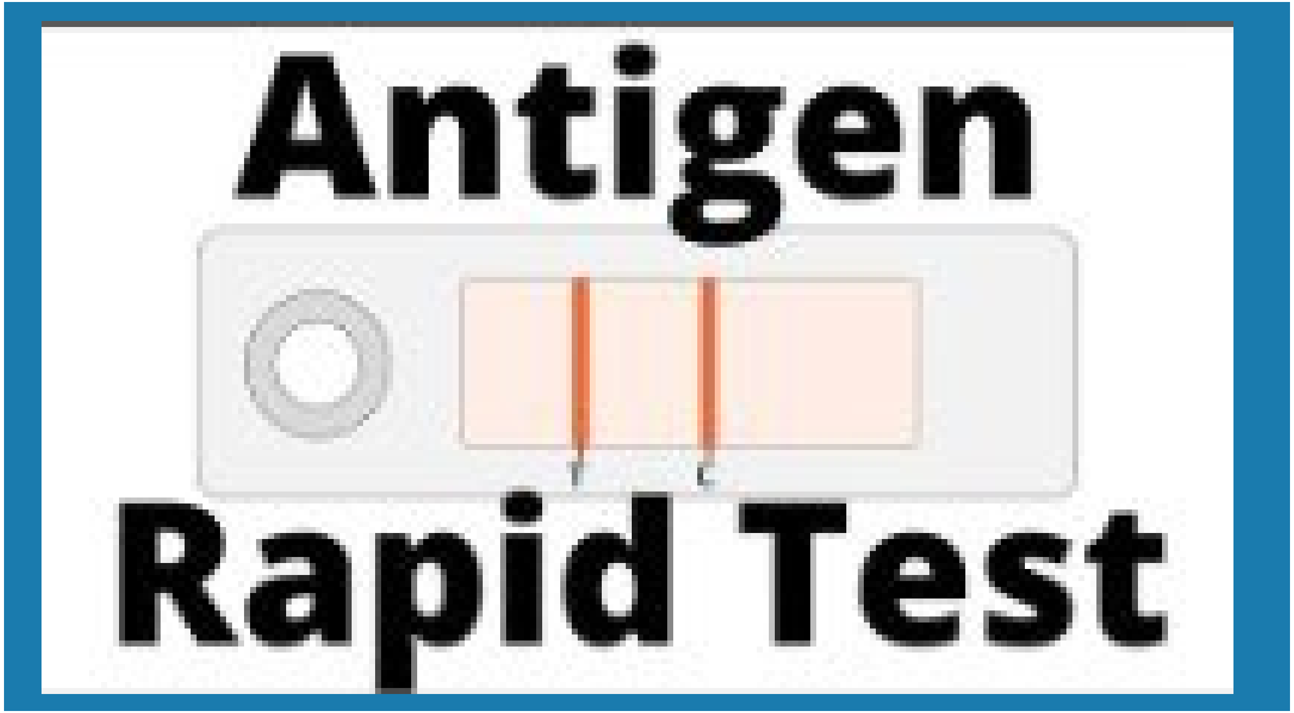


Day *et al*,
Nano Lett. **2015**, *15*, 1324



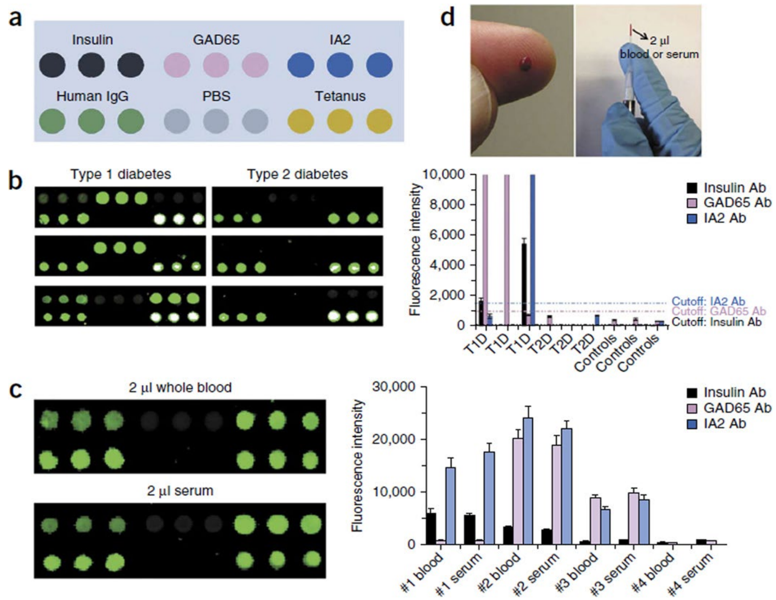
Gottheim *et al*,
ACS Nano **2015**, *9*, 3284

Application- ART Test

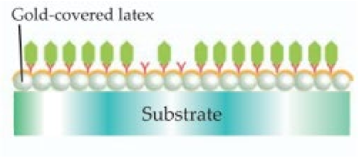


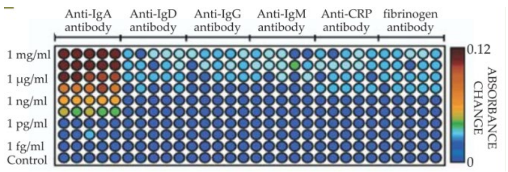
Applications

Diagnosing diabetes



Pregnancy tests





Nanospheres have a high polarizability which enables them to screen each others plasmonic Charges which reduces the restoring force and the Frequency of SP,redshifting their emission froma Vaguely green color evident in the initial gold Sphere suspension.Consequently the test strip acquires a red color-confirming pregancy.

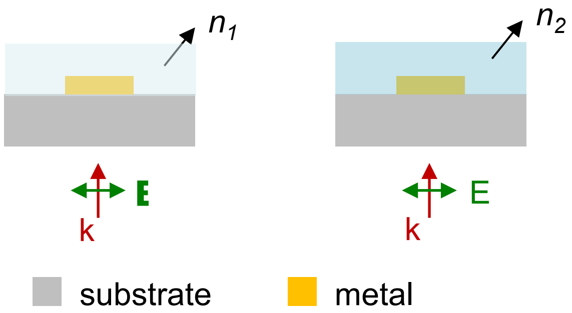
5

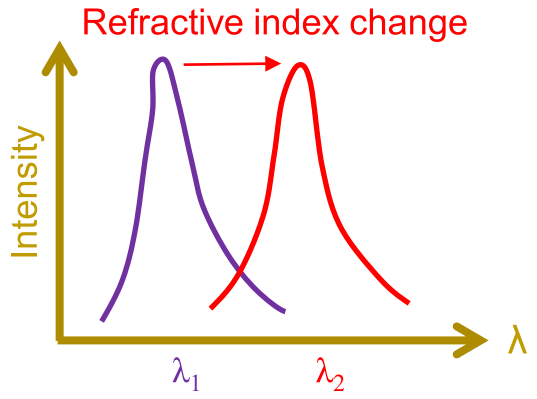
Sensors and Devices

Plasmonic Biosensing

Plasmonic Sensor Working Principle

- Shift the plasmonic resonance





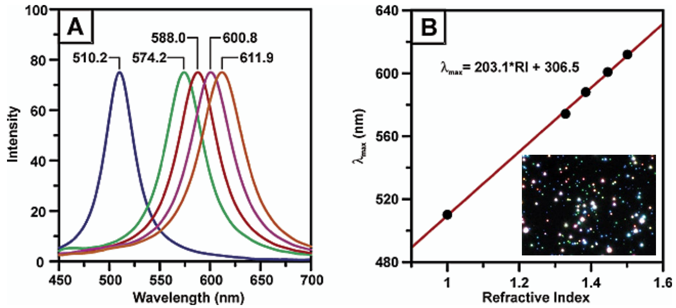
➢ Sensitivity S_λ

$$S_\lambda = \frac{\Delta\lambda_{res}}{\Delta n} = \frac{\lambda_2 - \lambda_1}{n_2 - n_1}$$

Unit: nm/RIU, RIU = refractive index unit

J. Becker et. al. *Plasmonics* **5**, 161-167 (2010)

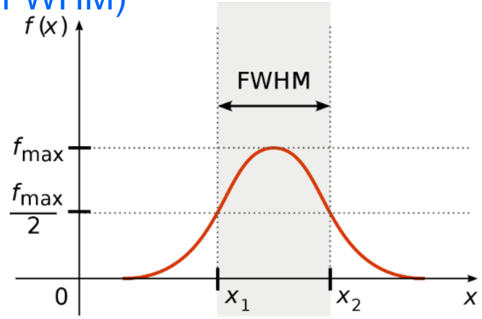
Adam D. McFarland and Richard P. Van Duyne *Nano Lett.* **3**, 1057-1062 (2003)



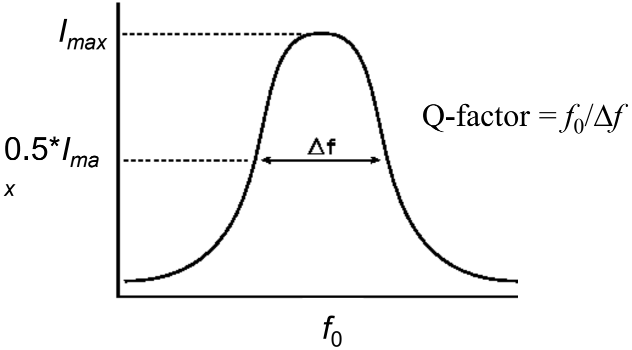
(Left) Scattering spectrum of Ag single nanoparticle in various solvent environments. (Right) The relationship between LSPR λ_{max} and solvent refractive index.(Inset) Dark field image of Ag nanoparticle

Evaluating the Performance of LSPR Biosensors

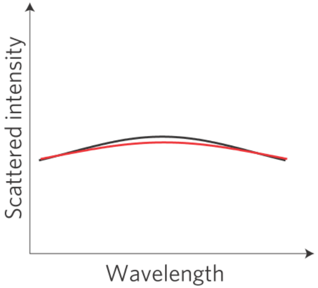
- Full width at half maximum (FWHM)

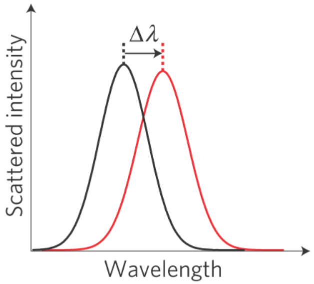


- Definition of Q-factor



- Importance of full width at half maximum (FWMH)



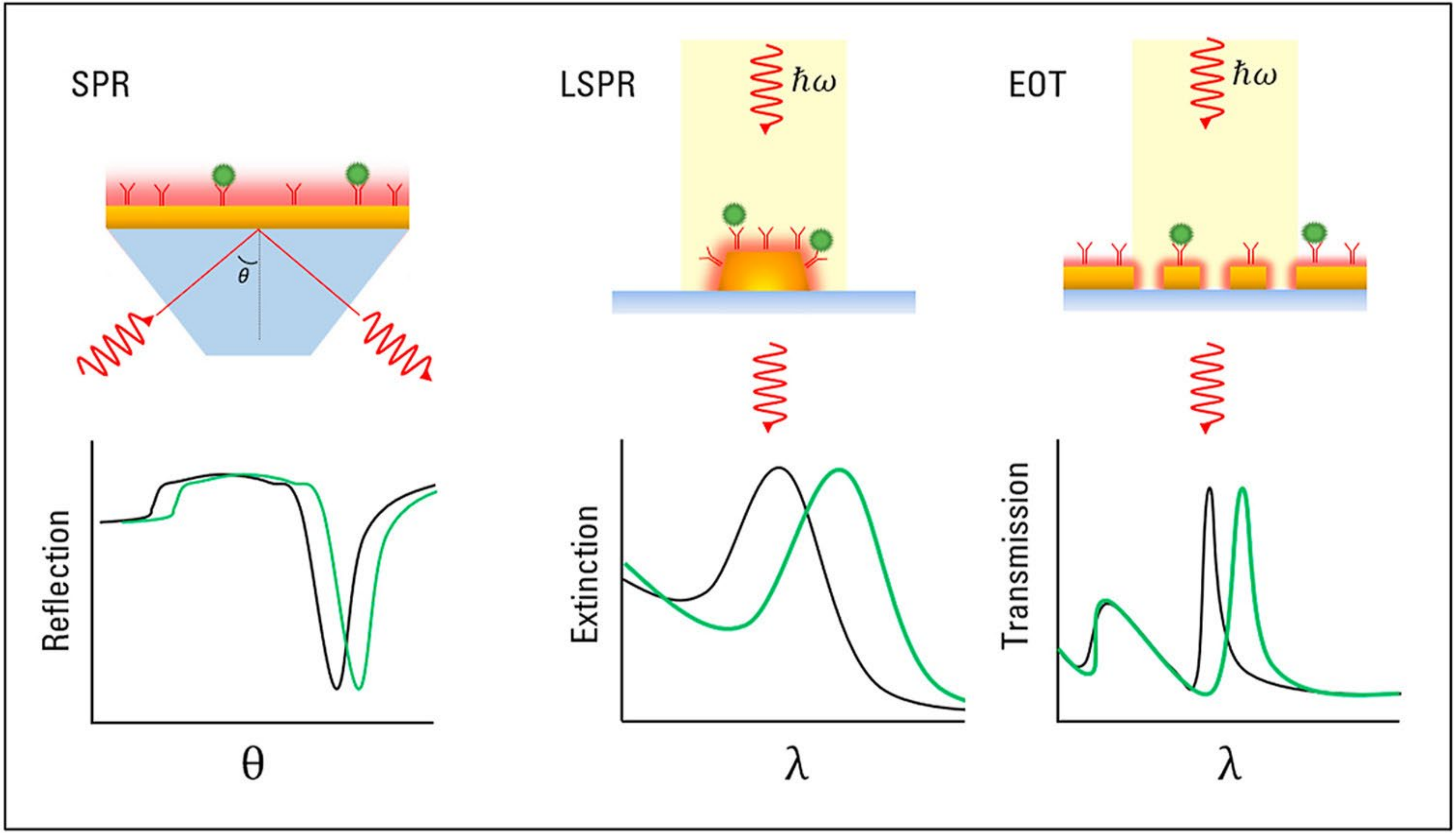


Na Liu et. al. *Nat. Mater.* **10**, 631-636 (2011)

- Figure of Merit (FOM)

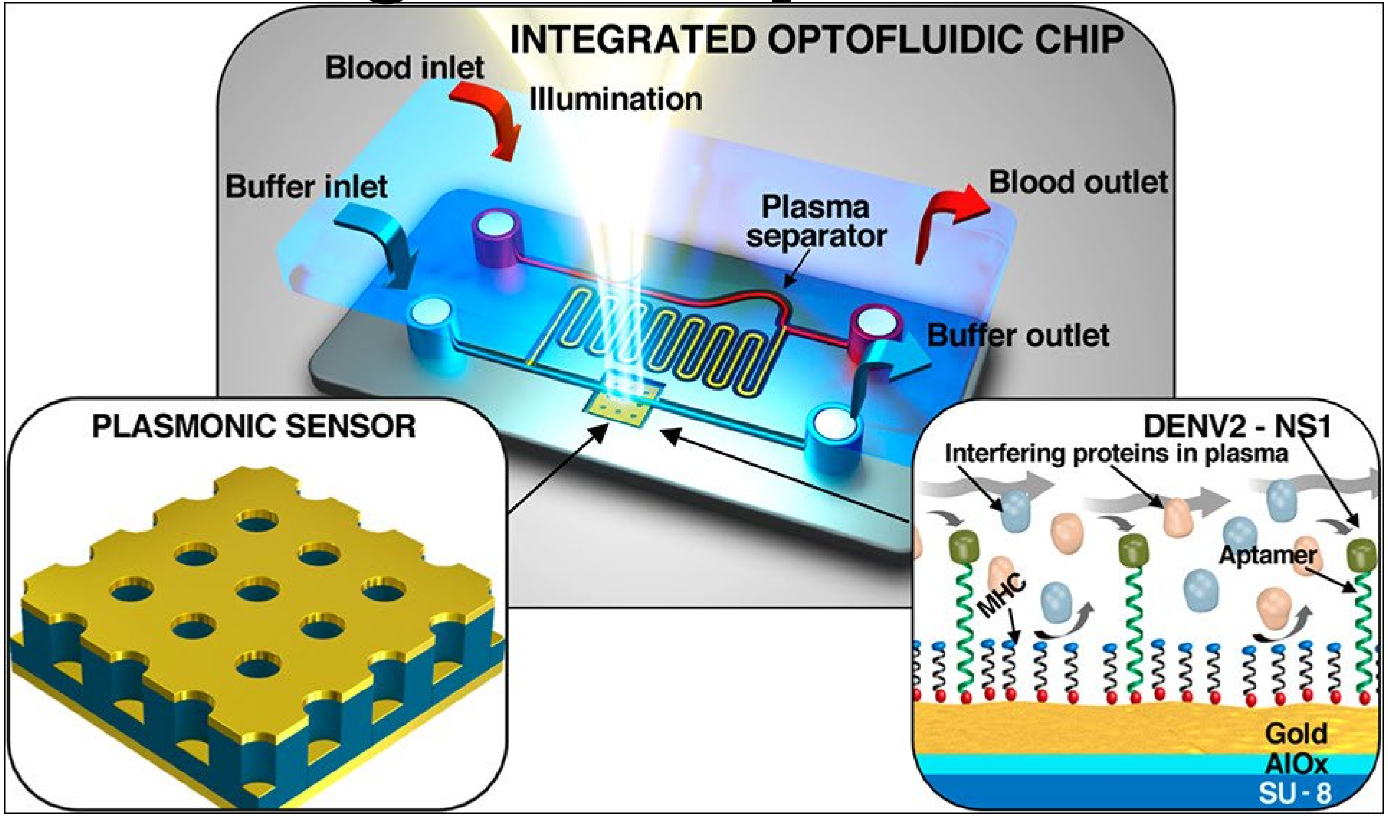
$$FOM = \frac{Sensitivity}{\Delta f}$$

A figure of merit (FOM) is a performance metric that characterizes the performance of a device

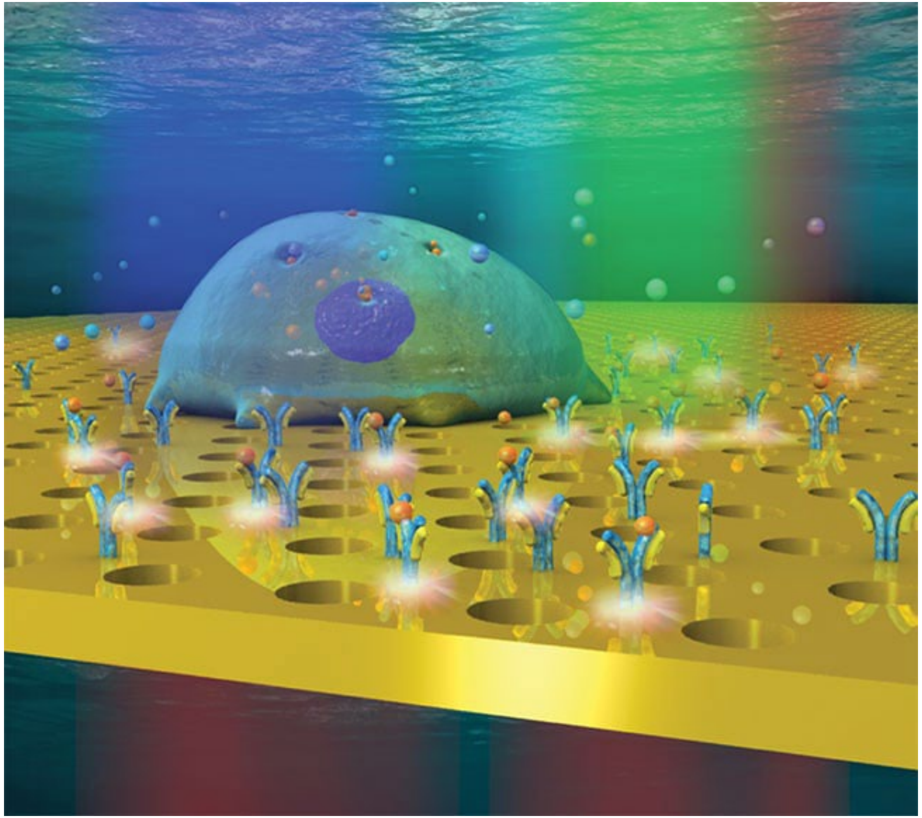


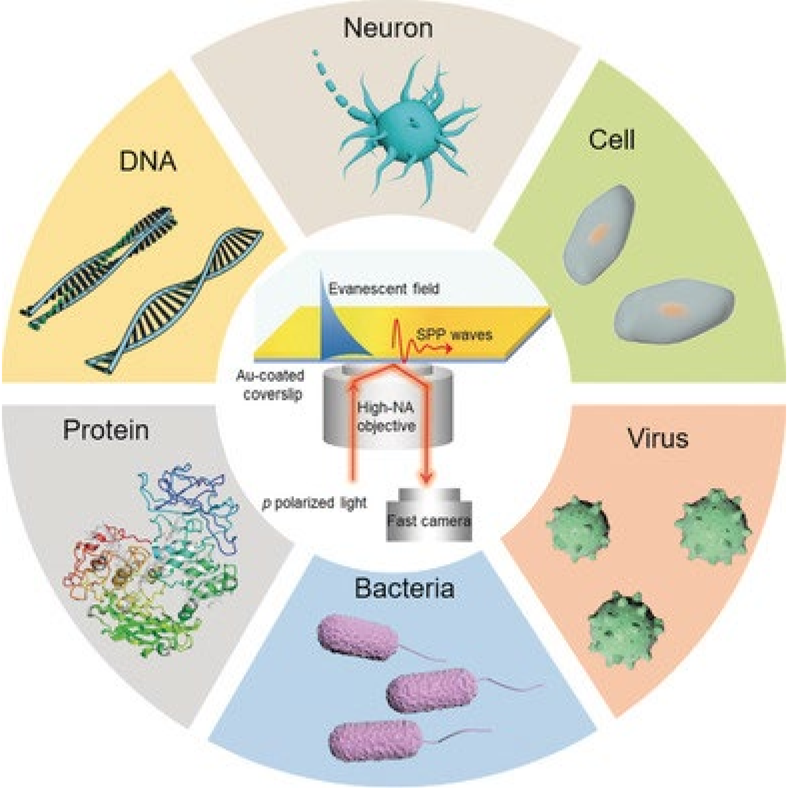
SPR
θ
Reflection
θ
LSPR
ℏω
Extinction
λ
EOT
ℏω
Transmission
λ

SPR Integrated Chip



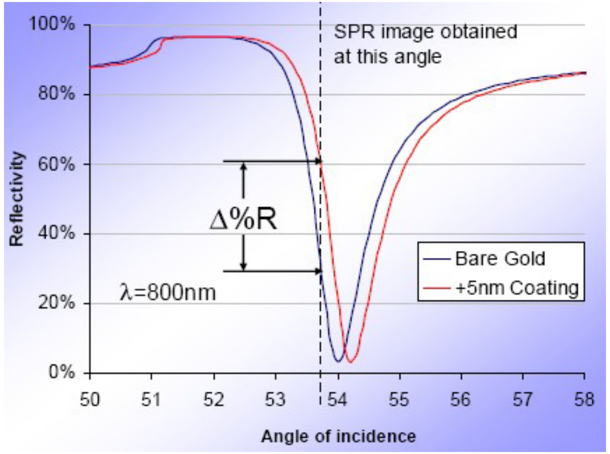
SPR Cell Sensing

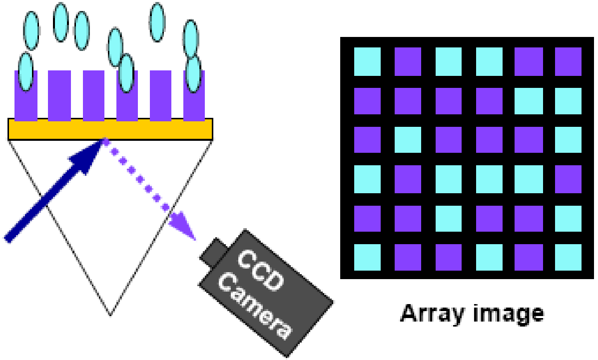


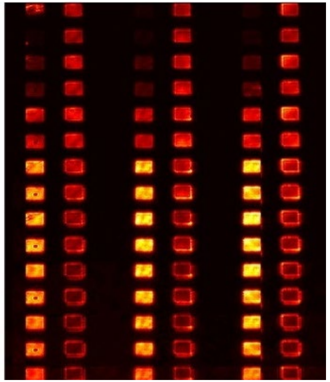


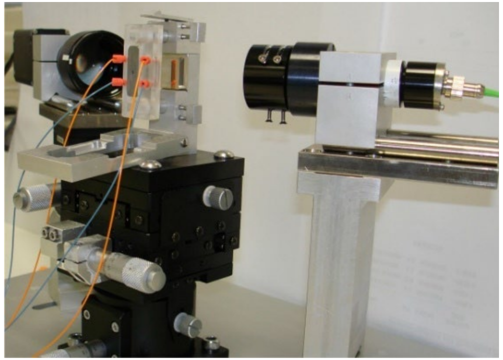
SPR Imaging

- To address multiplexed detection issues; greatly improve throughput





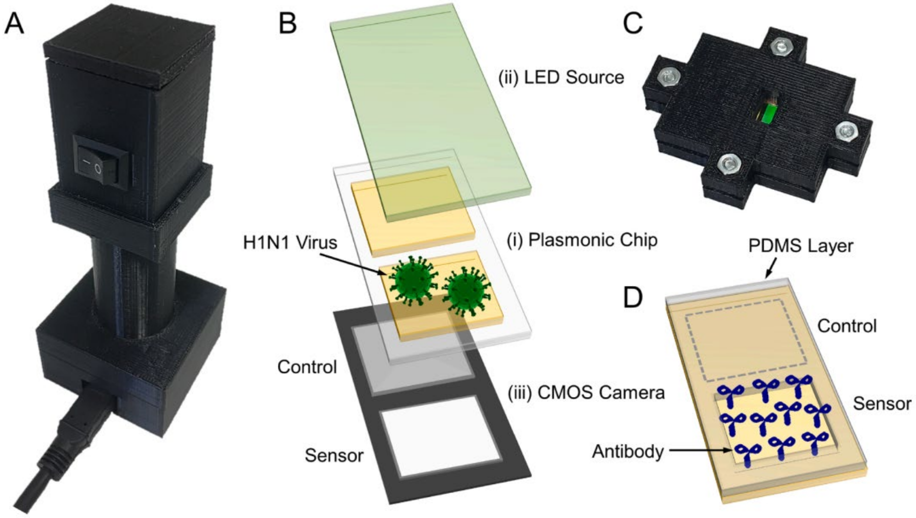


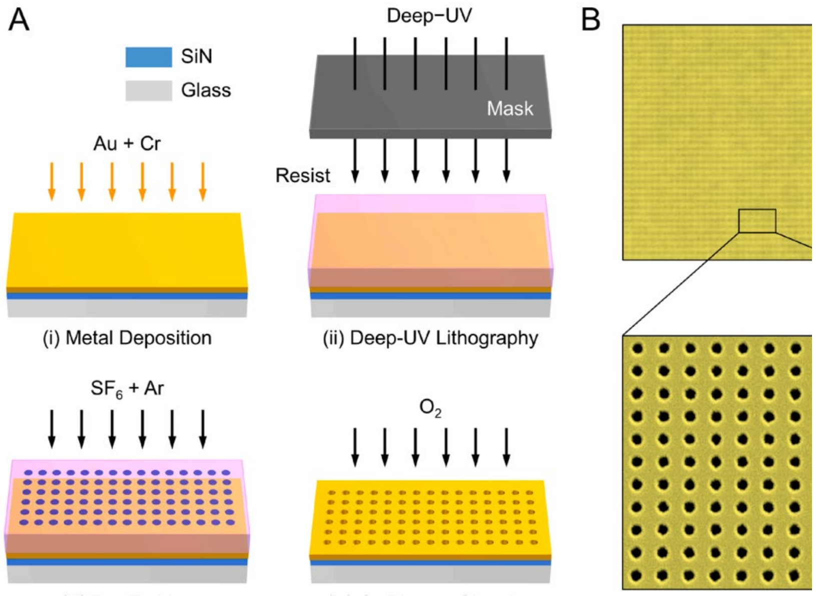


Broad-beam monochromatic polarized light from a laser diode (at a specific wavelength) illuminates the whole chip, over 400 spots.

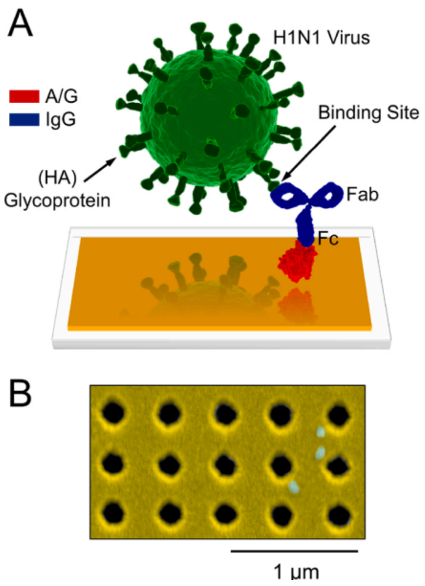
SPR imaging measures reflectivity changes at a fixed angle and wavelength.

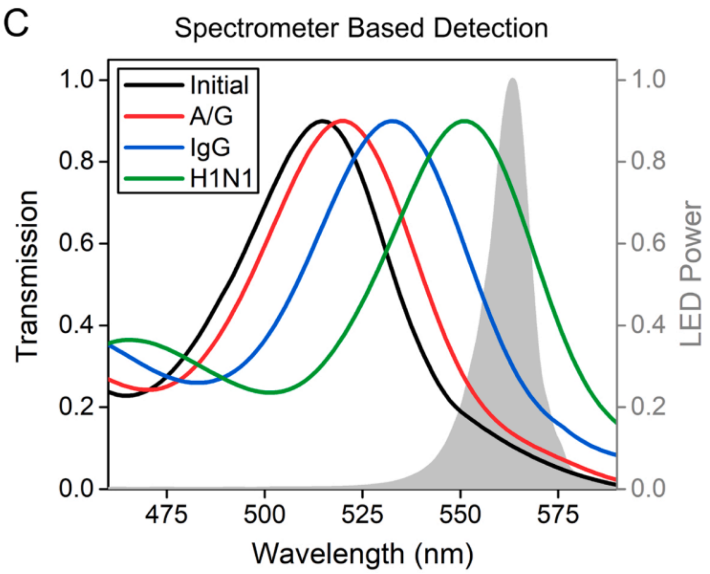
Plasmonic Arrays Sensors to Systems

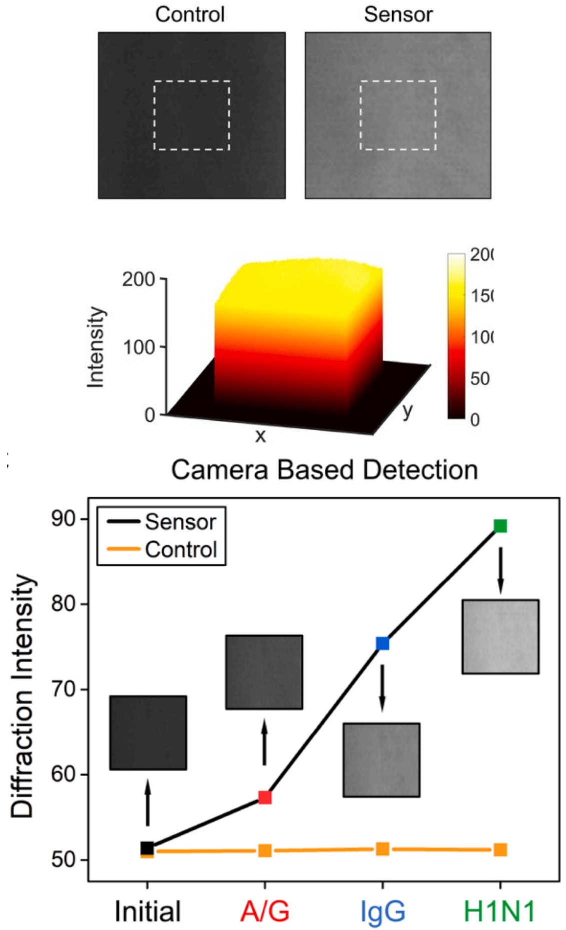


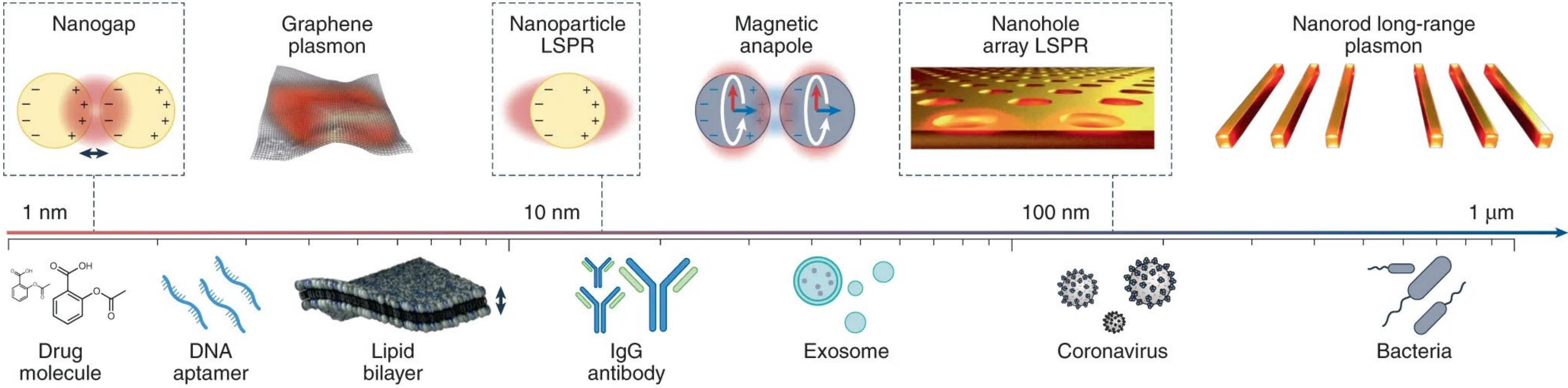


Plasmonic Arrays Sensors to Systems





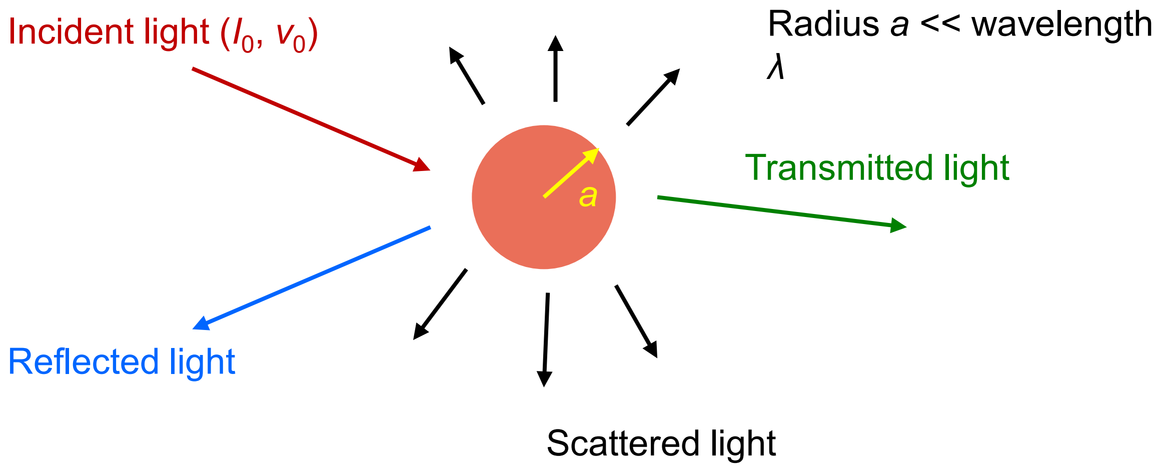




Nanogap
Graphene plasmon
Nanoparticle LSPR
Magnetic anapole
Nanohole array LSPR
Nanorod long-range plasmon
1 nm
10 nm
100 nm
1 µm
Drug molecule
DNA aptamer
Lipid bilayer
IgG antibody
Exosome
Coronavirus
Bacteria

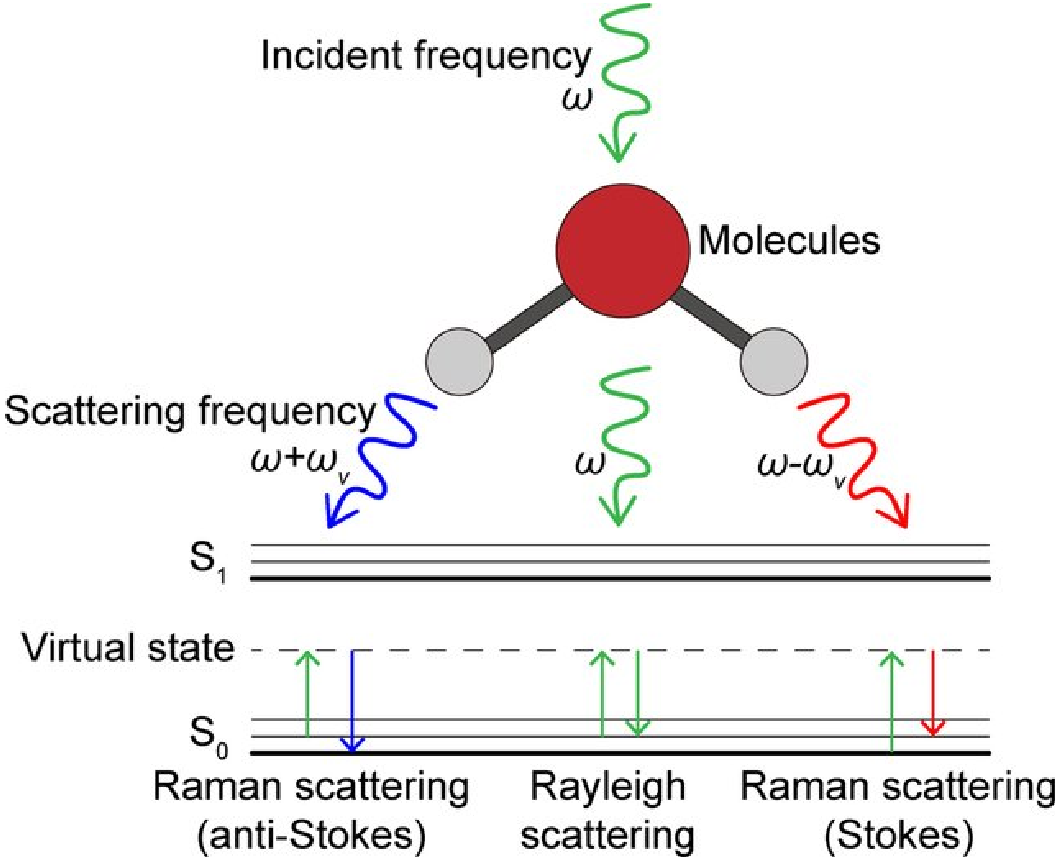
Surface-Enhanced Raman Scattering for Sensing

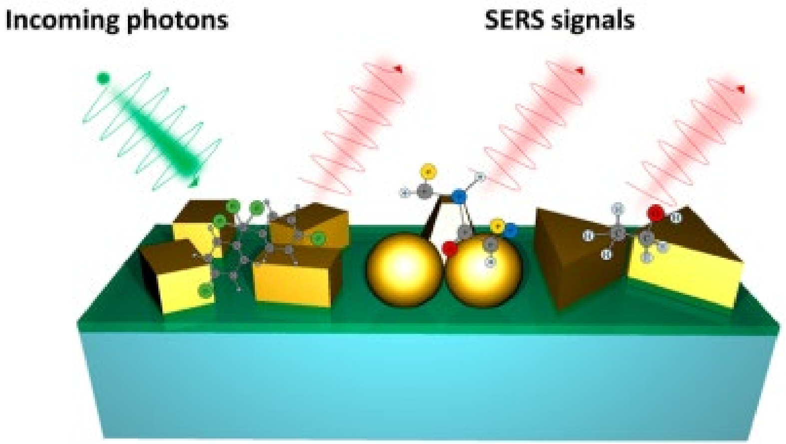
Scattered Radiation



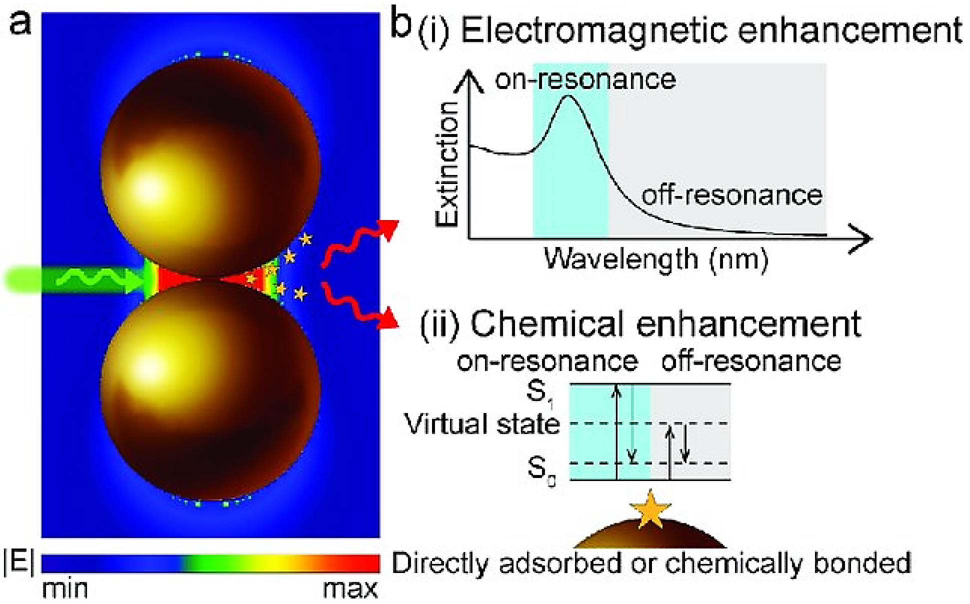
Scattering process	**Rayleigh scattering (elastic collision)**	$I_s \sim 10^{-3} I_0$	***particles***
	Raman scattering (inelastic collision)	$I_s \sim (10^{-6} - 10^{-9}) I_0$	***Molecular vibrations***

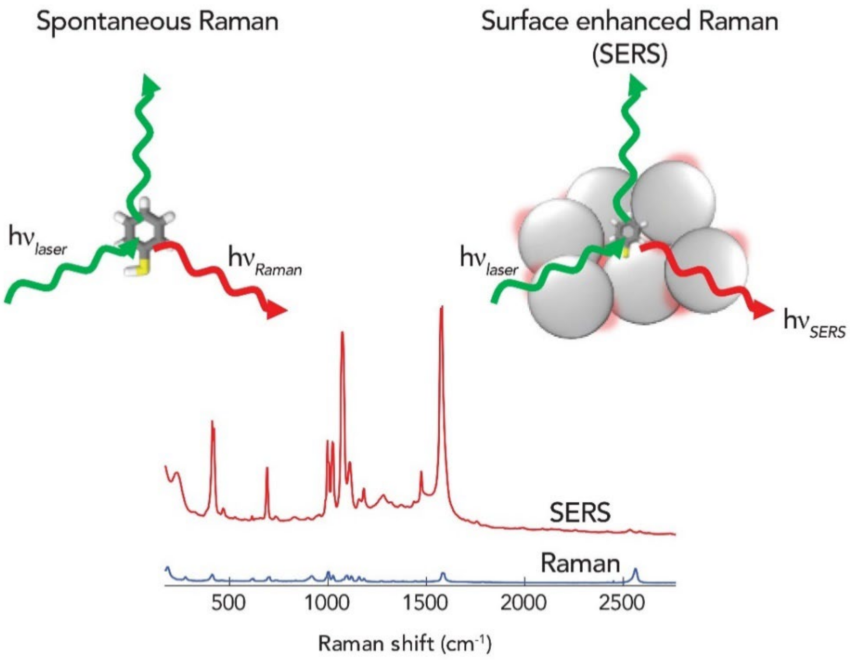
Scattering Processes

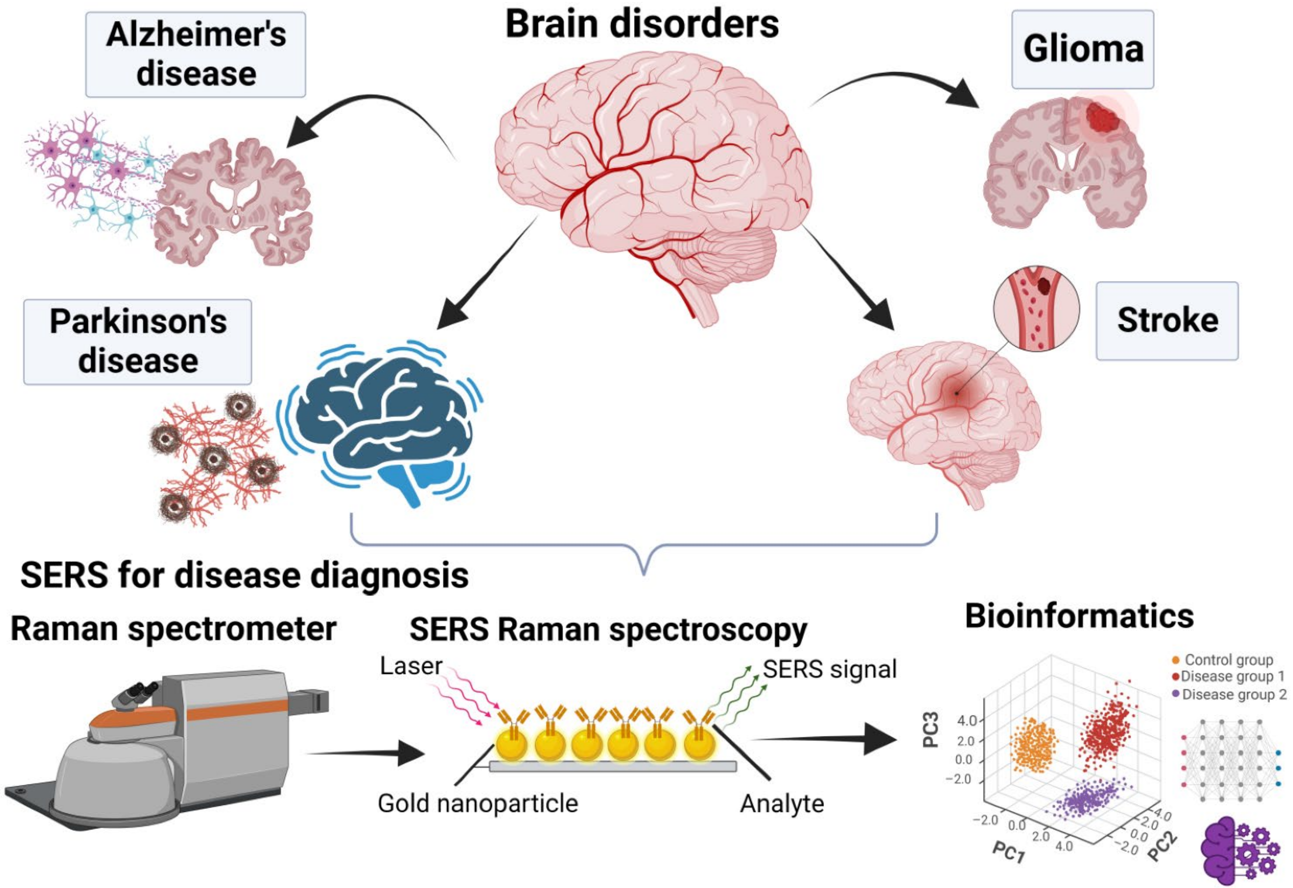




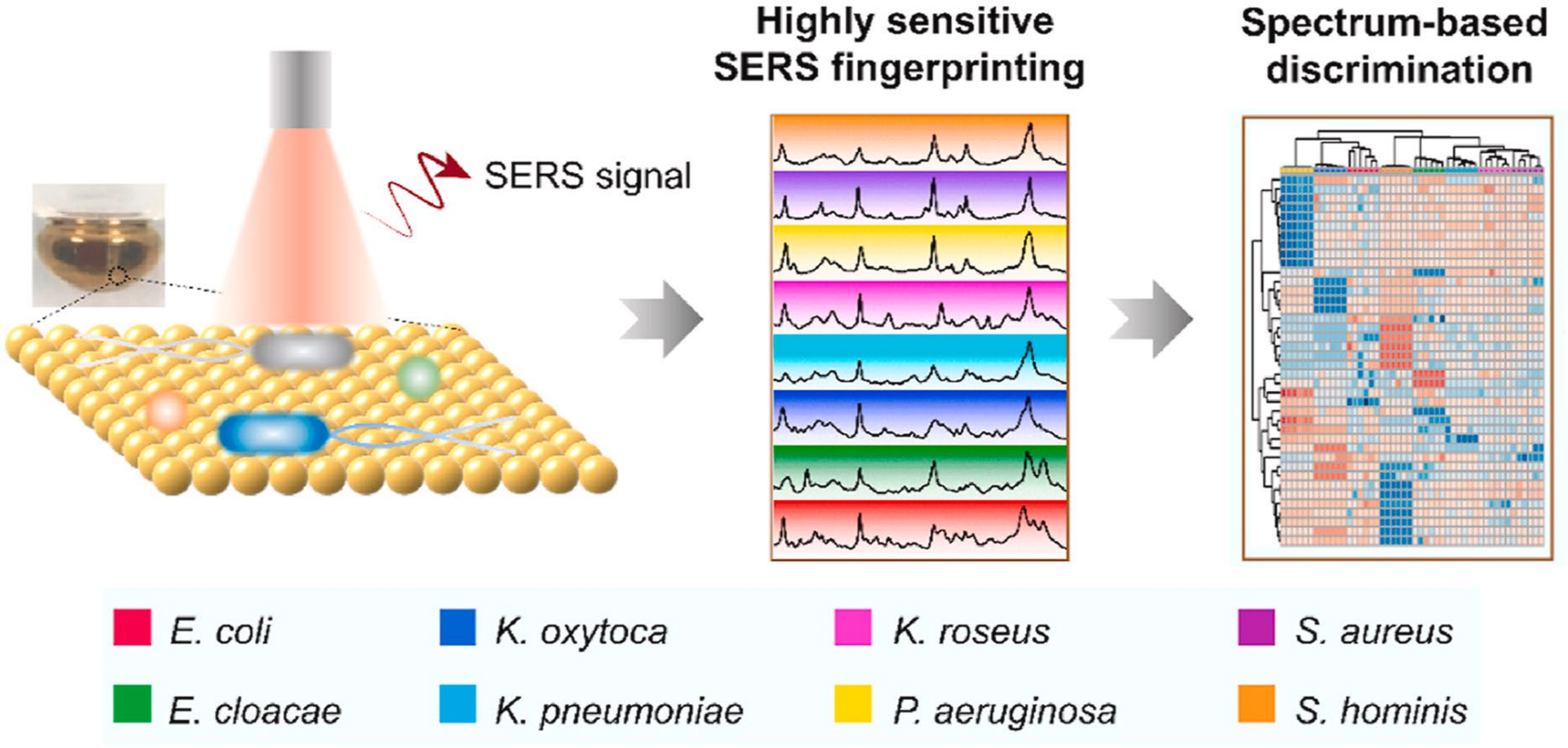
The enhancement factor can be as much as ~10^9 to ~10^{12}



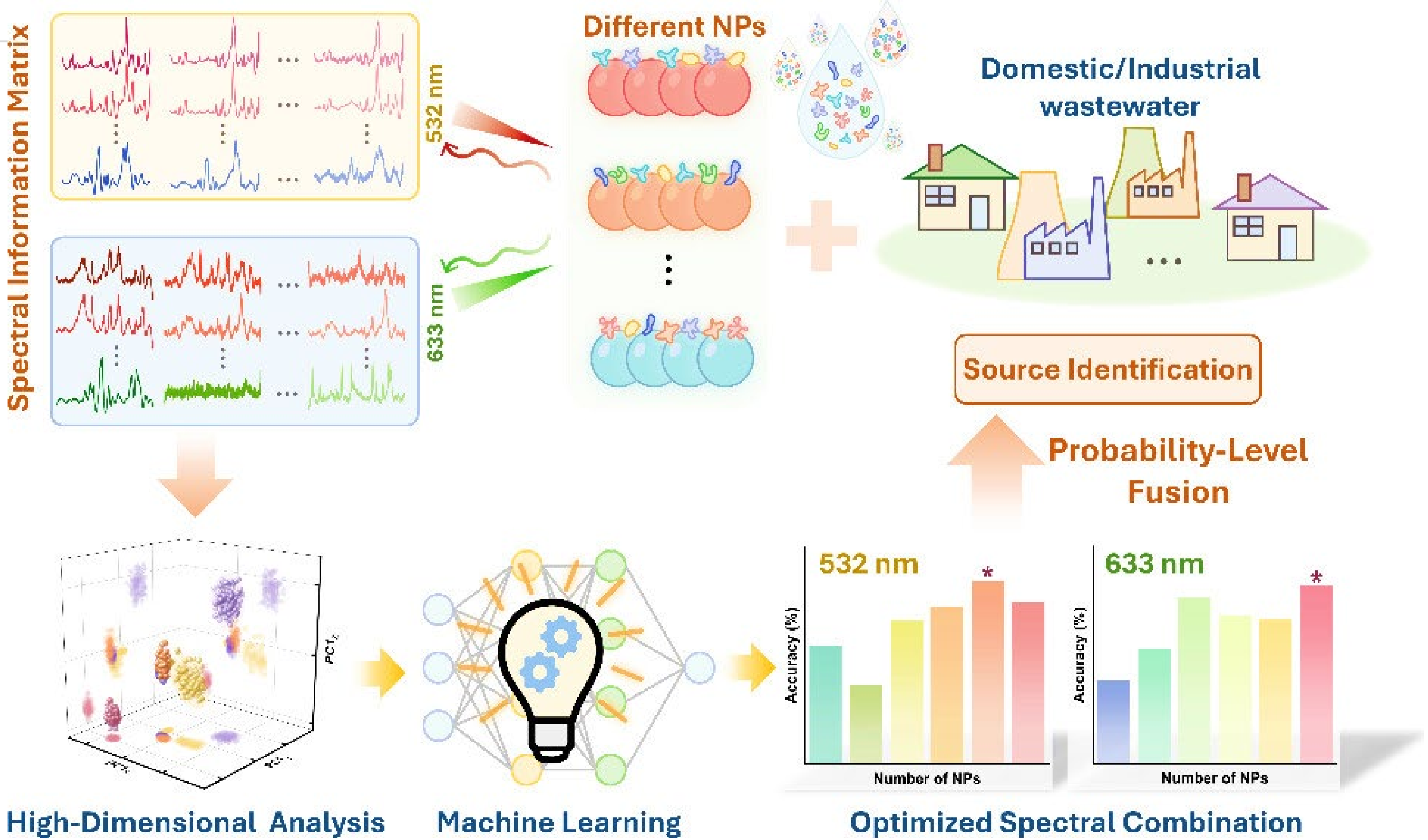




Brain disorders
Alzheimer's disease
Glioma
Parkinson's disease
Stroke
SERS for disease diagnosis
Raman spectrometer
SERS Raman spectroscopy
Laser
SERS signal
Gold nanoparticle
Analyte
Bioinformatics
Control group
Disease group 1
Disease group 2
PC1
PC2
PC3



SERS signal
Highly sensitive
SERS fingerprinting
Spectrum-based
discrimination
E. coli
K. oxytoca
K. roseus
S. aureus
E. cloacae
K. pneumoniae
P. aeruginosa
S. hominis


Spectral Information Matrix
532 nm
633 nm
Different NPs
Domestic/Industrial wastewater
Source Identification
Probability-Level Fusion
532 nm
633 nm
Accuracy (%)
Number of NPs
Accuracy (%)
Number of NPs
High-Dimensional Analysis
Machine Learning
Optimized Spectral Combination

THANKS FOR YOUR TIME