Basics of Plasmonics

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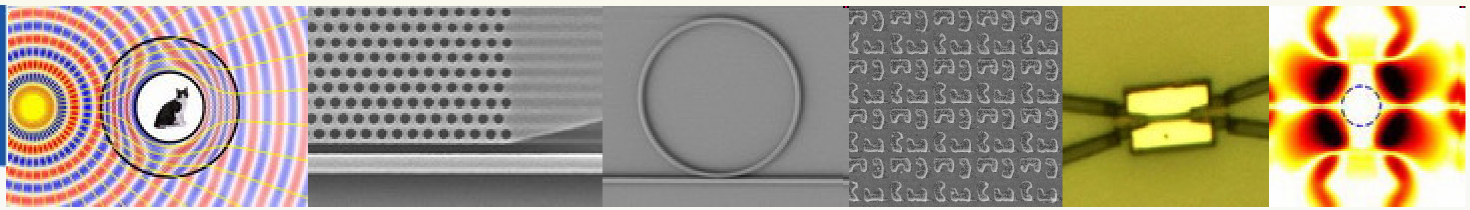
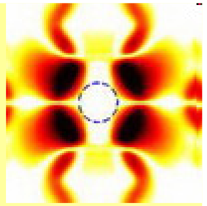


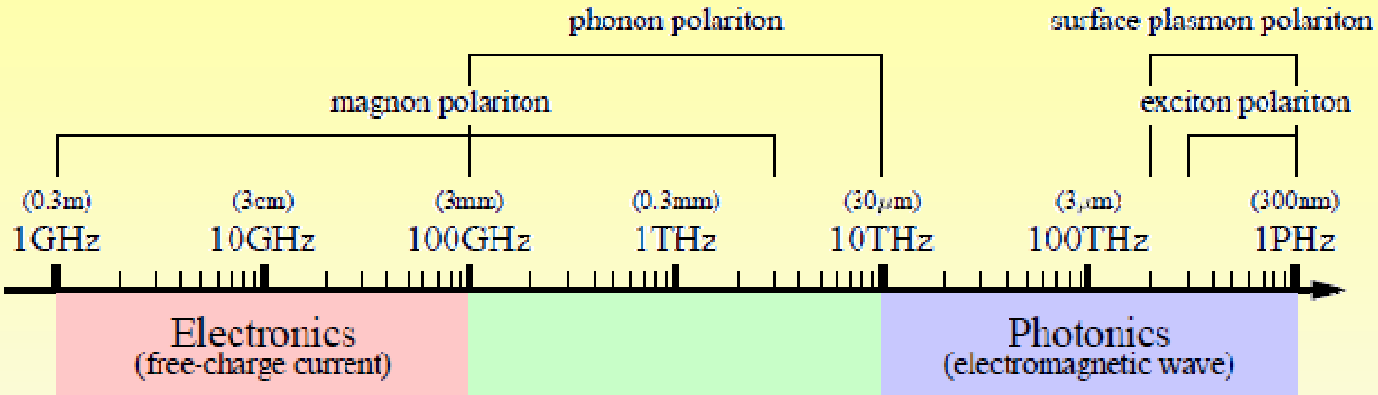
What is plasmonics?



The science of **plasmonics** is dealing with generation, manipulation, and detection of surface plasmon polaritons (SPPs).

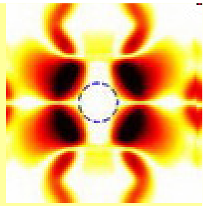
- SPP: Quasi-particle due to coupling of light and surface plasmon (SP).
- SP: electron oscillation wave at metal surfaces.

Broad picture of "polaritonics"



The frequency spectra of polaritonics (shown in the diagram as magnon polariton, phonon polariton, exciton polariton, and surface plasmon polariton) can cover both those of conventional electronics and photonics, as well as the frequency gap between the two.

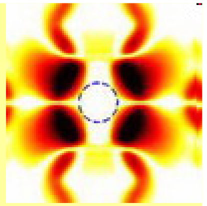
Noble metals: plasmonic materials at optical regime



Gold

Silver

Lycurgus cup
British Museum, AD fourth century



The cup illustrates the myth of King Lycurgus. He is seen being dragged into the underworld by the Greek nymph Ambrosia, who is disguised as a vine.

Viewed in reflected light (daylight)

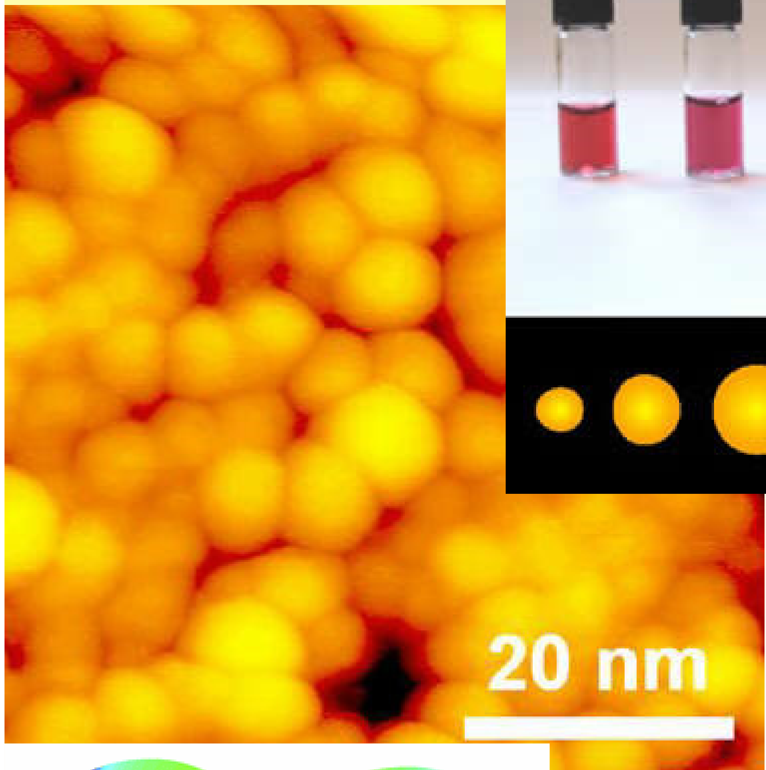
when a light is shone into the cup

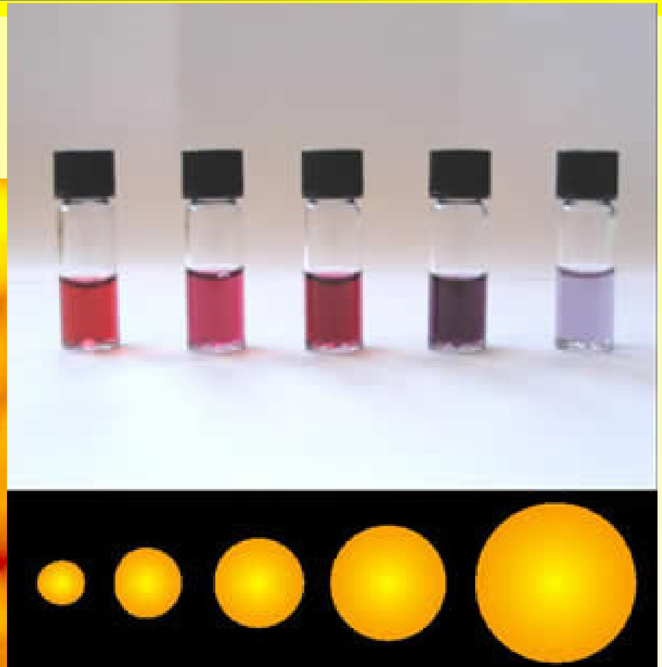
Gold nanoparticles in glass,~70 nm in diameter.
Color response different to that of gold in bulk

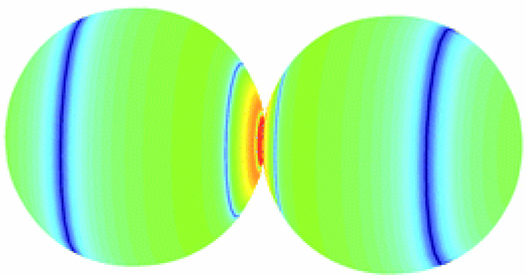
- **Particles resonantly reflect green light**
- **Strong absorbance around 500nm and below**

Plasmonic resonance!

Gold nano-particle plasmonic resonance





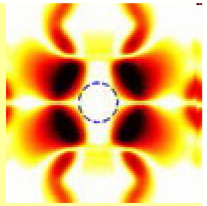


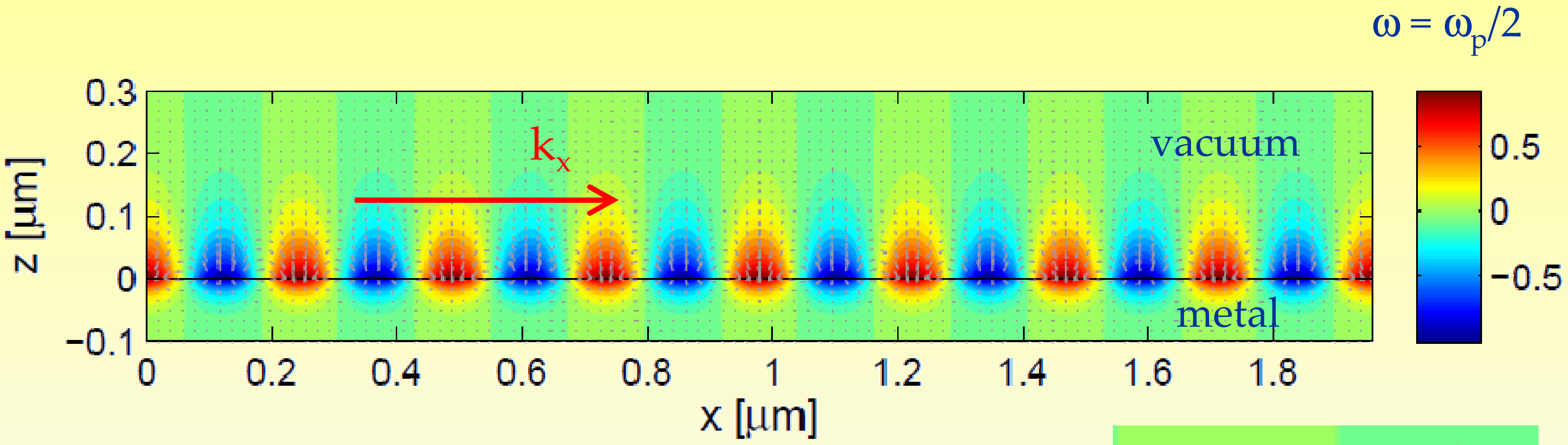
Stained glass window on a Gothic church. Colors are induced by gold particles of different sizes.

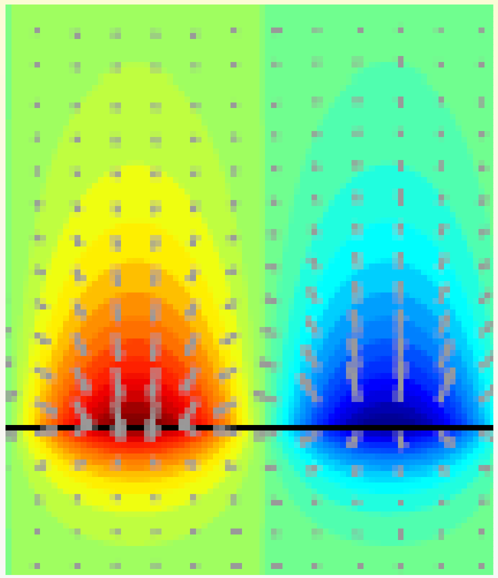
Surface waves give:

Plasmonic resonance

Field pattern of a SPP

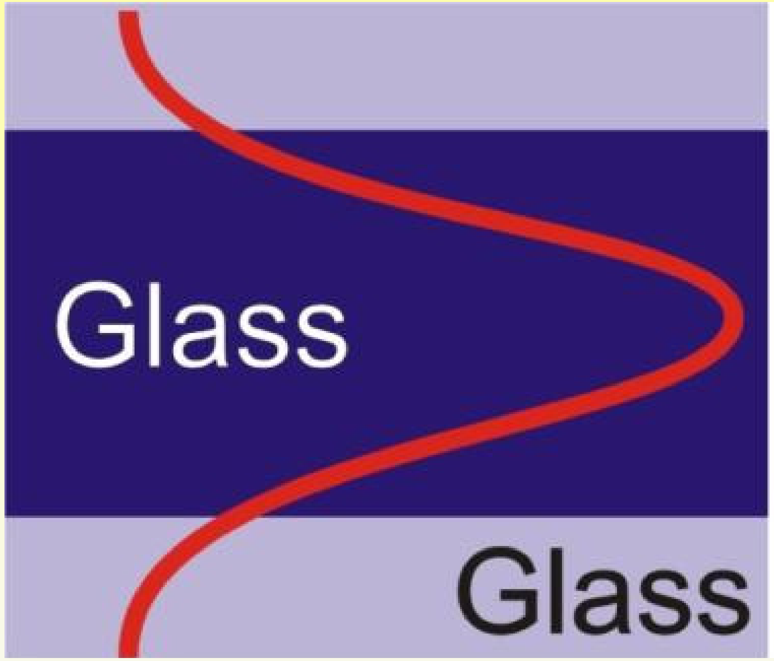


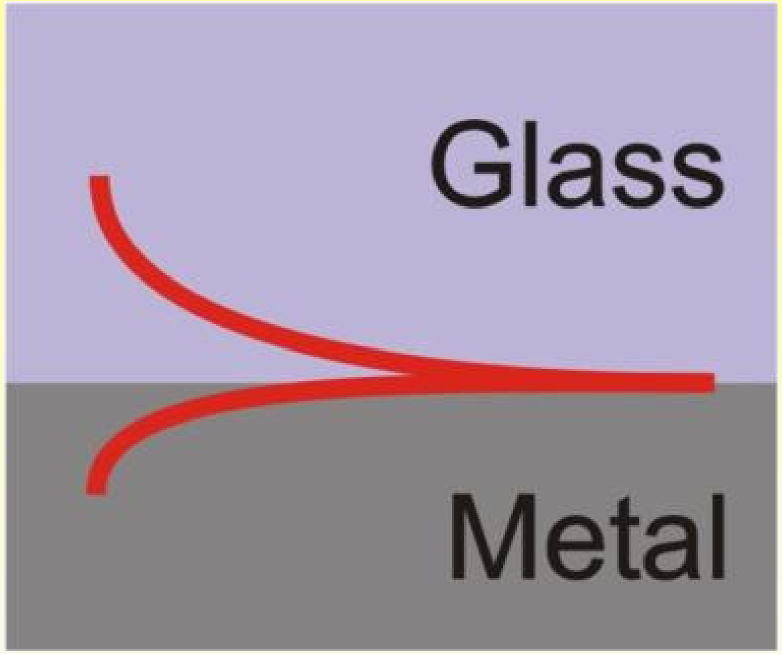




2D field distribution in xz plane. The colormap denotes H_y field, while the arrows indicate the **E** field (consisting both E_x and E_z).

Waveguiding with one interface





Metal has a negative ε.

Why does a surface wave exist?

By using the Drude model for metals, we can obtain the permittivities of metals as a function of frequency in the following form

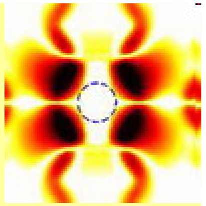
$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2\left(\frac{i}{\omega\tau} + 1\right)}.$$

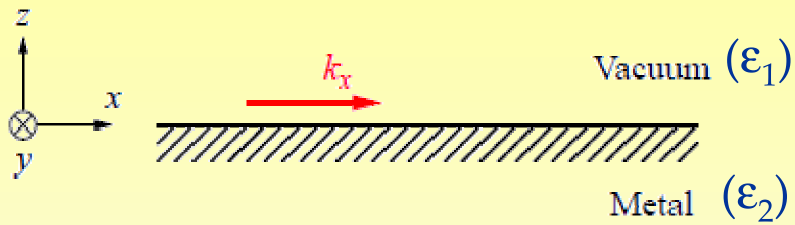
where ω_p is the plasmon frequency of the corresponding bulk metal, and τ is the electron relaxation time in that metal. When one neglect the collision (lossless), one has

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

Therefore, the permittivity is negative when the frequency is lower than ω_p. When such a metal meets another material with a positive permittivity, a wave can be bounded by their interface according to the Maxwell equations.

Maxwell equations and SPP solution



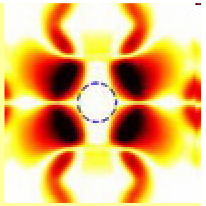


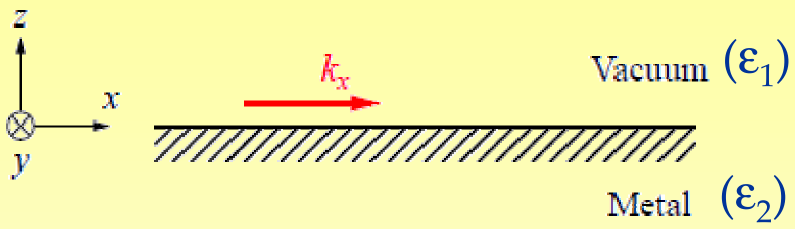
Maxwell equations: $$\nabla \times \mathbf{E} = i\omega \mathbf{B}, \quad \nabla \times \mathbf{H} = -i\omega \mathbf{D}, \quad \nabla \cdot \mathbf{E} = 0, \quad \nabla \cdot \mathbf{H} = 0.$$

TM equations:
$$\begin{aligned} \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= i\omega\mu_0 H_y, \\ -\frac{\partial H_y}{\partial z} &= -i\omega\epsilon_0\epsilon E_x, \\ \frac{\partial H_y}{\partial x} &= -i\omega\epsilon_0\epsilon E_z. \end{aligned}$$

TM wave equation: $$\frac{\partial^2 H_y}{\partial z^2} + (k_0^2\epsilon - k_x^2)H_y = 0$$

Maxwell equations and SPP solution





z > 0

$$\begin{cases} H_y = A\exp(-K_1 z)\exp(ik_x x), \\ E_x = -\dfrac{AK_1}{i\omega\epsilon_0\epsilon_1}\exp(-K_1 z)\exp(ik_x x), \\ E_z = -\dfrac{Ak_x}{\omega\epsilon_0\epsilon_1}\exp(-K_1 z)\exp(ik_x x). \end{cases}$$

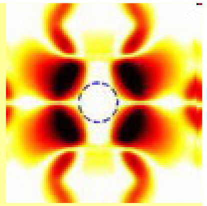
where $K_1 = \sqrt{k_x^2 - k_0^2\epsilon_1}$.

z < 0

$$\begin{cases} H_y = B\exp(K_2 z)\exp(ik_x x), \\ E_x = \dfrac{BK_2}{i\omega\epsilon_0\epsilon_2}\exp(K_2 z)\exp(ik_x x), \\ E_z = -\dfrac{Bk_x}{\omega\epsilon_0\epsilon_2}\exp(K_2 z)\exp(ik_x x), \end{cases}$$

where $K_2 = \sqrt{k_x^2 - k_0^2\epsilon_2}$.

Maxwell equations and SPP solution



Boundary conditions:

$$D_\perp^1 = D_\perp^2,$$
$$E_\parallel^1 = E_\parallel^2,$$

We have

$$\begin{cases} A = B. \\ \dfrac{AK_1}{\epsilon_1} + \dfrac{BK_2}{\epsilon_2} = 0. \end{cases}$$

Consider the expressions for K_1 and K_2, we have the dispersion relation

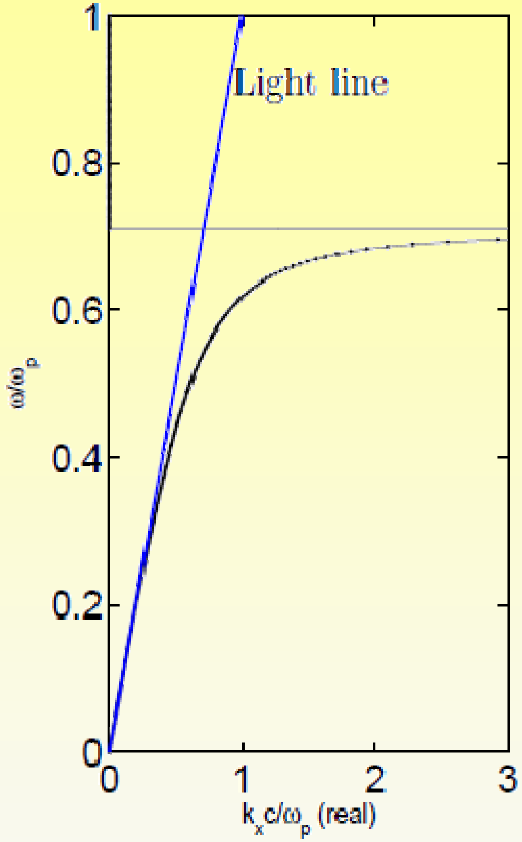
$$k_x^2 = \frac{\omega^2}{c^2}\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}.$$

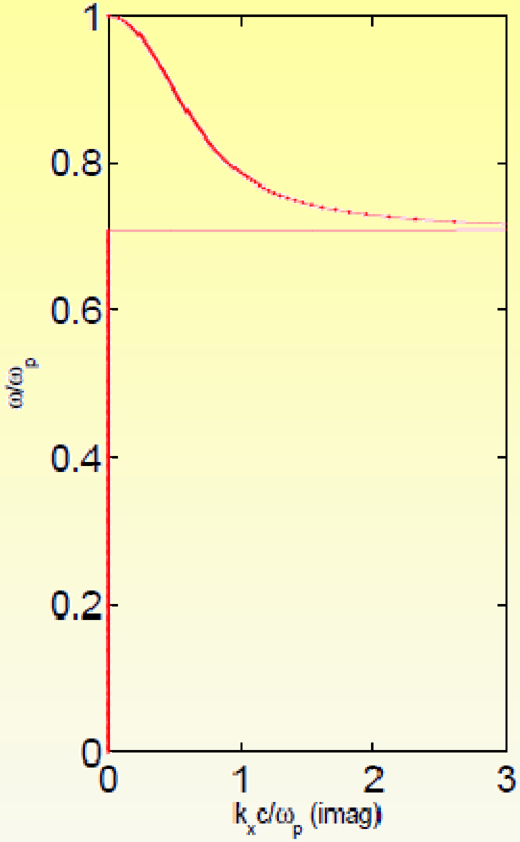
Further consider $\epsilon_2 = 1 - \omega_p^2/\omega^2$ we then have

$$\frac{k_x^2 c^2}{\omega_p^2} = \frac{\frac{\omega^2}{\omega_p^2}\left(\frac{\omega^2}{\omega_p^2} - 1\right)}{2\frac{\omega^2}{\omega_p^2} - 1}.$$

SPP dispersion

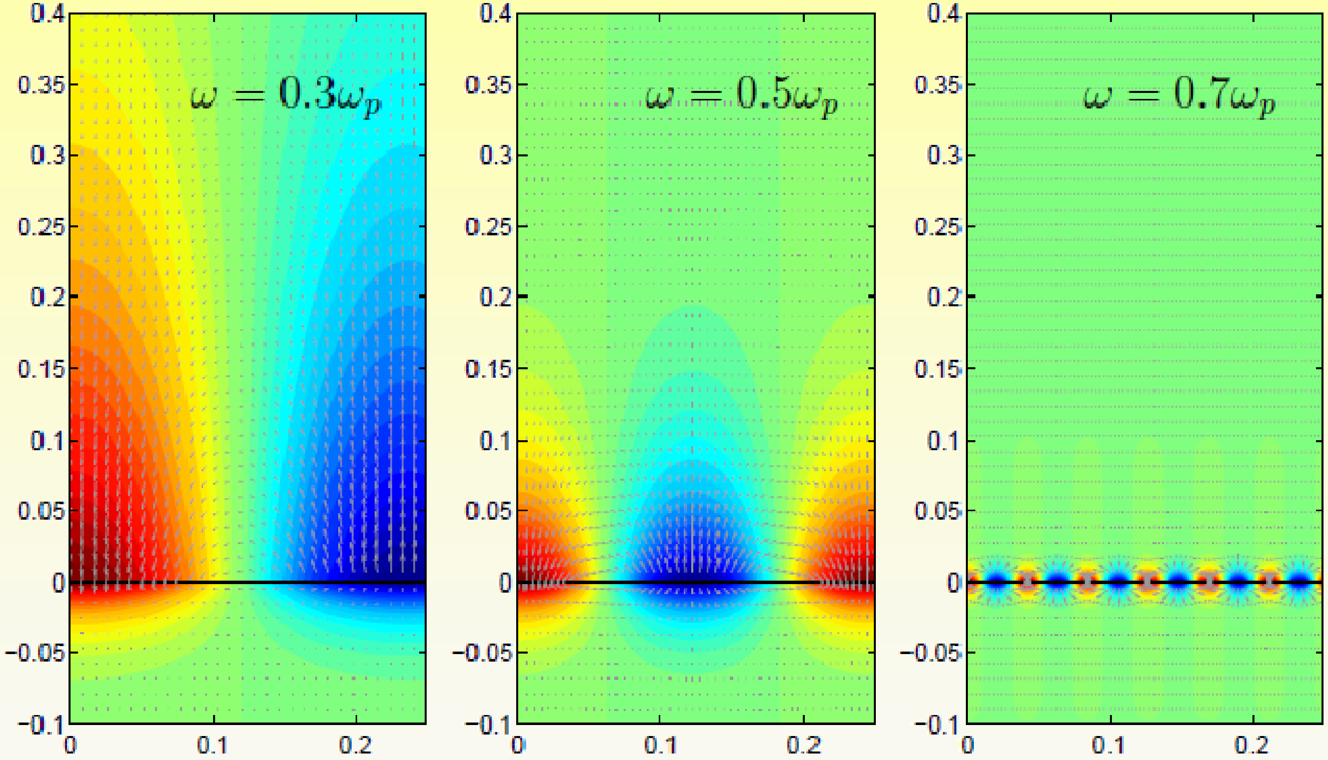
$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$





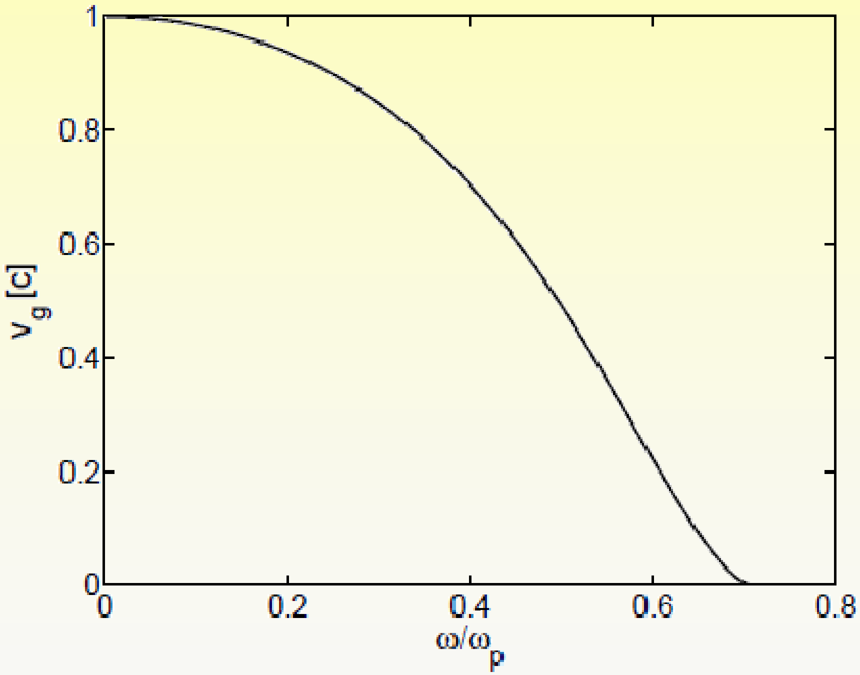
$$k_x = k'_x + ik''_x = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$$

Comparison of SPPs at different frequencies

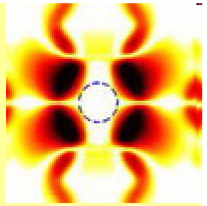


Group velocity dispersion

$$v_g = \frac{d\omega}{dk_x} = \frac{(2\frac{\omega^2}{\omega_p^2} - a)^{\frac{3}{2}}(\frac{\omega^2}{\omega_p^2} - 1)^{\frac{1}{2}}}{2s^4 - 2\frac{\omega^2}{\omega_p^2} + 1}c.$$



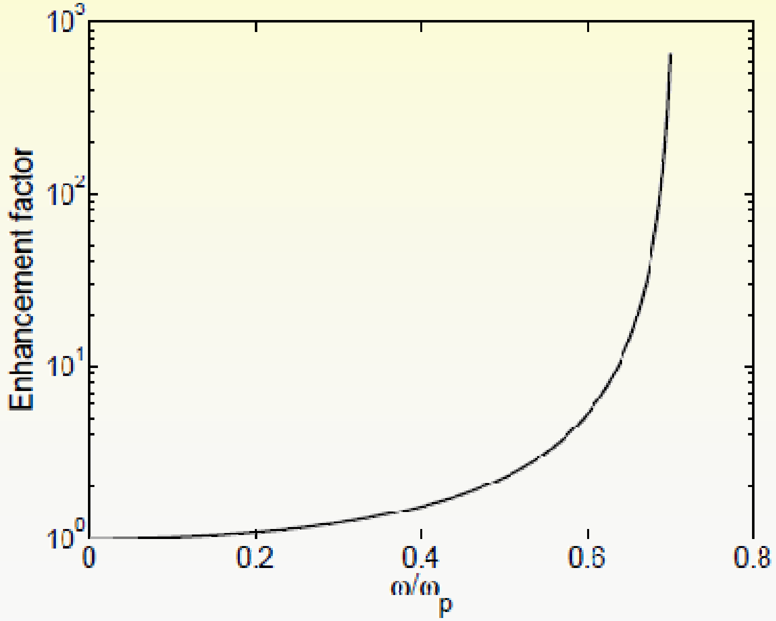
Field enhancement at the surface



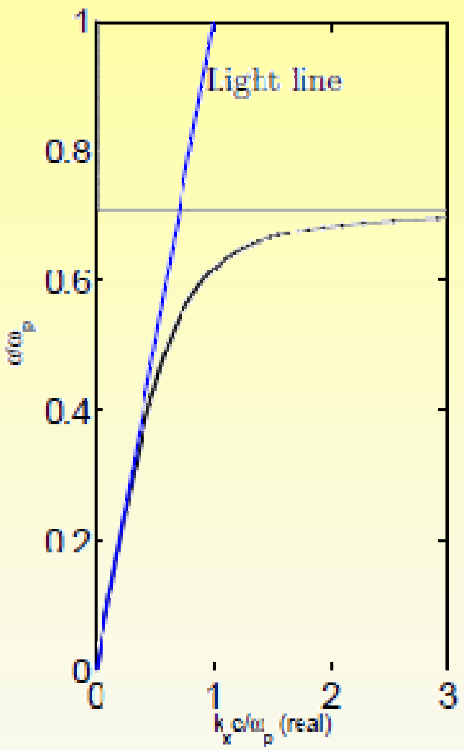
One can obtain the ratio between E and H field as $\dfrac{E_z}{H_y} = \dfrac{\frac{\omega^2}{\omega_p^2} - 1}{2\frac{\omega^2}{\omega_p^2} - 1} Z_0.$

We therefore define the field enhancement factor as $f = \left(\dfrac{\frac{\omega^2}{\omega_p^2} - 1}{2\frac{\omega^2}{\omega_p^2} - 1} \right)^2$

For a plane wave propagating in free space, f=1

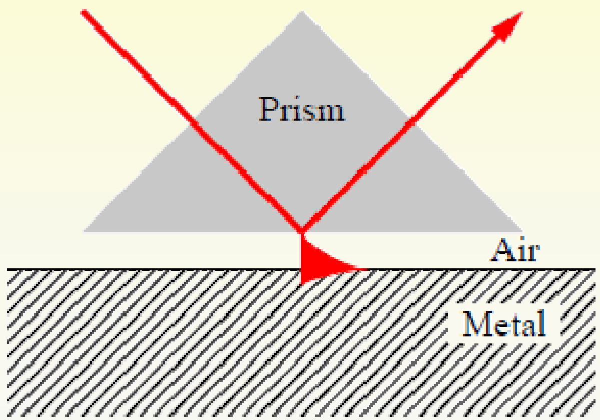


Excitation



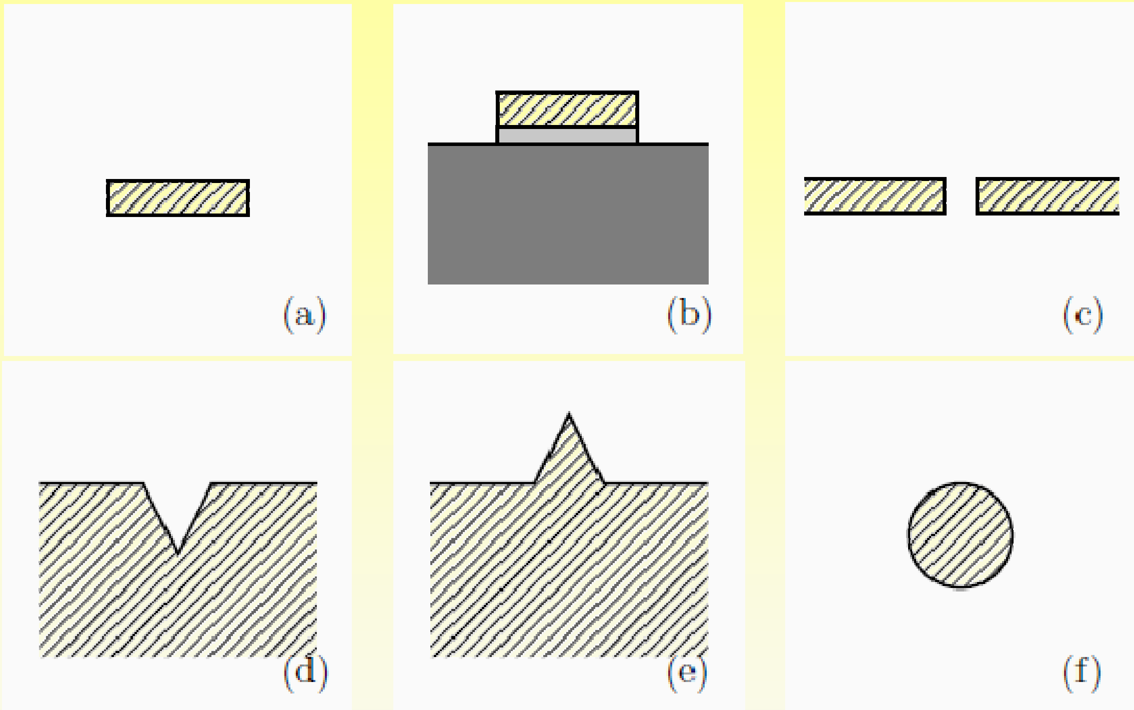
It is not possible to excite a SPP directly from free space using light due to momentum mismatch.

Excitation methods: (1) Otto setup; (2) Grating



Excitation of a SPP through the Otto setup.

SPP waveguides

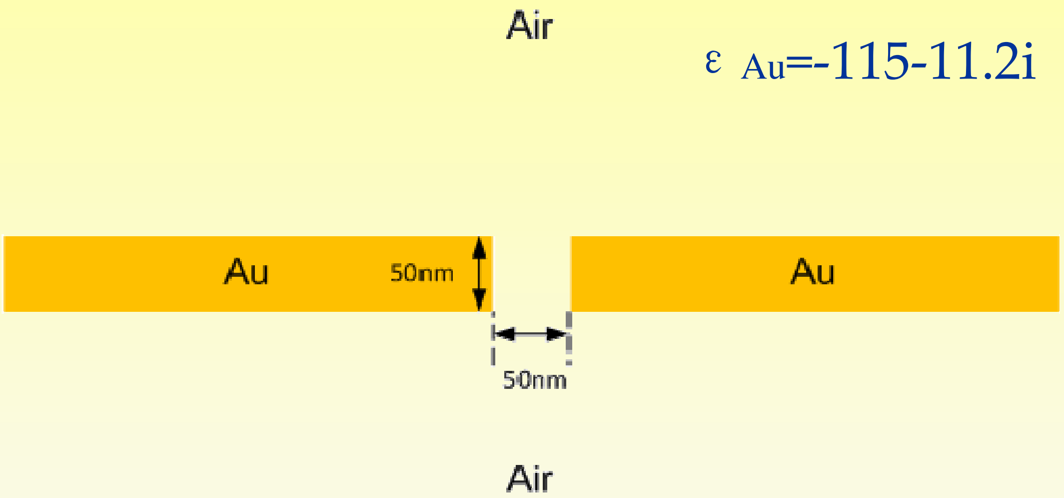


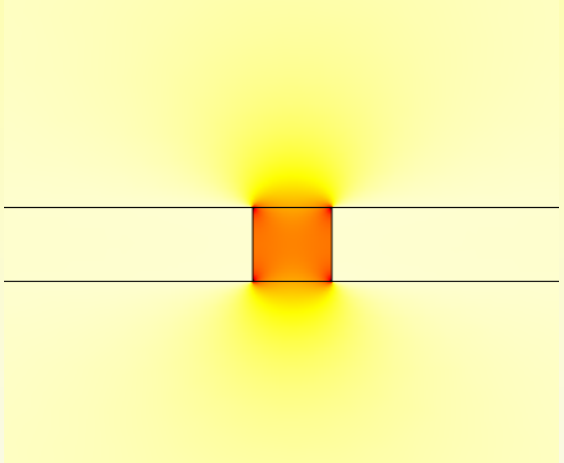
Various plasmonic waveguides with lateral confinement.
(a) Strip SPP waveguide; (b) Suspended strip waveguide; (c) Slot waveguide; (d) V-channel waveguide; (e) -wedge waveguide; (f) metallic fiber waveguide. Line-shaded regions are metal; grey-shaded regions are dielectric materials.

Plasmonic gap waveguides

$\lambda = 1.55\ \mu m$

$\varepsilon_{Au} = -115 - 11.2i$

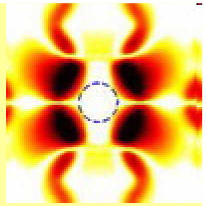


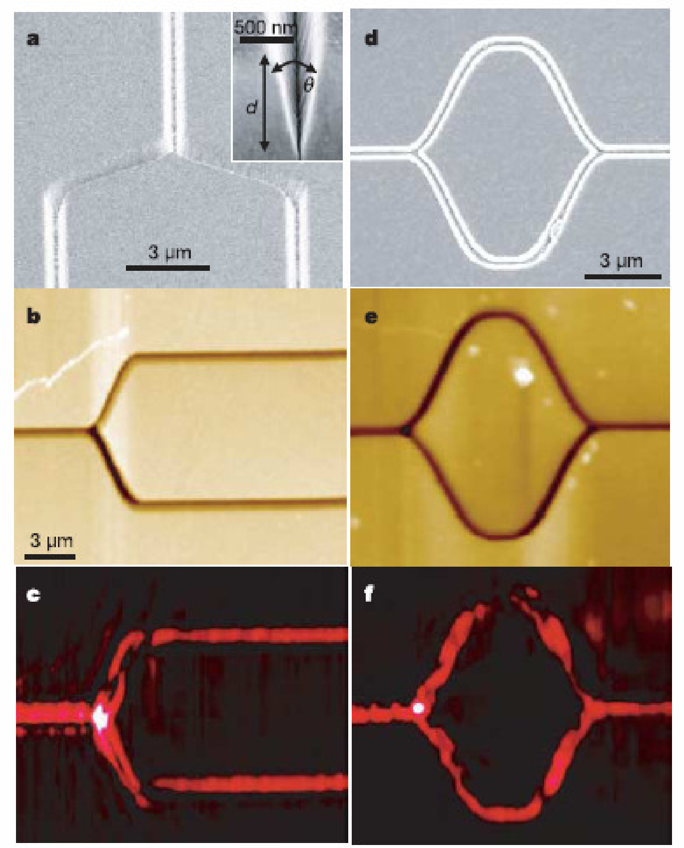


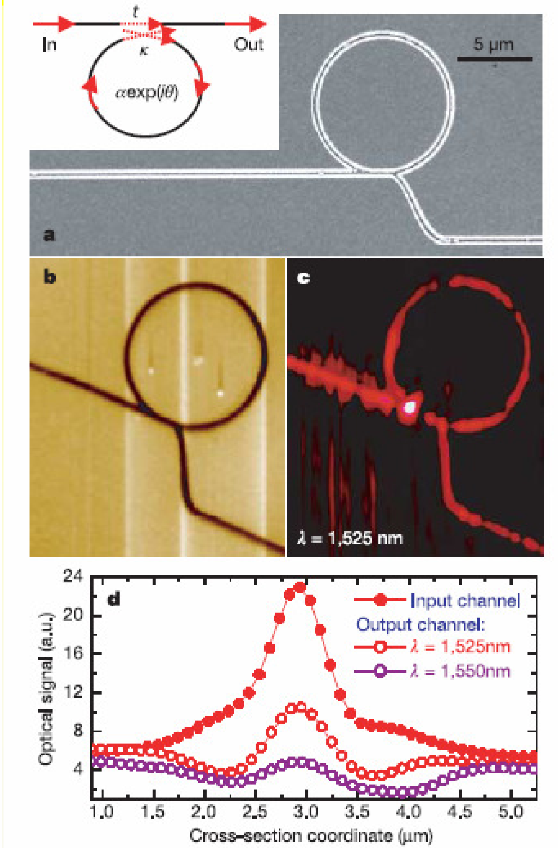
Subwavelength confinement!

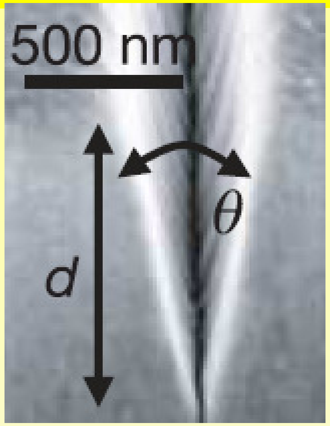
Loss is a big issue!

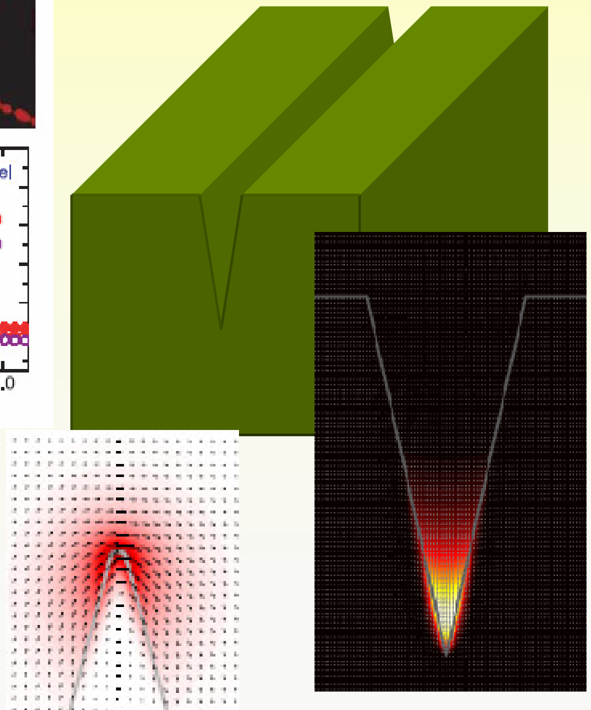
Channel plasmon subwavelength waveguide components









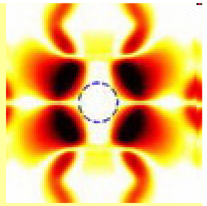


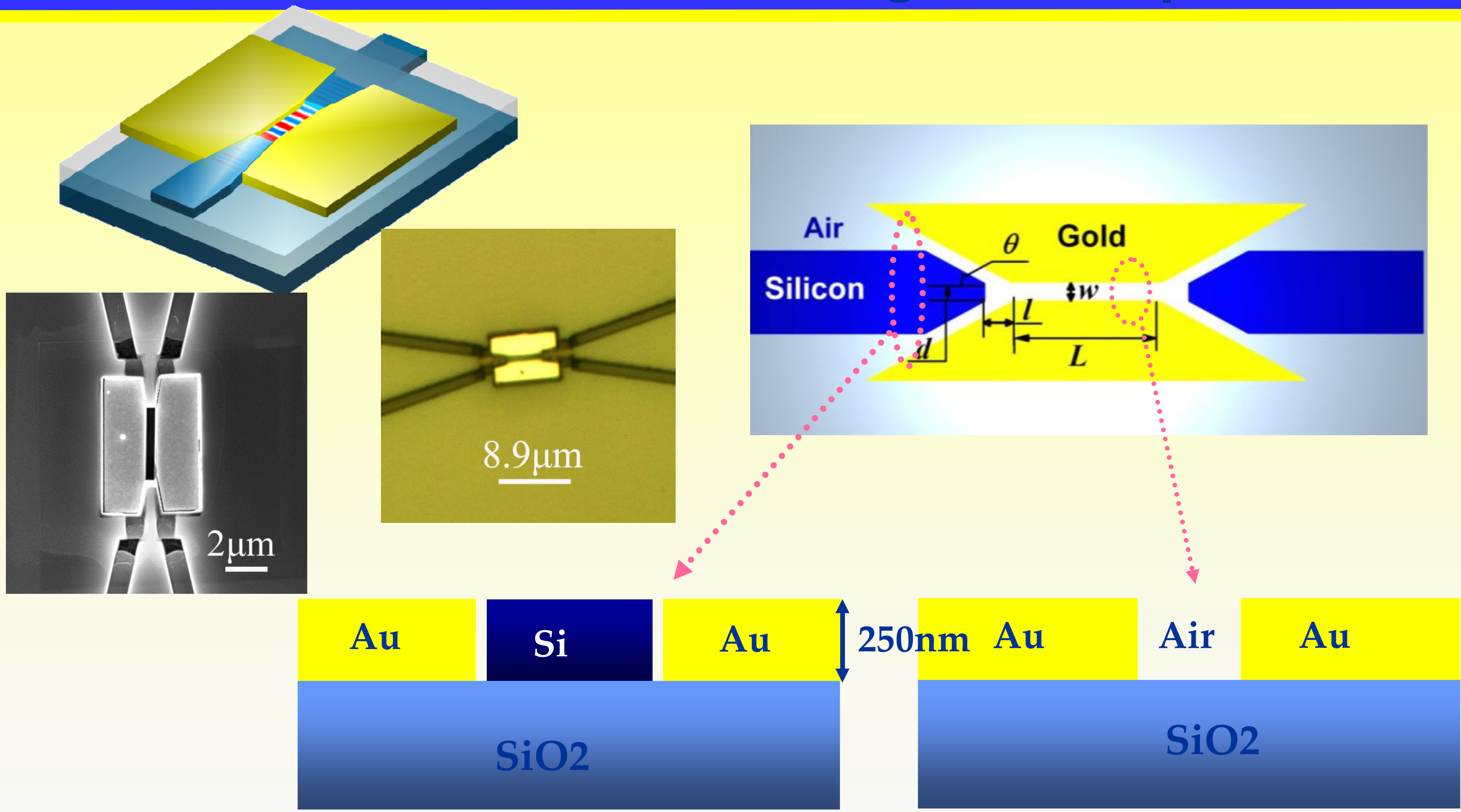
V-channel Plasmon polariton guide

Propagation length is only a few tens of micrometers

Bozhevolnyi, S.I., et.al., Nature, 440,508,2006
M. Yan and M. Qiu, J. Opt. Soc. Am. B 24, p. 2333 (2007)

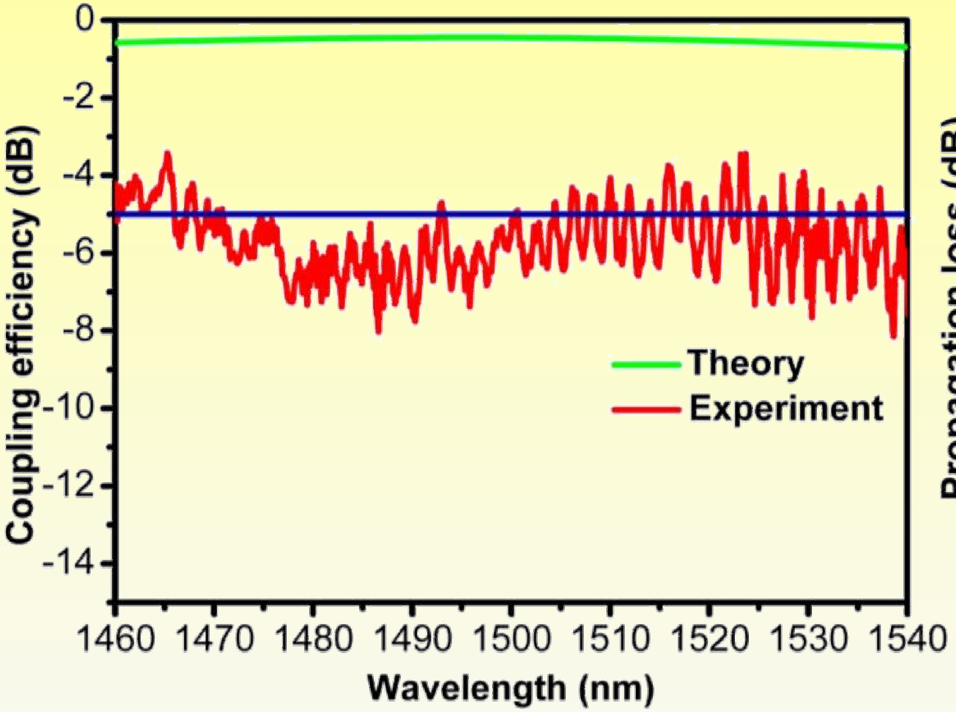
Broadband high-efficiency Plasmonic–Silicon waveguide coupler

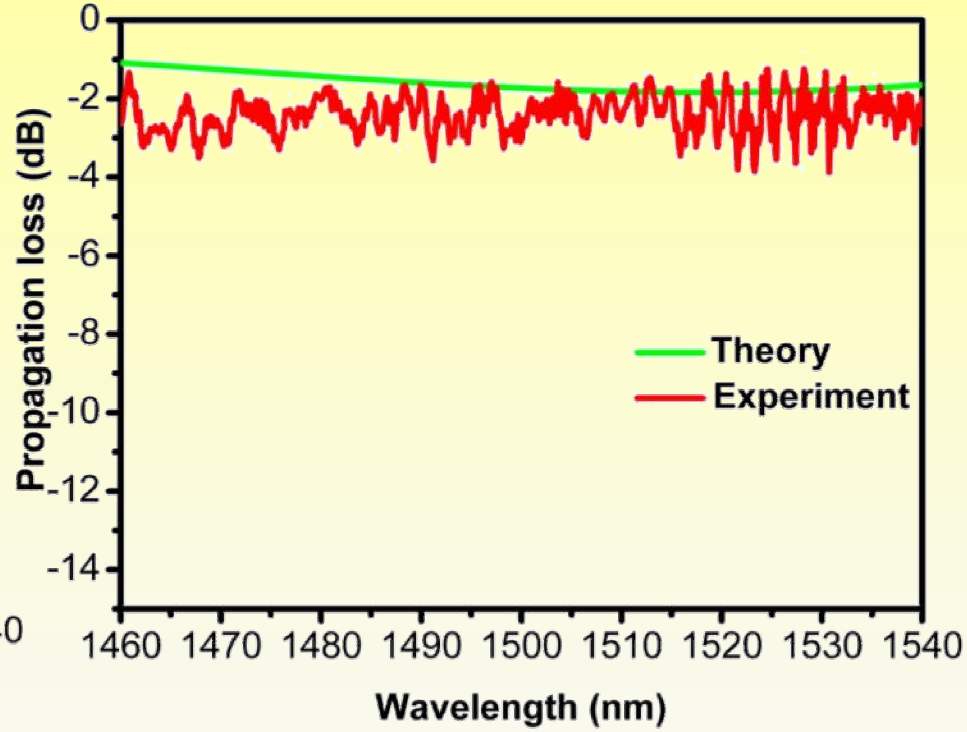




J. Tian et al, "Broadband high-efficiency surface-plasmon-polariton coupler with silicon-metal interface", **Appl. Phys. Lett. 95, 013504 (2009)**

Broadband coupler



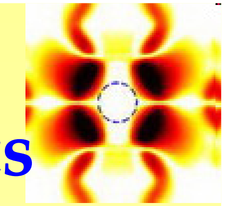


Average coupling efficiency is about 4.5 dB (35%).

The average loss is about –2.5 dB/μm (Simulation results –1.5 dB/μm)

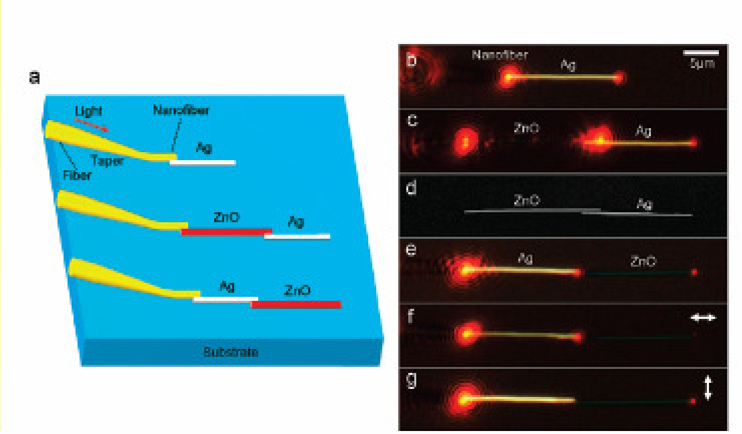
Appl. Phys. Lett. 95, 013504 (2009)

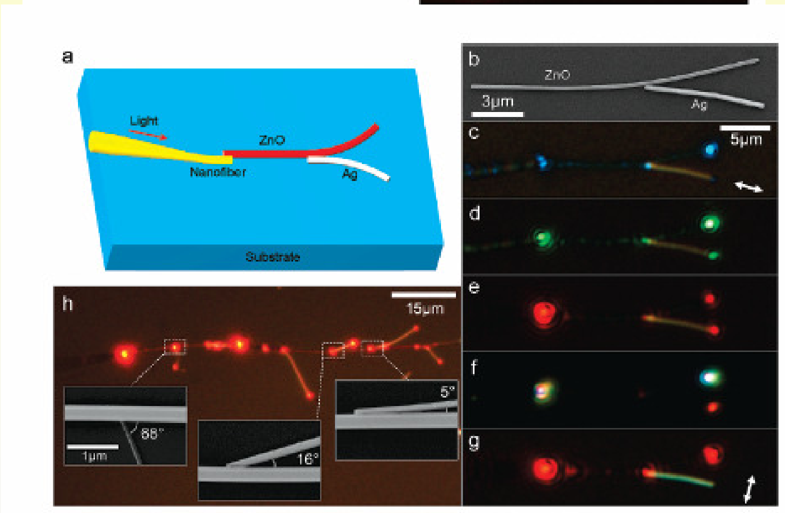
Coupling of Plasmonic and Photonic Nanowires for Hybrid Nanophotonic Circuits

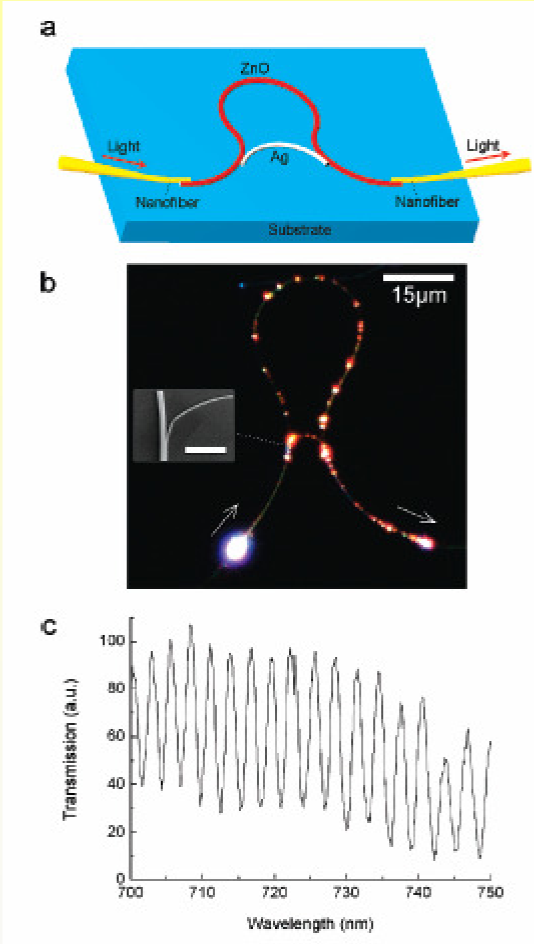


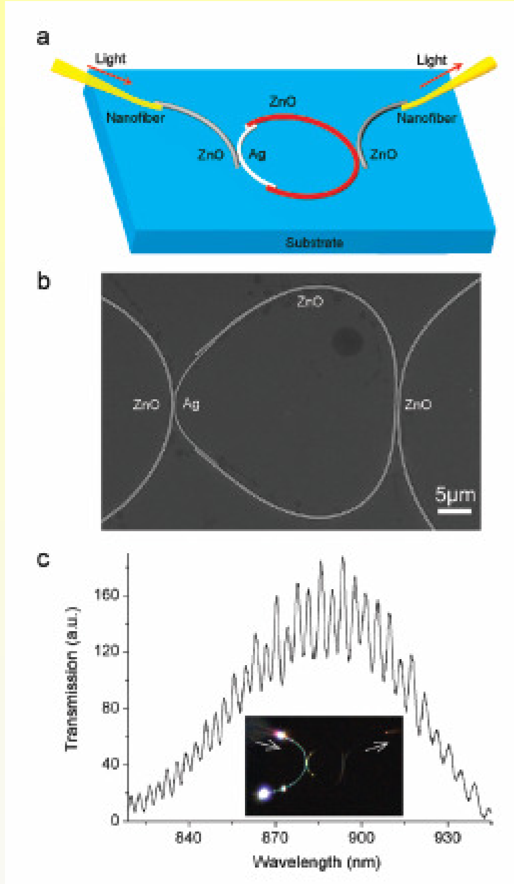
Prof. Limin Tong's group in Zhejiang U, China

Q factor 520!



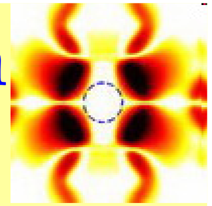




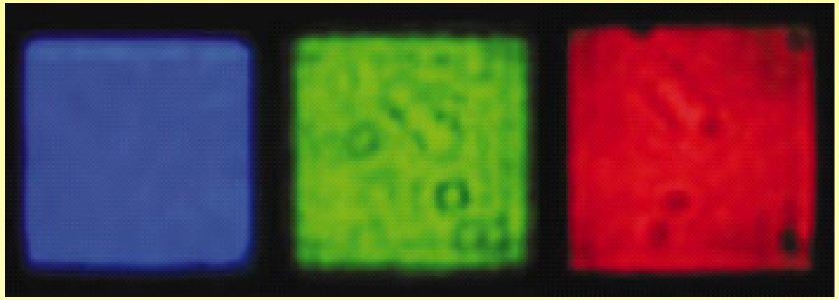


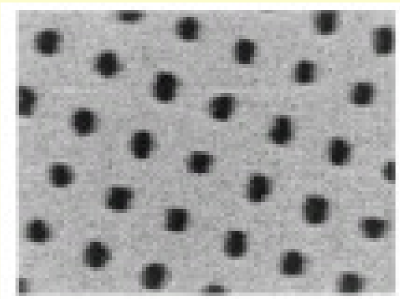
X. Guo, M. Qiu, et al, "Direct Coupling of Plasmonic and Photonic Nanowires for Hybrid Nanophotonic Components and Circuits", **Nano Lett. 9 (12), pp 4515–4519 (2009)**

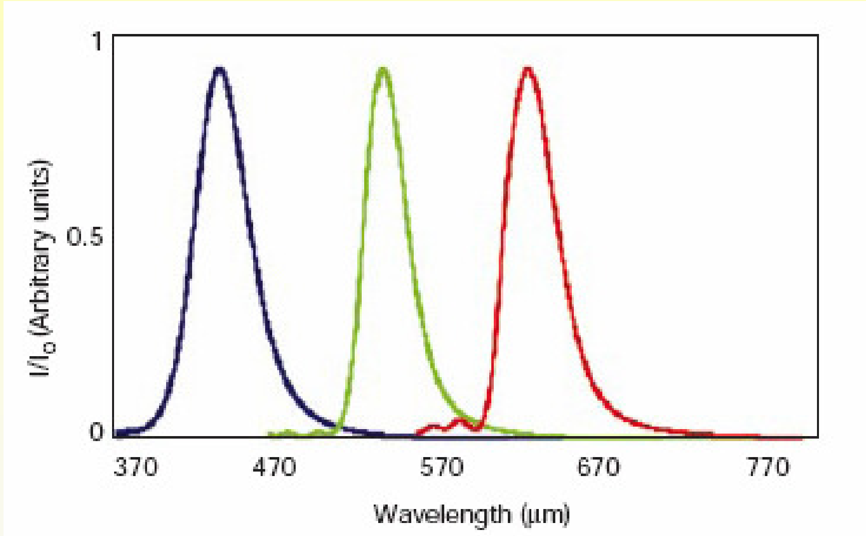
Extraordinary optical transmission through sub-wavelength hole arrays



For a hole in a metal film, it is well known that the transmission of the normal incidence is in the order of $(r/\lambda)^4$, where r is the hole radius. Therefore, the transmission is very weak through a subwavelength hole.







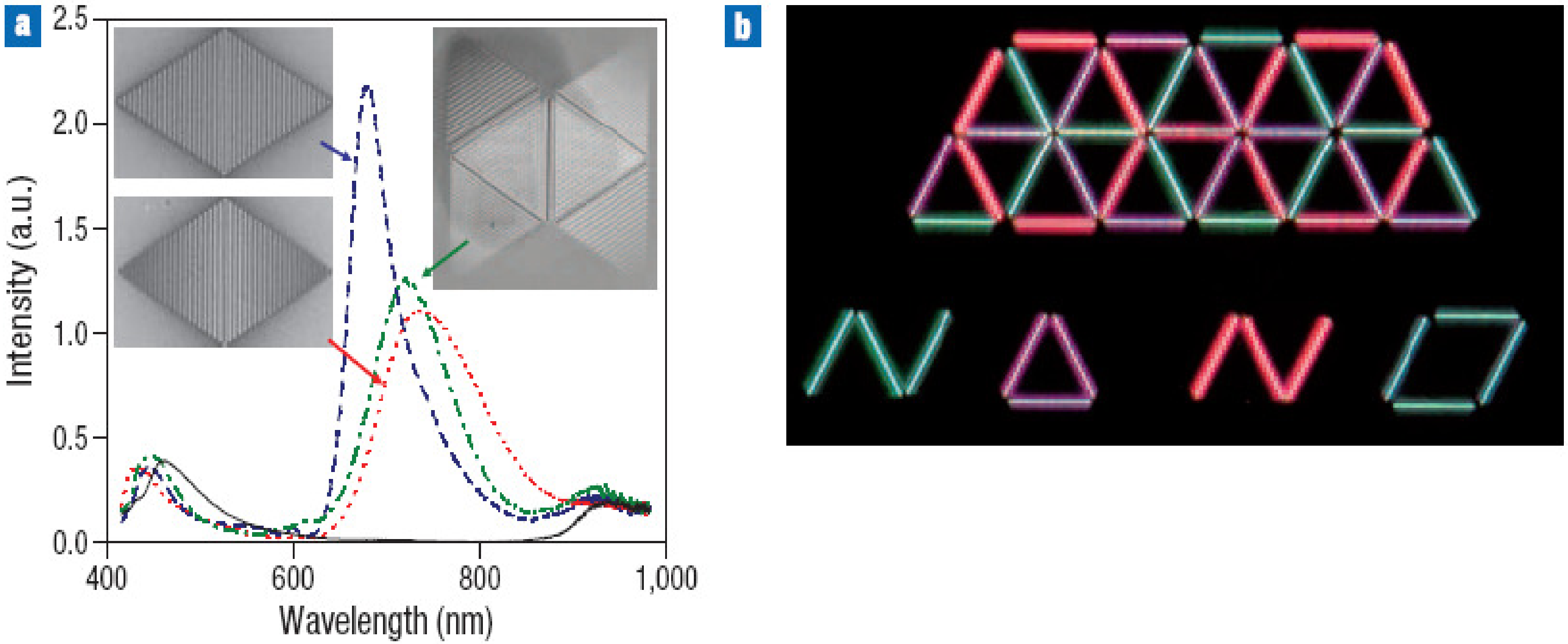
For a subwavelength hole array, extraordinary optical transmission is observed. This is usually attributed to the surface plasmon resonance.

Wavelength of the peak transmission is usually the same as the lattice constant (distance between holes).

Nature, 391, 667, 1998
Thomas Ebbesen

Potential applications for LED, PV, Detector, etc

Colored nano-slits



(a) single slit (length 15 μm, width 170 nm) surrounded by periodic grooves (period 600 nm). Blue:constant groove depth of 100 nm; Red:from 150 nm to 5 nm; Green:light polarized perpendicular to the slits; Black: parallel to the slits
(b) 450 nm (purple), 500 nm (green) and 580 nm (red)

Ebbesen group Nature Photonics , March 2008

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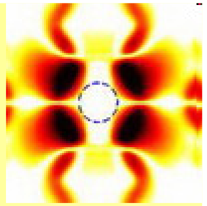
PLasmon EnhAnced PhotonicS



FP6 project

•Exploratory plasmon research aimed at concepts and phenomena that can be exploited in the targeted applications.

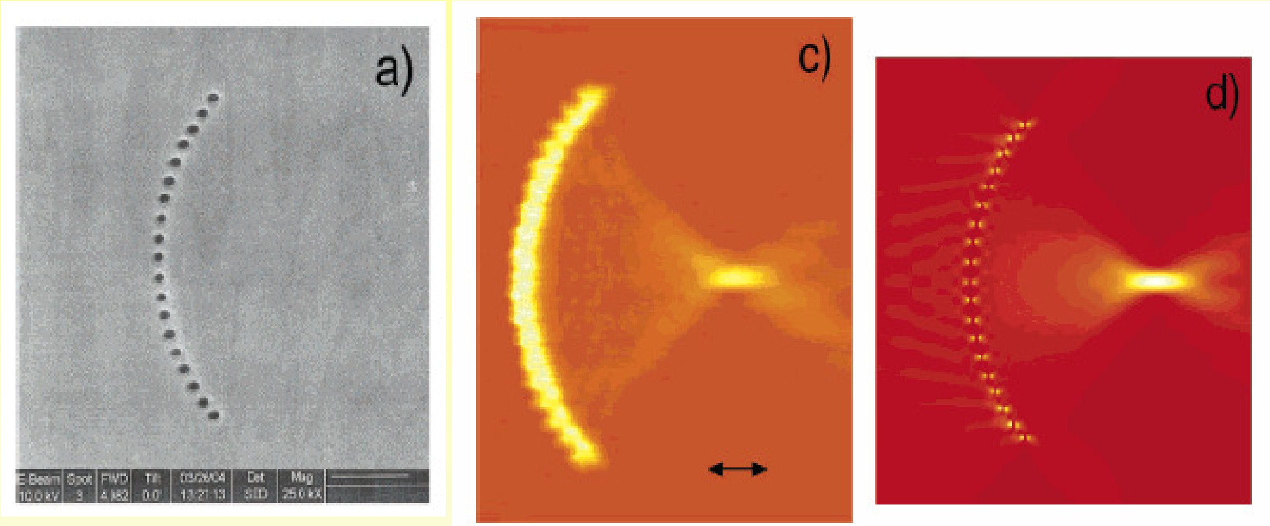
•Investigation of specific plasmon enhancing structures for emitters and detectors, along with an investigation of the technologies to implement them.

•Achieve a proof of concept of plasmon enhanced photonics devices in 2 applications:

(a) Inorganic LEDs: enhancing electrical to optical energy conversion.

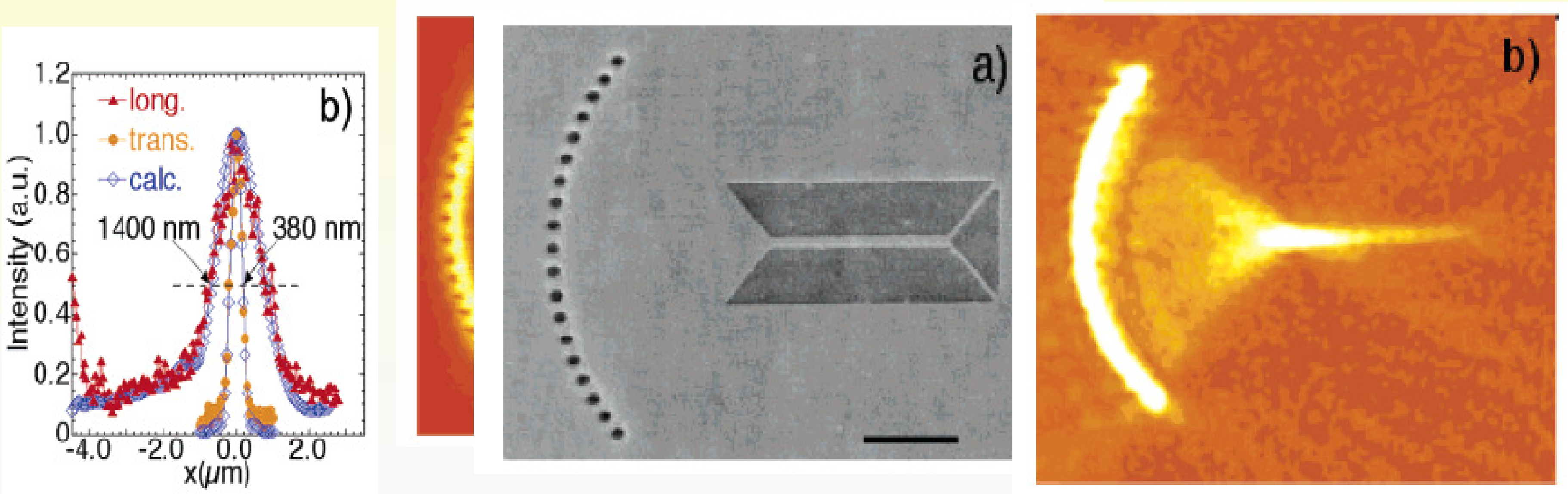
(b) Silicon photodetectors: Improving signal-to-noise ratio and increasing speed.

Light focusing

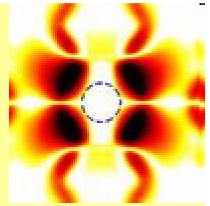


(a)19 200-nm holes arranged on a quarter circle with a 5- μ m radius.

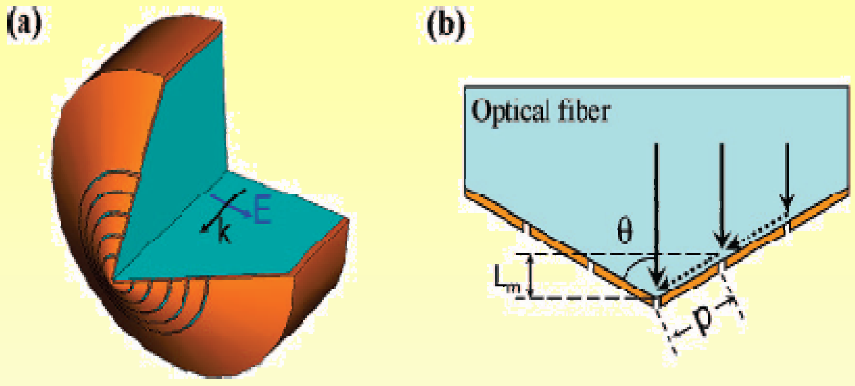
(c) horizontal polarization.



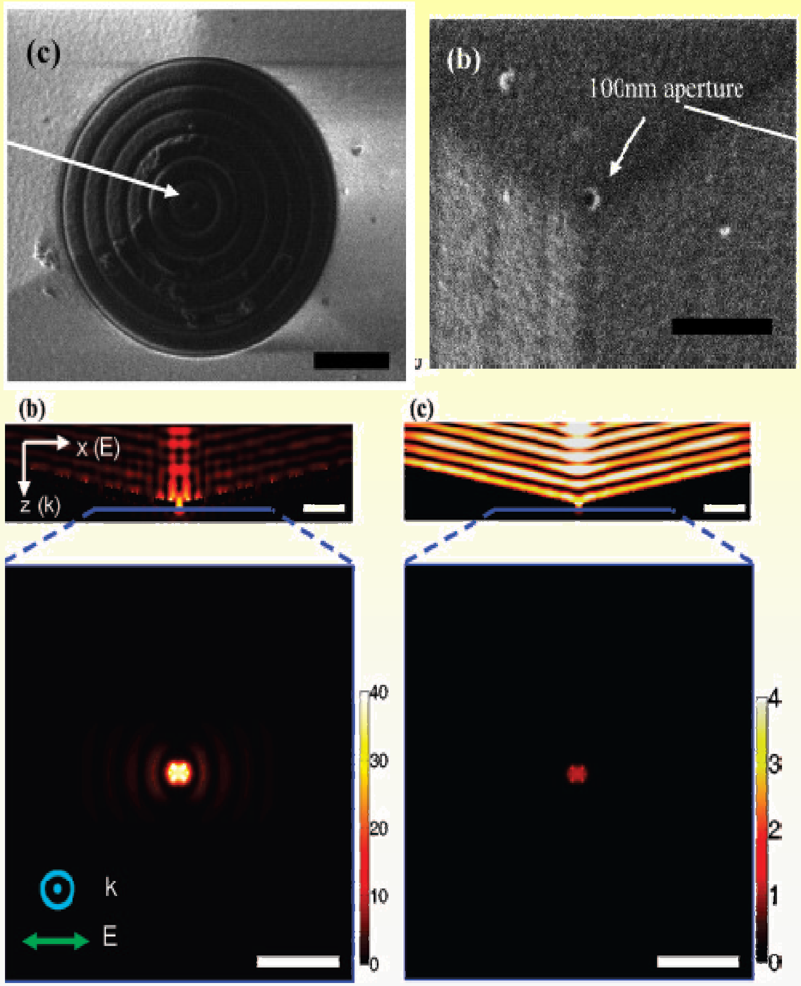
Yin et al, Nano Lett., Vol. 5, No. 7, **2005**



Plasmonic Nearfield Scanning Probe with High Transmission



plasmonic lens   single aperture

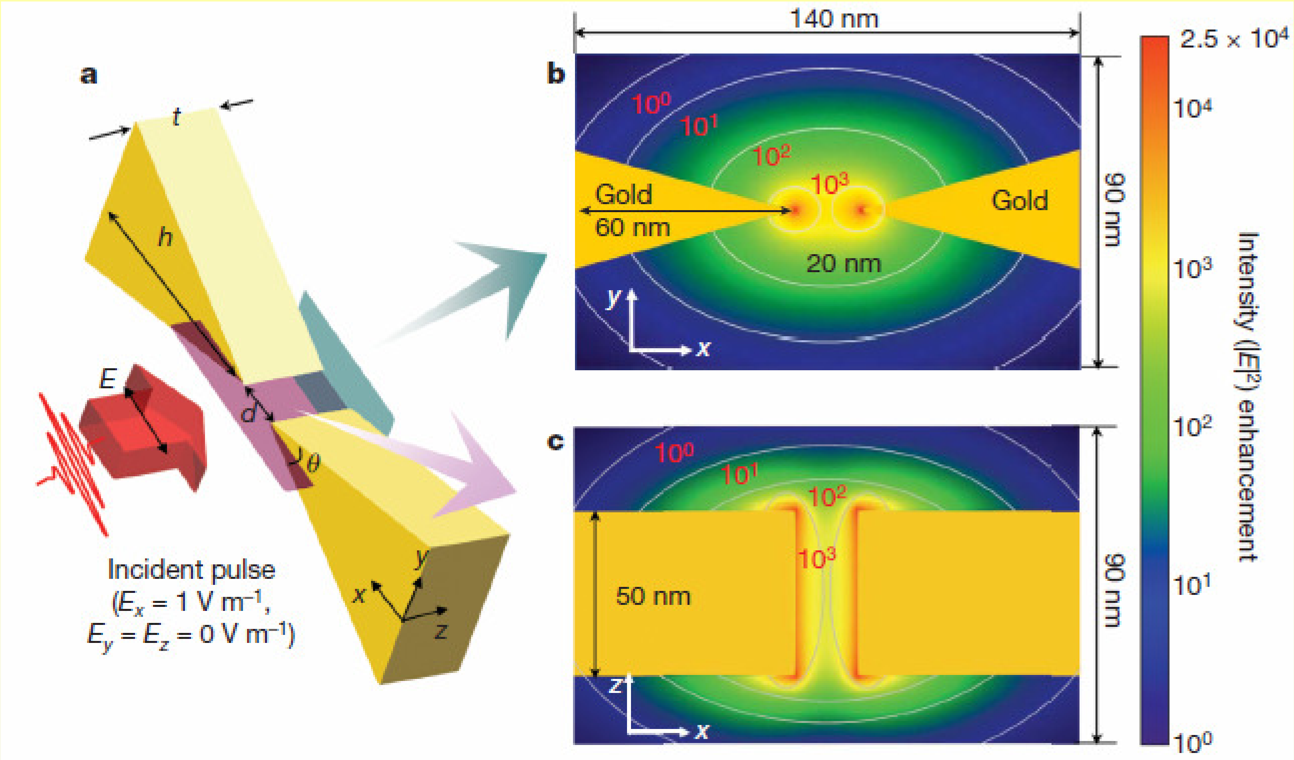


Al layer thickness 100nm
aperture diameter 100nm
ring periodicity   300nm
ring width   50nm
Cone angle   75°

wavelength is 365 nm.

NANO LETTERS 2008 Vol. 8, No. 9 3041-3045

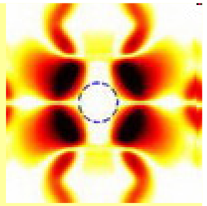
Plasmonics-based high nonlinear effect



High-harmonic generation by focusing a femtosecond laser onto a gas, assisted by plasmonic modes.

Seungchul Kim et al., Nature 453 p.757

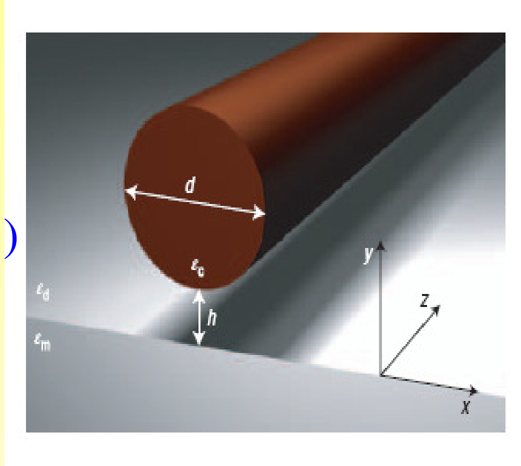
Hybrid plasmonic waveguides

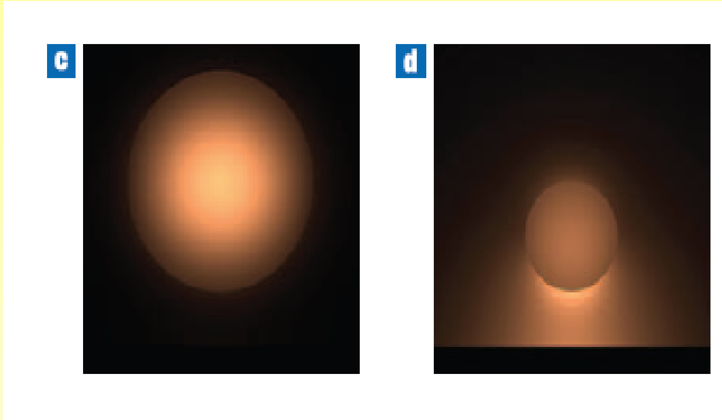


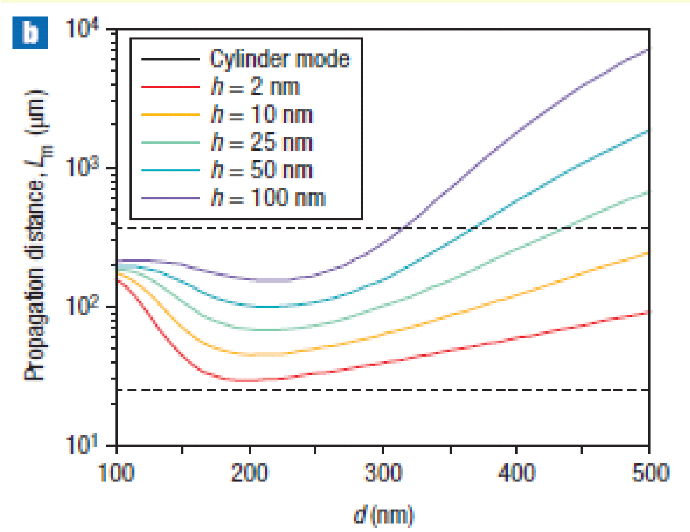
$\varepsilon_c = 12.25(GaAs)$

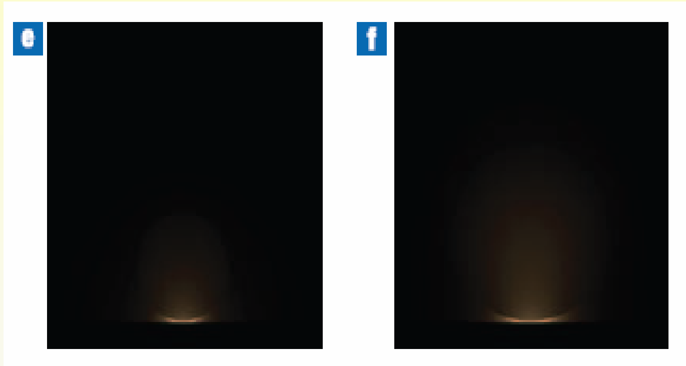
$\varepsilon_d = 2.25(SiO_2)$

$\varepsilon_m = -129 + 3.3i(Ag)$







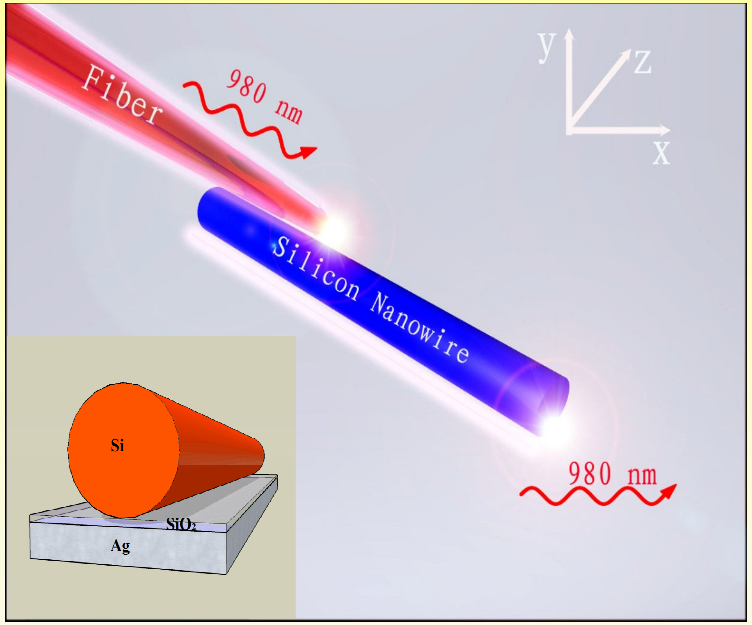


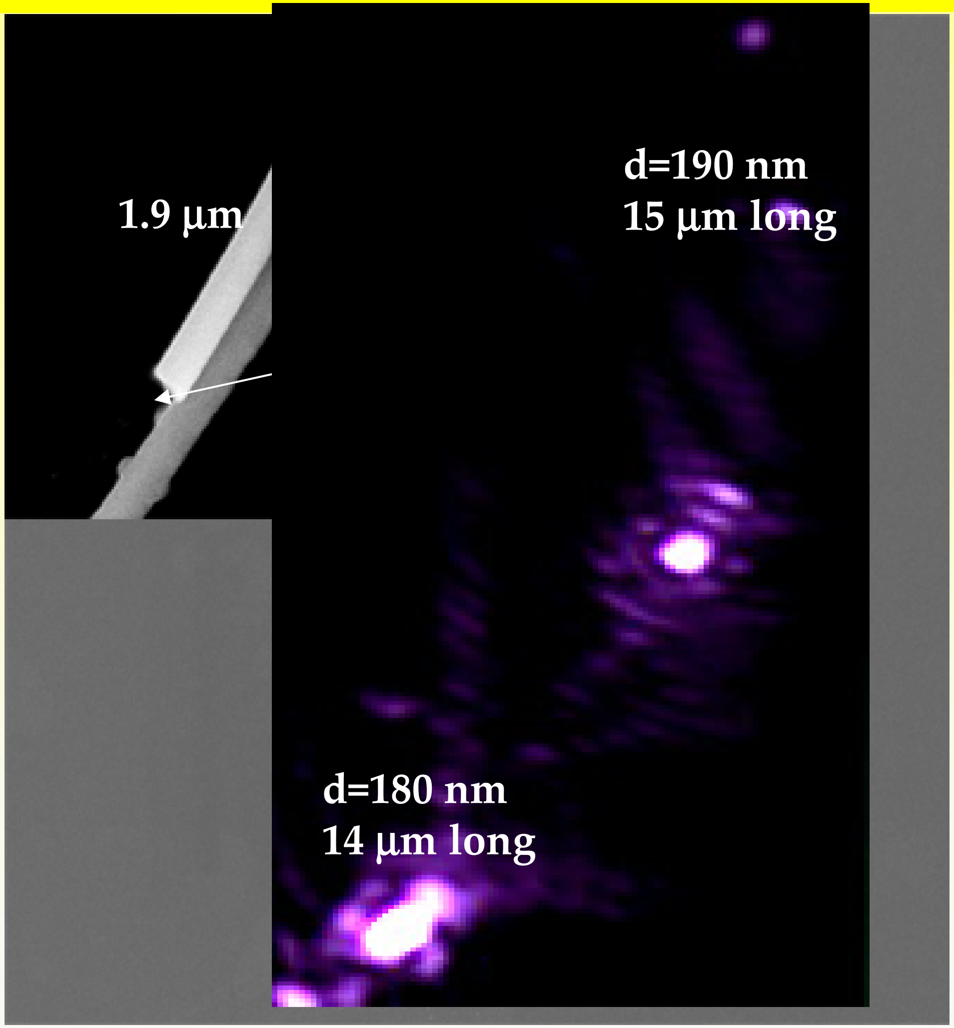
(c)[d,h] = [400, 100] nm (d)[d,h] = [200, 100] nm

(e) [d,h] = [**200, 2**] nm (f) [d,h] = [400, 2] nm

Oulton, R. F. *et al*, *Nature Photon*. 2008, 2, 495-500.

Coupling from silica nano-fiber to hybrid plasmonic waveguide





Diameter of silicon nanowire 130-230 nm

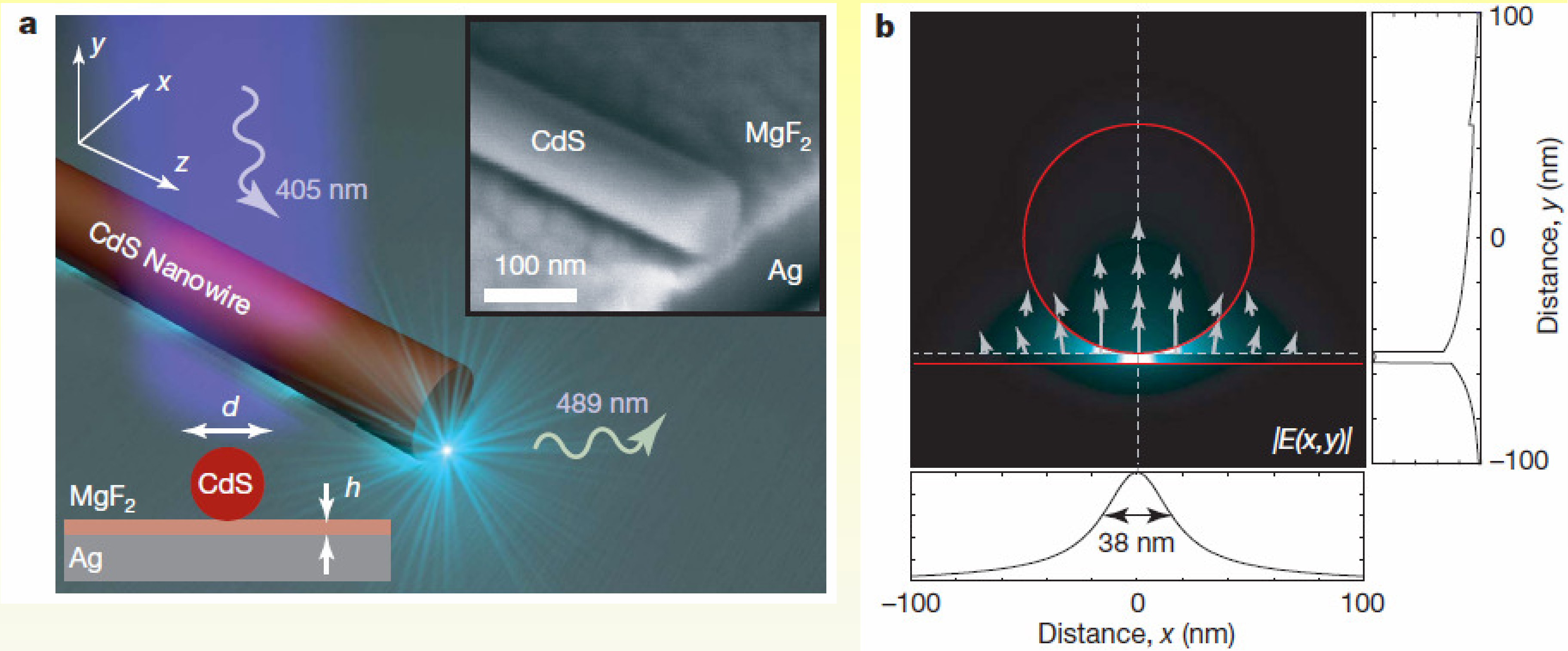
Thickness of the silica layer h=13 nm

Thickness of silver: >70 nm

Propagation length ~30 μm

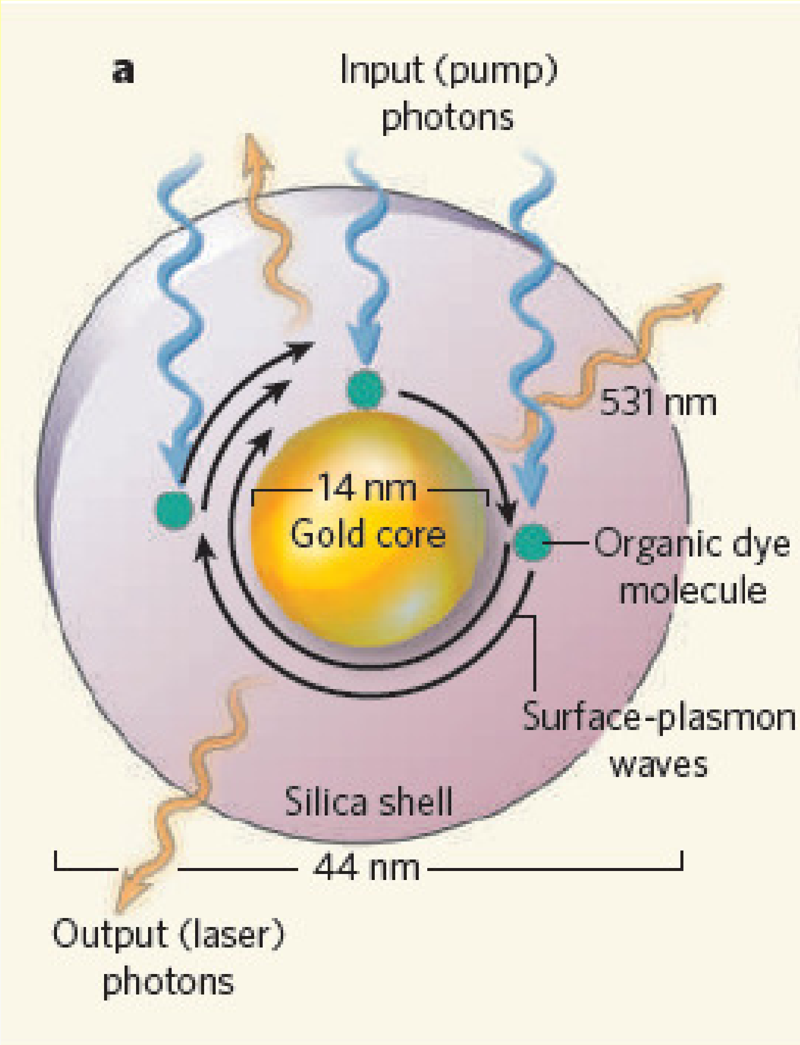
To be submitted

Plasmon lasers



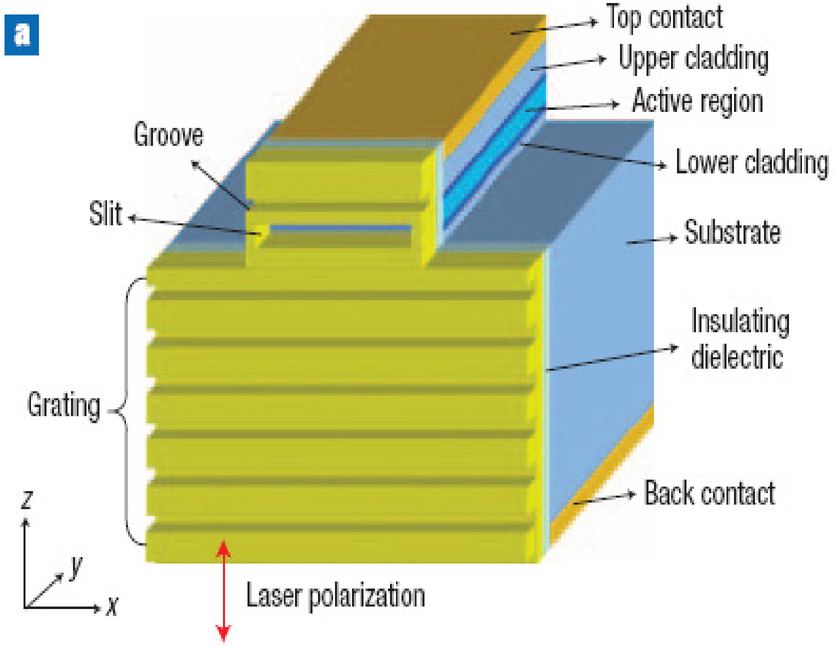
Rupert F. Oulton et al, "Plasmon lasers at deep subwavelength scale," Nature 461, p 629 (2009).

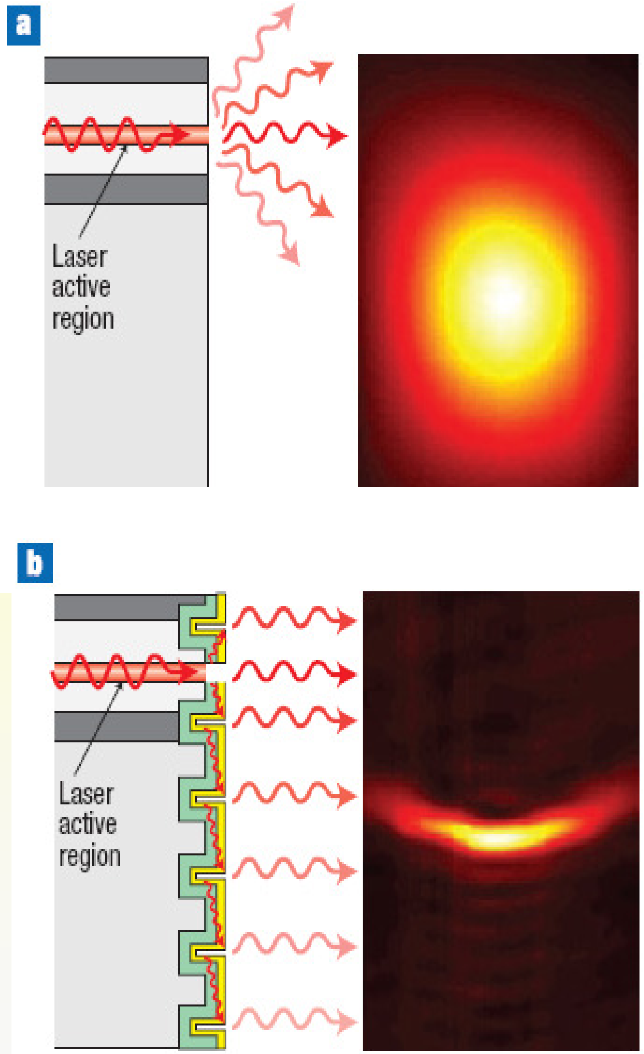
Spaser-based laser



Noginov, M. A. et al. Nature 460, 1110–1112 (2009).

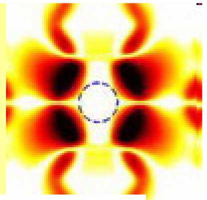
Small-divergence semiconductor lasers by plasmonic collimation

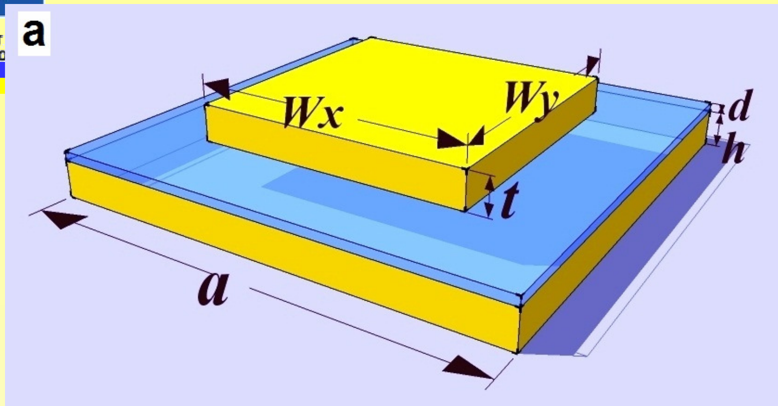




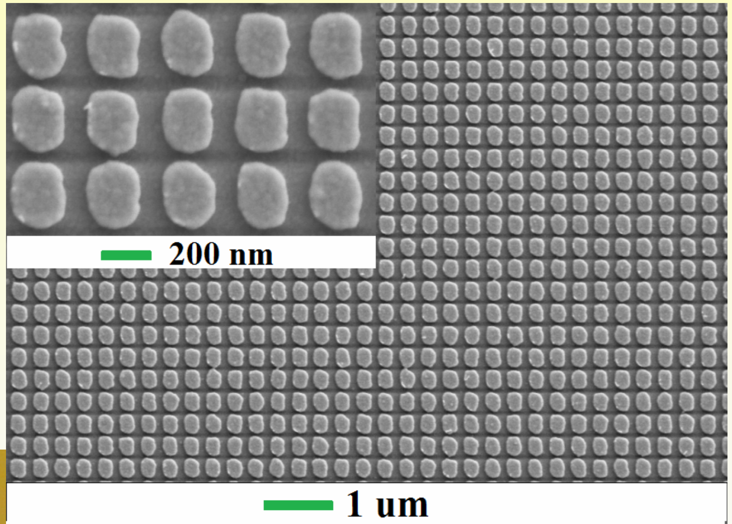
wavelength is 9.9 μm with 15 grooves
s =2 μm, Λ =8.9 μm, w =0.8 μm,
h =1.5 μm, d1 =7.3 μm , d2 =3.5 μm.

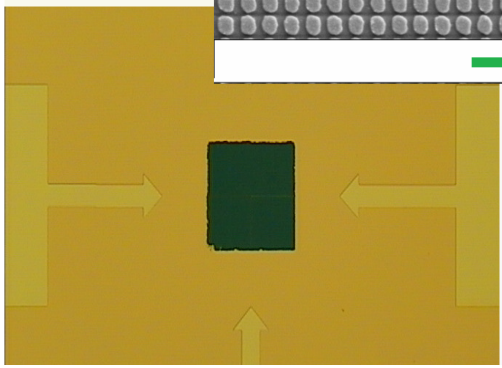
Plasmonic metamaterial absorber

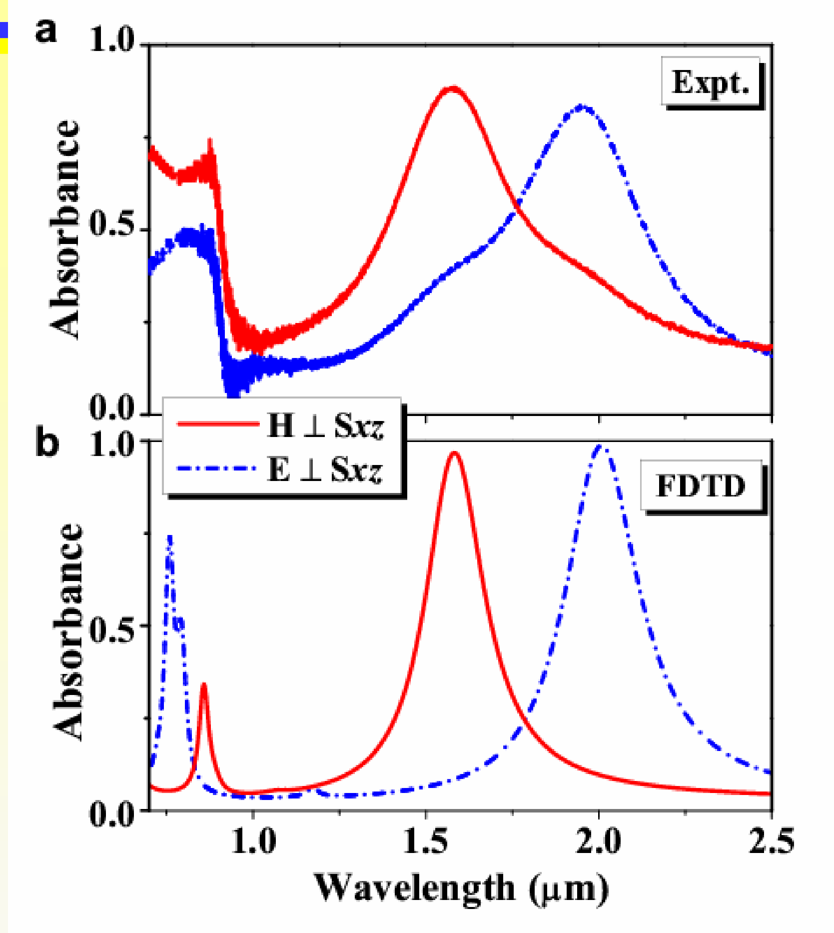




Au- Dielectric -Au





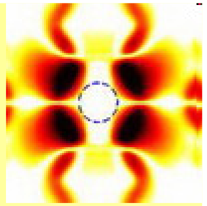


Polarization indepedent
Angle indepedent

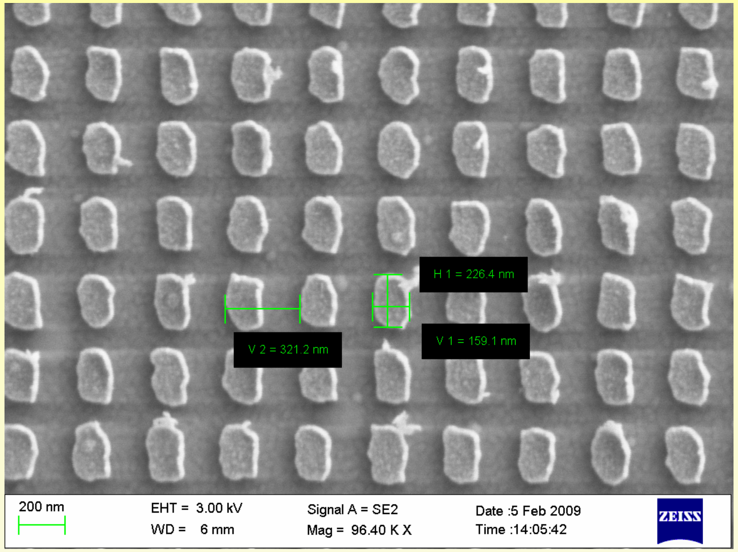
Submitted for publication

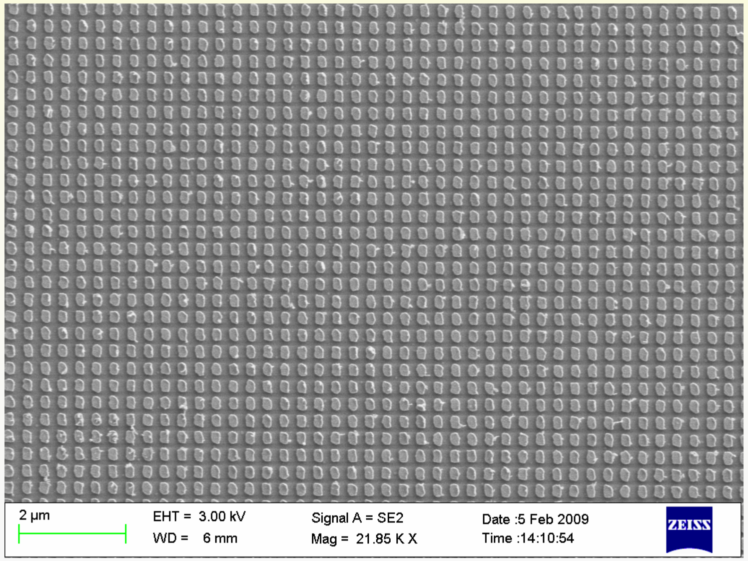
ROYAL INSTITUTE OF TECHNOLOGY

Highly efficient absorber!

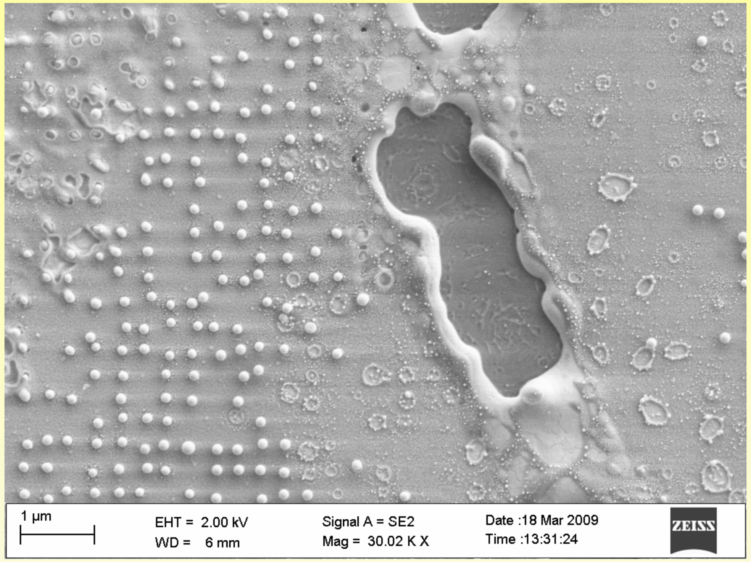


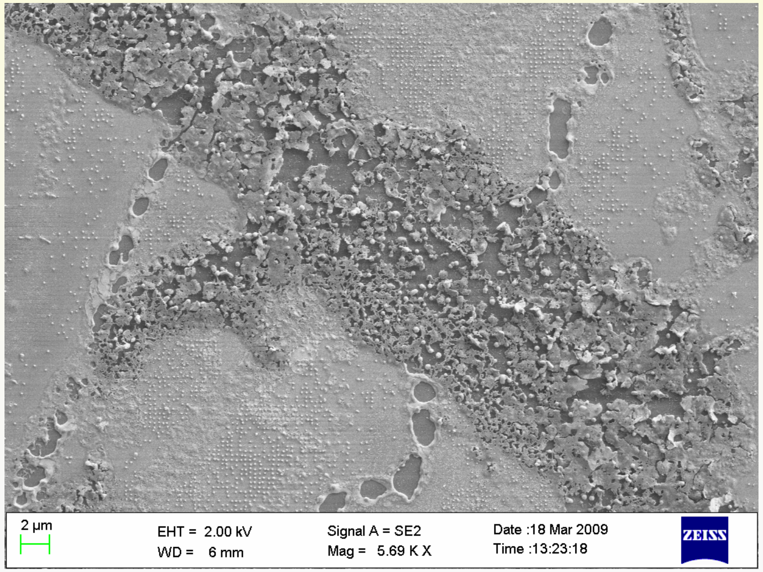
Before test



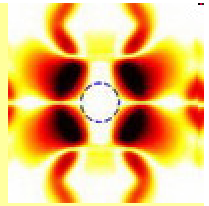


After test

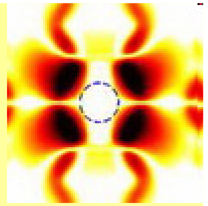




Applications of plasmonic devices



- SERS
- Bio-imaging
- Near-field optical microscope
- Lithography
- Nano antenna
- Surface-enhanced Raman spectroscopy
- Nanolaser (field enhancement)
- Plasmon Enhanced Fluorescence
- Solar cells!
- …



- Waveguiding using plasmonics (for high density integration) has no clear future unless the loss problem is solved
- Field enhancement with pasmonics (PV, LED, SERS, detector, small laser, etc) has a better future