Plasmonics

Fundamentals & Applications

Photonics
(ELEC-E3240)

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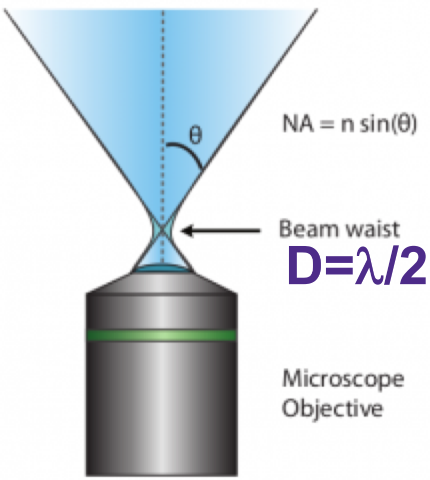
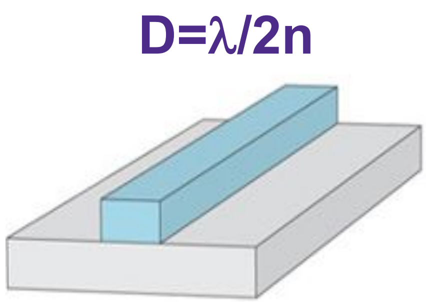
What is plasmonics?

Technological limits of photons

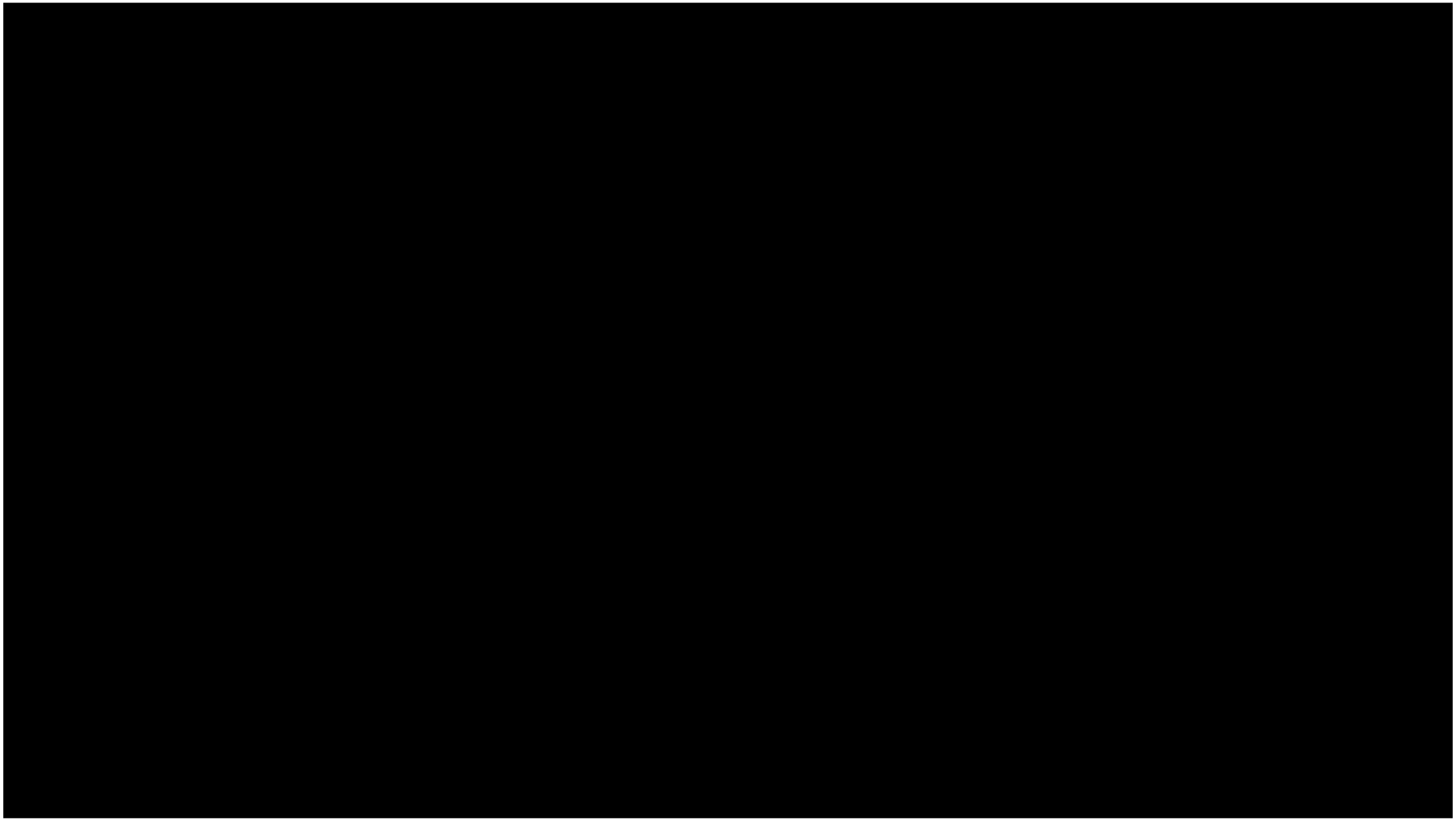
Diffraction limit





Absorption limit

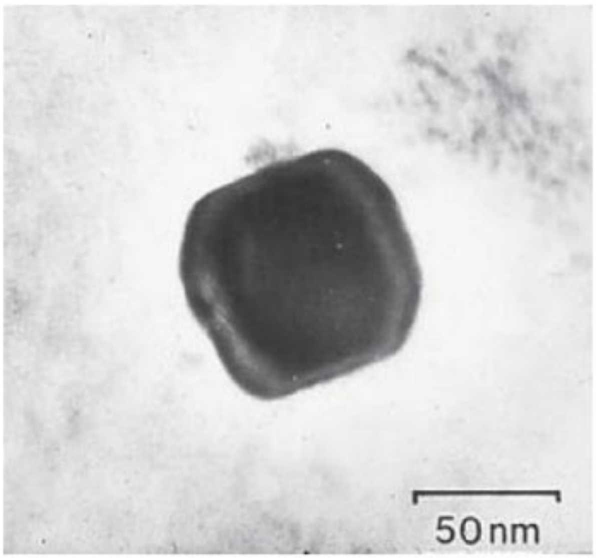
The unique properties of metallic particles

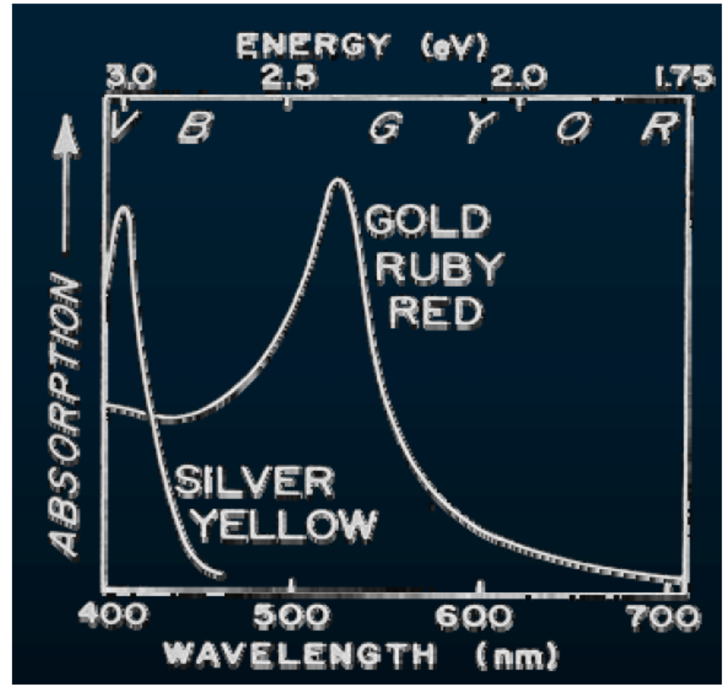


Lycurgus Cup is a 4th-century Roman glass cage cup made of a dichroic glass.

The unique properties of metallic particles

Figure 4
Transmission electron microscopy (TEM) image of a silver-gold alloy particle within the glass of the Lycurgus Cup [21]. © The Trustees of the British Museum.

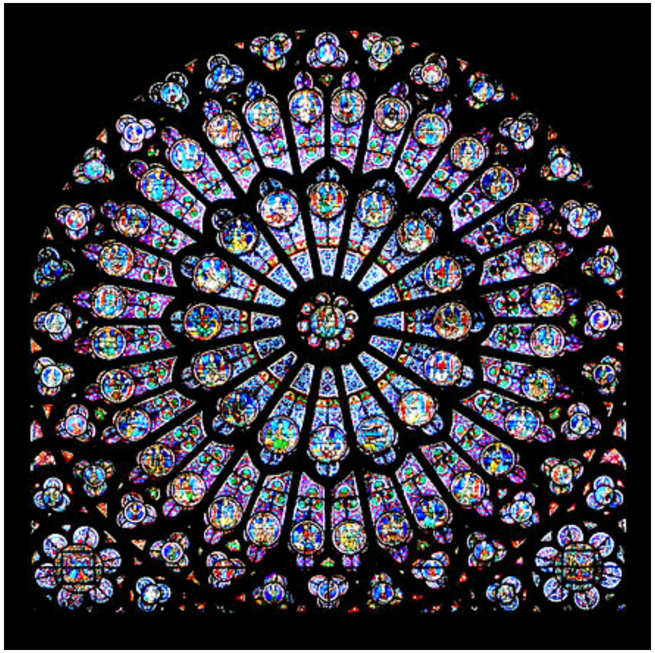




Au nanoparticles for red coloration
Ag nanoparticles for yellow coloration

Archaeometry, (1990)

The unique properties of metallic particles



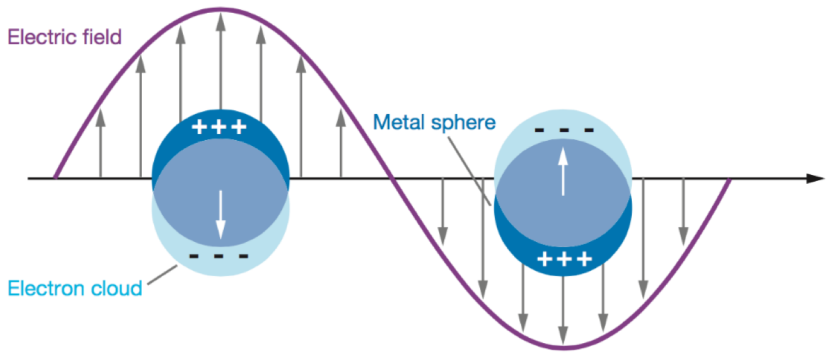
Gothic stained glass rose window of Notre-Dame de Paris. (13th century A.D.)

Gold colloidal suspension made by Michel Faraday in 1857

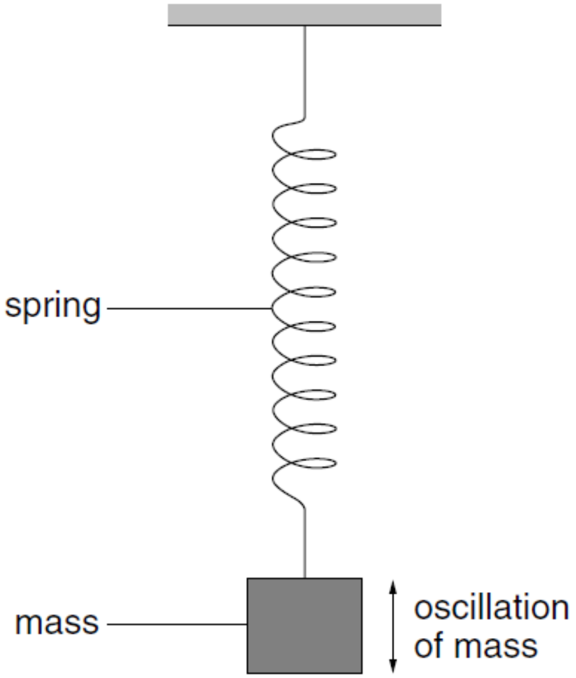
Phil. Trans. R. Soc. Lond. (1857)

Credit: Royal institution of Great Britain

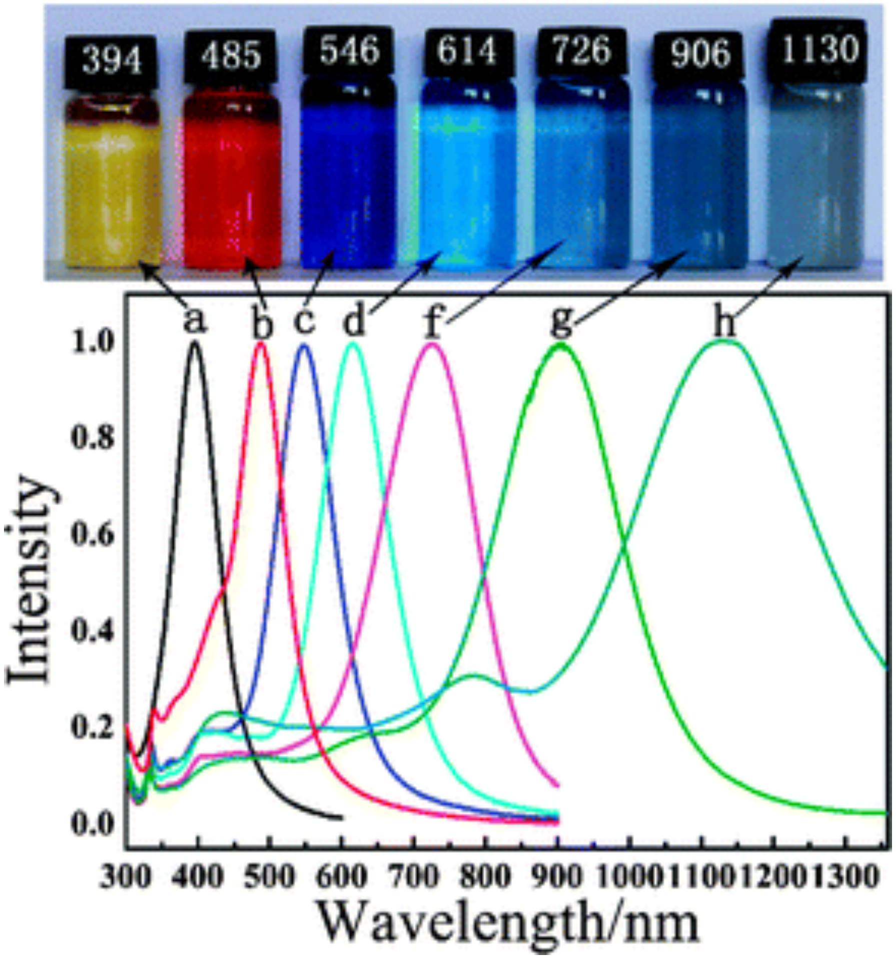
Localized plasmonic resonance

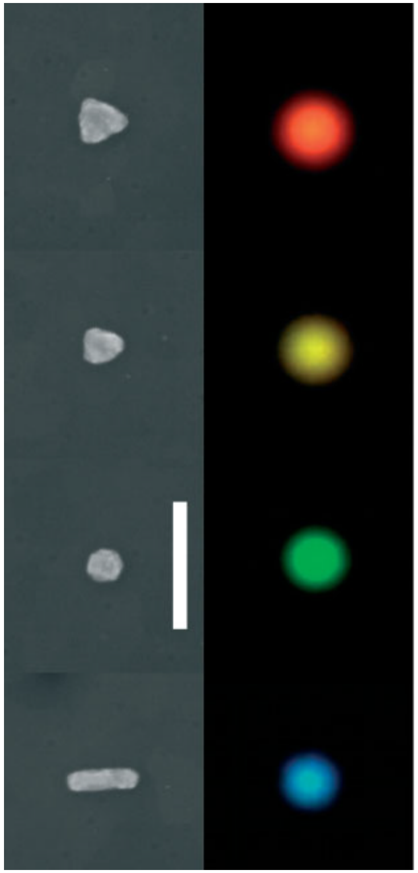


$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_0 m_e}}$$



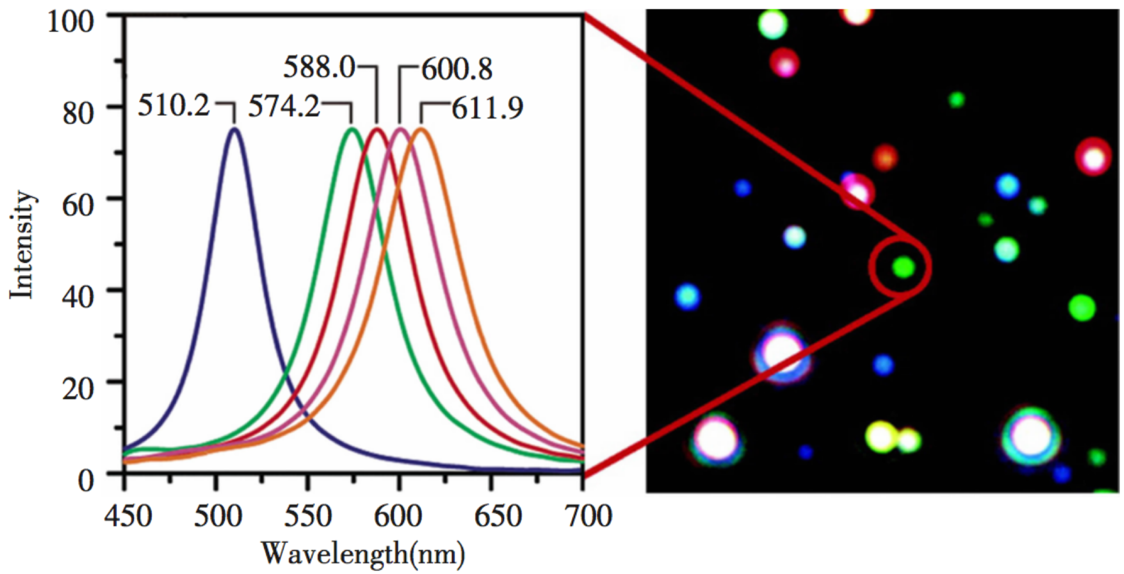
Localized plasmonic resonance





W. A. Murray, W. L. Barnes,
Adv. Mater. 19, 3771 (2007) .

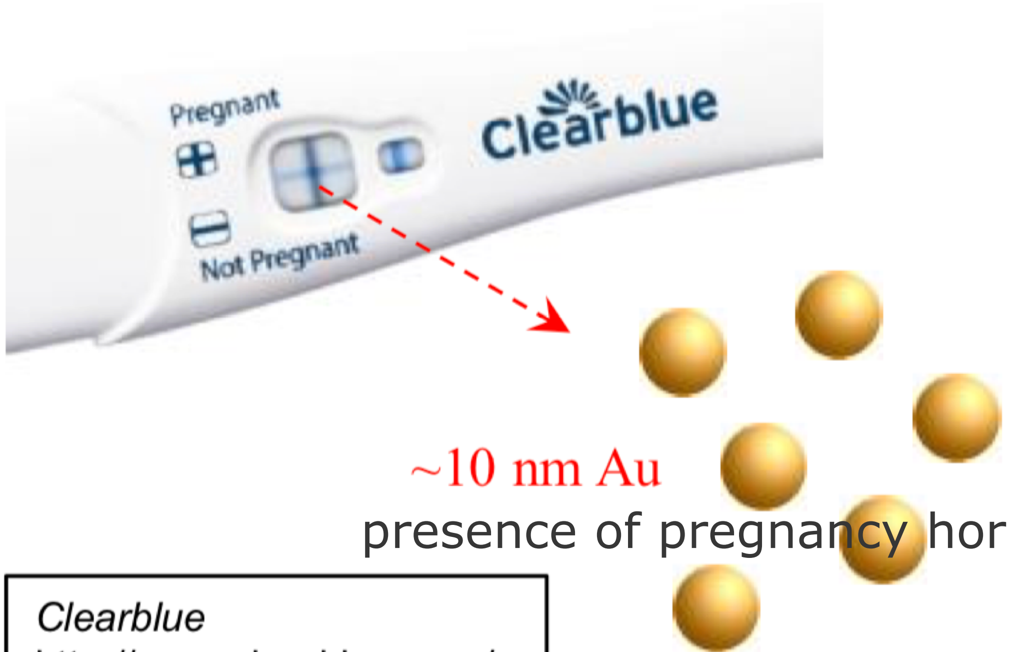
Biosensing with plasmonics



Single Ag nanoparticle resonant Rayleigh scattering spectrum in various solvent environments (left to right): nitrogen, methanol, 1-propanol, chloroform, and benzene .

Adam D. McFarland, Nano letter (2003)

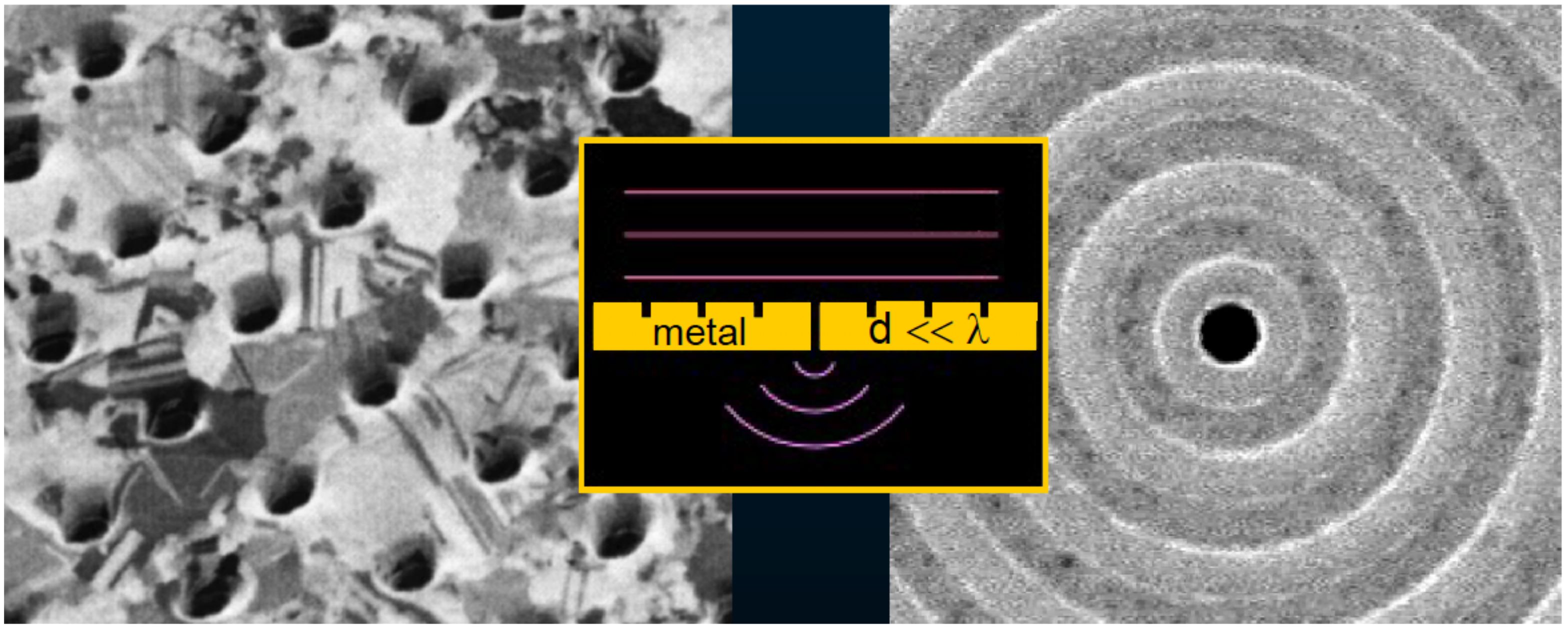
Biosensing with plasmonics



Clearblue
http://www.clearblue.com/

Pregnancy tests (a *lateral flow assay*) detect human chorionic gonadotropin from urine (Also for ovulation.)

Localized Plasmonics Applications



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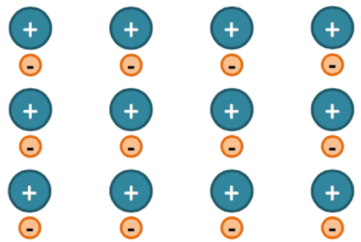
H.F. Ghaemi, et al., Phys. Rev. B 58, 6779 (1998)
T.Thio et al., Optics Letters 26, 1972-1974 (2001)

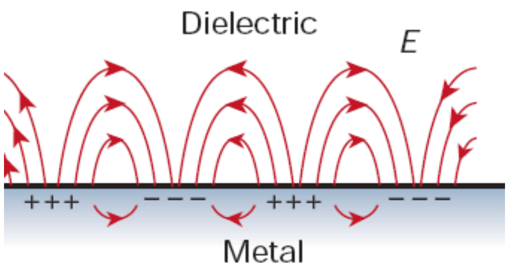
What is plasmonics?

Plasmon Collective oscillation of free electrons



Surface Collective oscillation of free electrons at surface

Surface Plasmon Polariton Surface Plasmon + Photon



Polariton: quasi-particle resulting from coupling of EM waves with an electric or magnetic excitation.

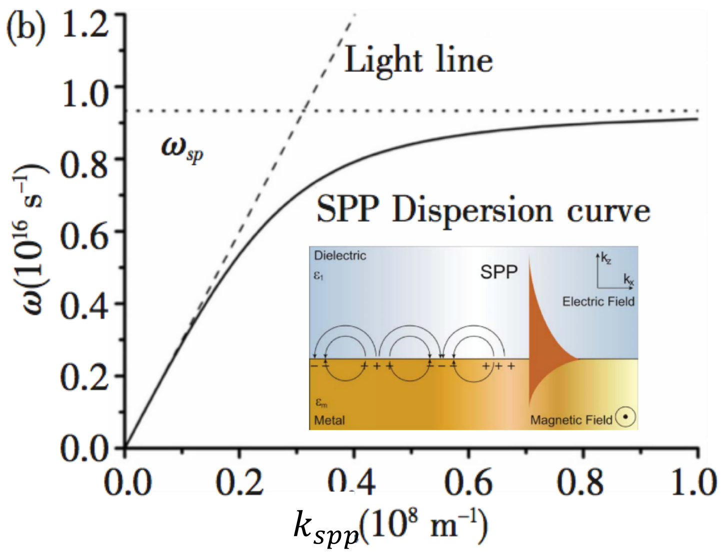
Ebbesen *et al.*, Nature **391**, 667 (1998)

Dispersion and Properties

Maxwell's equations
Boundary conditions

Dispersion (Wavevector, frequency)

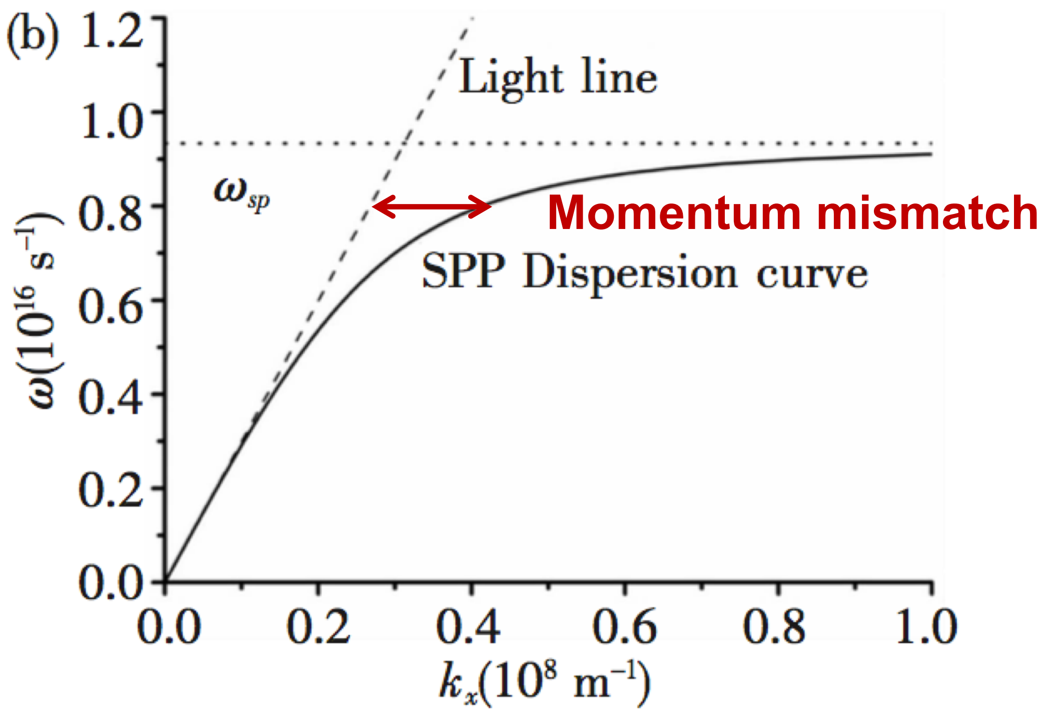
$$k_{spp} = k_x = \frac{\omega}{c}\left(\frac{\varepsilon_1 \varepsilon_m}{\varepsilon_1 + \varepsilon_m}\right)^{1/2}$$



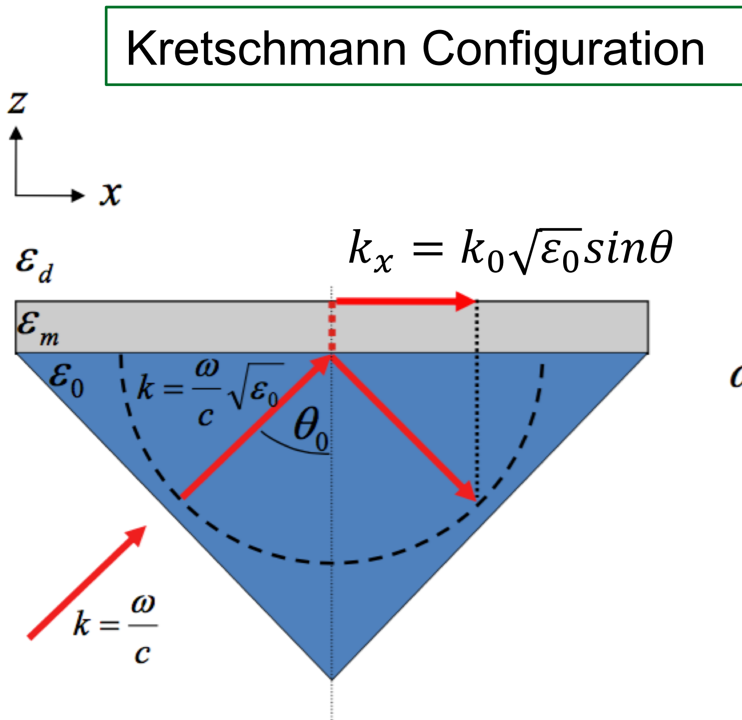
- Subwavelength $\lambda_{spp} = \frac{2\pi}{k_{spp}}$
- Propagating along the surface
- Confinement at the surface
- Enhancement of Optical fields

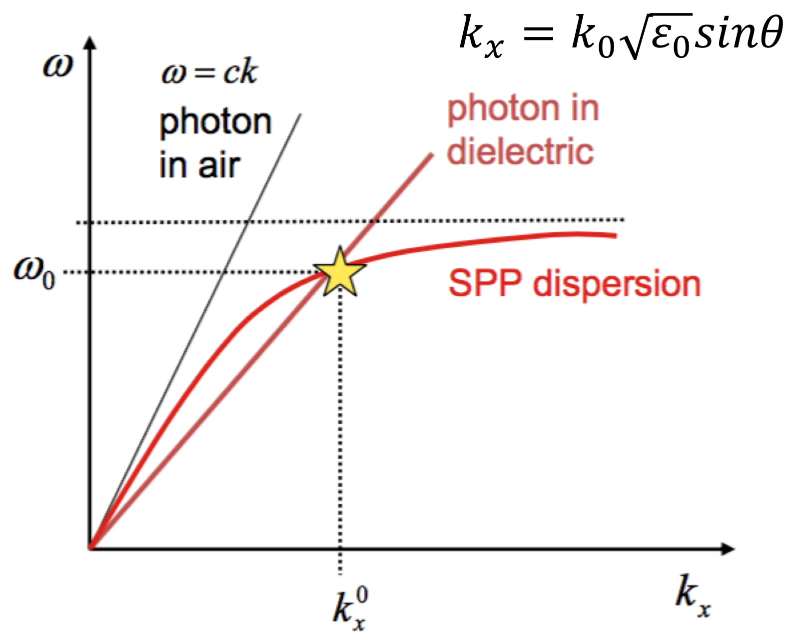
Excitation

1. Energy Conservation
2. Momentum(k) Conservation



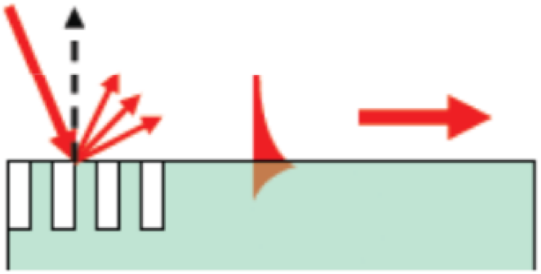
Excitation: Prism Coupling





Excitation condition: $k_{spp} = k_0\sqrt{\varepsilon_0}sin\theta$

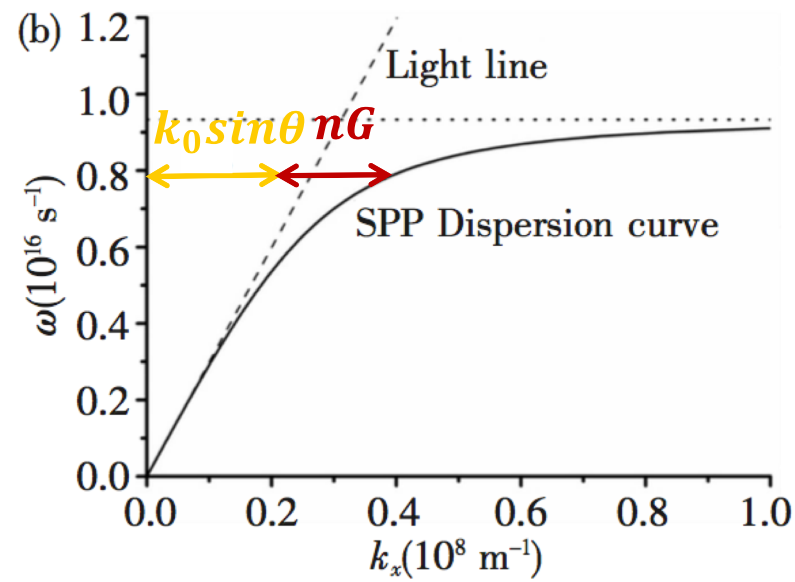
Excitation: Grating Coupling



Period: a

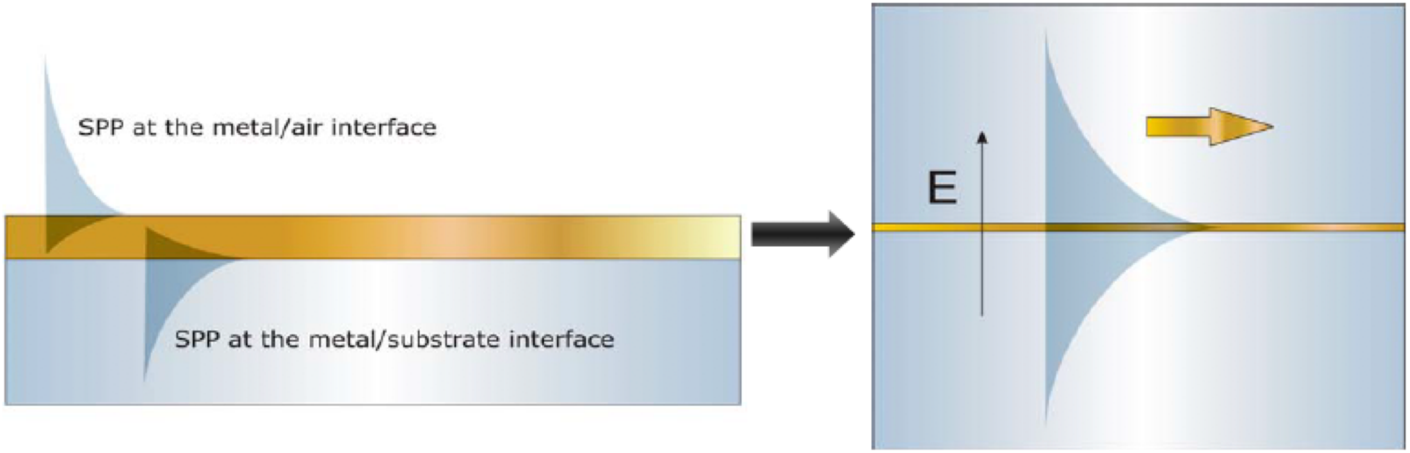
Reciprocal lattice vector

$$G = \frac{2\pi}{a}$$



Excitation condition: $k_{spp} = k_0 sin\theta + nG$

Plasmonics waveguide

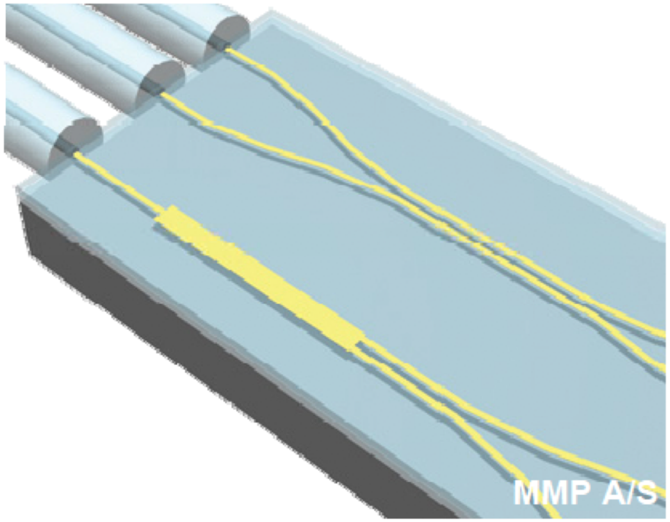


Propagation length:	~ tens of μm	~ mm
Confinement:	~ hundreds of μm	~ several μm

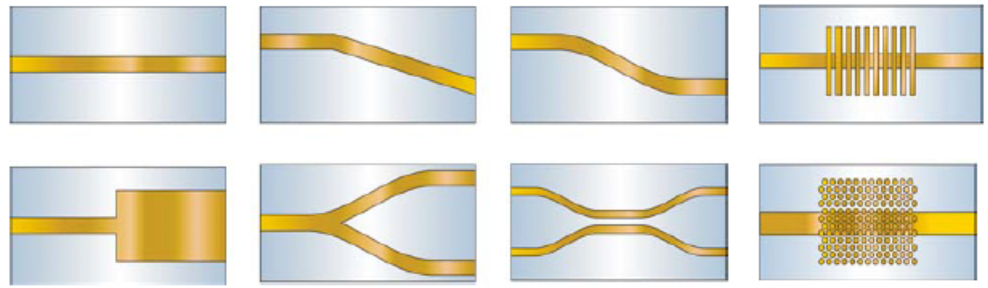
Phys. Rev. Lett. 47, 1927 (1981)
Phys. Rev. B 33, 5186 (1986)

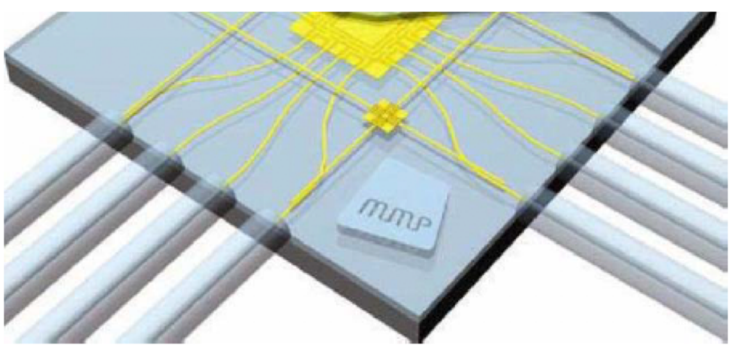
Plasmonics devices

Interfacing with external world



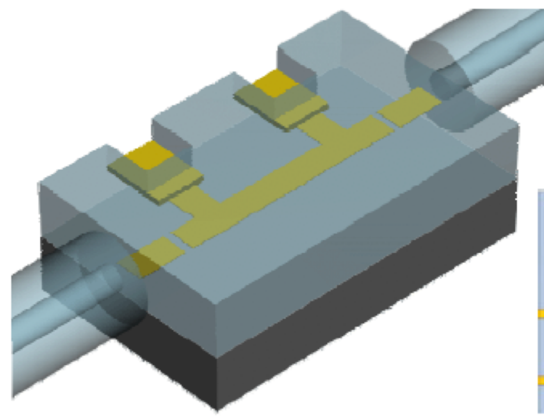
Passive components





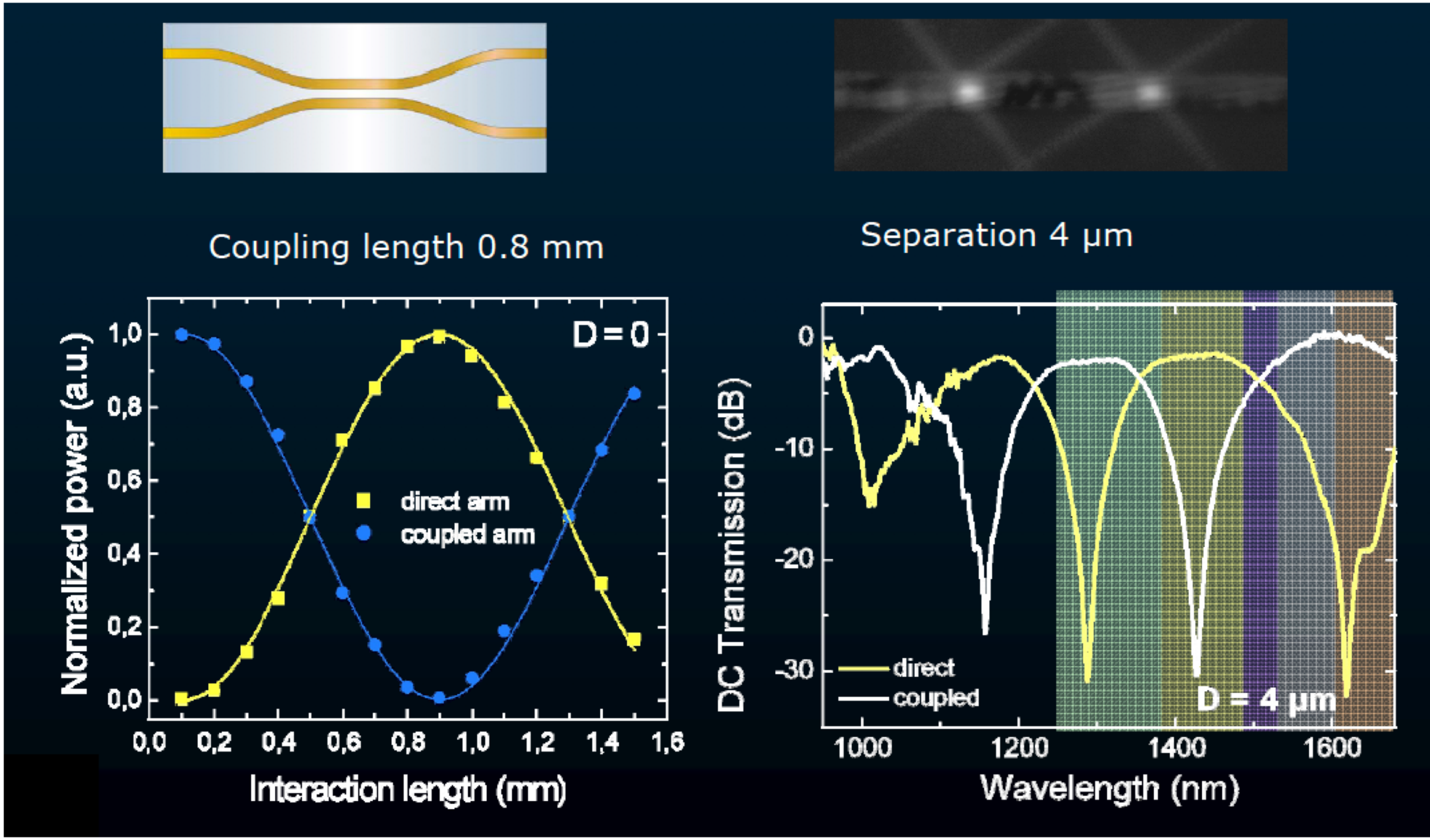
Active components

VOA



DCS

Directional Couplers

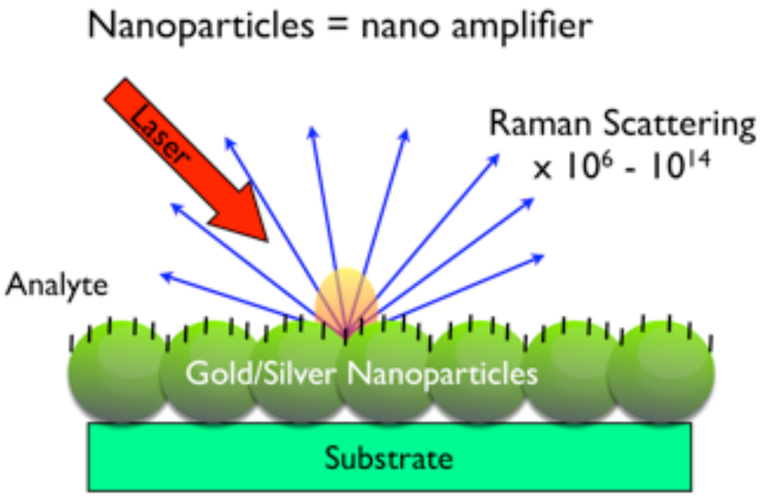


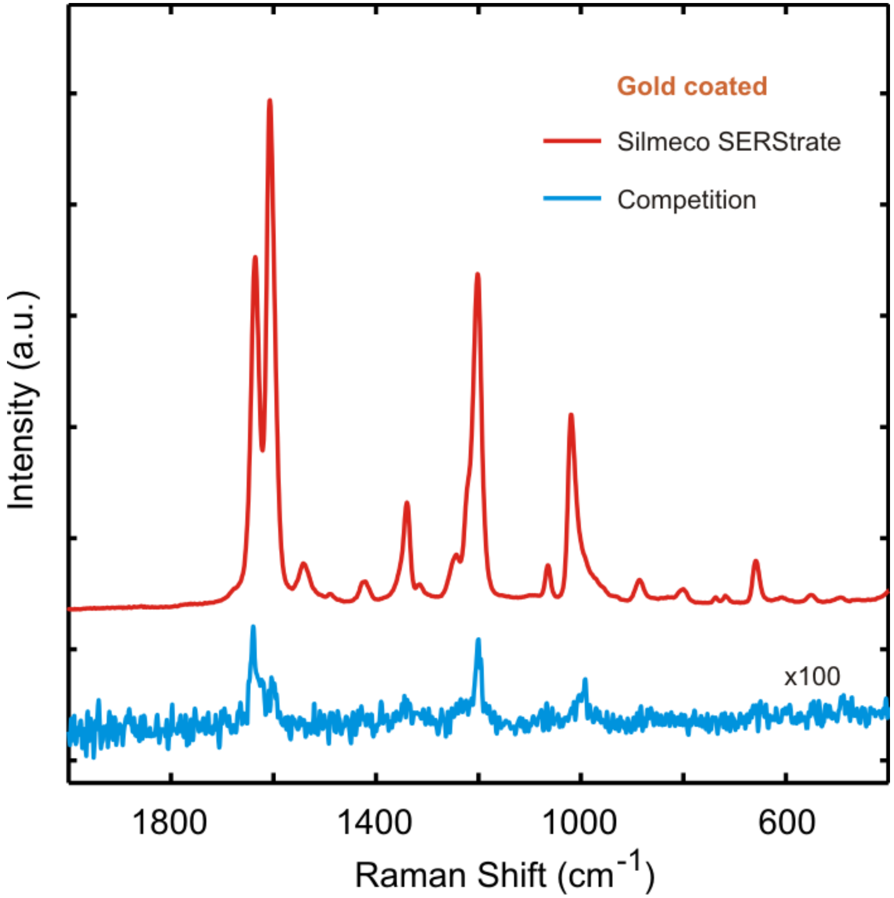
The Key Strength of Plasmonics

- Light concertation below the diffractive limits
- Simple building blocks offer tremendous design flexibility
- Scalable fabrication routes
- Simultaneous electrical and optical functionalities
- Light guiding and manipulation well below the diffraction limit

Light concertation below the diffractive limits

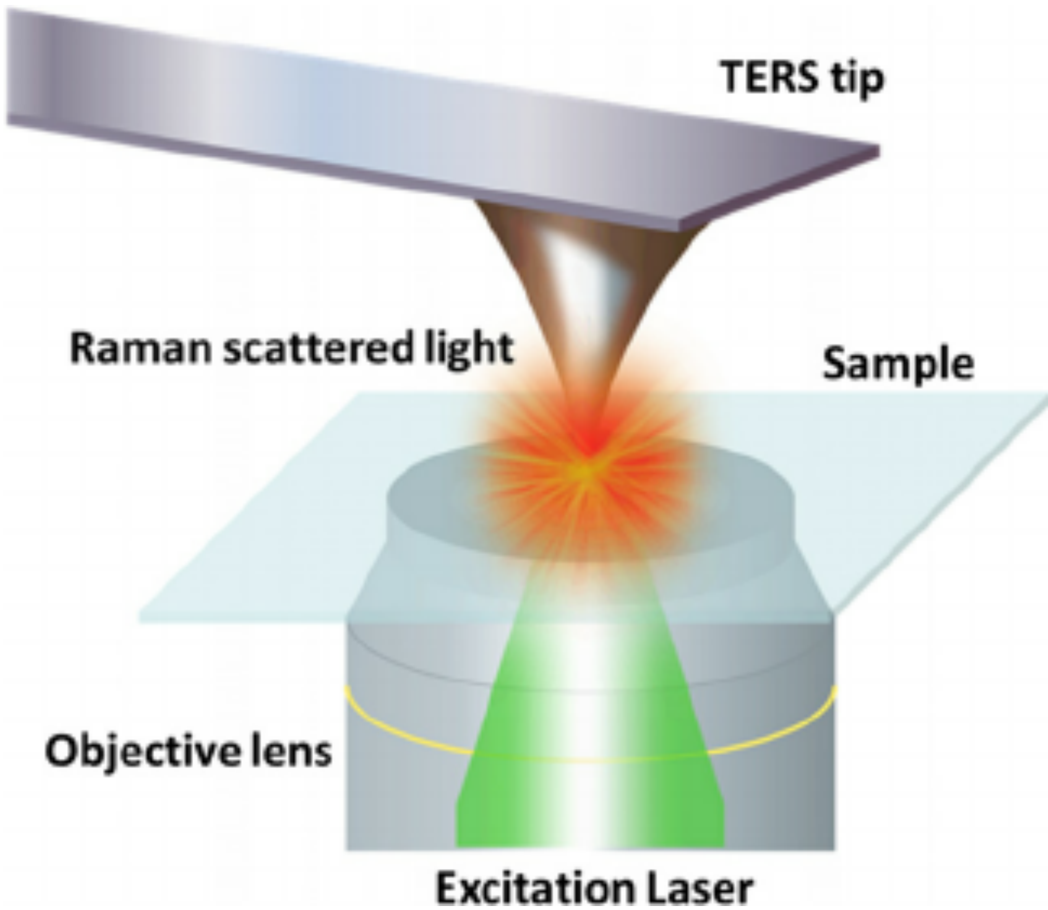
Surface enhanced Raman spectroscopy (SERS)



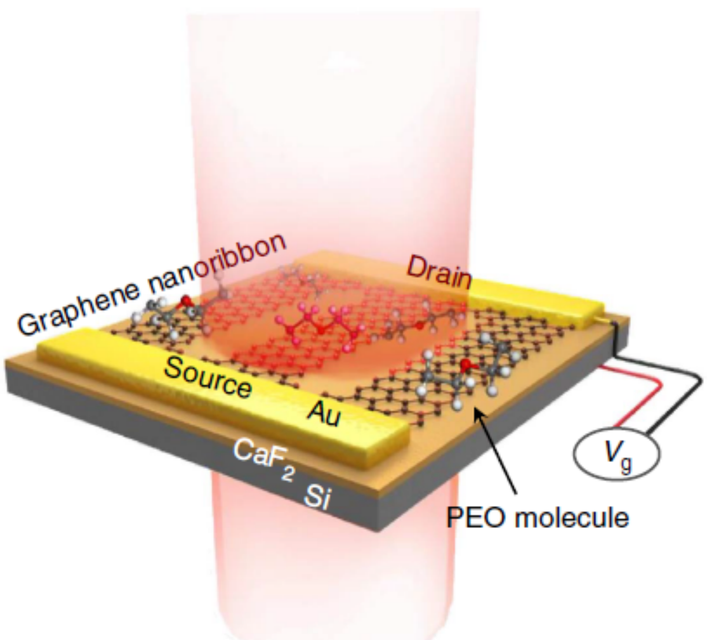


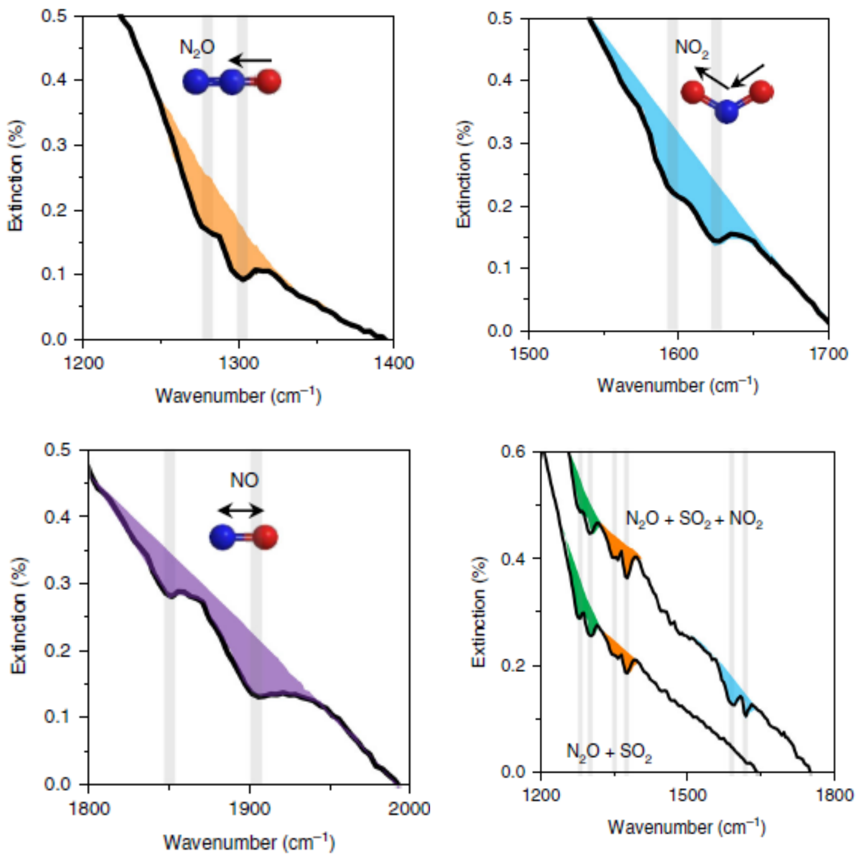
Light concertation below the diffractive limits

Tip-enhanced Raman spectroscopy (SERS)



On-chip gas sensing





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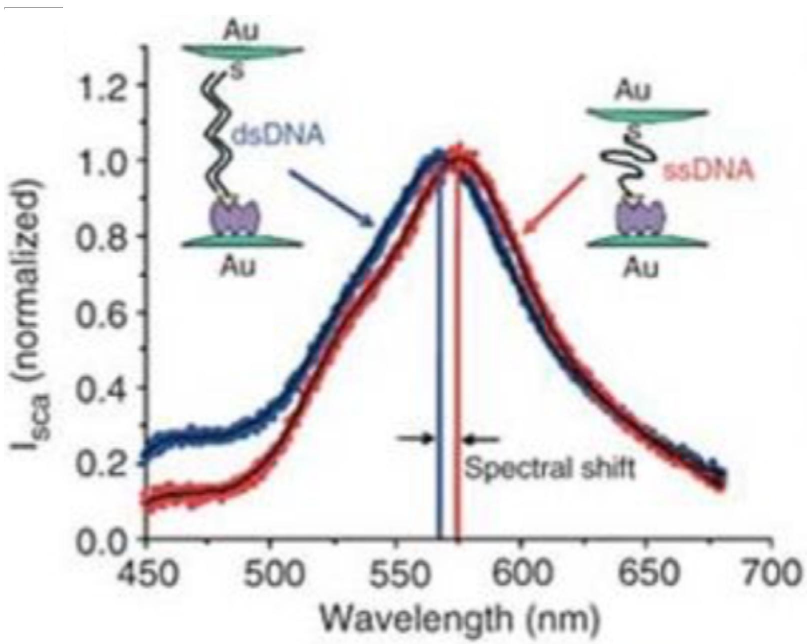
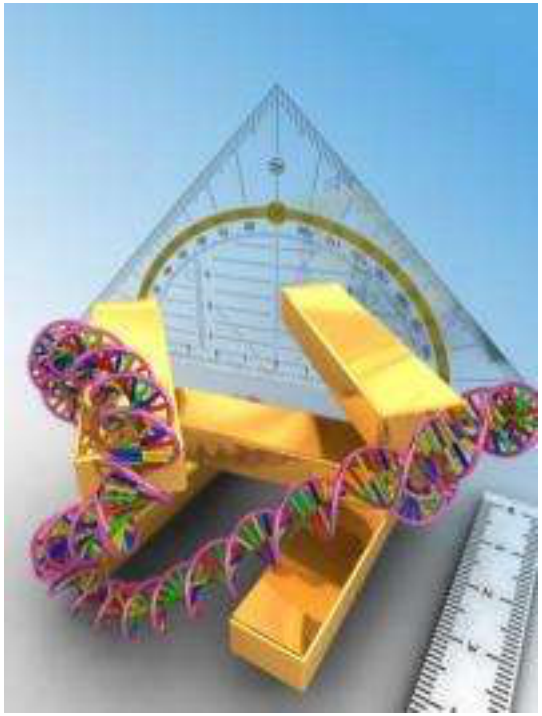
School of Electrical Engineering

Nature Communications 7, 12334 (2016).
Nat. Commun. **10**, 1131 (2019).

Simple building blocks offer tremendous design flexibility

Plasmonic rulers





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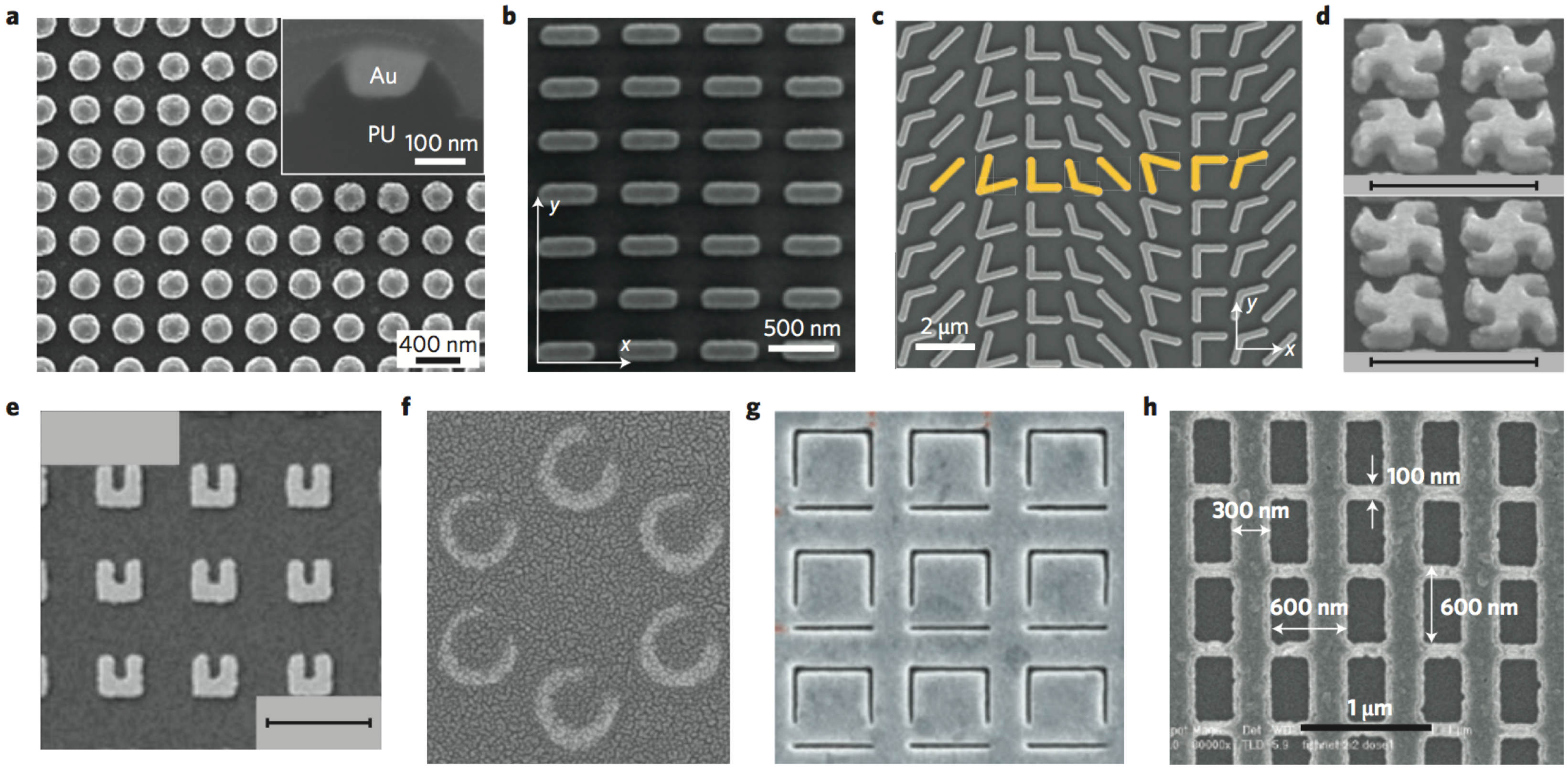
Nature biotech 23, 741 (2005)
Science, 332, 1407 (2011)

Scalable fabrication routes



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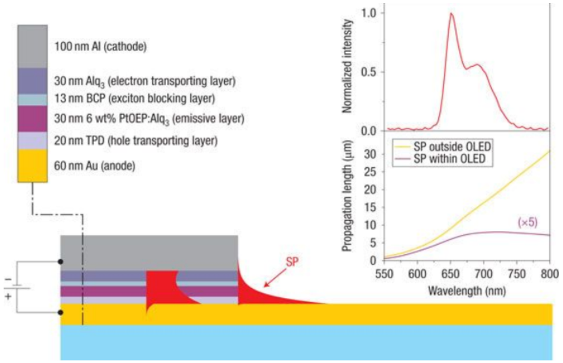
Simultaneous electrical and optical functionalities

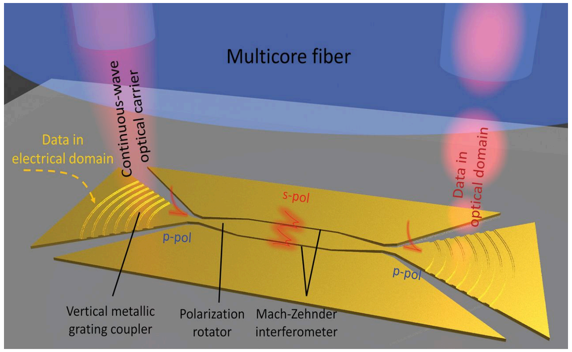
Is it possible to simultaneously conduct electricity and manipulate light?

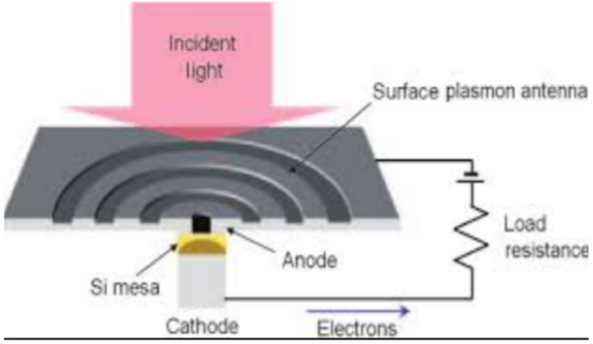
Electrically switchable surface plasmon source

Electrooptic Plasmonic Modulators

Plasmonic Photodetector



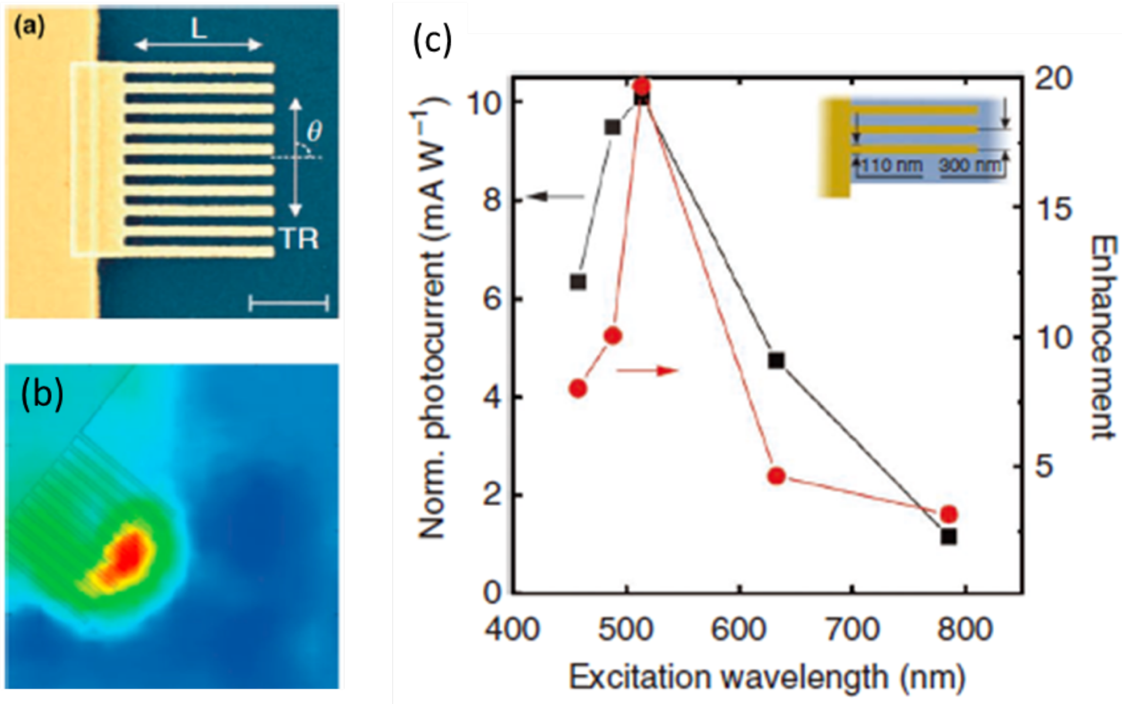




Nature Photonics **2**, 684–687 (2008)
Nano Lett. **9**, 12, 4403-4411 (2009)
JJAP. 44, 12-15 (2005)

Plasmon enhanced photocurrents

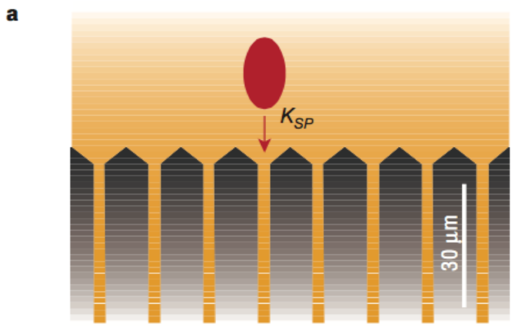
Graphene photodetector:
weak interaction with light due to thickness less than 1 nm



Enhancement of photocurrents is obtained at the plasmon resonant frequency.

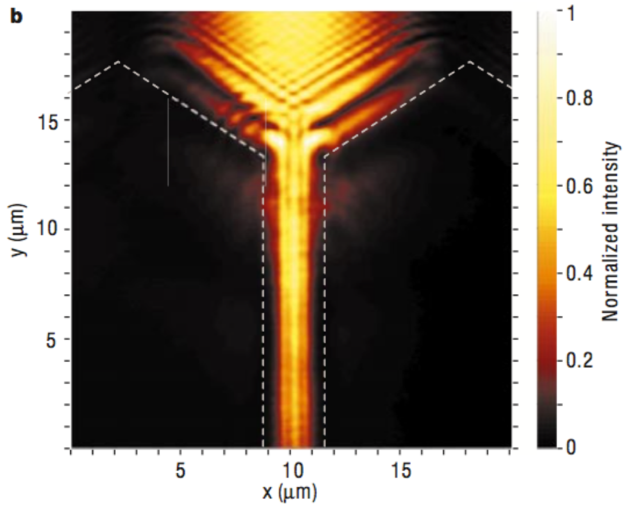
Plasmonic waveguide

SP waveguide



40 nm thick, 2.5 μm wide gold stripe.

wavelength=800 nm



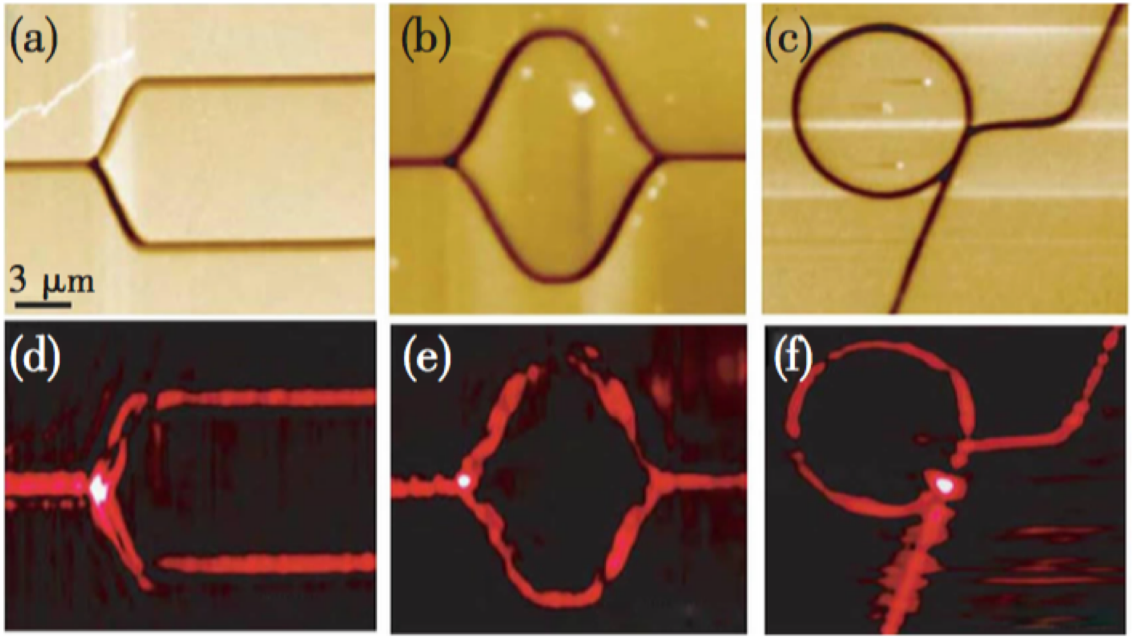
- Plasmonic waveguide mode is much better confined to the guiding material than would be the case in dielectric-based waveguides.

Light guiding and manipulation well below the diffraction limit

Integrated photonic chips

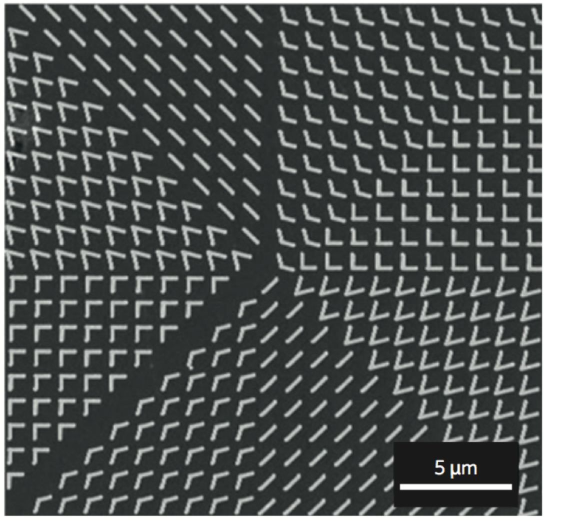
Metal split

Width 50nm Propagation length 10 um



λ=1 600 nm   λ=1 600 nm   λ=1 525 nm

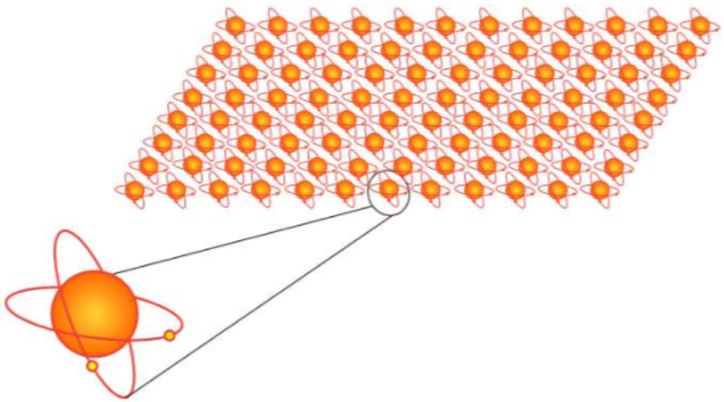
Spliter   interferer   harmonic resonator



Metamaterial

Metamaterial

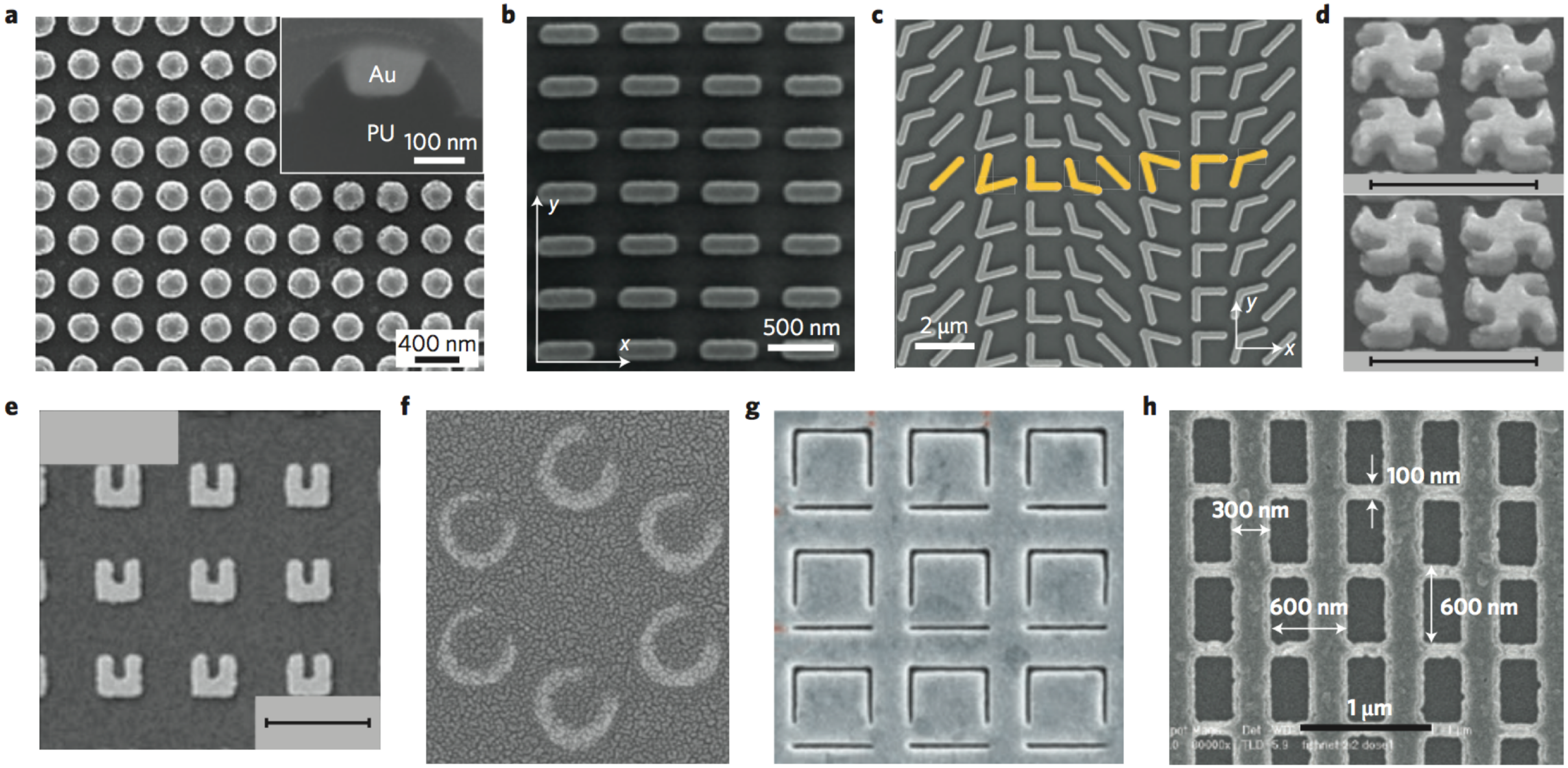
Greek word *Meta* means *beyond*



- Metamaterials are composed of subwavelength structures (called meta-atoms).
- Electromagnetic response of metamaterials can be described via *effective* permittivity $\epsilon(\omega)$ and permeability $\mu(\omega)$, which are different from the base materials.

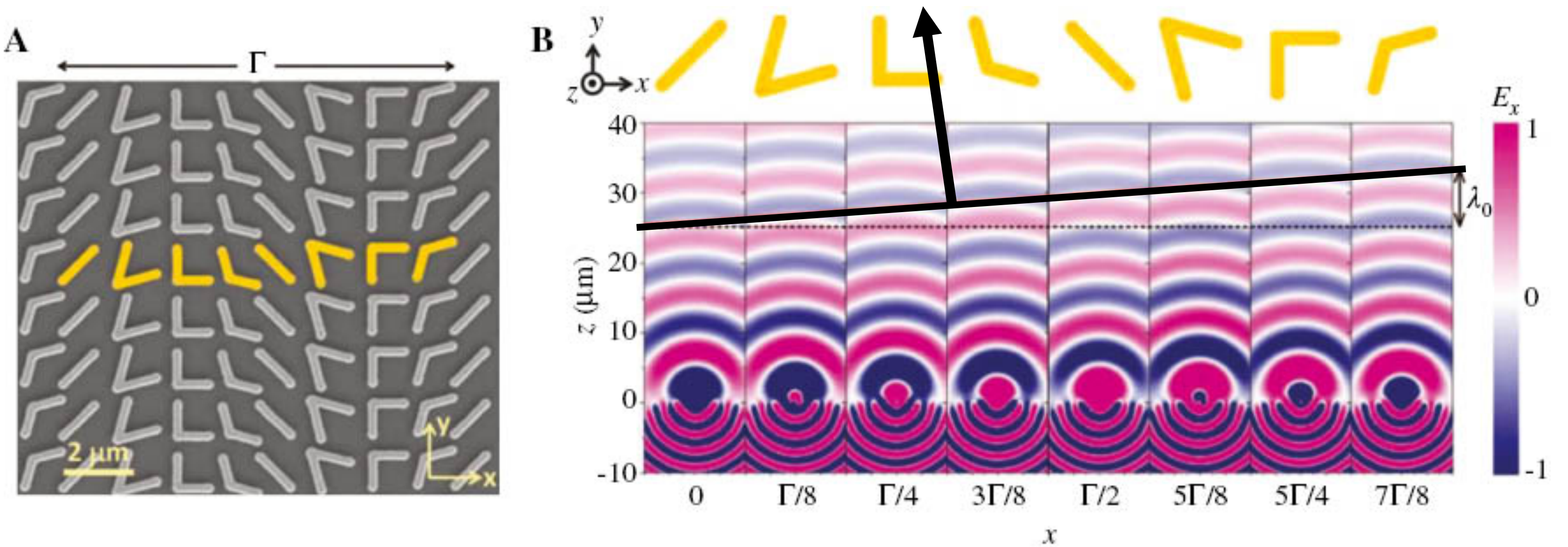
Plasmonic metasurfaces

Phase control



Plasmonic metasurfaces

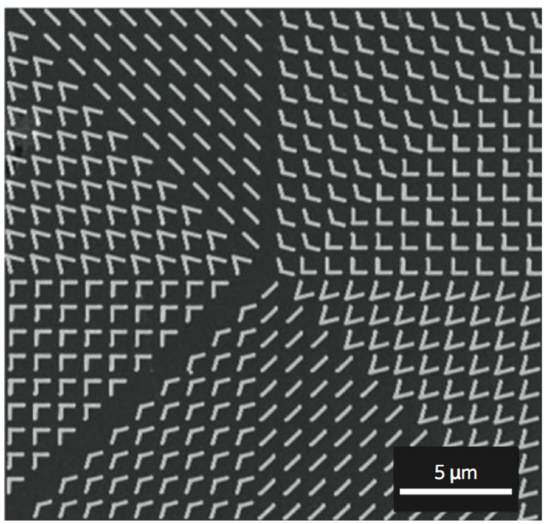
Phase shift → Reshape of wavefront

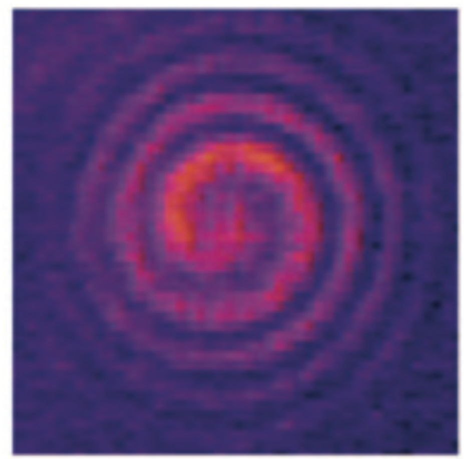


directed radiation

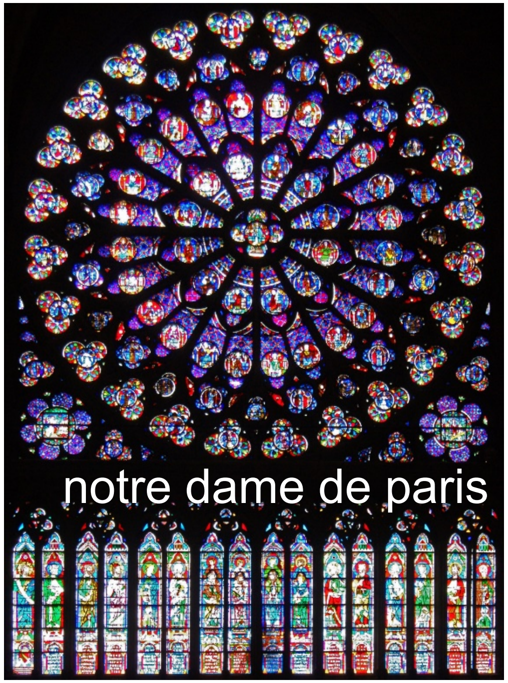
Plasmonic metasurfaces

Vortex beam generators
phase-gradient metasurface elements





The generated vortex beam



Plasmonic coloration

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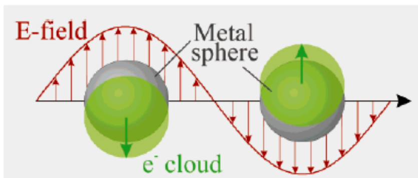
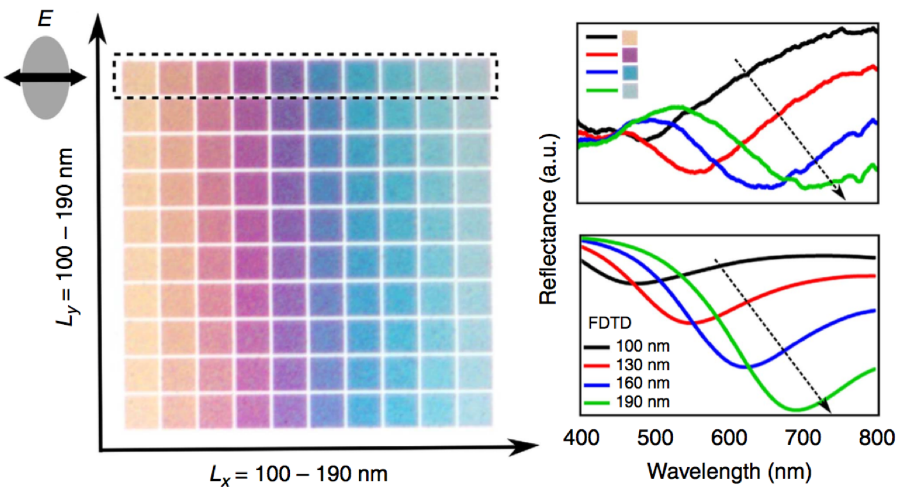
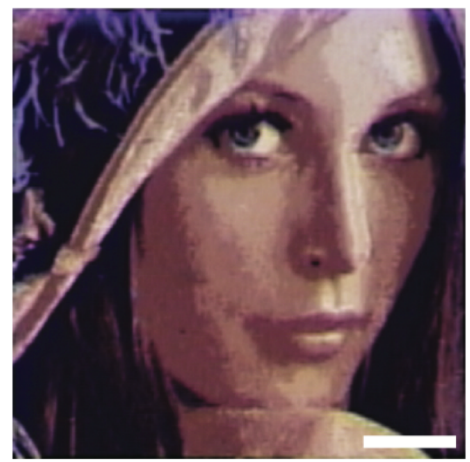
Plasmonics and plasmonic coloration

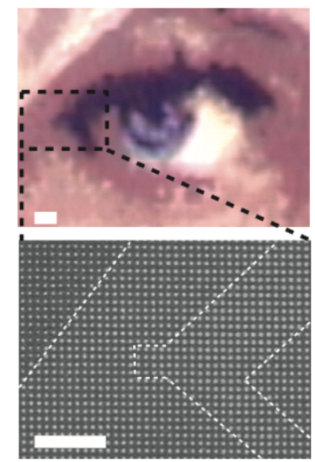
Interactions between light and metal nanostructures



High resolution



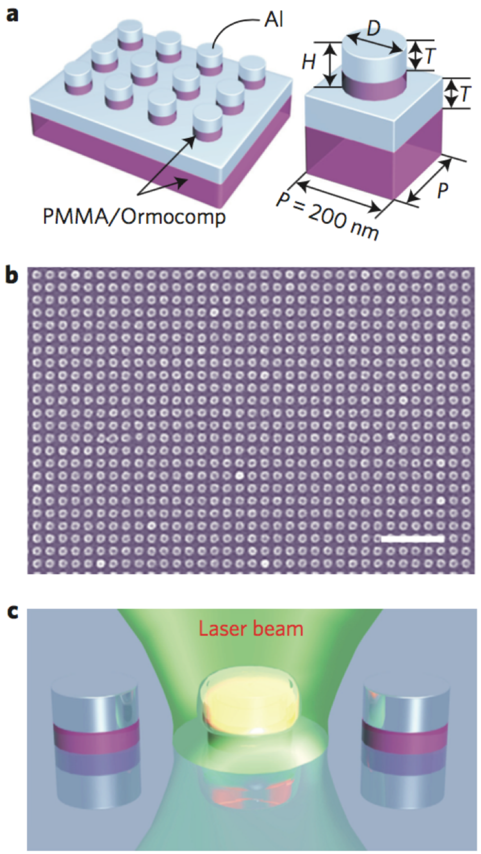


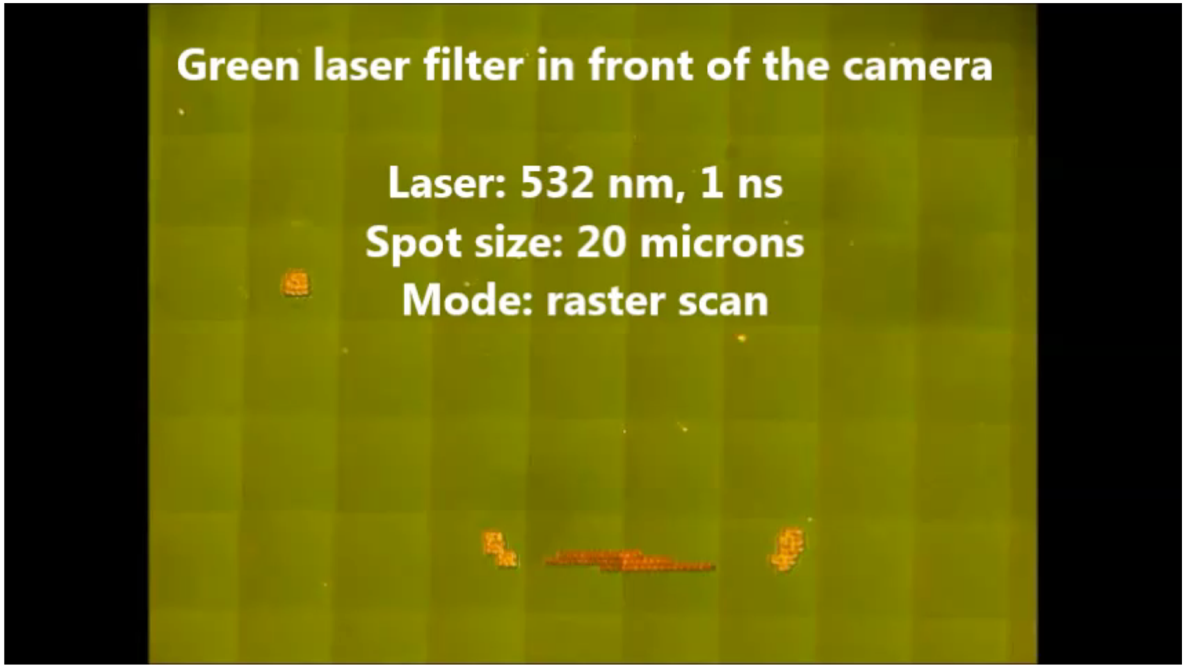


X..M. Goh et al., Nature Comm. (2014)

K. Kumar et al., Nature Nanotech. (2012)

Plasmonic color laser printing





X. L. Zhu et al., Nature Nanotech. (2016)

Plasmonics Color

Photonic structure colors

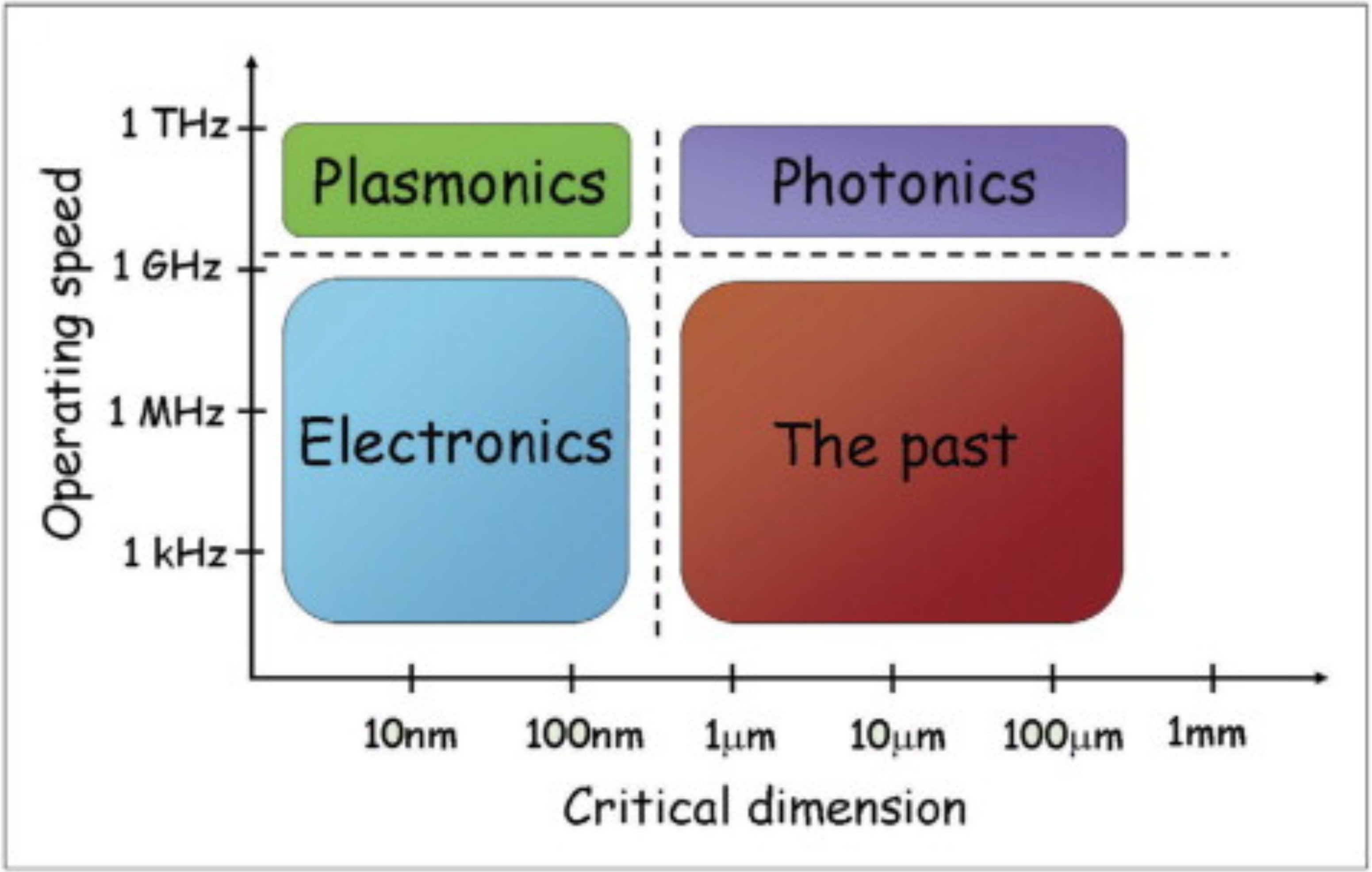
Properties: Iridescence, Metallic color, fadeless, tunable color…..

Artificial plasmonic colors

Properties: High resolution, active printing, tunable colors…..

- Nature takes the strategy of maximal achievement at minimal cost.
- Photonic structures in the biological world should be always optimal in the sense of functionality such as biological, physical, or even physiological functions.
- Natural photonic structures may have been a great source of inspiration in our design and fabrication of new optical materials and devices for future technological applications.

Plasmonics Vs Photonics



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https://doi.org/10.1016/S1369-7021(06)71572-3