Plasmonics and Metamaterial

Tao Li

taoli@nju.edu.cn

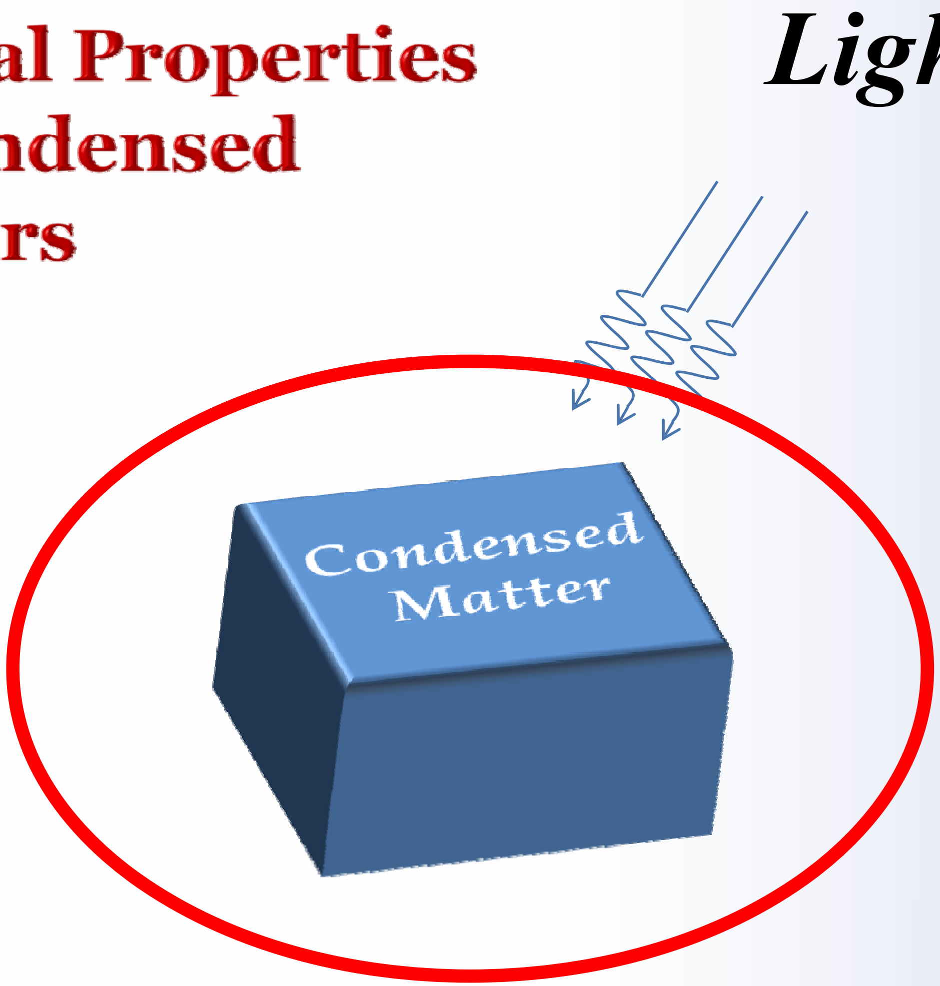
Nat. Lab. of Solid State Microstructures
Department of Materials Science and Engineering
Nanjing University

Outline

- Concepts
- Basic principles
- Surface Plasmon
- Metamaterial
- Summary

Dr. Tao Li taoli@nju.edu.cn

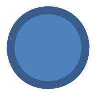
Optical Properties in Condensed Matters



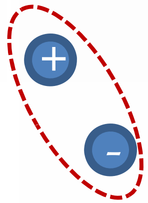
Dr. Tao Li taoli@nju.edu.cn

Concepts : Plasmonics

SOLID, LIQUID, GAS

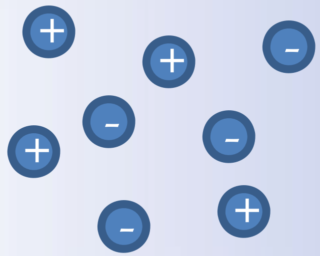


atom or molecule



decoupled positive and negative charges

PLASMA



free electron gas

metal

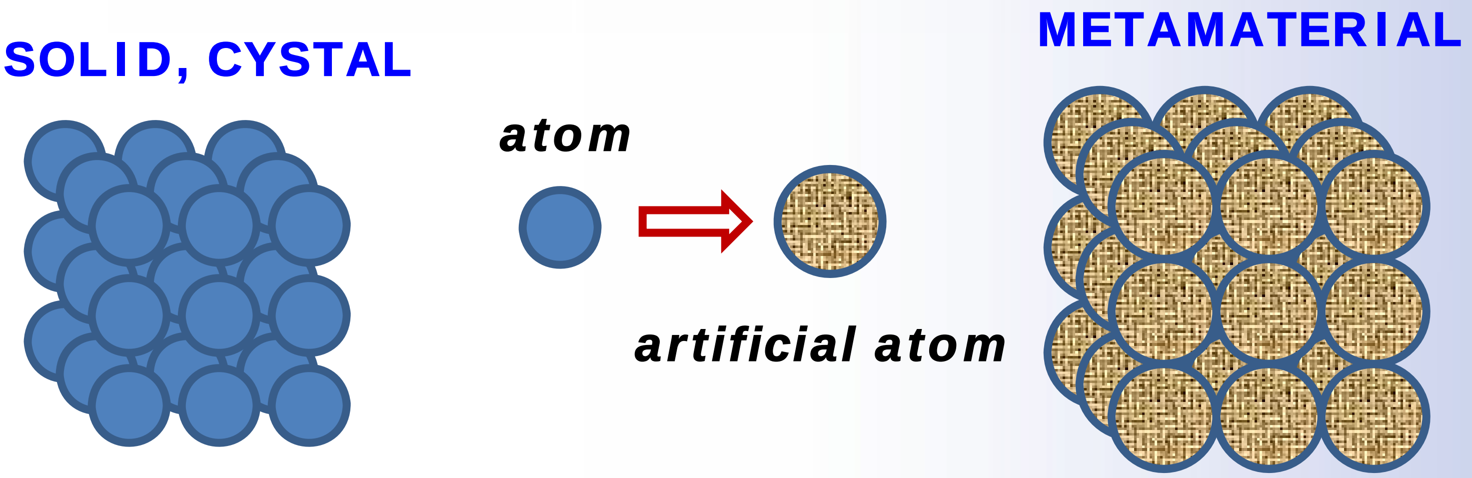
Jellium model

Collective oscillation of free elctrons→ quanta $h\omega_q$

Plasmonics ← **Plasmon**

Dr. Tao Li taoli@nju.edu.cn

Concepts : Metamaterial



Notice:

- *This artificial material (atom) is not exist naturally!*

  "meta" is "beyond"

- *The property is with respect to the EM wave, so a key point is the unit cell is sub-wavelength.*

  Light cannot "see" the structure

Outline

- Concepts
- **Basic principles**
- Surface Plasmon
- Metamaterial
- Summary

Basic Principle

Objective: Electromagneitcs of Metals

$$\begin{cases} \nabla \cdot \vec{D} = \rho_f \\ \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} = 0 \\ \nabla \times \vec{H} = \vec{j}_f + \dfrac{\partial \vec{D}}{\partial t} \end{cases}$$

$$\begin{cases} \vec{D} = \varepsilon\varepsilon_0 \vec{E} \\ \vec{B} = \mu\mu_0 \vec{H} \\ \vec{j} = \sigma \vec{E} \end{cases}$$

$$\varepsilon = \varepsilon(\omega)$$
$$\mu = \mu(\omega)$$
$$\omega = \omega(k)$$

- *Field distribution: E and H*
- *Media response: ε and μ*

Dr. Tao Li taoli@nju.edu.cn

Basic Principle

Commonly, magnetic response is neglected for the optical material

$$\mu = 1$$

Electric part can be described by

$$\mathbf{D}(\mathbf{r},t) = \varepsilon_0 \int dt' d\mathbf{r}' \varepsilon(\mathbf{r}-\mathbf{r}', t-t')\mathbf{E}(\mathbf{r}', t')$$

$$\mathbf{J}(\mathbf{r},t) = \int dt' d\mathbf{r}' \sigma(\mathbf{r}-\mathbf{r}', t-t')\mathbf{E}(\mathbf{r}', t')$$

Taking Fourier Transformation

$$\mathbf{D}(\mathbf{K},\omega) = \varepsilon_0 \varepsilon(\mathbf{K},\omega)\mathbf{E}(\mathbf{K},\omega)$$

$$\mathbf{J}(\mathbf{K},\omega) = \sigma(\mathbf{K},\omega)\mathbf{E}(\mathbf{K},\omega)$$

Fourier domain of ***k-ω*** space

Basic Principle

According to Equations $\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}, \quad \mathbf{J} = \frac{\partial \mathbf{P}}{\partial t}$

We get the **dielectric function** *of metal*

$$\varepsilon(\mathbf{K}, \omega) = 1 + \frac{i\sigma(\mathbf{K}, \omega)}{\varepsilon_0 \omega}$$

For a spatially local response, $\varepsilon(\mathbf{K} = 0, \omega) = \varepsilon(\omega)$

From wave equation $\nabla \times \nabla \times \mathbf{E} = -\mu_0 \frac{\partial^2 \mathbf{D}}{\partial t^2}$

$$\Rightarrow \quad K^2 = \varepsilon(\mathbf{K}, \omega) \frac{\omega^2}{c^2}$$

Generic dispersion relation

Basic Principle

Dielectric function of free electron gas

We have dynamic equation of an electron of plasma sea in an external E field

$$m\ddot{\mathbf{x}} + m\gamma\dot{\mathbf{x}} = -e\mathbf{E}$$

$$\mathbf{x}(t) = \frac{e}{m(\omega^2 + i\gamma\omega)}\mathbf{E}(t)$$

$$\mathbf{P} = -\frac{ne^2}{m(\omega^2 + i\gamma\omega)}\mathbf{E}$$

$$\mathbf{D} = \varepsilon_0(1 - \frac{\omega_P^2}{\omega^2 + i\gamma\omega})\mathbf{E}$$

$$\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega^2 + i\gamma\omega}$$

Plasma frequency

$$\omega_p^2 = \frac{Ne^2}{\varepsilon_0 m_0}$$

$$\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega^2}$$

If neglecting the loss

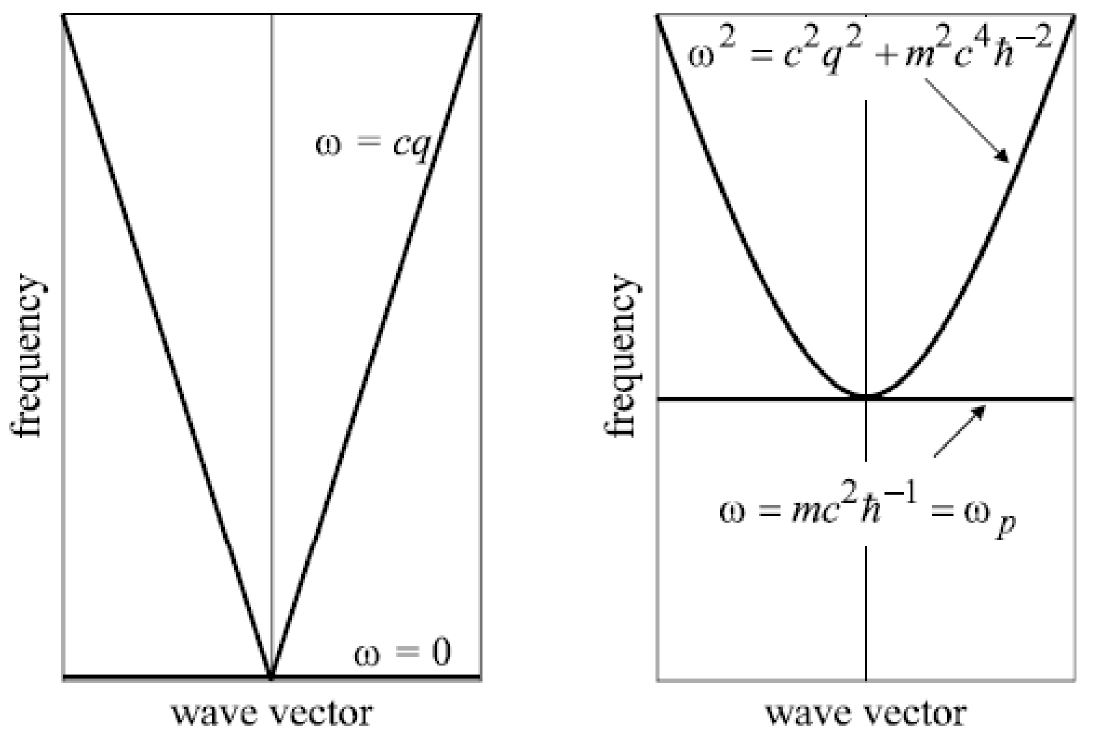
Drude Model

$$\omega^2 = \omega_P^2 + K^2c^2$$

Dispersion of volume plasmons

Dr. Tao Li taoli@nju.edu.cn

Basic Principle



Dispersion of light in free space and perfect metal

Basic Principle

Considering the bound electron with resonance frequency ω_0

e.g. geometric boundary, interband transition, or other forces…

It is more popular case in real metallic system

$$m\ddot{\mathbf{x}} + m\gamma\dot{\mathbf{x}} + m\omega_0\mathbf{x} = -e\mathbf{E}$$

$$\varepsilon(\omega) = 1 + \frac{\omega_P^2}{\omega_0^2 - \omega^2 - i\gamma\omega}$$

Lorentz Model

Basic Principle

Optical property of medium

refractive index n, extinction coefficient κ

$$\varepsilon_1 = n^2 - \kappa^2, \quad \varepsilon_2 = 2n\kappa$$

and

$$n = \frac{1}{\sqrt{2}}(\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}})^{\frac{1}{2}}$$

$$\kappa = \frac{1}{\sqrt{2}}(-\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}})^{\frac{1}{2}}.$$

$\tilde{n}$ *and* $\tilde{\varepsilon}_r$ *are not independent variables*

Basic Principle

Considering the plasmon

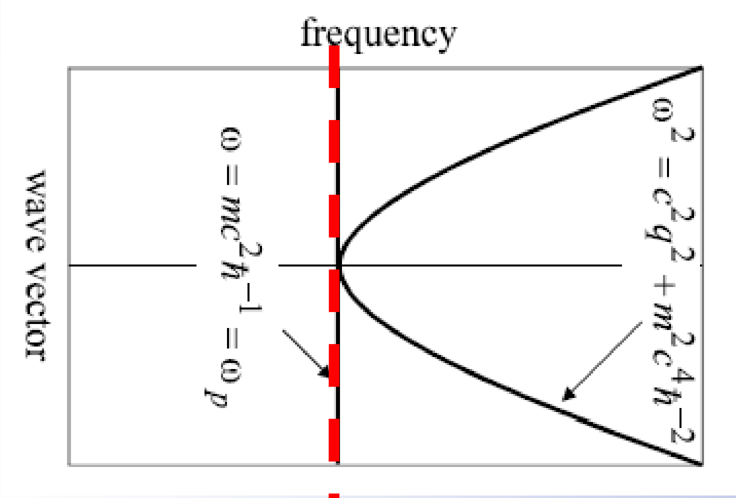
$$\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega^2}$$

$$\tilde{n} = \sqrt{\varepsilon_r}$$

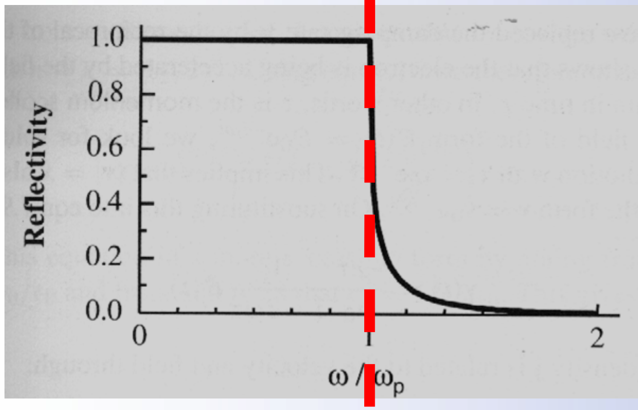
$\omega > \omega_p$, ***n is real***

$\omega = \omega_p$, ***n=0***

$\omega < \omega_p$, ***n is imaginary***



Plasma frequency



Optical reflectivity

$$R = \left|\frac{\tilde{n} - 1}{\tilde{n} + 1}\right|^2 = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}.$$

Outline

- Concepts
- Basic principles
- Surface Plasmon
    - **SPP at flat metal surfaces**
    - Optical excitation of SPP
    - Localized Surface plasmon (LSP)
    - Application of SPP
- Metamaterial
- Summary

Dr. Tao Li taoli@nju.edu.cn

Surface plasmon polariton (SPP)

From Maxwell's Eqs, we can get the wave equation

$$\nabla^2 \mathbf{E} + k_0^2 \varepsilon \mathbf{E} = 0,$$

Considering the waveguide modes in x direction, then

$$\frac{\partial^2 E_y}{\partial z^2} + \left(k_0^2 \varepsilon - \beta^2\right) E_y = 0.$$

$$H_x = i \frac{1}{\omega \mu_0} \frac{\partial E_y}{\partial z}$$

$$H_z = \frac{\beta}{\omega \mu_0} E_y,$$

For TE mode

$$\frac{\partial^2 H_y}{\partial z^2} + \left(k_0^2 \varepsilon - \beta^2\right) H_y = 0.$$

$$E_x = -i \frac{1}{\omega \varepsilon_0 \varepsilon} \frac{\partial H_y}{\partial z}$$

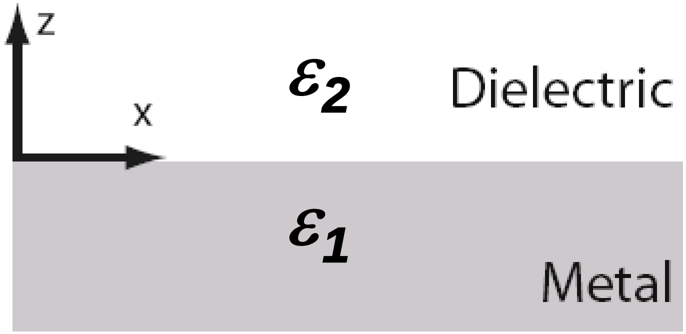
$$E_z = -\frac{\beta}{\omega \varepsilon_0 \varepsilon} H_y,$$

For TM mode

Dr. Tao Li taoli@nju.edu.cn

Surface plasmon polariton (SPP)

For TE case



$$E_y(z) = A_2 e^{i\beta x} e^{-k_2 z}$$
$$H_x(z) = -iA_2 \frac{1}{\omega\mu_0} k_2 e^{i\beta x} e^{-k_2 z}$$
$$H_z(z) = A_2 \frac{\beta}{\omega\mu_0} e^{i\beta x} e^{-k_2 z}$$

Z > 0

$$E_y(z) = A_1 e^{i\beta x} e^{k_1 z}$$
$$H_x(z) = iA_1 \frac{1}{\omega\mu_0} k_1 e^{i\beta x} e^{k_1 z}$$
$$H_z(z) = A_1 \frac{\beta}{\omega\mu_0} e^{i\beta x} e^{k_1 z}$$

Z < 0

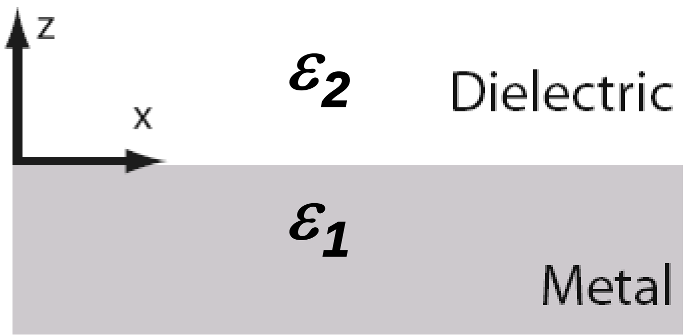
According to the continuity of H_y and εE_z at the interface

$$A_1 (k_1 + k_2) = 0. \qquad A_2 = A_1 = 0.$$

No mode for TE wave

Surface plasmon polariton (SPP)

For TM case



$$H_y(z) = A_2 e^{i\beta x} e^{-k_2 z}$$
$$E_x(z) = i A_2 \frac{1}{\omega\varepsilon_0\varepsilon_2} k_2 e^{i\beta x} e^{-k_2 z}$$
$$E_z(z) = -A_1 \frac{\beta}{\omega\varepsilon_0\varepsilon_2} e^{i\beta x} e^{-k_2 z}$$

Z > 0

$$H_y(z) = A_1 e^{i\beta x} e^{k_1 z}$$
$$E_x(z) = -i A_1 \frac{1}{\omega\varepsilon_0\varepsilon_1} k_1 e^{i\beta x} e^{k_1 z}$$
$$E_z(z) = -A_1 \frac{\beta}{\omega\varepsilon_0\varepsilon_1} e^{i\beta x} e^{k_1 z}$$

Z < 0

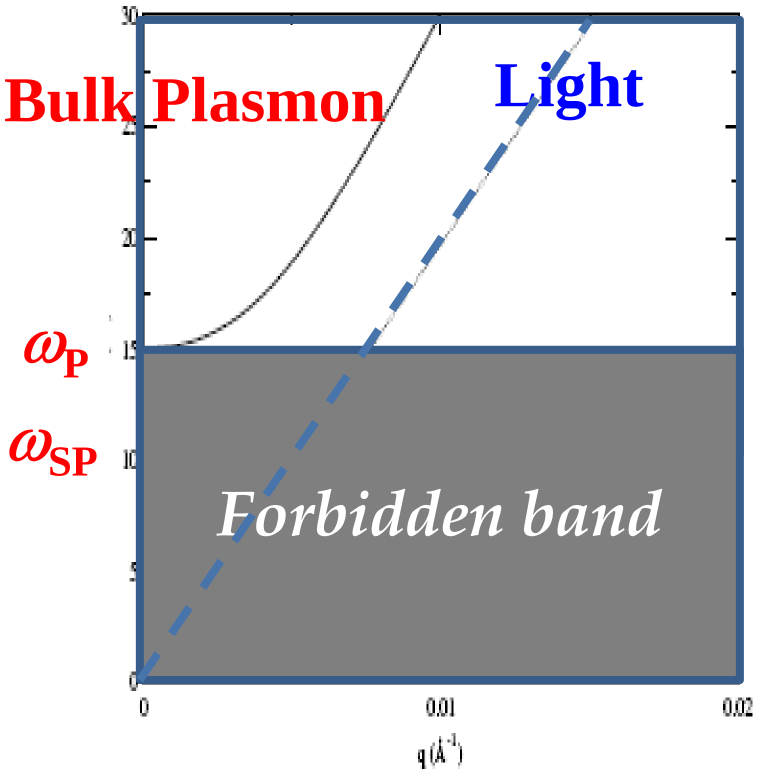
According to the continuity of H_y and εE_z at the interface

$$\frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1}. \quad \Rightarrow \quad k_1^2 = \beta^2 - k_0^2\varepsilon_1, \quad k_2^2 = \beta^2 - k_0^2\varepsilon_2. \quad \Rightarrow \quad \beta = k_0\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}.$$

A surface wave!

Dr. Tao Li taoli@nju.edu.cn

Surface plasmon polariton (SPP)



The God close a door with a window open!

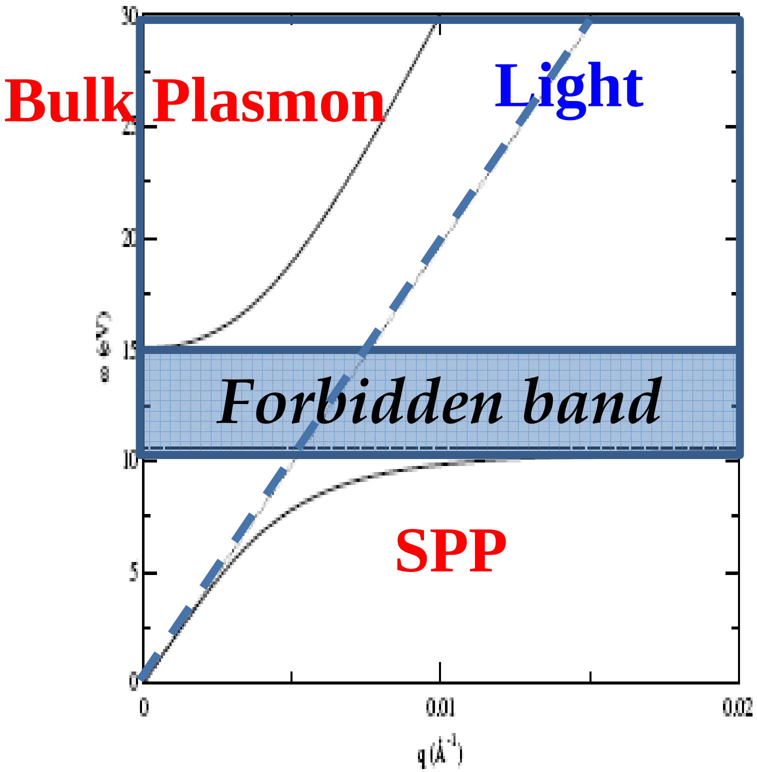
when $k \to \infty$

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

$$\omega_{sp} = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$$

Dr. Tao Li taoli@nju.edu.cn

Surface plasmon polariton (SPP)



SPP: $k_{spp} > k_{light}$

$$k_0^2 = k_x^2 + k_y^2 + k_z^2$$

$$k_y = 0, \quad for\ TM\ mode$$

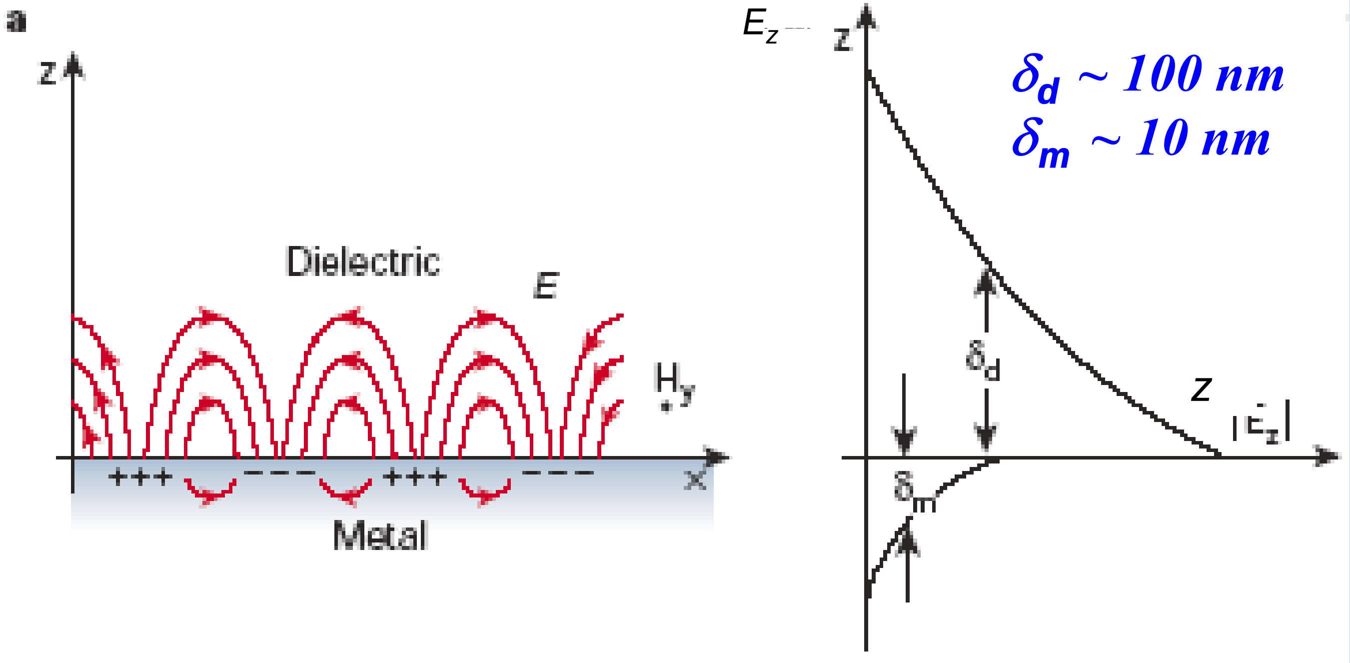
$$and\ \ k_x > k_0$$

$$So,\ \ k_z^2 < 0,\ \ k_z is\ an\ \ \mathrm{Im}$$

SPP is also an ***evanescent wave***

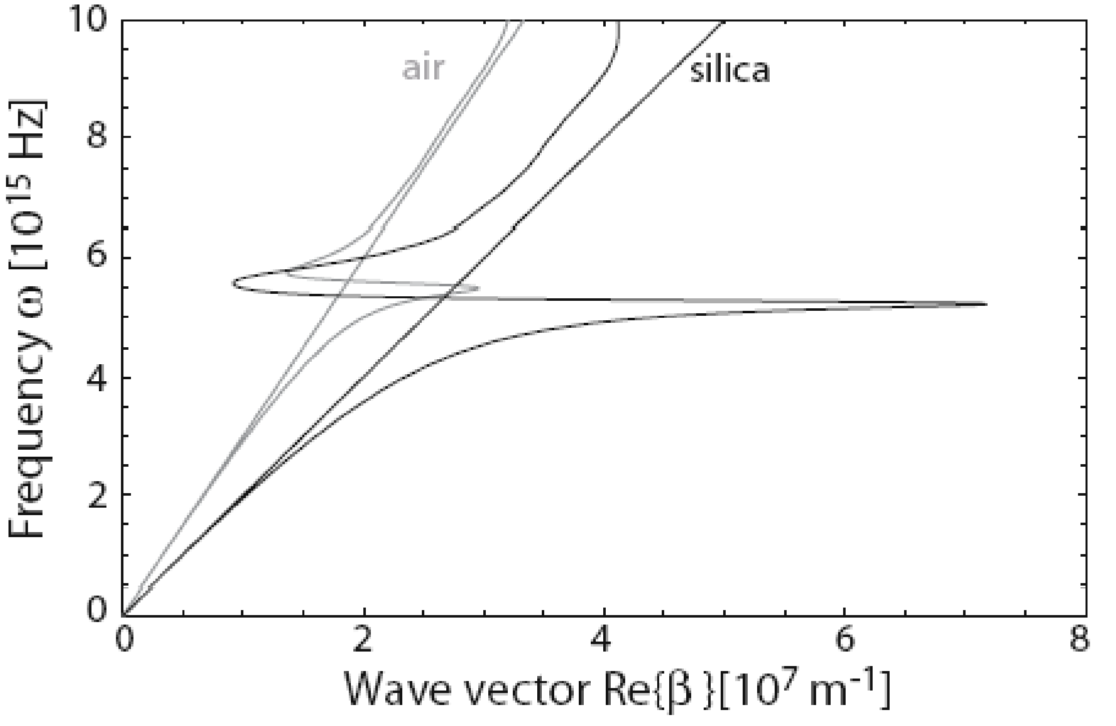
Surface plasmon polariton (SPP)

Electric field distribution of SPP



δ_d ~ 100 nm
δ_m ~ 10 nm

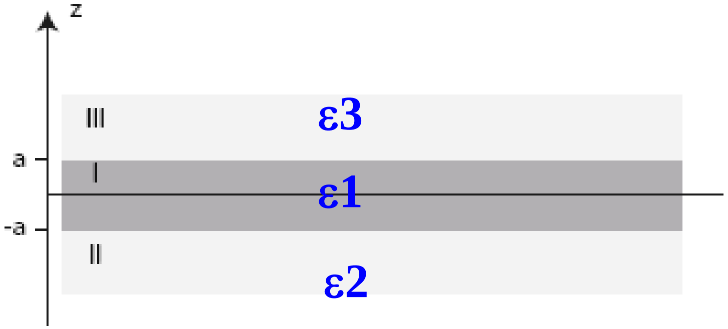
Surface plasmon polariton (SPP)



Dispersions of true SPPs at *a real system*
(silver/air and silver/silica interfaces)

Coupled SPP in multilayer system

IMI multilayer



$$H_y = A e^{i\beta x} e^{-k_3 z}$$

$$E_x = iA \frac{1}{\omega\varepsilon_0\varepsilon_3} k_3 e^{i\beta x} e^{-k_3 z}$$

$$E_z = -A \frac{\beta}{\omega\varepsilon_0\varepsilon_3} e^{i\beta x} e^{-k_3 z},$$

$$H_y = C e^{i\beta x} e^{k_1 z} + D e^{i\beta x} e^{-k_1 z}$$

$$E_x = -iC \frac{1}{\omega\varepsilon_0\varepsilon_1} k_1 e^{i\beta x} e^{k_1 z} + iD \frac{1}{\omega\varepsilon_0\varepsilon_1} k_1 e^{i\beta x} e^{-k_1 z}$$

$$E_z = C \frac{\beta}{\omega\varepsilon_0\varepsilon_1} e^{i\beta x} e^{k_1 z} + D \frac{\beta}{\omega\varepsilon_0\varepsilon_1} e^{i\beta x} e^{-k_1 z}.$$

$$H_y = B e^{i\beta x} e^{k_2 z}$$

$$E_x = -iB \frac{1}{\omega\varepsilon_0\varepsilon_2} k_2 e^{i\beta x} e^{k_2 z}$$

$$E_z = -B \frac{\beta}{\omega\varepsilon_0\varepsilon_2} e^{i\beta x} e^{k_2 z}.$$

Coupled SPP in multilayer system

The requirement of continutity of H_y and E_x leads to

$$A\mathrm{e}^{-k_3 a} = C\mathrm{e}^{k_1 a} + D\mathrm{e}^{-k_1 a}$$

$$\frac{A}{\varepsilon_3} k_3 \mathrm{e}^{-k_3 a} = -\frac{C}{\varepsilon_1} k_1 \mathrm{e}^{k_1 a} + \frac{D}{\varepsilon_1} k_1 \mathrm{e}^{-k_1 a} \quad \textbf{(1)}$$

at z=a

$$B\mathrm{e}^{-k_2 a} = C\mathrm{e}^{-k_1 a} + D\mathrm{e}^{k_1 a}$$

$$-\frac{B}{\varepsilon_2} k_2 \mathrm{e}^{-k_2 a} = -\frac{C}{\varepsilon_1} k_1 \mathrm{e}^{-k_1 a} + \frac{D}{\varepsilon_1} k_1 \mathrm{e}^{k_1 a} \quad \textbf{(2)}$$

at z=a

$$k_i^2 = \beta^2 - k_0^2 \varepsilon_i \quad \textbf{(3)}$$

Dispersion of coupled SPP

$$\mathrm{e}^{-4k_1 a} = \frac{k_1/\varepsilon_1 + k_2/\varepsilon_2}{k_1/\varepsilon_1 - k_2/\varepsilon_2} \frac{k_1/\varepsilon_1 + k_3/\varepsilon_3}{k_1/\varepsilon_1 - k_3/\varepsilon_3}.$$

Dr. Tao Li taoli@nju.edu.cn

Coupled SPP in multilayer system

$$e^{-4k_1 a} = \frac{k_1/\varepsilon_1 + k_2/\varepsilon_2}{k_1/\varepsilon_1 - k_2/\varepsilon_2}\frac{k_1/\varepsilon_1 + k_3/\varepsilon_3}{k_1/\varepsilon_1 - k_3/\varepsilon_3}.$$

If a→∞, this dispersion degenerate to

$$\frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1}. \quad \Rightarrow \quad \beta = k_0\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}.$$

Decoupled

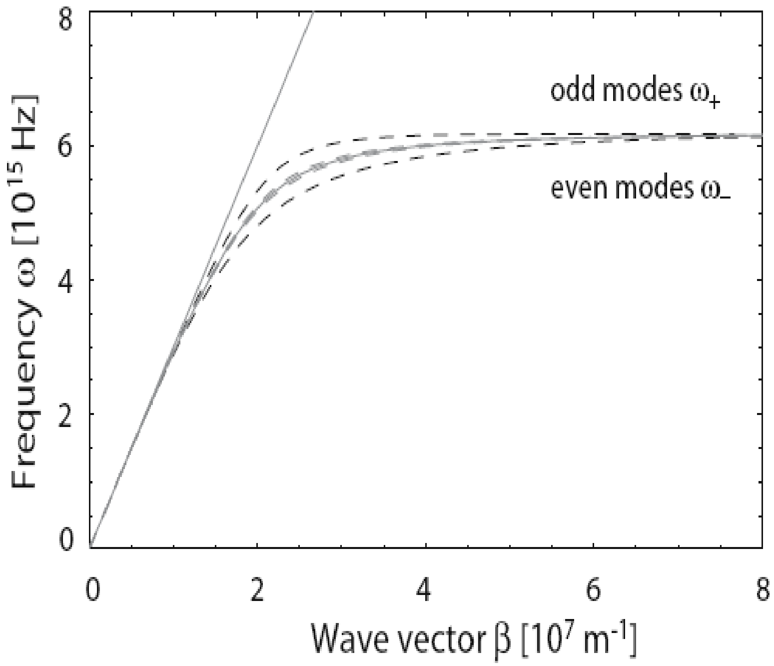
If ε2=ε3, this dispersion splits to two Eqs.

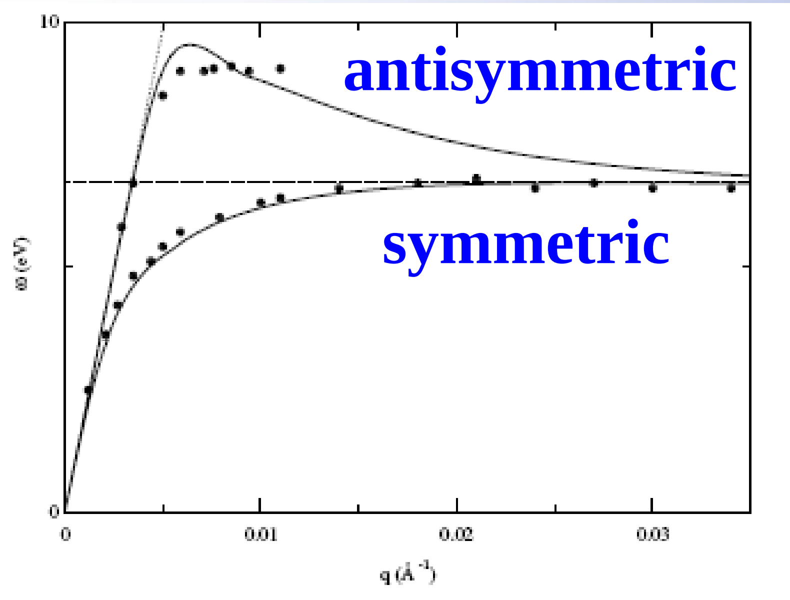
$$\tanh k_1 a = -\frac{k_2\varepsilon_1}{k_1\varepsilon_2}$$

$$\tanh k_1 a = -\frac{k_1\varepsilon_2}{k_2\varepsilon_1}.$$

Coupled SPP modes

Coupled SPP in multilayer system





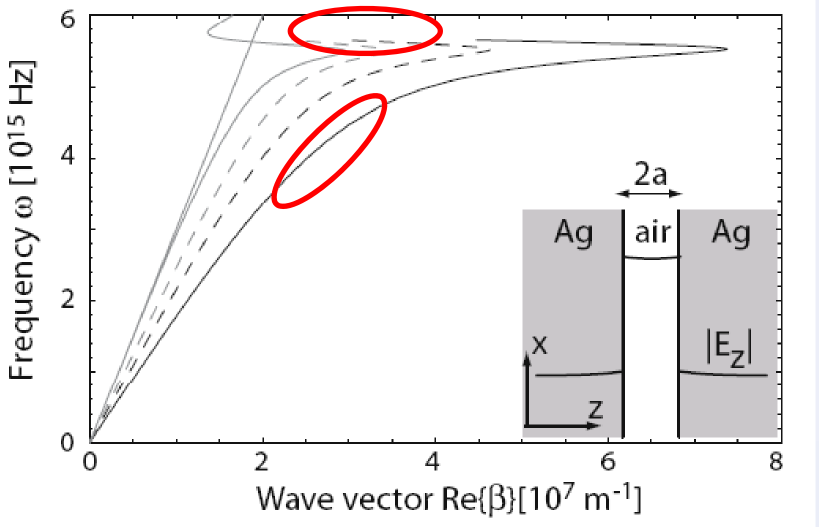
a= 50nm, large **a= 4 nm, small**

Coupled SPP in multilayer system

MIM multilayer case

$$\begin{cases} \tanh k_1 a = -\dfrac{k_2\varepsilon_1}{k_1\varepsilon_2} \\ \tanh k_1 a = -\dfrac{k_1\varepsilon_2}{k_2\varepsilon_1}. \end{cases}$$

Still valid, with reverse of ε1 and ε2



Outline

- Concepts
- Basic principles
- Surface Plasmon
  - SPP at flat metal surfaces
  - **Optical excitation of SPP**
  - Localized Surface plasmon (LSP)
  - Application of SPP
- Metamaterial
- Summary

Dr. Tao Li taoli@nju.edu.cn

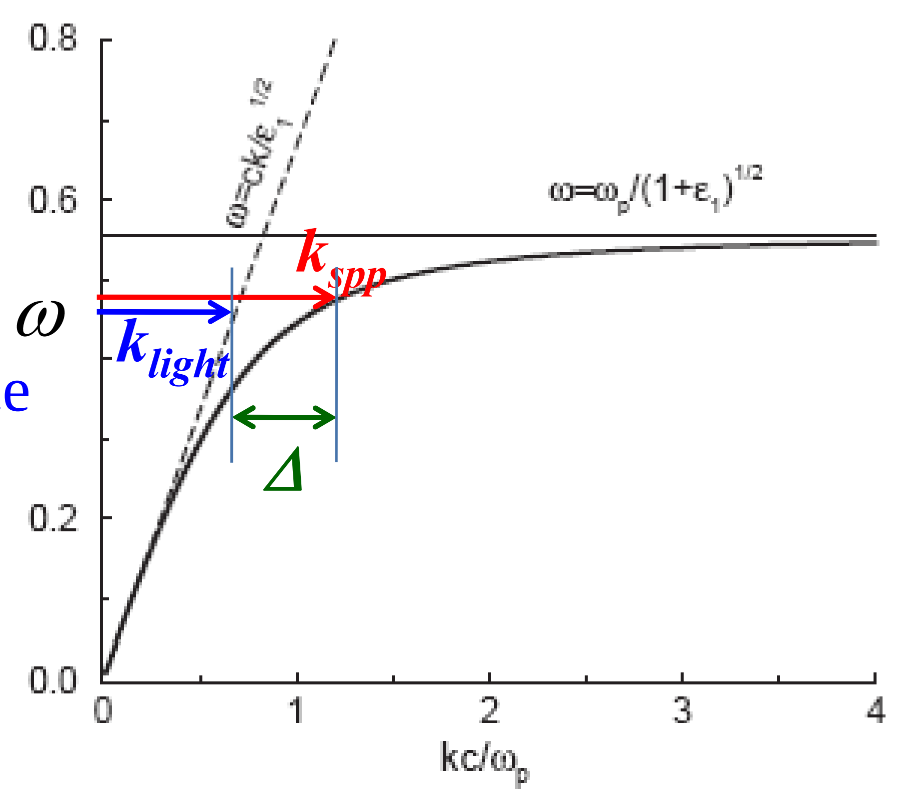
Optical excitation of SPP

Bare light cannot couple to SPP, due to the ***mismatch of wave vectors***

If the light is not along surface and incident with an angle θ, Then

$$\Delta' = \Delta + (1 - \sin\theta)\, k_{light}$$

The mismatch is bigger

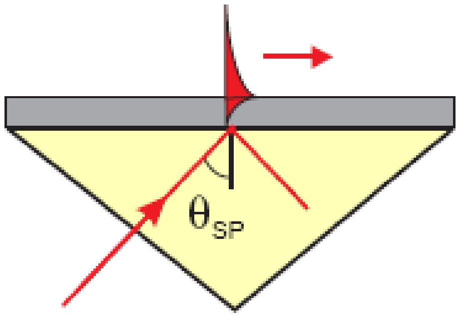


To overcome this problem, there are several approaches

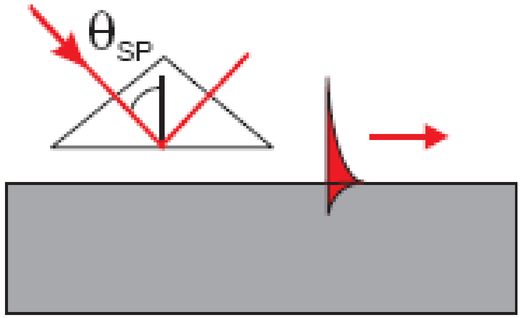
Dr. Tao Li taoli@nju.edu.cn

Optical excitation of SPP

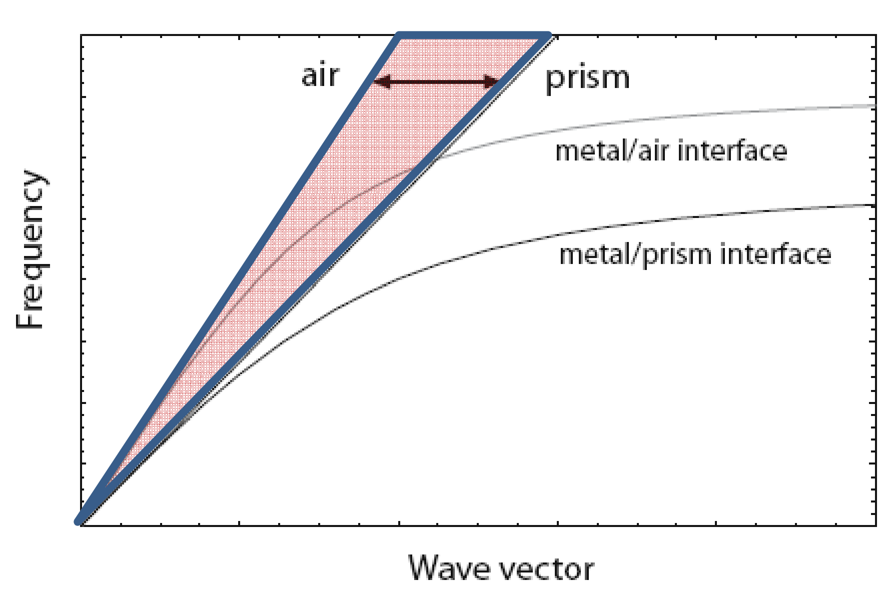
(a) Prism coupling



Kretschmann geometry



Otto geometry

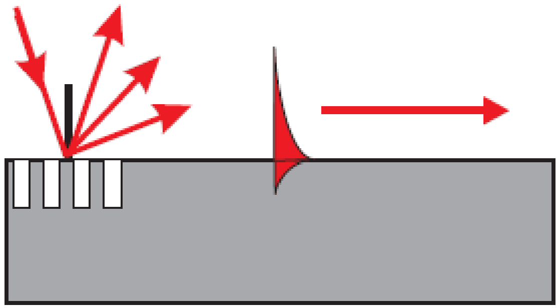


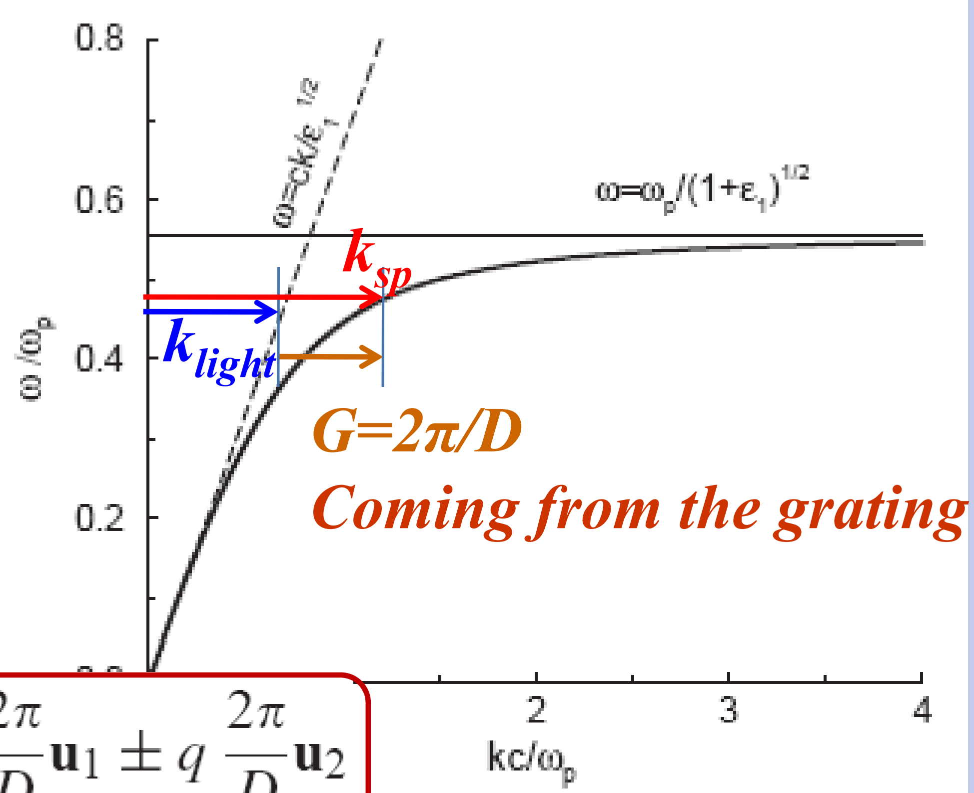
$\varepsilon_{prism}>1$

$$k_{sp} = \frac{\omega}{c}\sqrt{\epsilon_{prism}}\,\sin\ \theta$$

Optical excitation of SPP

(b) Grating coupling





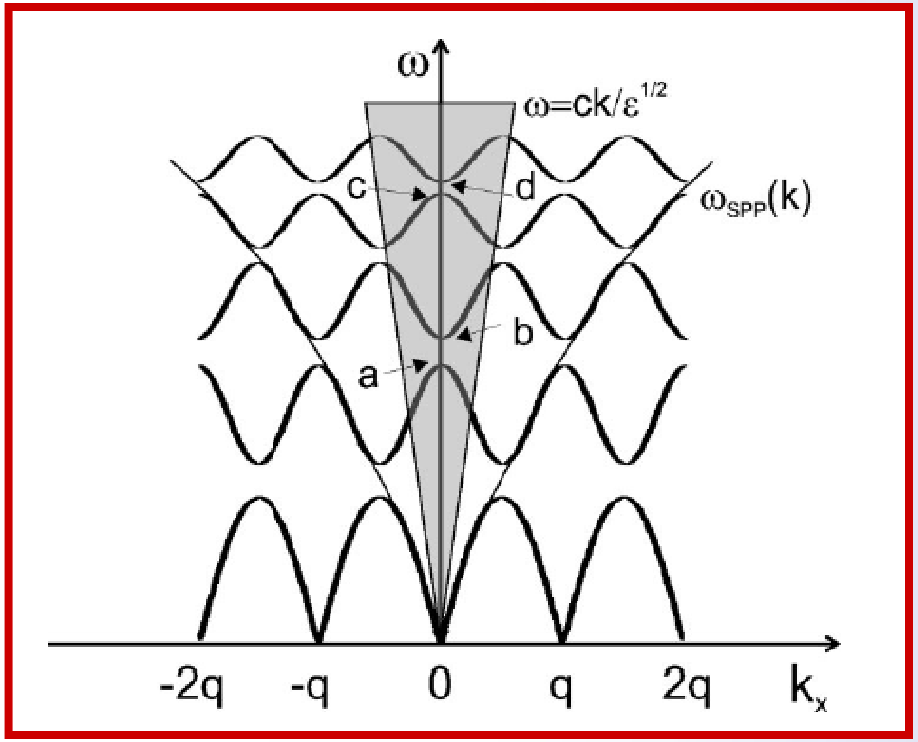
$$\mathbf{k}_{sp} = \frac{\omega}{c} n_s \sin\ \theta \mathbf{u}_{12} \delta_p \pm p\frac{2\pi}{D}\mathbf{u}_1 \pm q\frac{2\pi}{D}\mathbf{u}_2$$

Polarization
1→TM
0→TE

Reciprocal vectors

Optical excitation of SPP

(b) Grating coupling



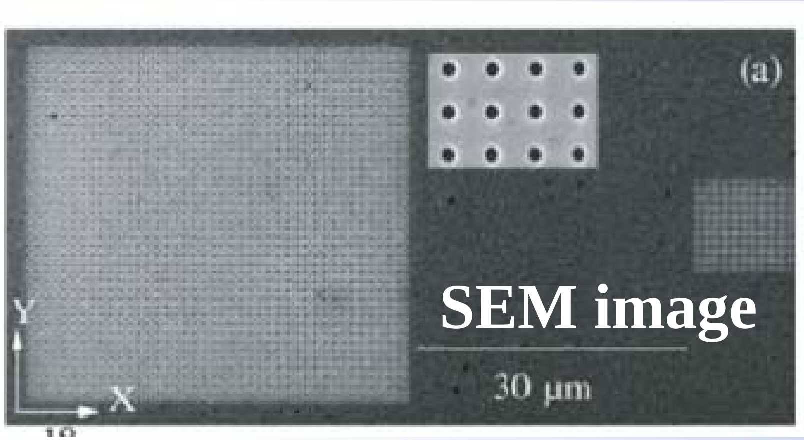
Overlap of the dispersion

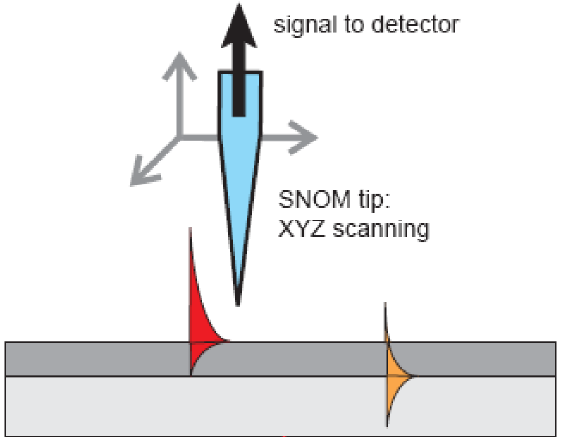
Dr. Tao Li taoli@nju.edu.cn

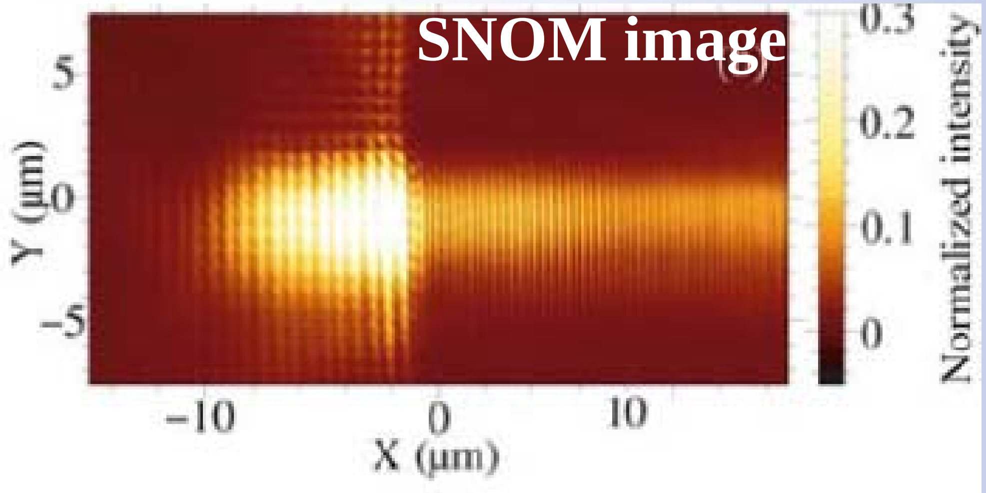
Optical excitation of SPP

Grating image

Detecting: SNOM

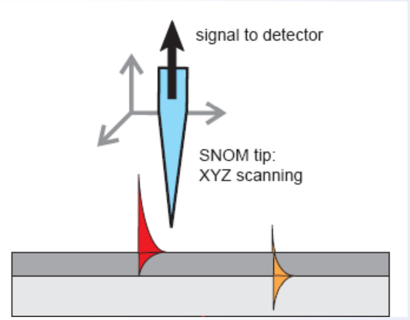




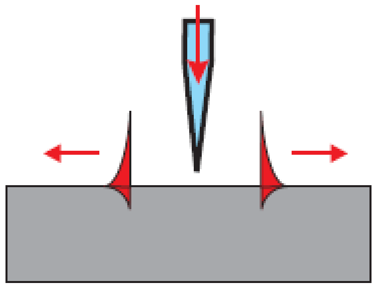


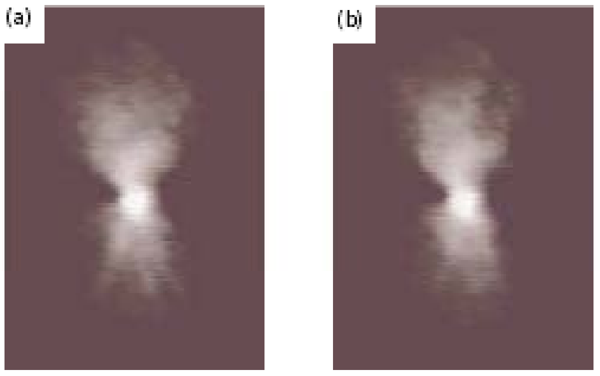
Optical excitation of SPP

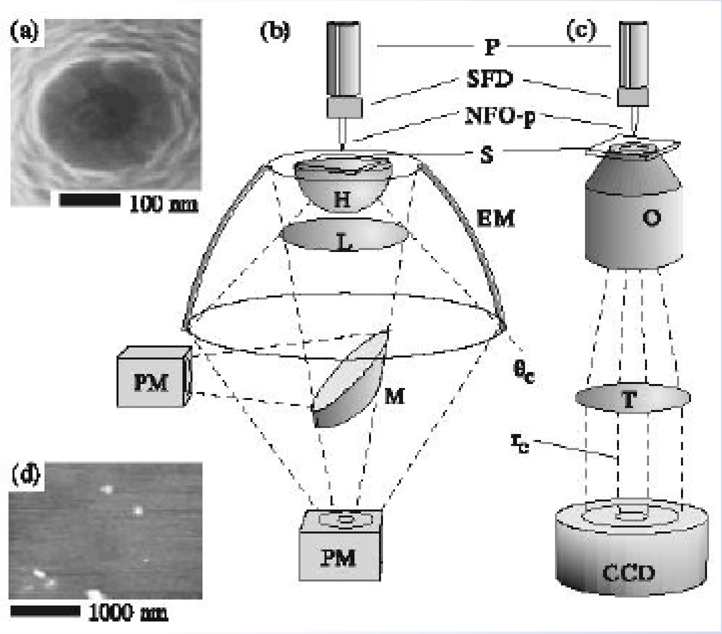
(c) Near-field excitation



SNOM

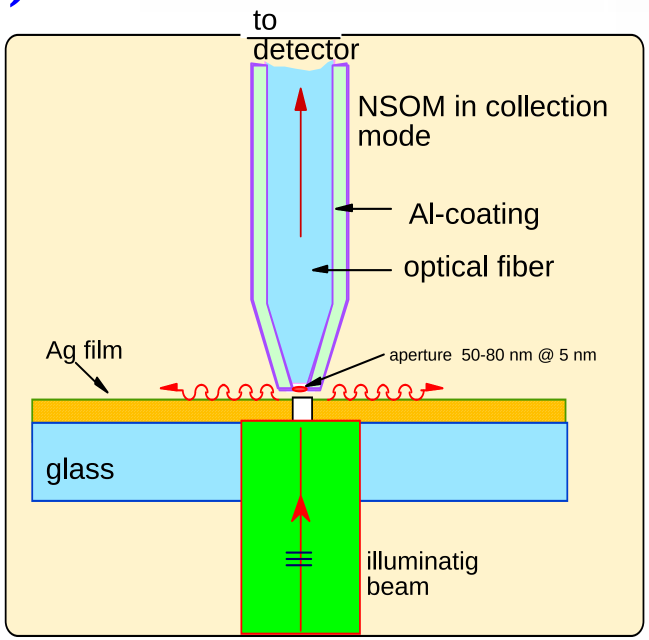


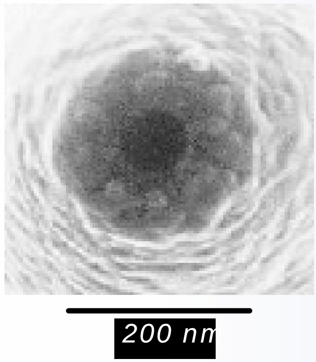


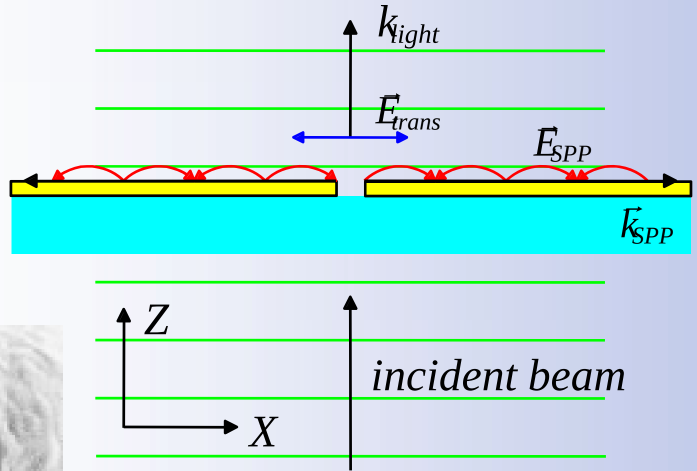


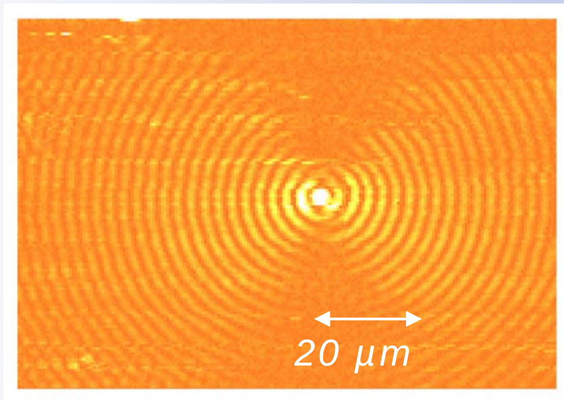
Optical excitation of SPP

(c) Near-field excitation







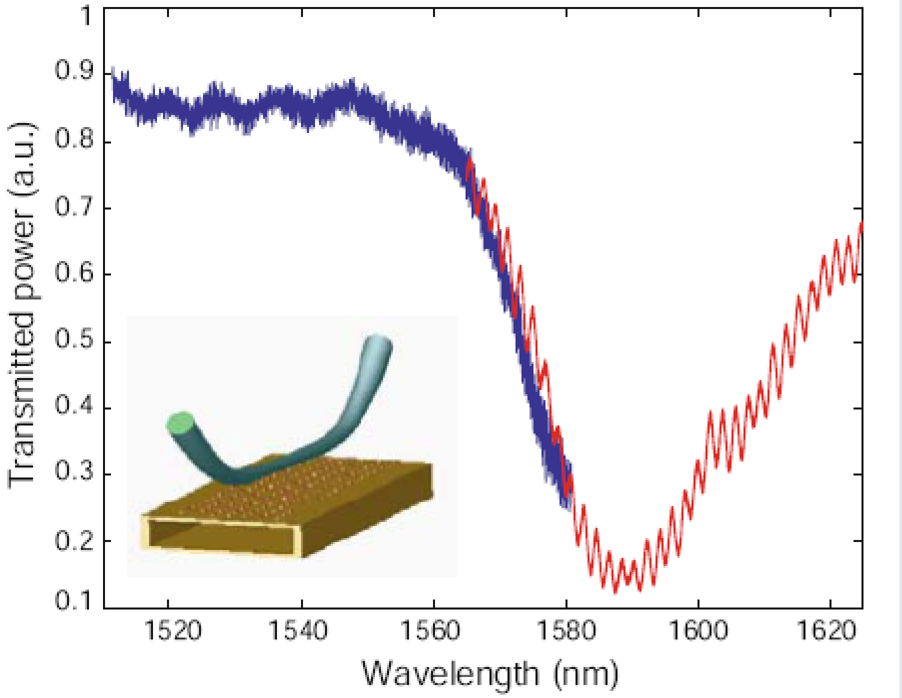


Near-field Scanning Optical Microscope (NSOM) in collection mode λ_{inc} *= 532 nm*

Optical excitation of SPP

(d) Coupling with conventional Photonic elements

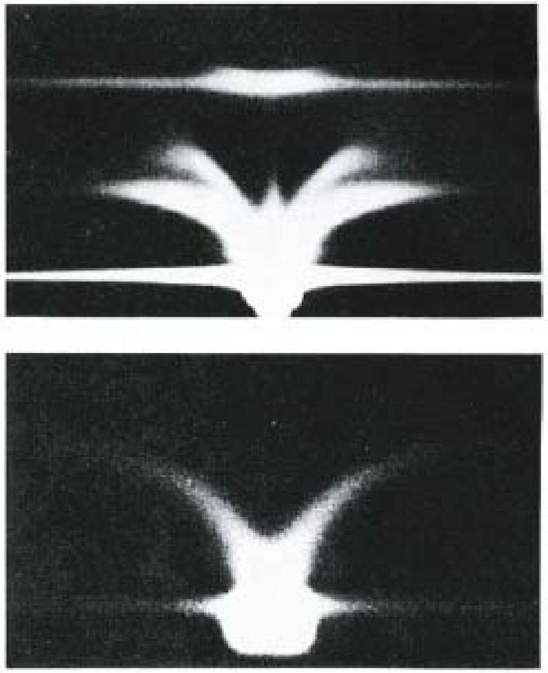
e.g. fiber taper

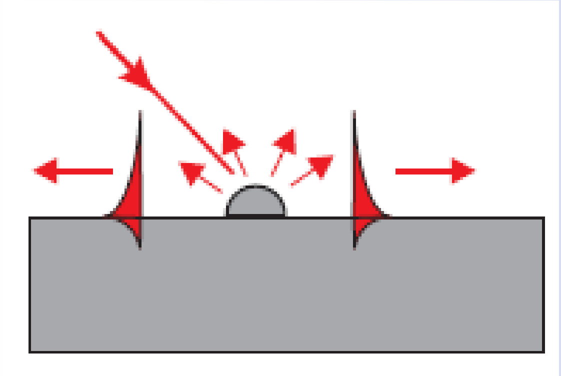


Optical excitation of SPP

(d) Others:

e.g. charge impact, surface feature, surface roughness


(a)
(b)



Dr. Tao Li taoli@nju.edu.cn

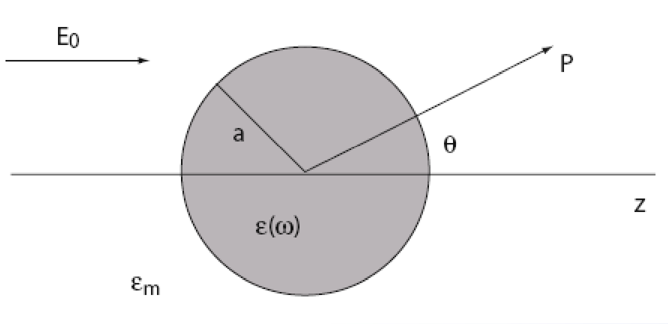
Outline

- Concepts
- Basic principles
- Surface Plasmon
  - SPP at flat metal/insulator surfaces
  - Optical excitation of SPP
  - **Localized Surface plasmon (LSP)**
  - Application of SPP
- Metamaterial
- Summary

Dr. Tao Li taoli@nju.edu.cn

Localized Surface Plasmon (LSP)

Modes of Sub-wavelength metal particle



$$\Phi_{\text{in}}(r,\theta) = \sum_{l=0}^{\infty} A_l r^l P_l(\cos\theta)$$

$$\Phi_{\text{out}}(r,\theta) = \sum_{l=0}^{\infty} \left[B_l r^l + C_l r^{-(l+1)}\right] P_l(\cos\theta).$$

Boundary condition

$$\Phi_{\text{in}} = -\frac{3\varepsilon_m}{\varepsilon + 2\varepsilon_m} E_0 r \cos\theta$$

$$\Phi_{\text{out}} = -E_0 r \cos\theta + \frac{\mathbf{p}\cdot\mathbf{r}}{4\pi\varepsilon_0\varepsilon_m r^3}$$

$$\mathbf{p} = 4\pi\varepsilon_0\varepsilon_m a^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m}\mathbf{E}_0.$$

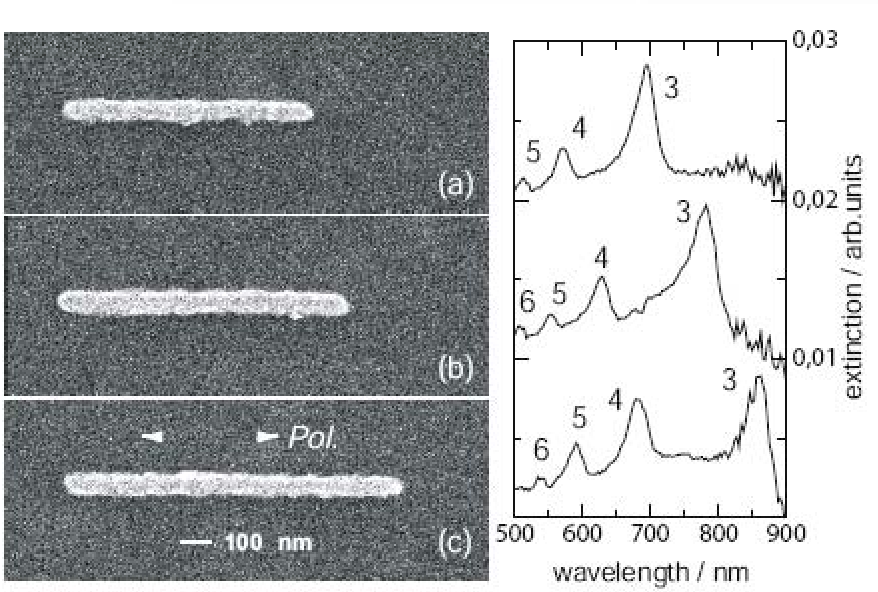
polarizability

$$\alpha = 4\pi a^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m}$$

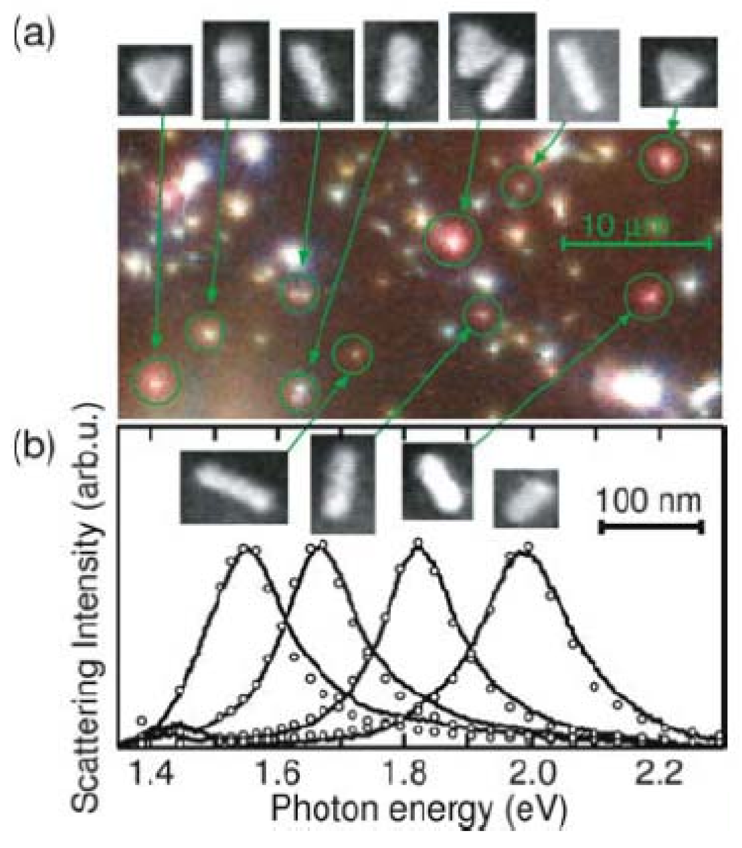
Determine the resonance!

Localized Surface Plasmon (LSP)

Observation of Particle Plasmon



Klar et al



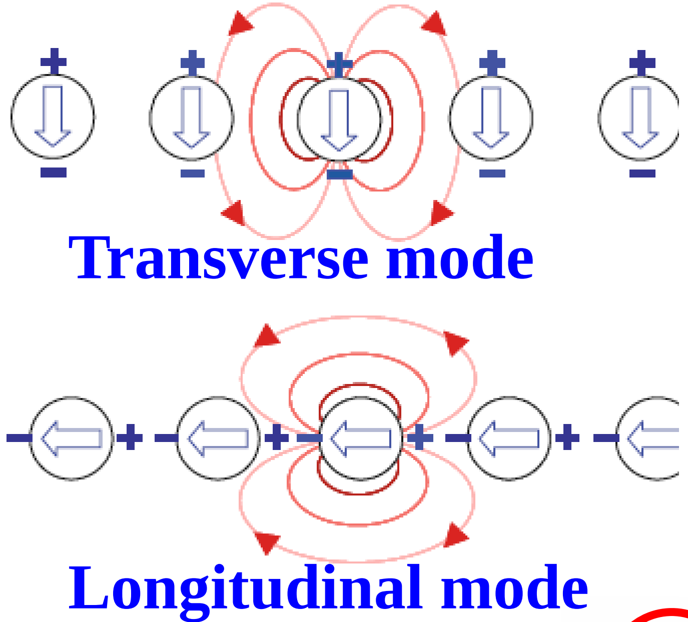
$$\alpha \approx \frac{V}{\left(L + \frac{\varepsilon_m}{\varepsilon - \varepsilon_m}\right) + A\varepsilon_m x^2 + B\varepsilon_m^2 x^4 - i\frac{4\pi^2 \varepsilon_m^{3/2}}{3}\frac{V}{\lambda_0^3}},$$

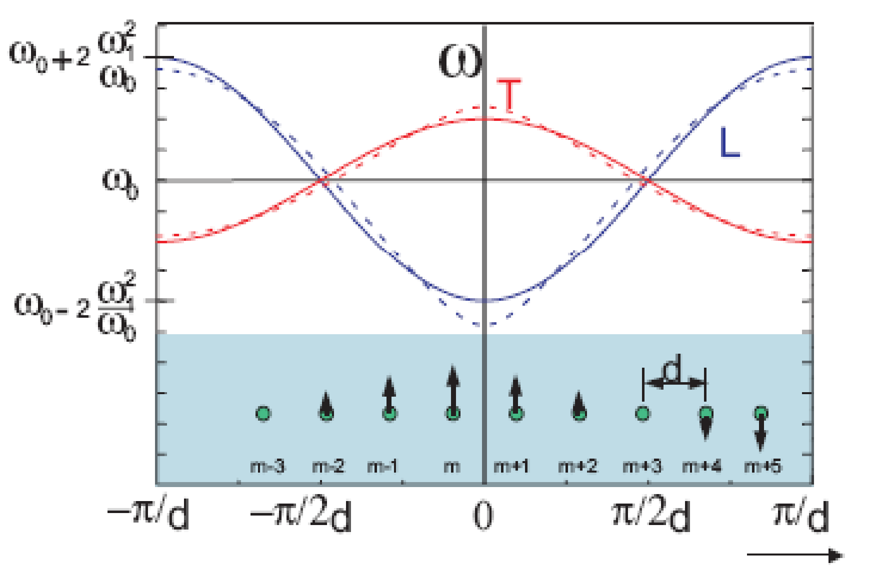
$$A(L) = -0.4865L - 1.046L^2 + 0.8481L^3$$

$$B(L) = 0.01909L + 0.1999L^2 + 0.6077L^3$$

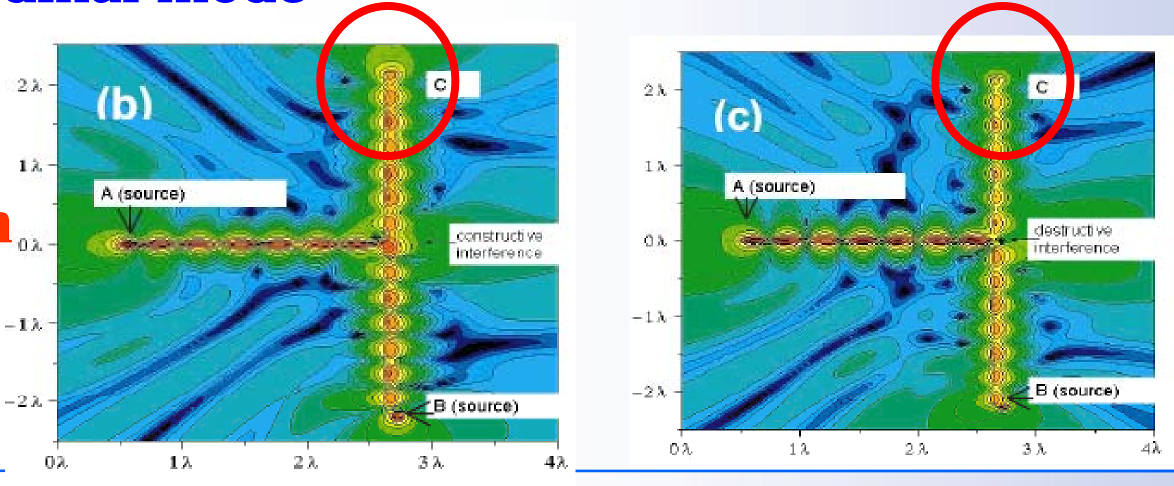
Kuwata et al

Coupling of LSP





Selective Switch



Outline

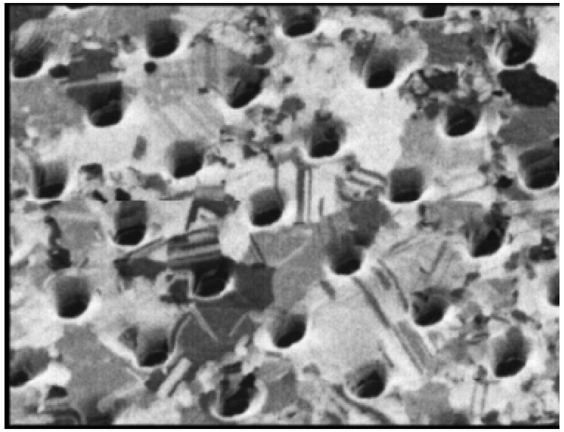
- Concepts
- Basic principles
- Surface Plasmon
  - SPP at flat metal surfaces
  - Optical excitation of SPP
  - Localized Surface plasmon (LSP)
  - **Application of SPP**
- Metamaterial
- Summary

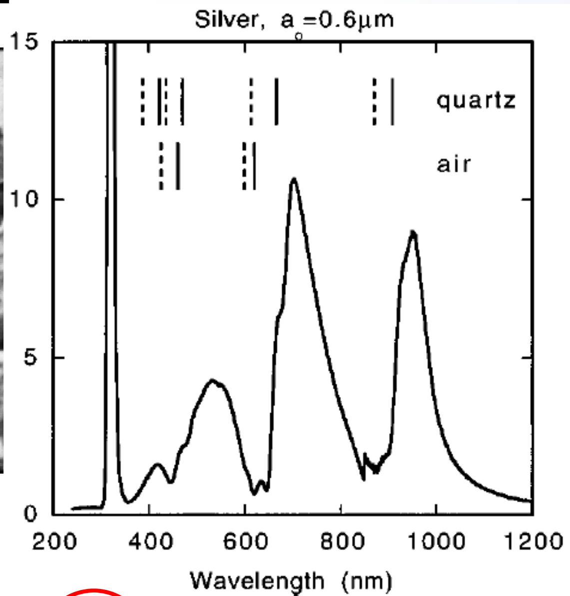
 Dr. Tao Li taoli@nju.edu.cn

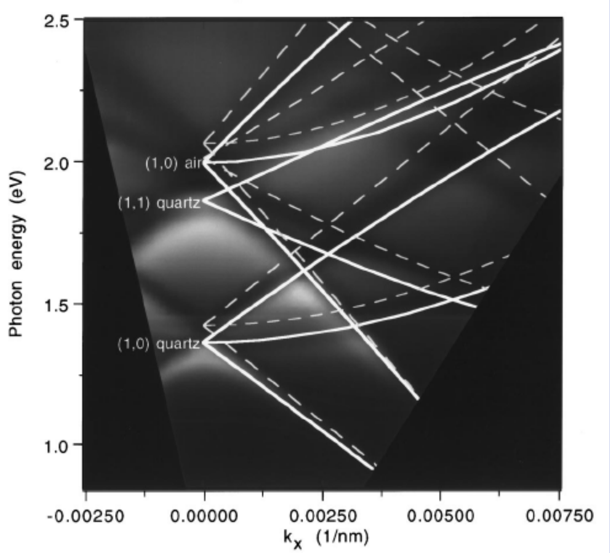
Application of SPP and Pioneering Researches

Modulating light:

Extraordinary Optical Transmission (EOT)







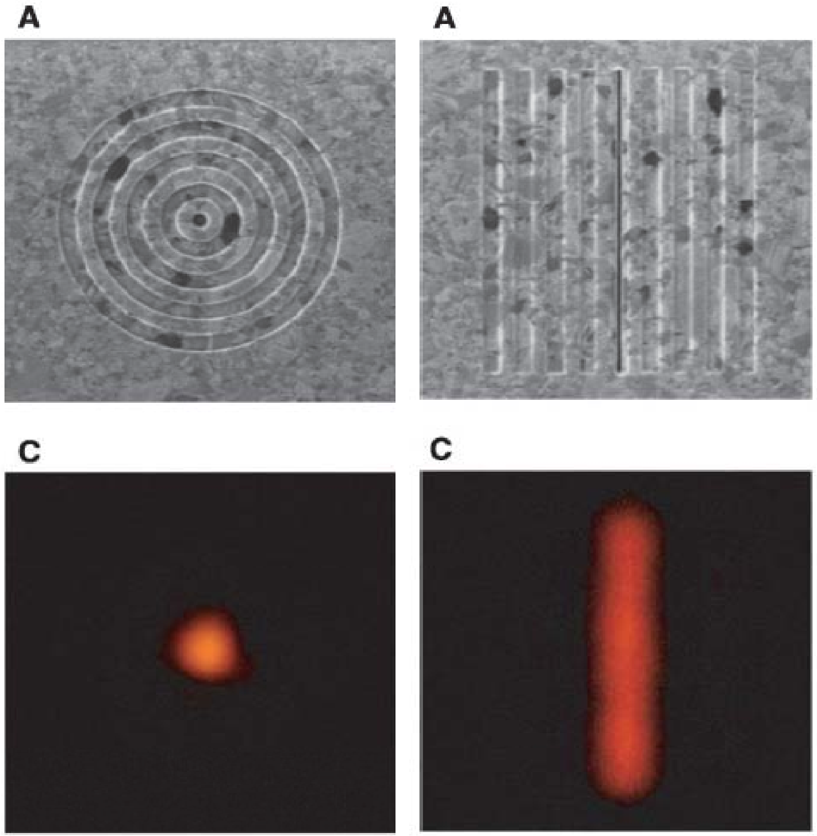
Ebbesen et al,
Nature, PRB, (1998)

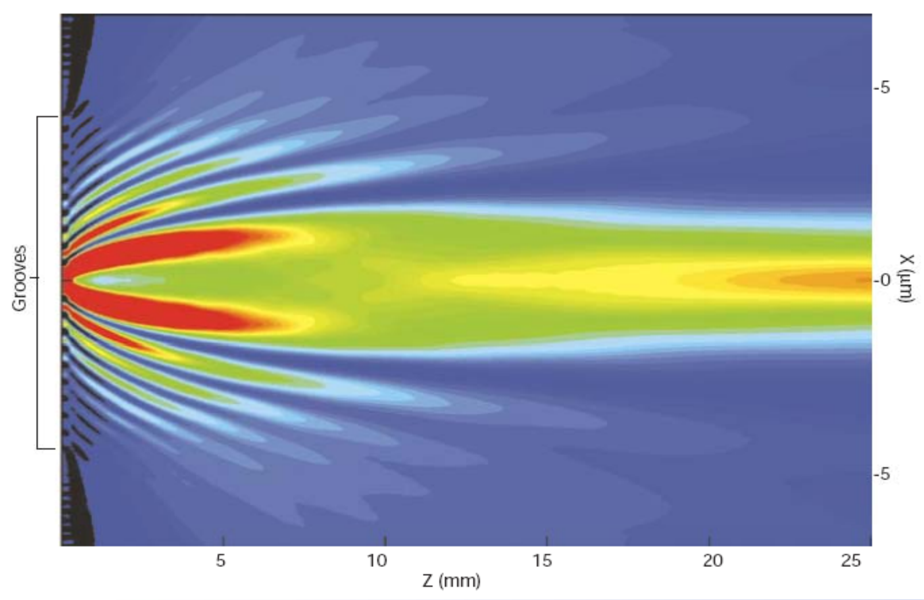
$$\vec{k}_{sp} = \vec{k}_x \pm i\vec{G}_x \pm j\vec{G}_y$$

$$(i^2 + j^2)^{1/2}\lambda = a_0\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{1/2}$$

Angle dispersion

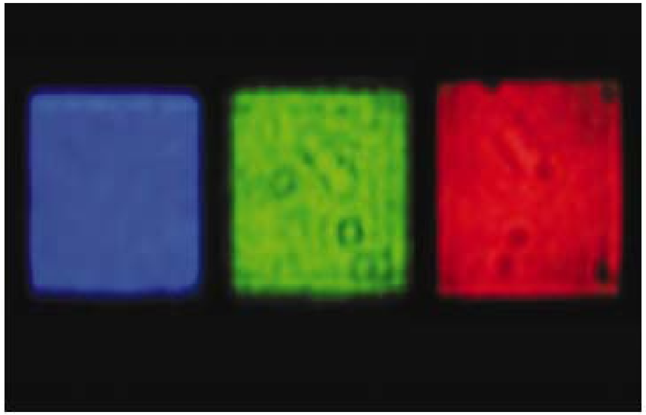
Modulating light: Directional Beaming

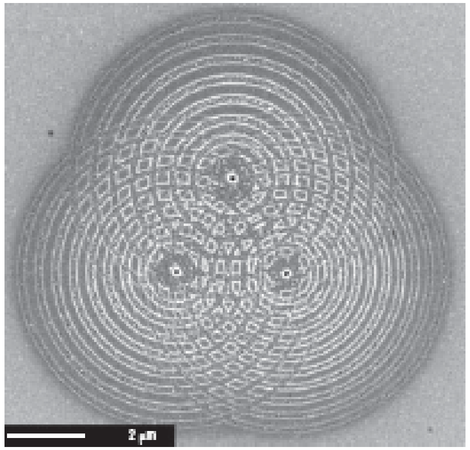


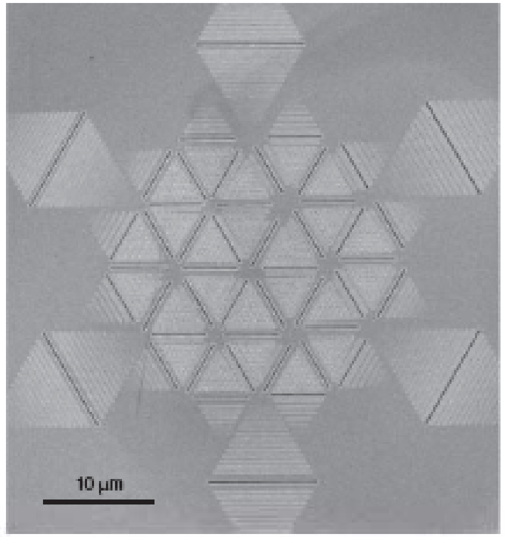


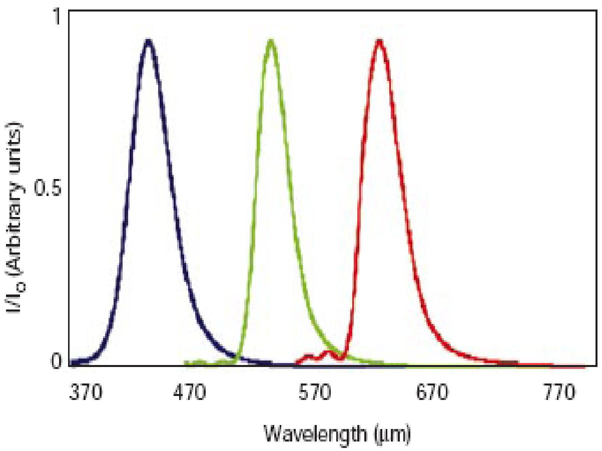
Lezec et al, Nature (2002)

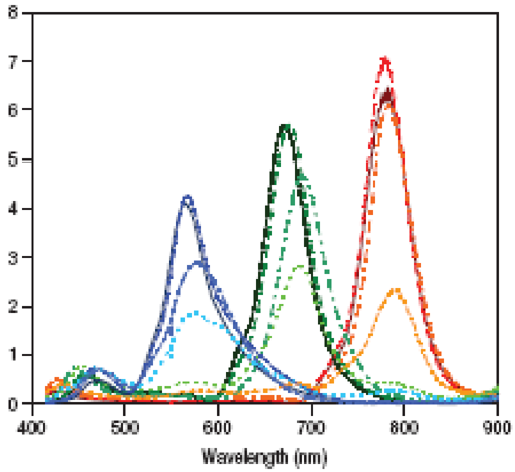
Modulating light: Color Sorting

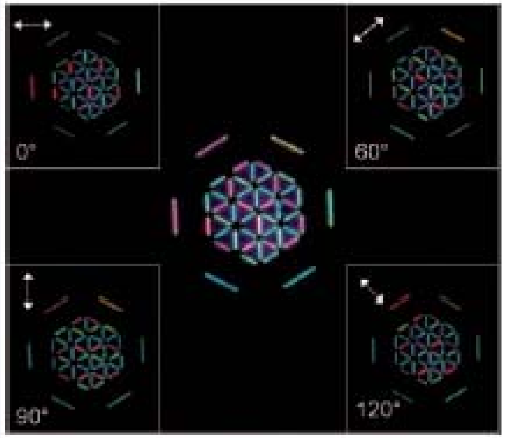






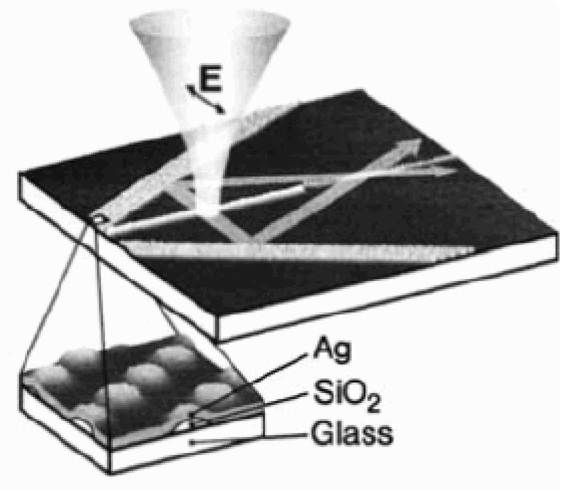


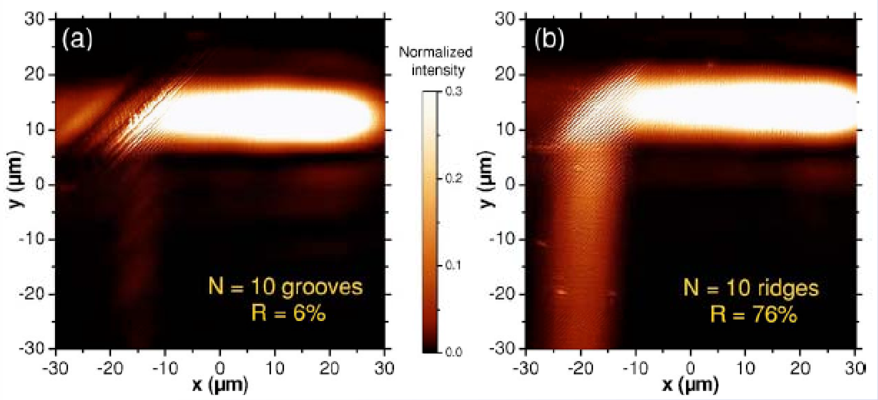




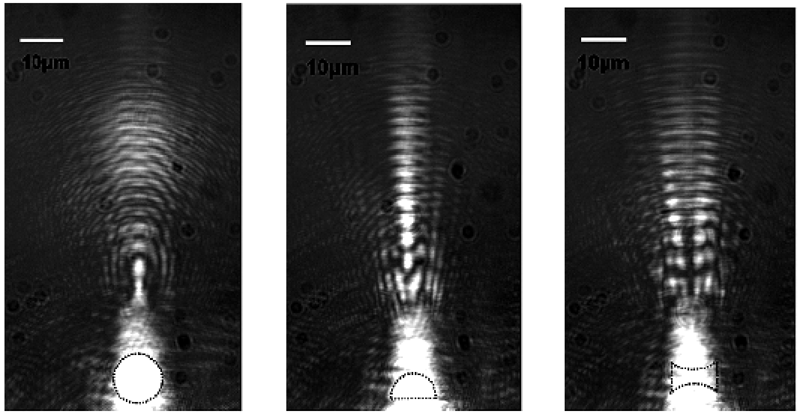
Dr. Tao Li taoli@nju.edu.cn

2 D Optics – Plasmonic circuit

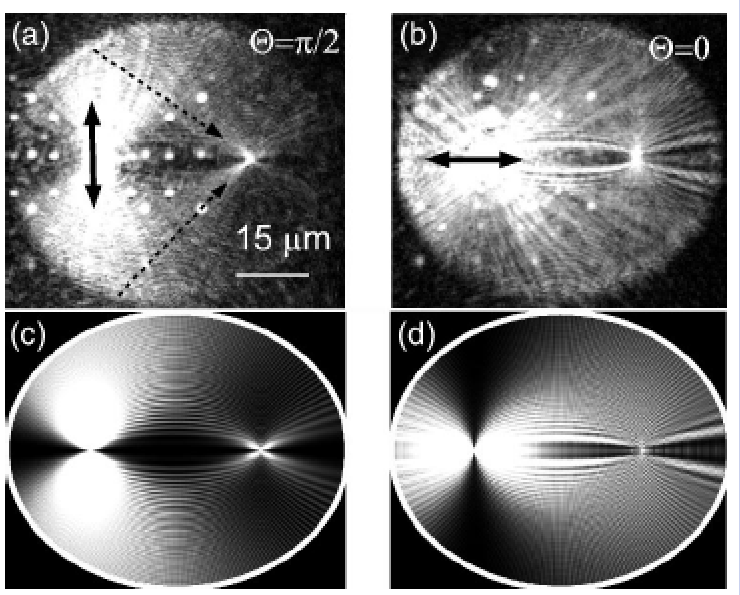




SPP Brag reflector

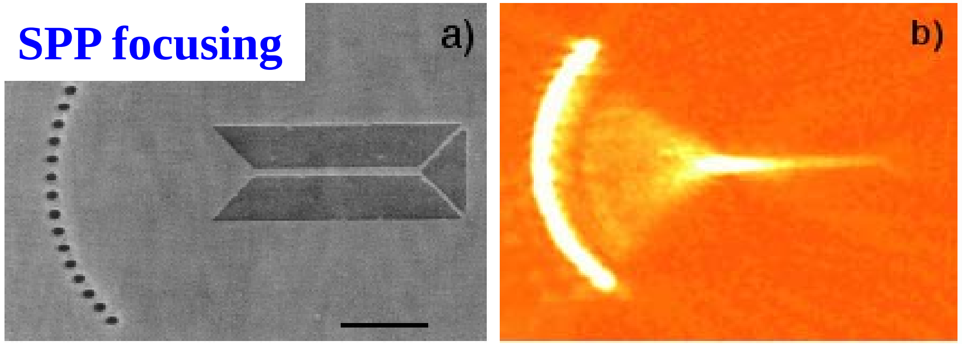


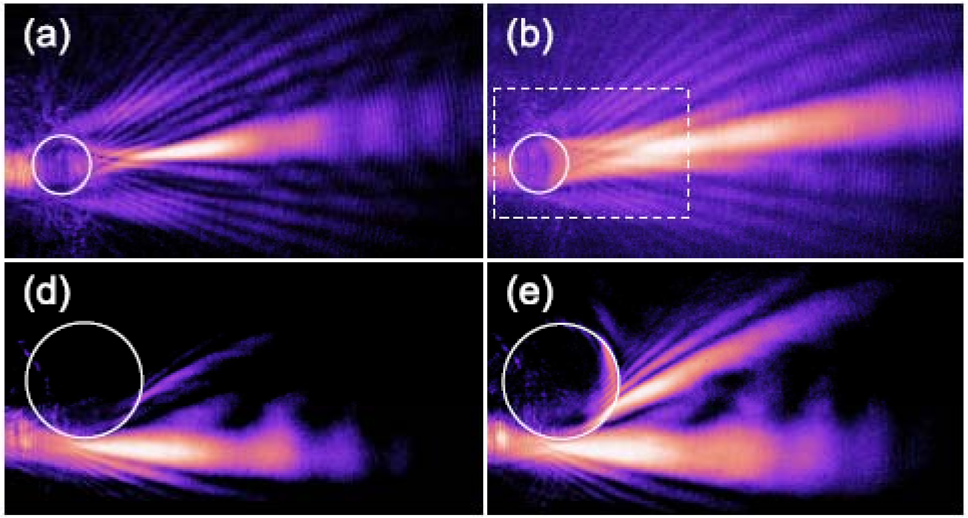
SPP lens



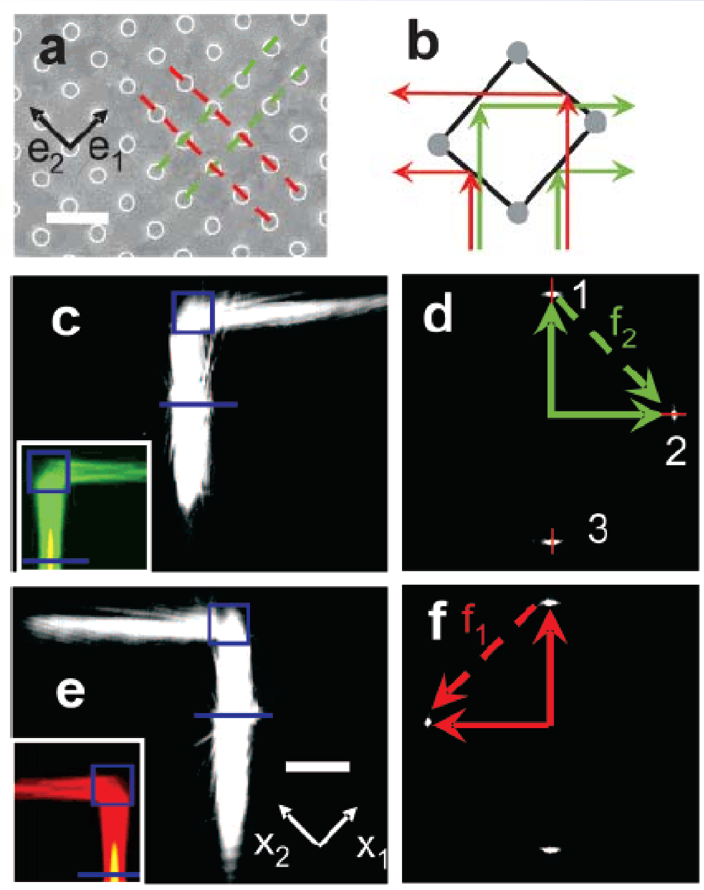
2 D Optics – Plasmonic circuit

SPP focusing



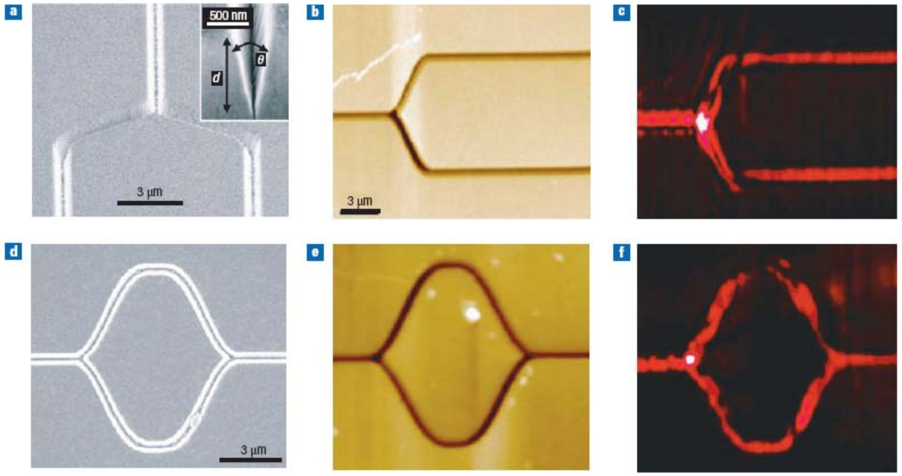


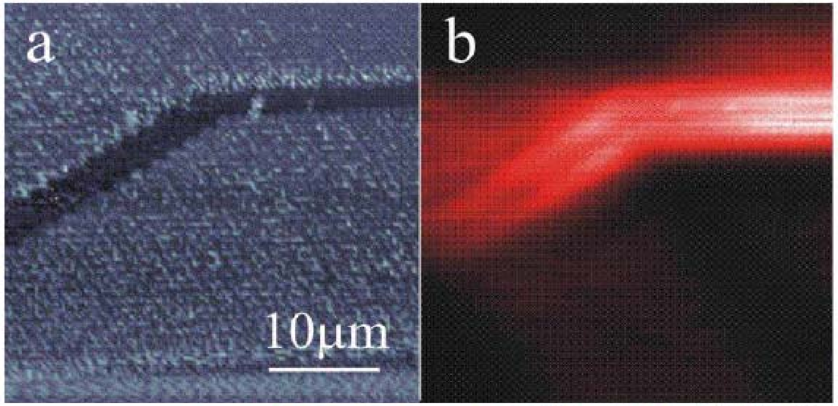
Refracting SPP wave

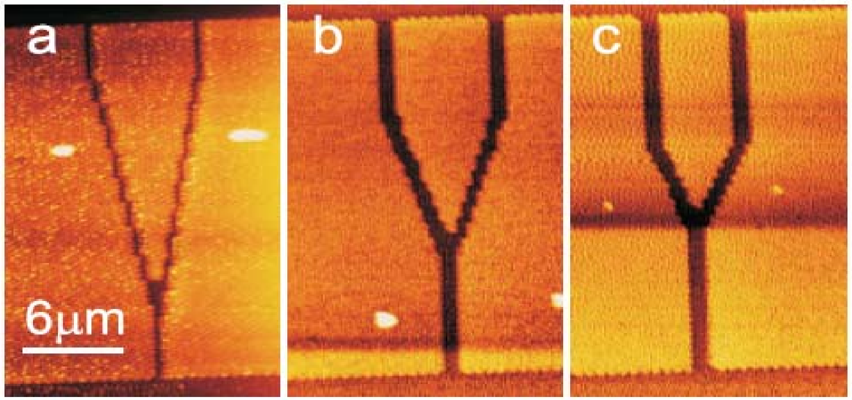


SPP Demultiplexer

2 D Optics – Plasmonic circuit

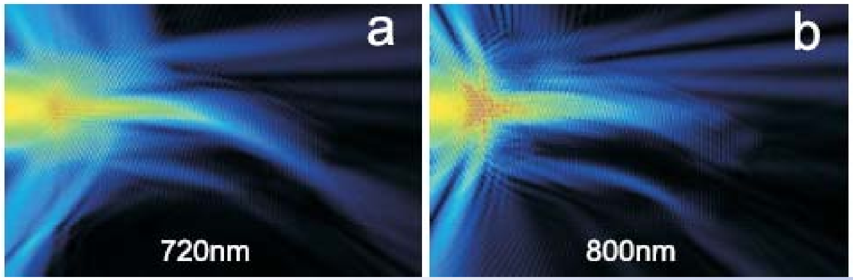






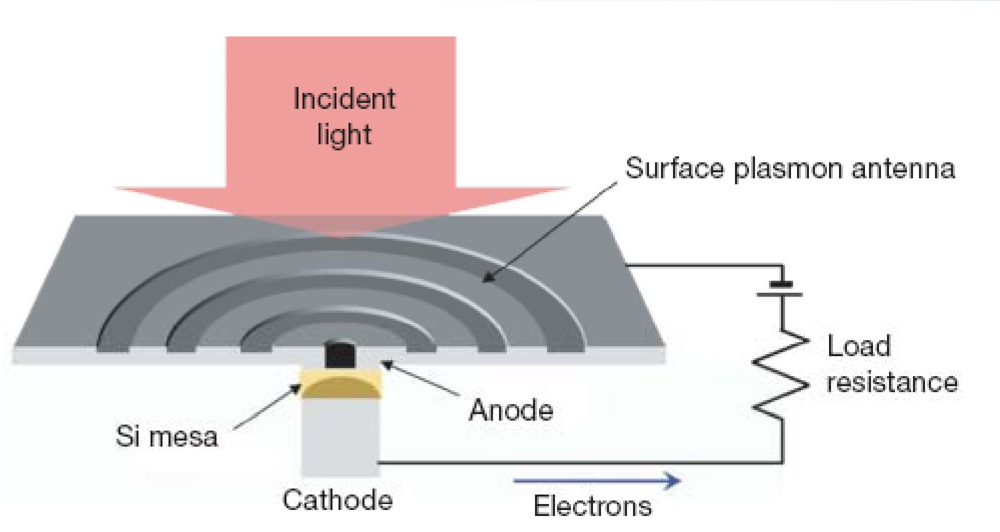
Subwavelength waveguide by grooves

Plasmonic BG waveguides

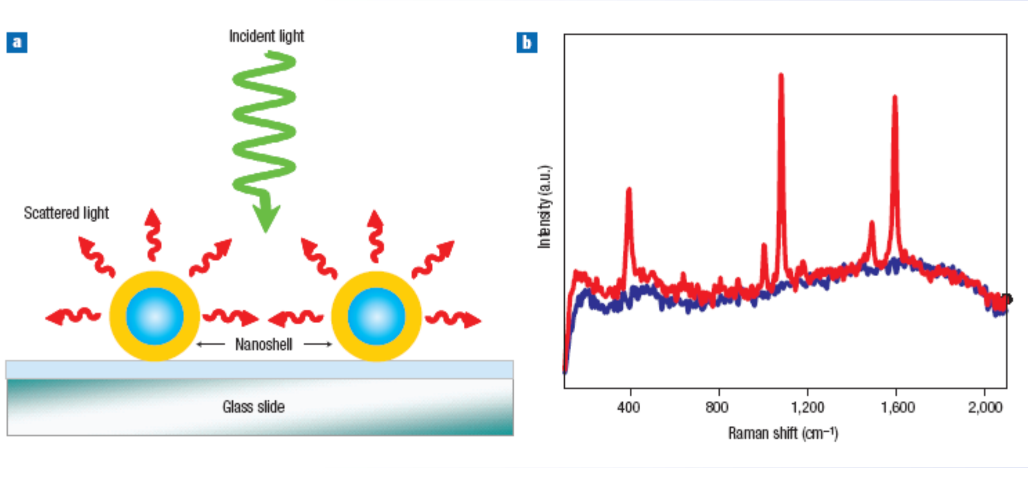


Strongly localized field

Enhanced detector

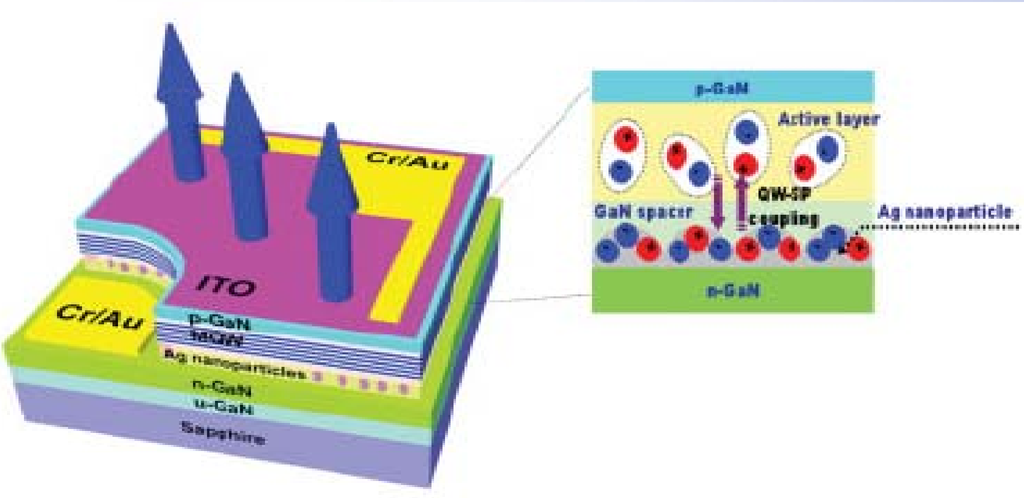


Enhanced Raman Scattering

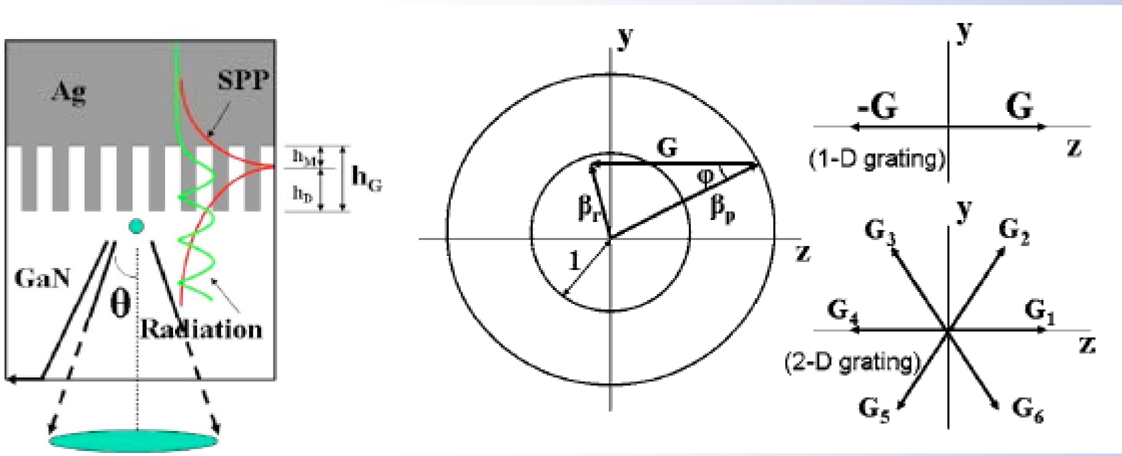


Enhance the light emission

Strong field and enhanced DOS of SPP to improve the internal Quantum effeciency



Reciprocal vectors to extract the light from LED to improve the external Quantum Effeciency



有望实现LED白光照明

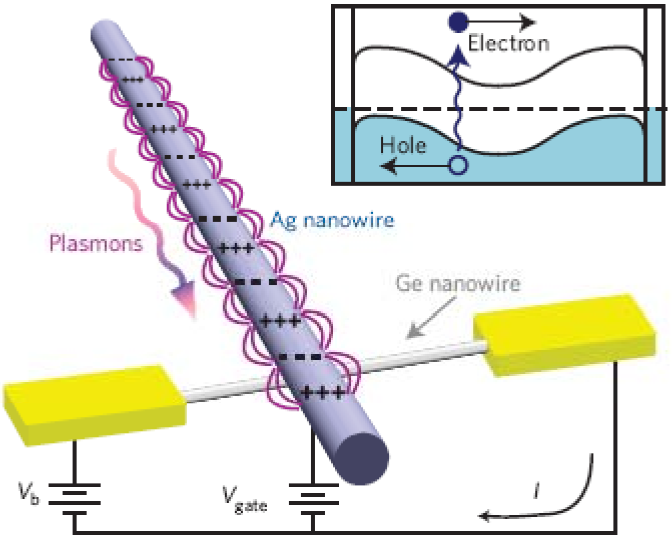
Dr. Tao Li taoli@nju.edu.cn

nature physics
LETTERS
PUBLISHED ONLINE: 24 MAY 2009 | DOI: 10.1038/NPHYS1284

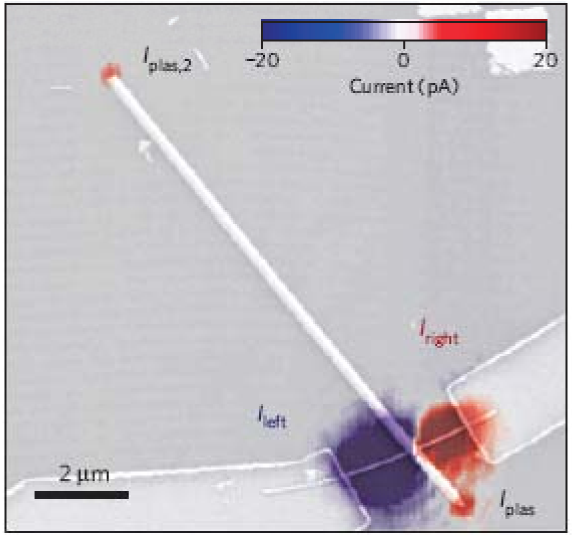
Near-field electrical detection of optical plasmons and single-plasmon sources

Abram L. Falk[1]*, Frank H. L. Koppens[1]*, Chun L. Yu[2], Kibum Kang[3], Nathalie de Leon Snapp[2], Alexey V. Akimov[1], Moon-Ho Jo[3], Mikhail D. Lukin[1†] and Hongkun Park[1,2†]

a



b



Outline

- Concepts
- Basic principles
- Surface Plasmon
- Metamaterial
  - **Artificial Magnetism**
  - Negative Index Material (NIM)
  - Transformation Optics
  - Illumination Optics
- Summary

Dr. Tao Li taoli@nju.edu.cn

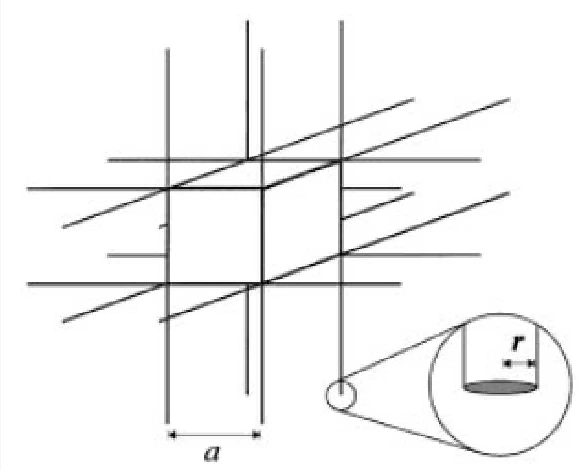
Artificial Plasma

Reconsider the plasma of metal

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m_{\text{eff}}}$$

n is the electron density
it is fixed for a certain metal



1996, Pendry propose a dilute metal – nanowire mesh

Changes n to $n_{\text{eff}} = n\frac{\pi r^2}{a^2}$

$$\omega_p^2 = \frac{n_{\text{eff}} e^2}{\varepsilon_0 m_{\text{eff}}} = \frac{2\pi c_0^2}{a^2 \ln(a/r)}$$

For example: Al

$r = 1.0 \times 10^{-6}$ m , $a = 5 \times 10^{-3}$ m
$n = 1.806 \times 10^{29}$ m^{-3} (aluminum)

ω_p : 3.82e^{12}GHz→ 8.2 GHz

Magnetism

$$\vec{D} = \varepsilon\varepsilon_0\vec{E}$$

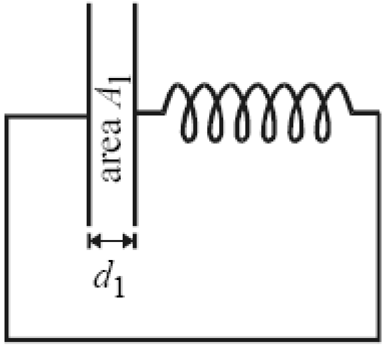
$$\vec{B} = \mu\mu_0\vec{H}$$ Always be neglected for optical material

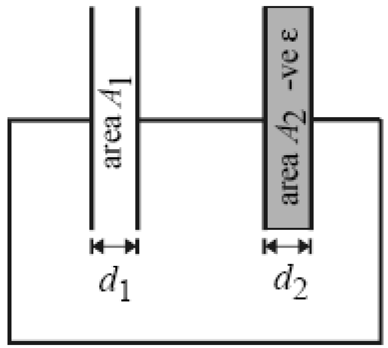
Natural magnetism (μ) main comes from the spin,
In dynamic system, spin response to the external alternative field, but frequency of the spin process is limited up to **GHz**!

So at optical frequency, we regard μ = 1 for almost all natural material

It is also the right reason we usually do not consider μ in Maxwell's Equations

Two circuits





$$Z_C + Z_L = \frac{1}{i\omega C_1} + i\omega L = 0$$

$$C_1 = \frac{\varepsilon_0 A_1}{d_1}$$

$$C_2 = \frac{\varepsilon\varepsilon_0 A_2}{d_2} = \left(1 - \frac{\omega_p^2}{\omega^2}\right)\frac{\varepsilon_0 A_2}{d_2} \approx -\frac{\omega_p^2 \varepsilon_0 A_2}{\omega^2 d_2},$$

Circuit resonance at

$$\omega_0 = (LC)^{-1/2}$$

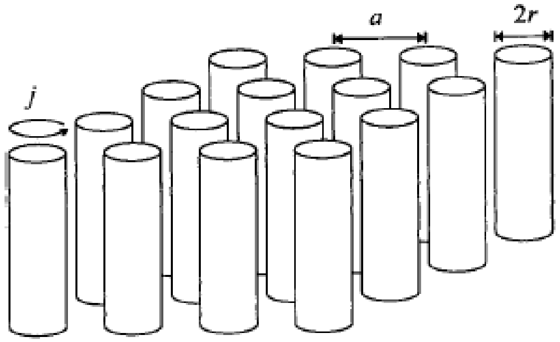
$$Z_2 = \frac{1}{i\omega C_2} \approx \frac{-\omega d_2}{i\omega_p^2 \varepsilon_0 A_2} = i\omega L_2$$

$$L_2 = \frac{d_2}{\omega_p^2 \varepsilon_0 A_2}$$

Resonant Circuit

Magnetism without magnets

Array of metallic cylinder



$$H = H_0 + j - \frac{\pi r^2}{a^2} j,$$

$$i\omega\mu_0\pi r^2 \left(H_0 + j - \frac{\pi r^2}{a^2} j \right) = 2\pi r \rho j,$$

$$B_{\text{eff}} = \mu_0 H_0,$$ **Out**

$$H_{\text{eff}} = H_0 - \frac{\pi r^2}{a^2} j.$$ **In**

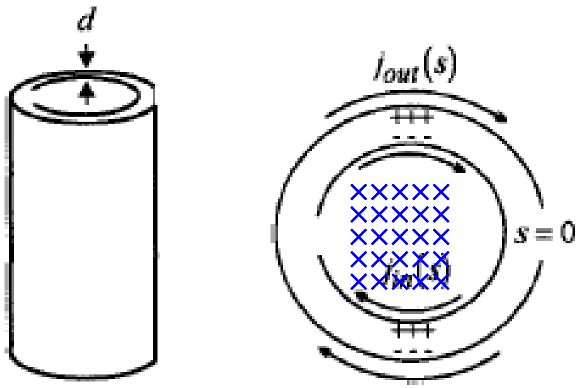
$$\mu = 1 - \frac{F}{1 + i2\rho / \omega r \mu_0}$$

$$\mu_{\text{eff}} = \frac{B_{\text{eff}}}{\mu_0 H_{\text{eff}}} = 1 - \frac{\pi r^2/a^2}{1 + i2\rho/(\mu_0\omega r)}.$$

"magnetic" Drude model

Magnetism without magnets

Array of metallic cylinder

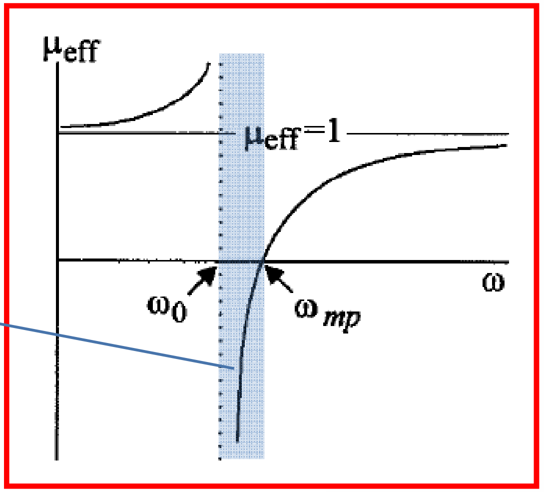


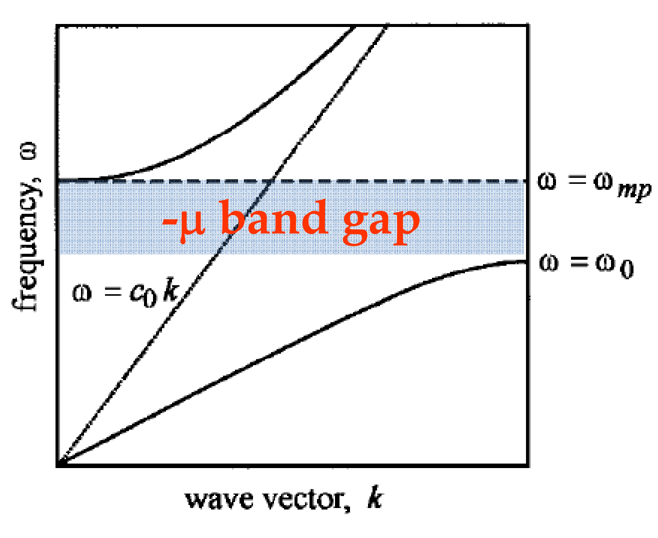
$$-\mathrm{i}\omega\mu_0\pi r^2\left(H_0 + j - \frac{\pi r^2}{a^2} j\right) = 2\pi r\rho j - \frac{j}{\mathrm{i}\omega C}$$

$$\mu = 1 - \frac{f\omega^2}{\omega_0^{\ 2} - \omega^2 + i\Gamma\omega}$$

"magnetic" Lonretz model

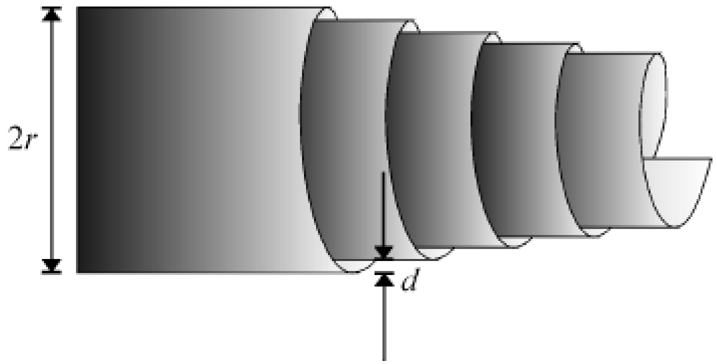
Negative μ

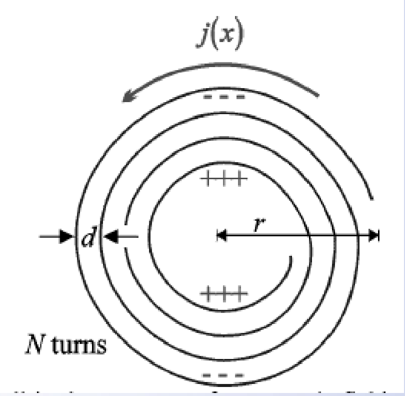




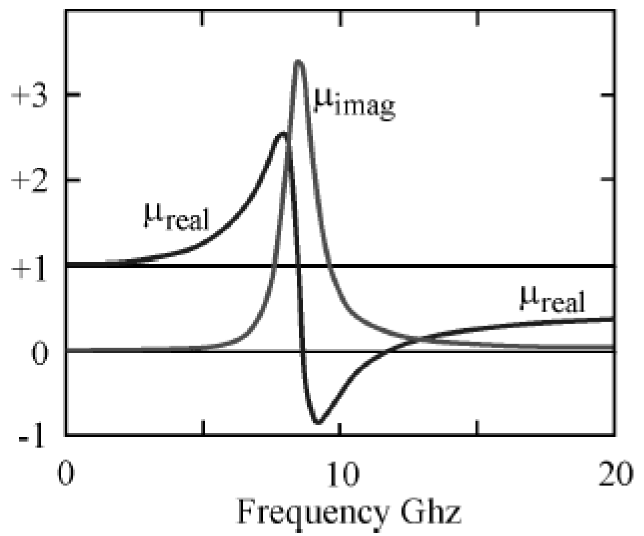
Artificial Magnetism

Swiss roll





$$\mu_{eff} = 1 - \frac{\dfrac{\pi r^2}{a^2}}{1 + \dfrac{2Ri}{\omega r \mu_0 (N-1)} - \dfrac{d c_0^2}{2\pi^2 r^3 (N-1)\omega^2}}$$

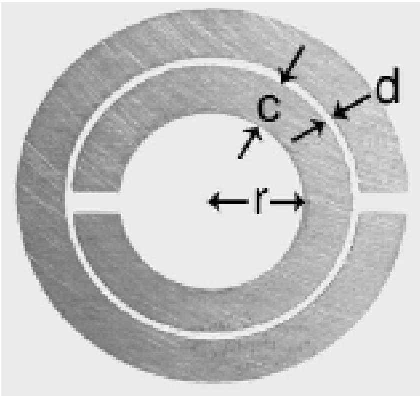


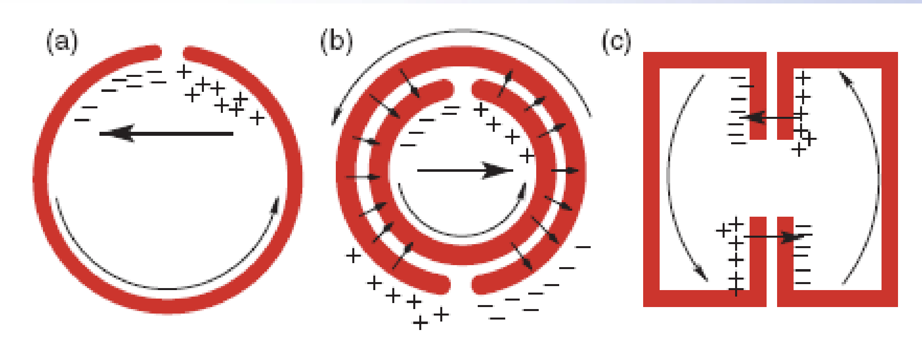
Artificial Magnetism

SRR

Split Resonant Ring

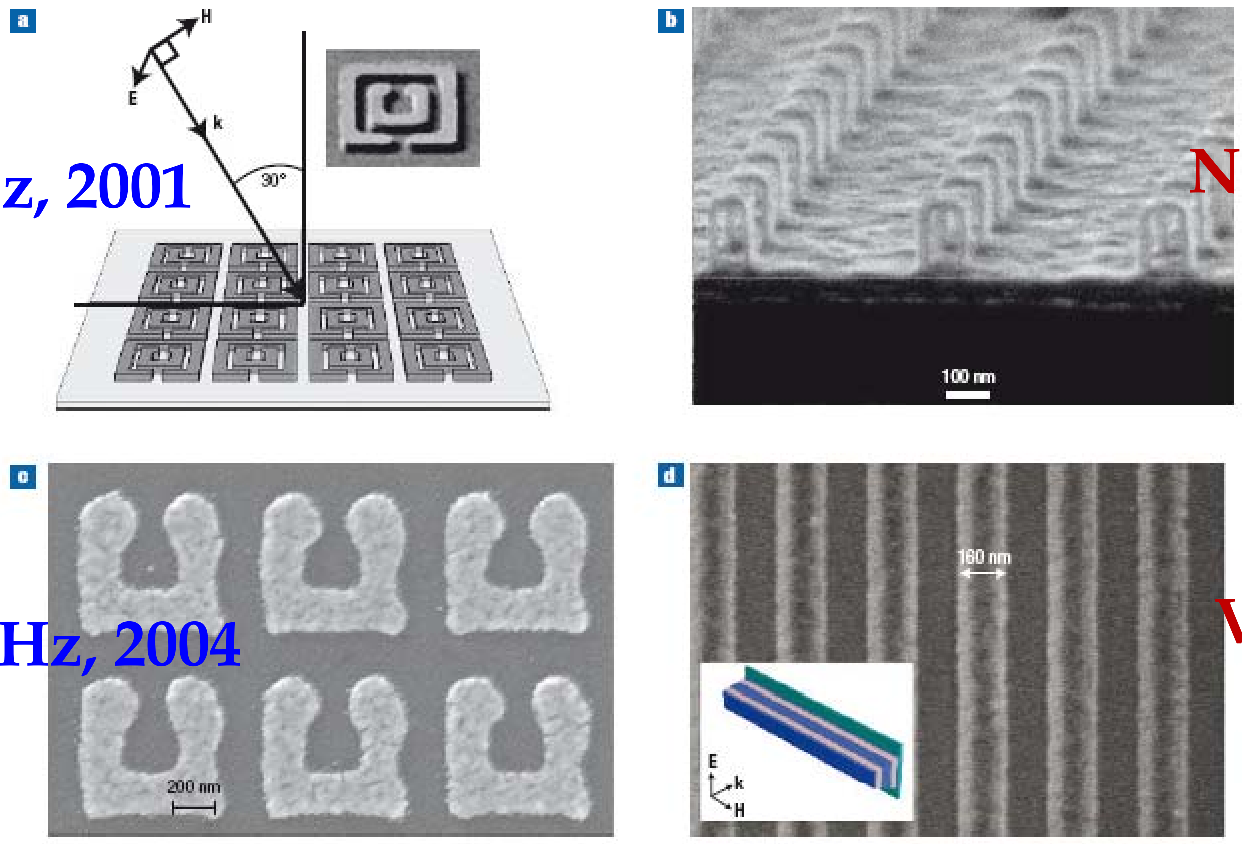
$$\mu = 1 - \frac{f\,\omega^2}{\omega_0^{\ 2} - \omega^2 + i\Gamma\omega}$$





Strong dipole **weak dipole** **quadruple**

Experimental Progress



~THz, 2001

NIR, 2005

~100THz, 2004

VIS, 2007

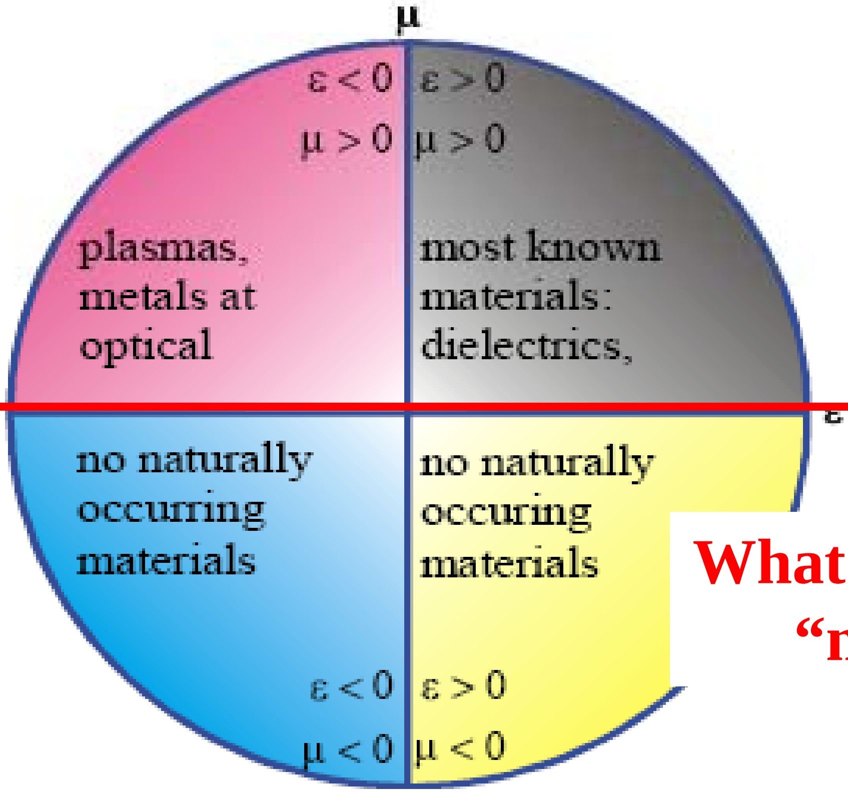
Outline

- Concepts
- Basic principles
- Surface Plasmon
- Metamaterial
  - Artificial Magnetism
  - **Negative Index Material (NIM)**
  - Transformation Optics
  - Illumination Optics
- Summary

Dr. Tao Li taoli@nju.edu.cn

Negative Refraction

Diagram of Classification by ε and μ



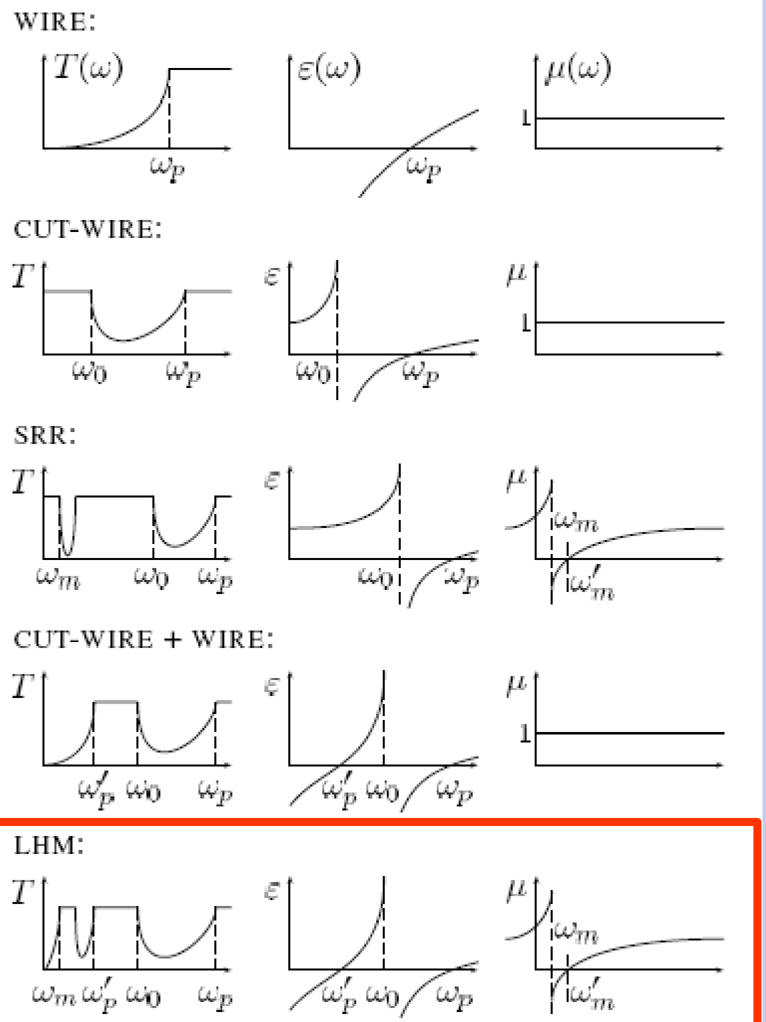
What we are interested "metamaterial"

Negative Refraction

$$\epsilon_{\text{eff}}^{\text{wire}}(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}.$$

$$\mu_{\text{eff}}^{\text{SRR}}(\omega) = 1 - \frac{\omega_m'^2 - \omega_m^2}{\omega^2 - \omega_m^2 + i\omega\gamma}.$$

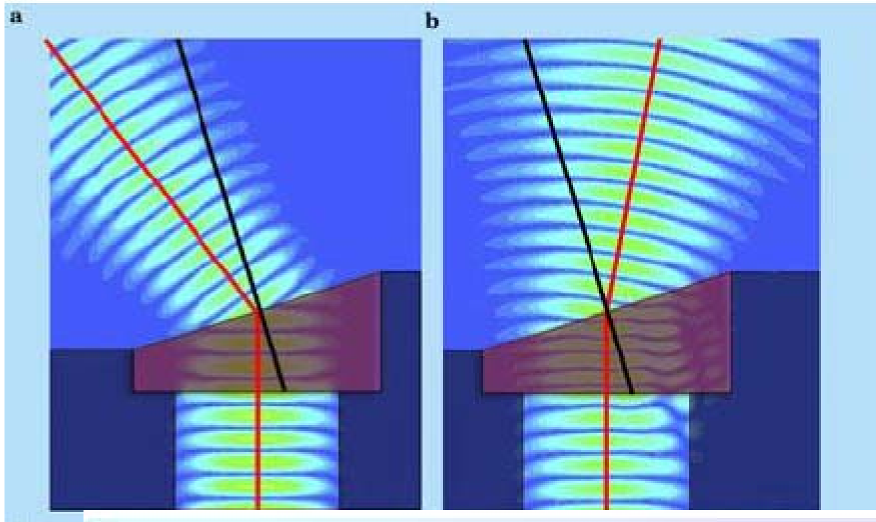
$$\epsilon_{\text{eff}}^{\text{SRR}}(\omega) = 1 - \frac{\omega_p^2 - \omega_0^2}{\omega^2 - \omega_0^2 + i\omega\gamma}.$$



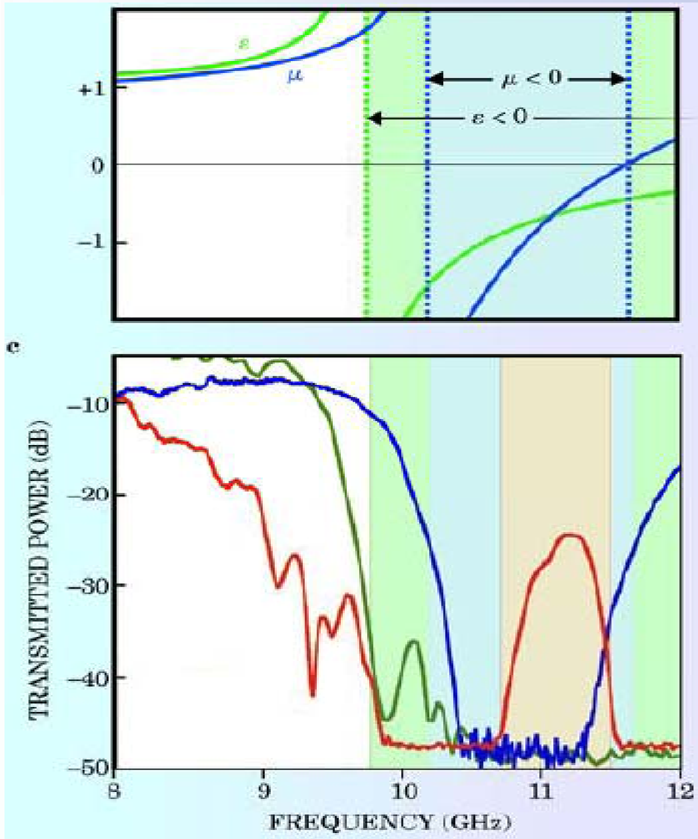
SRR+wire

Negative Refraction

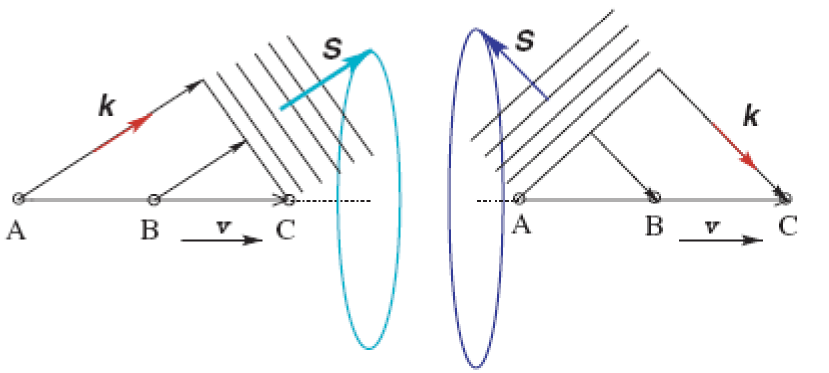
Simulation



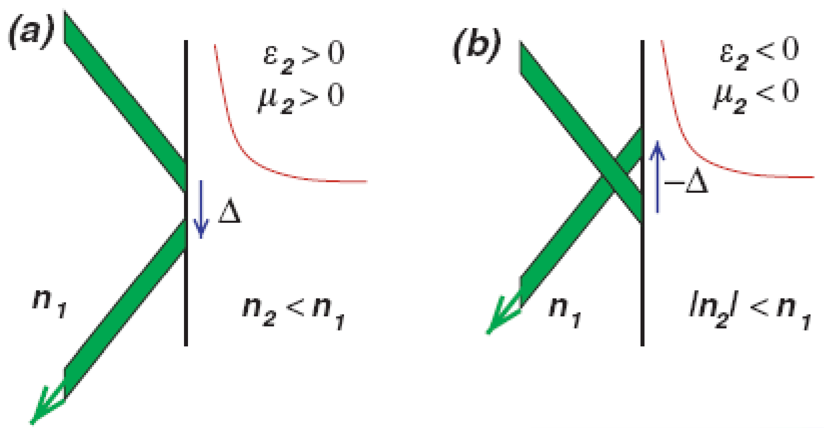
Experimental realizations



Fancy Phenomena



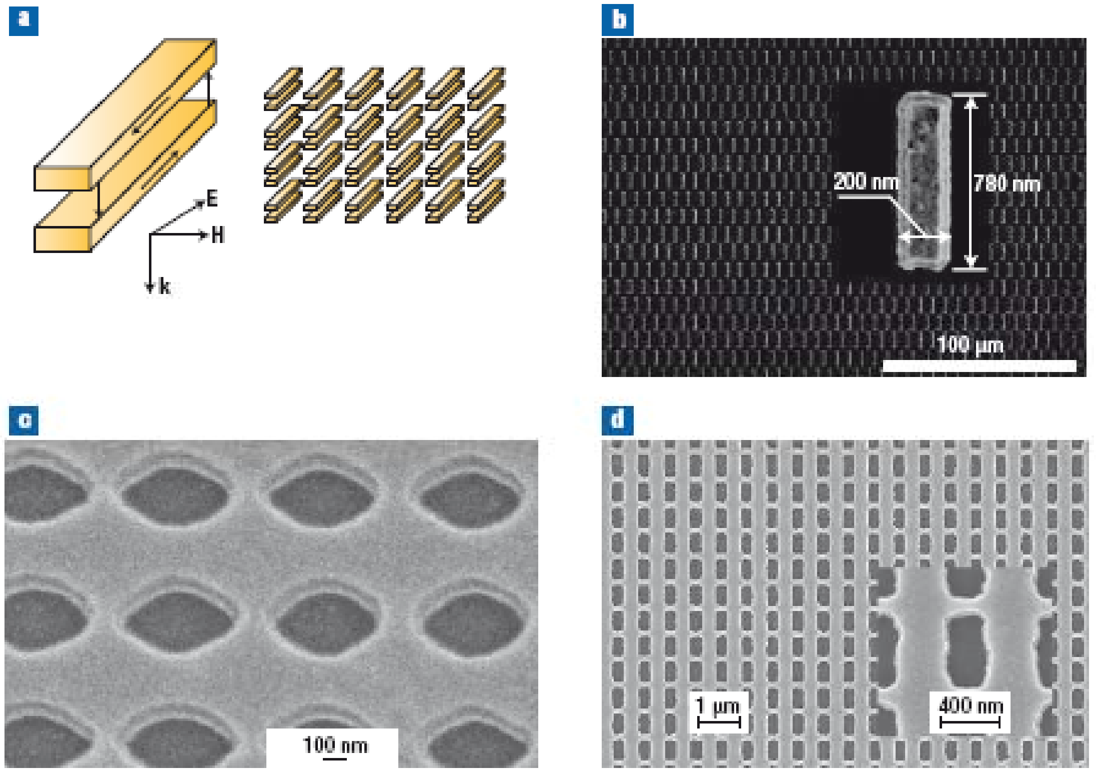
An obtuse angle cone for Cerenkov radiation



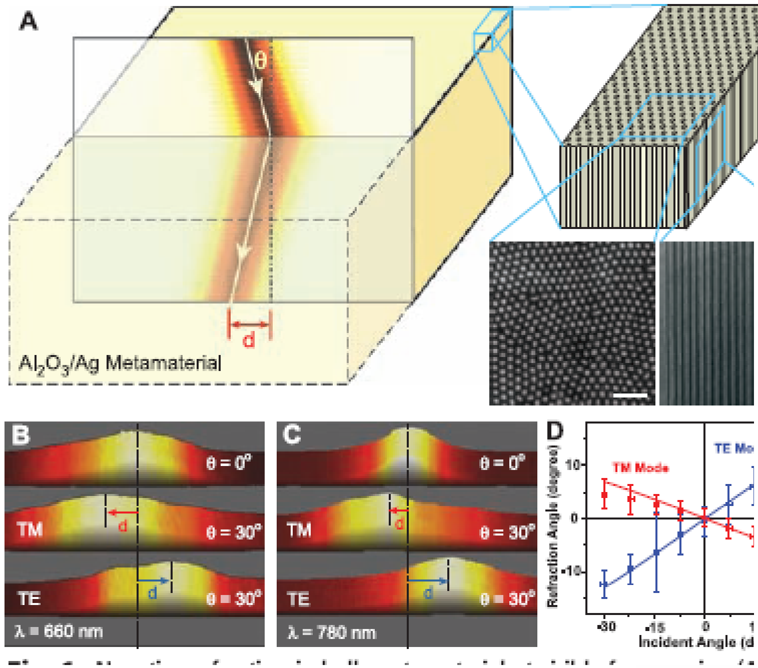
Reversed Goos–Hanchen shift

Nanjing University

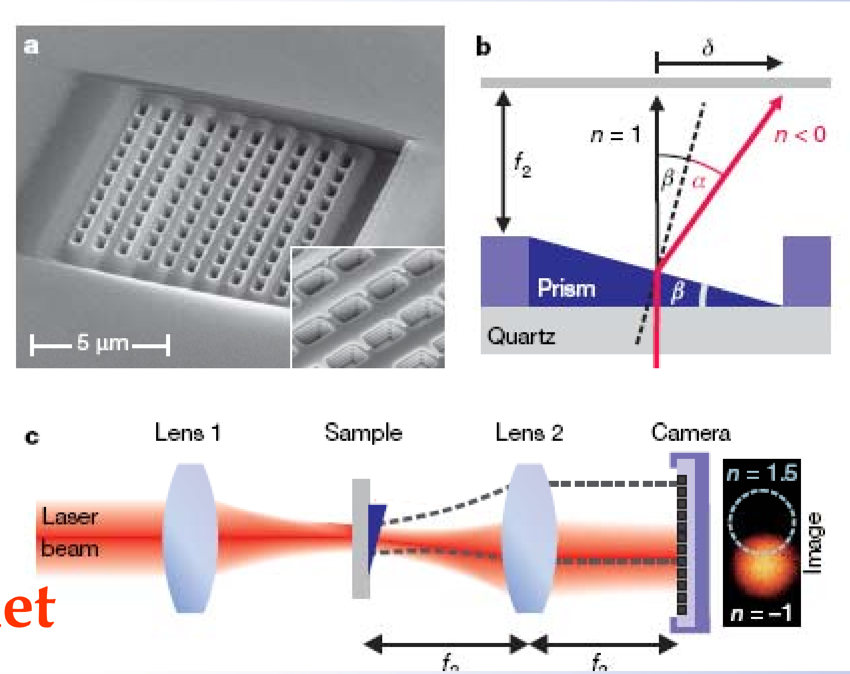
Recent Progress
-- VIS Frequency



Recent Progress
-- VIS Frequency



Effective media



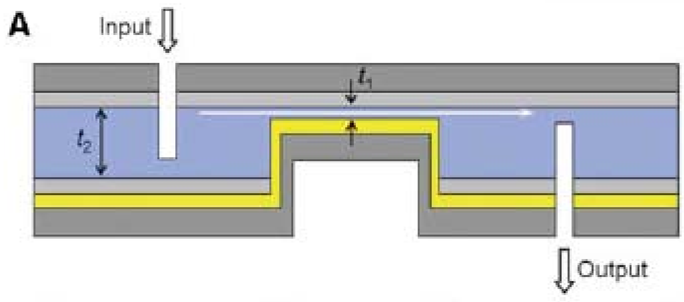
Prism 3D fishnet

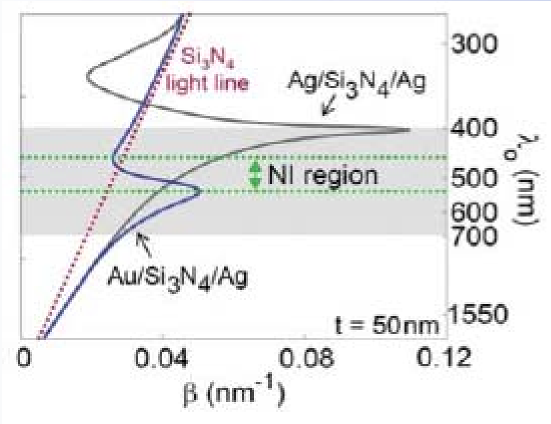
Other NIMs

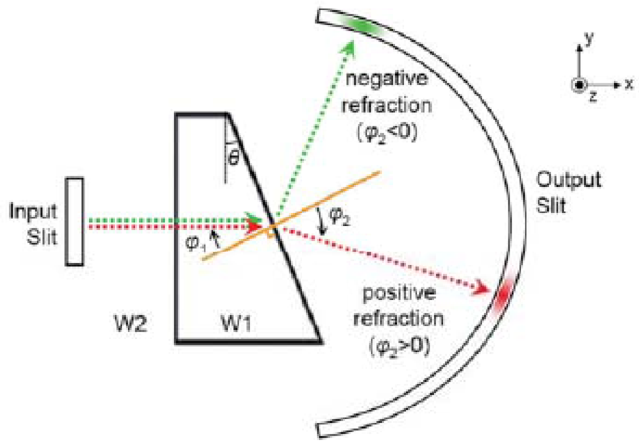
Photonic Crystal

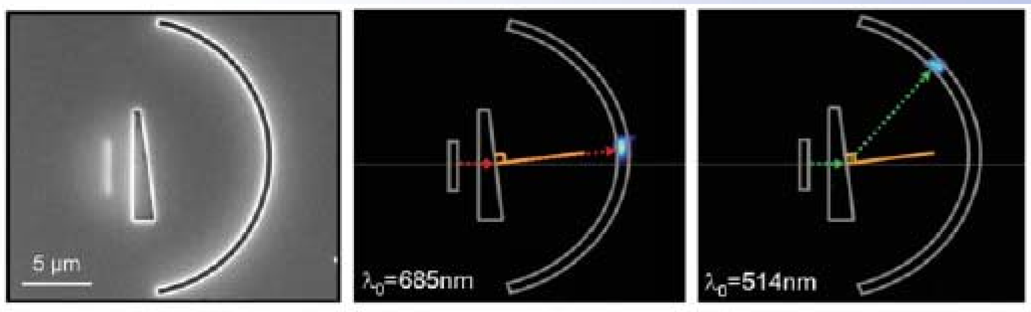
Effective anisotropic media

Negative dispersion waveguide









Outline

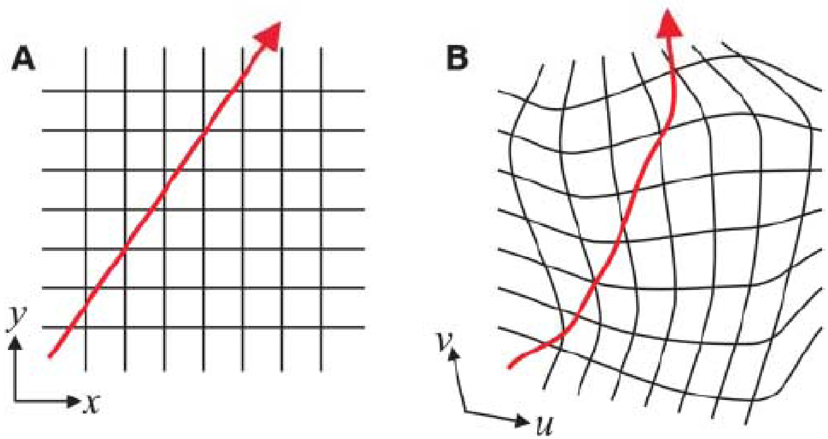
- Concepts
- Basic principles
- Surface Plasmon
- Metamaterial
  - Artificial Magnetism
  - Negative Index Material (NIM)
  - **Transformation Optics**
  - Illumination Optics
- Summary

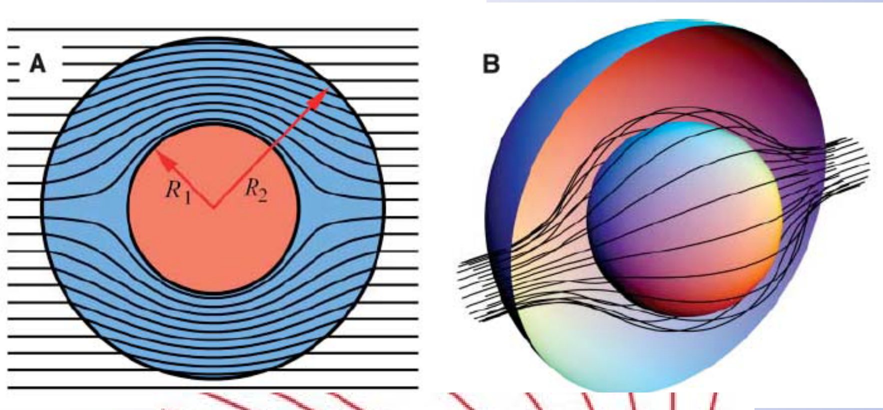
Dr. Tao Li taoli@nju.edu.cn

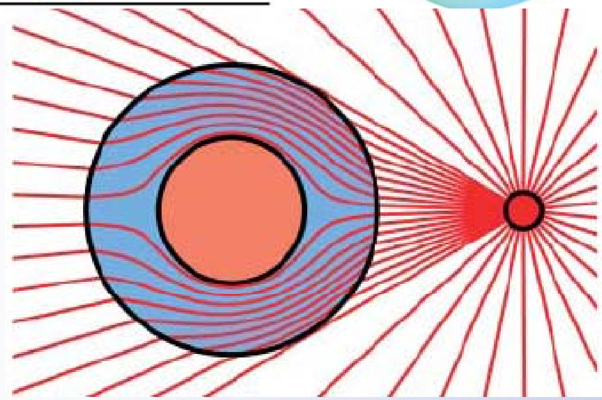
Transformation Optics

Controlling Electromagnetic Fields

J. B. Pendry,[1*] D. Schurig,[2] D. R. Smith[2]







Spatial transferred by parameters

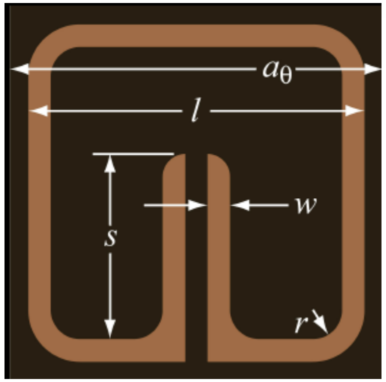
$$\varepsilon'_u = \varepsilon_u \frac{Q_u Q_v Q_w}{Q_u^2}, \qquad Q_u^2 = \left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial z}{\partial u}\right)^2$$

$$\mu'_u = \mu_u \frac{Q_u Q_v Q_w}{Q_u^2}, \text{ etc.} \qquad Q_v^2 = \left(\frac{\partial x}{\partial v}\right)^2 + \left(\frac{\partial y}{\partial v}\right)^2 + \left(\frac{\partial z}{\partial v}\right)^2$$

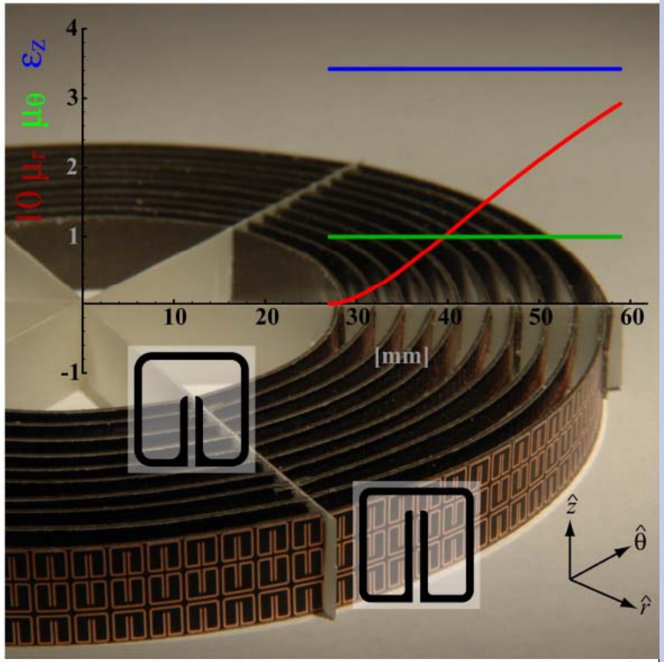
$$E'_u = Q_u E_u,\ H'_u = Q_u H_u,\ Q_w^2 = \left(\frac{\partial x}{\partial w}\right)^2 + \left(\frac{\partial y}{\partial w}\right)^2 + \left(\frac{\partial z}{\partial w}\right)^2$$

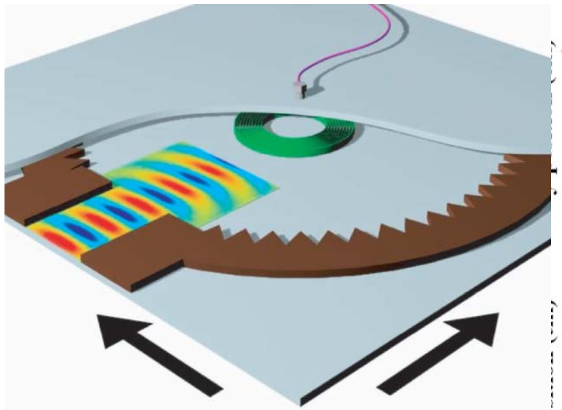
Optical Cloaking

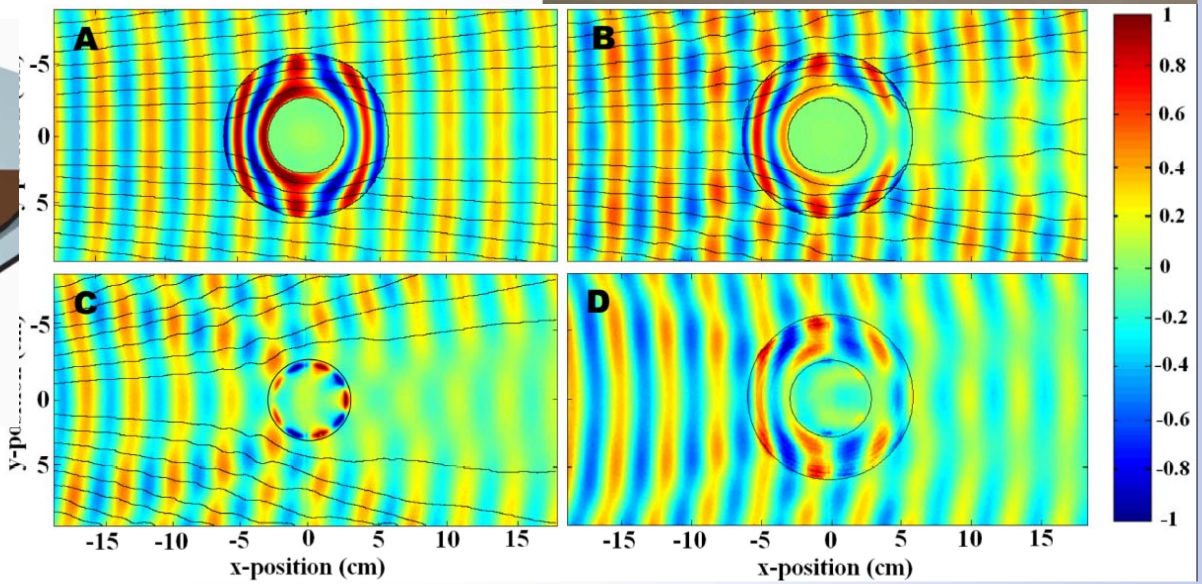
Cloak realized at microwave frequency by Smith group, 2006



cyl.	r	s	μ_r
1	0.260	1.654	0.003
2	0.254	1.677	0.023
3	0.245	1.718	0.052
4	0.230	1.771	0.085
5	0.208	1.825	0.120
6	0.190	1.886	0.154
7	0.173	1.951	0.188
8	0.148	2.027	0.220
9	0.129	2.110	0.250
10	0.116	2.199	0.279

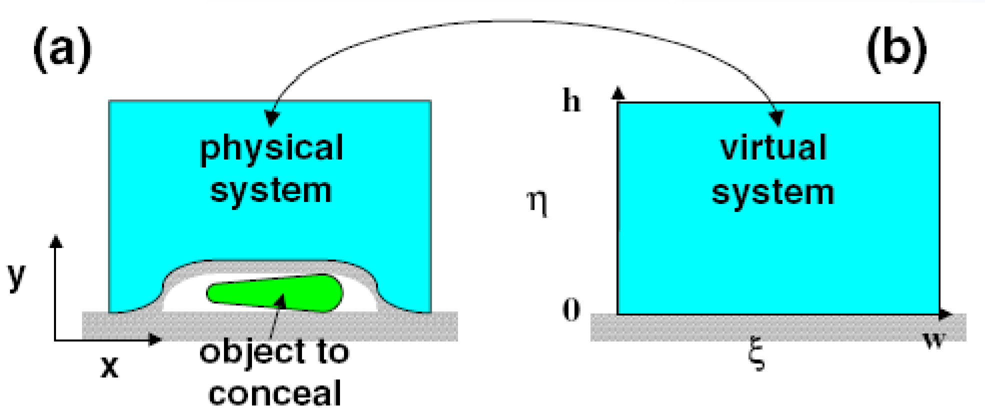


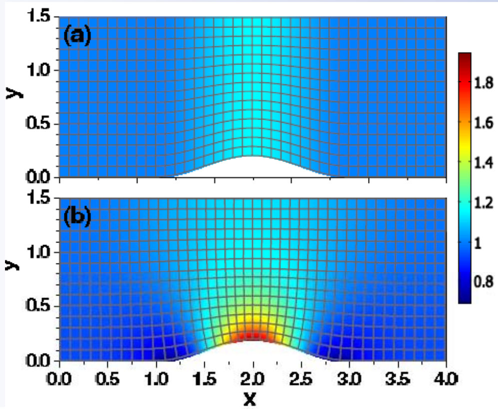


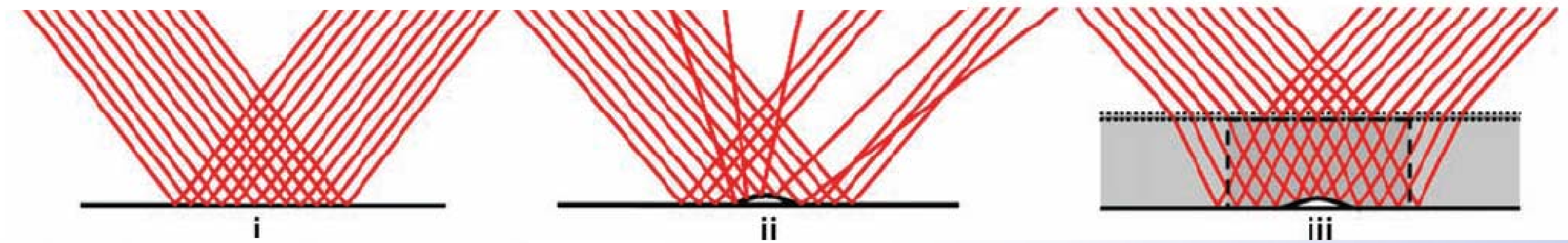


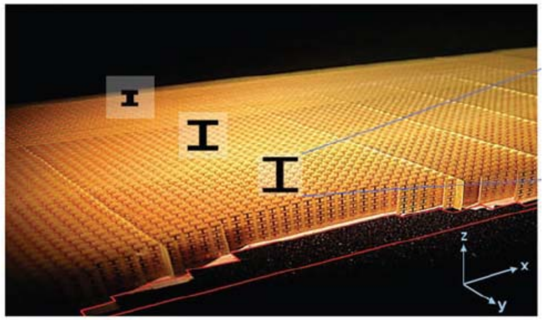
Ground plane cloak

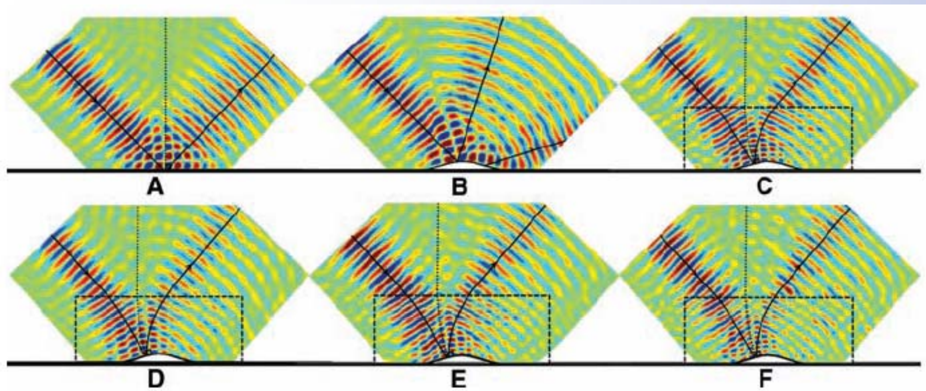
Proposed byJensen LI and realized by Smith group



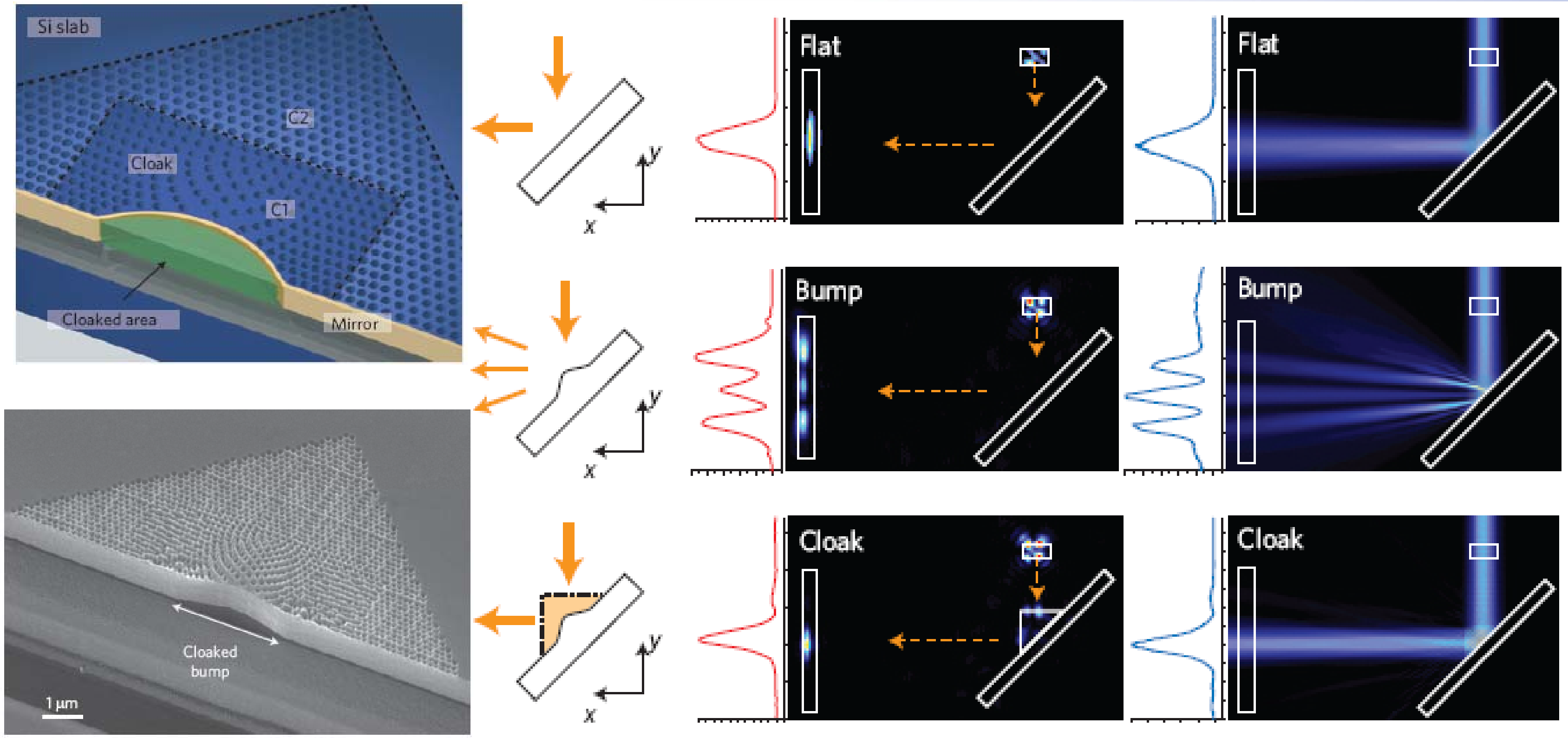








Experiment at optical frequency (X. Zhang's group, 2009)

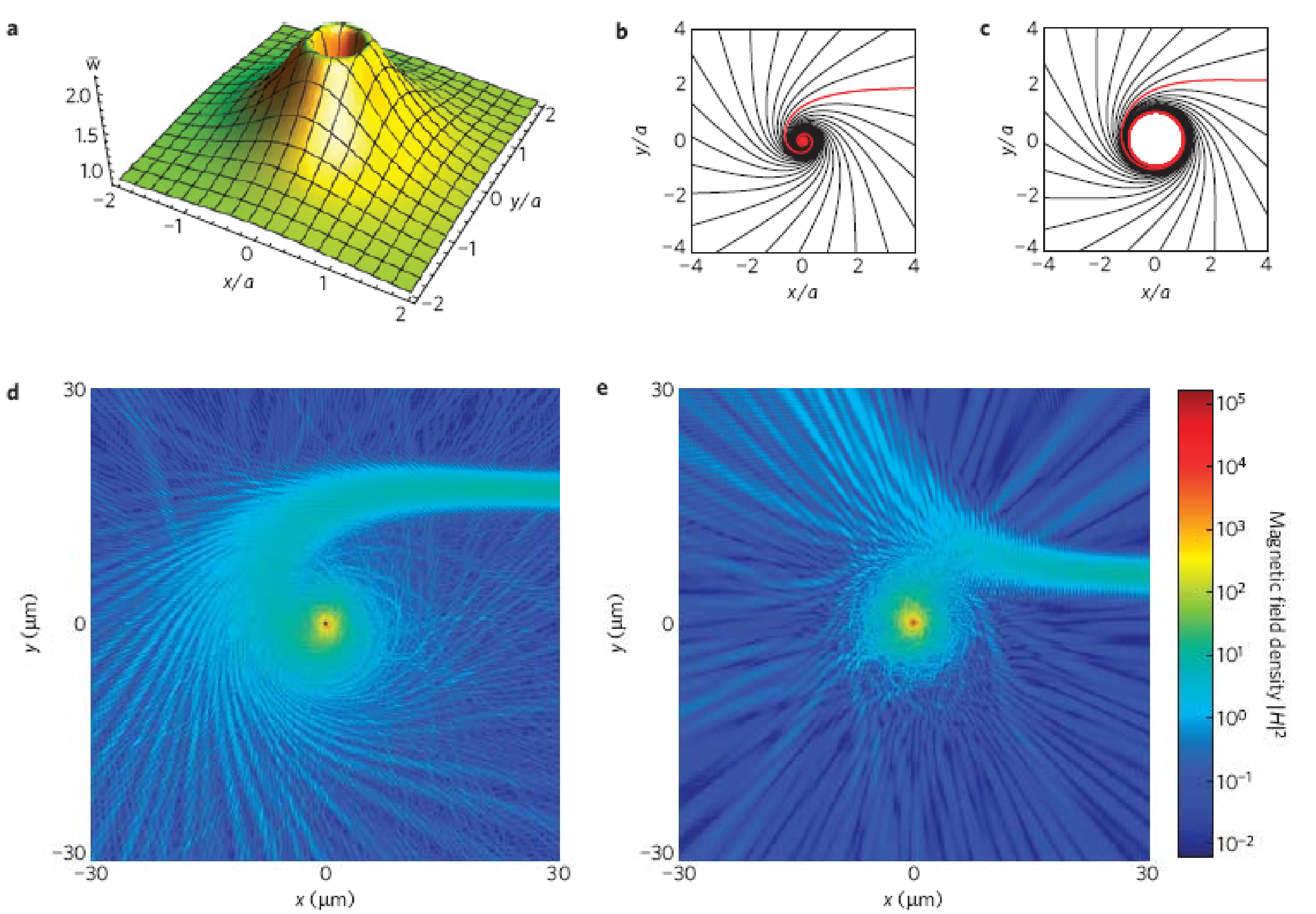


Dr. Tao Li taoli@nju.edu.cn

Nanjing University

Mimick the black hole

X. Zhang Group, 2009



Outline

- Concepts
- Basic principles
- Surface Plasmon
- Metamaterial
  - Artificial Magnetism
  - Negative Index Material (NIM)
  - Transformation Optics
  - **Illumination Optics**
- Summary

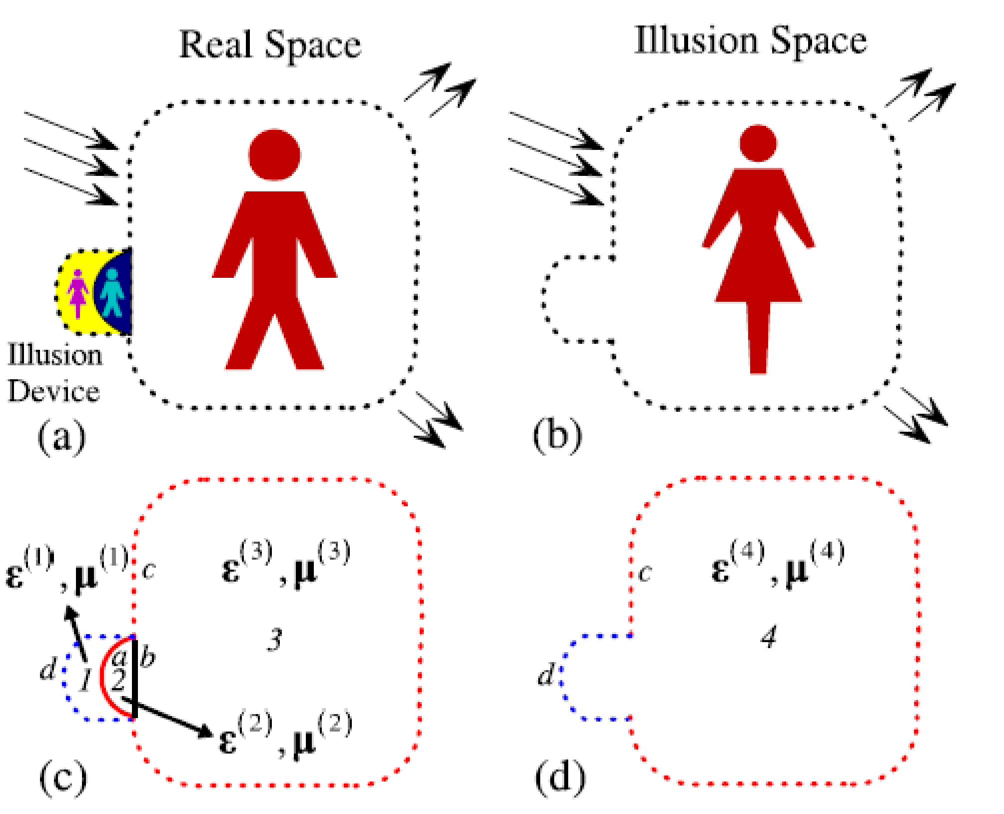
Dr. Tao Li taoli@nju.edu.cn

Illumination Optics

C.T. Chan Group, 2009

Illusion Optics:
The Optical Transformation of an Object into Another Object

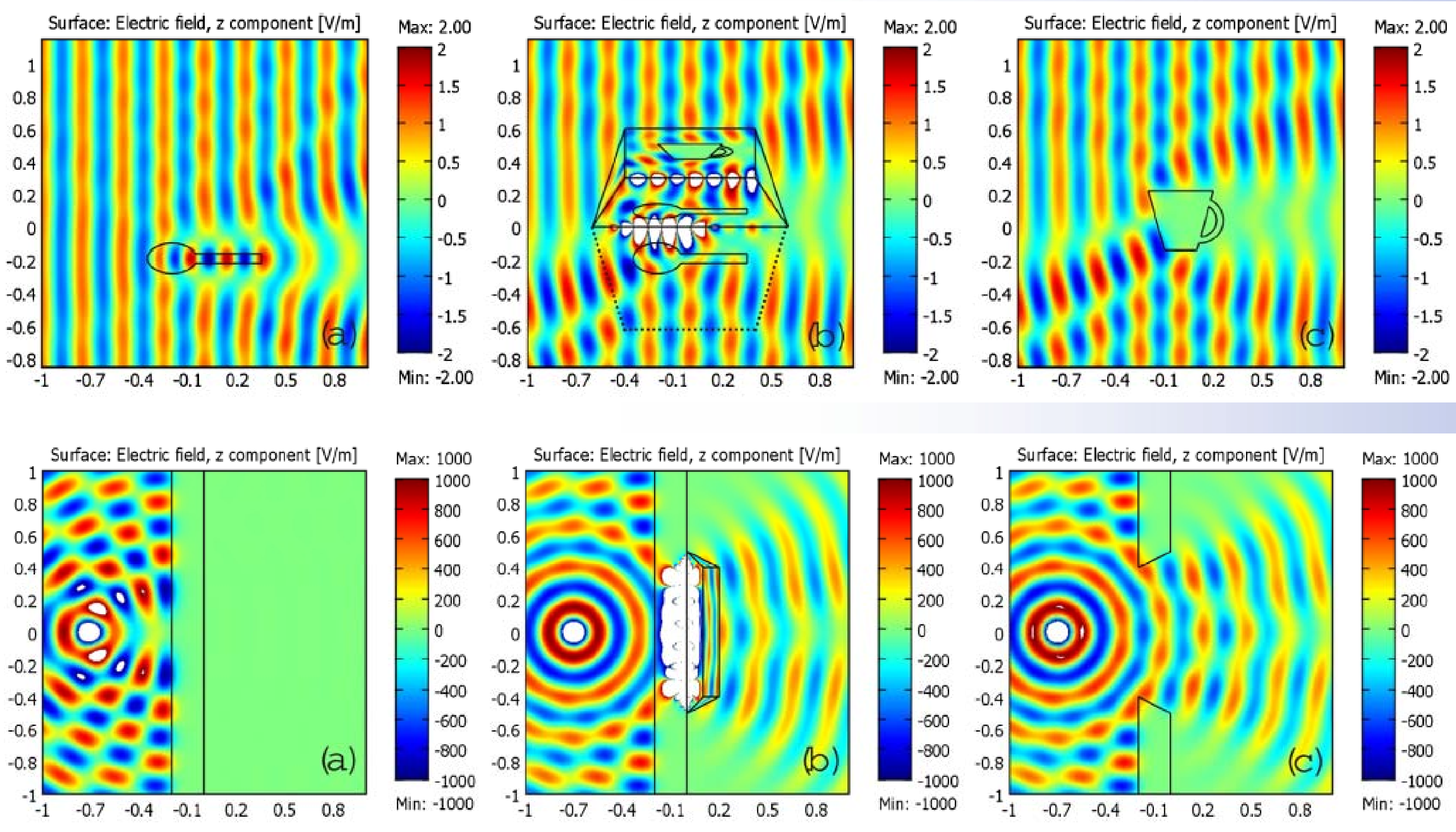
A further development of Transformation Optics



Nanjing University

Illumination Optics

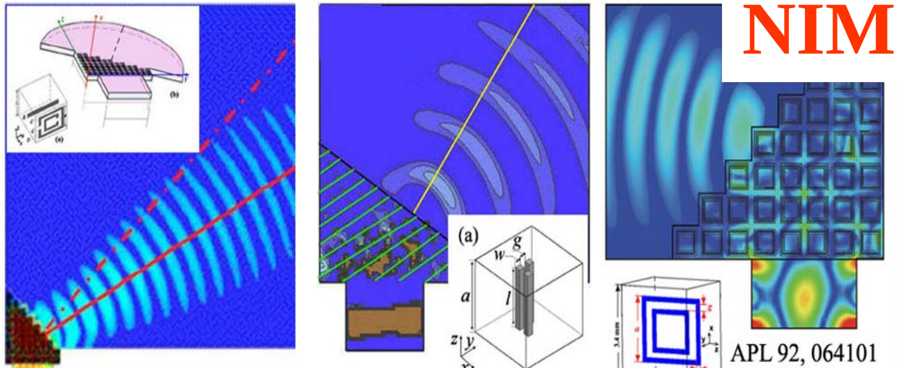
C.T. Chan Group, 2009



Nanjing University

Work of Our Group

NIM

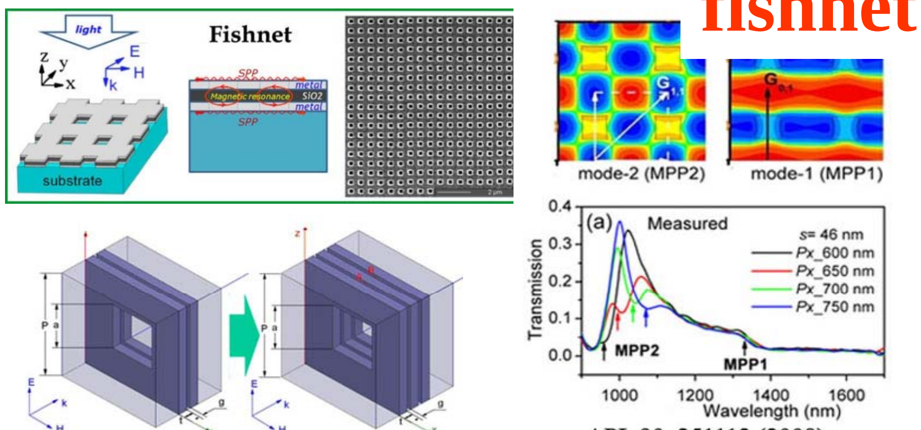


PRE 72, 016607 (2005)

PRB 76, 075110 (2007)

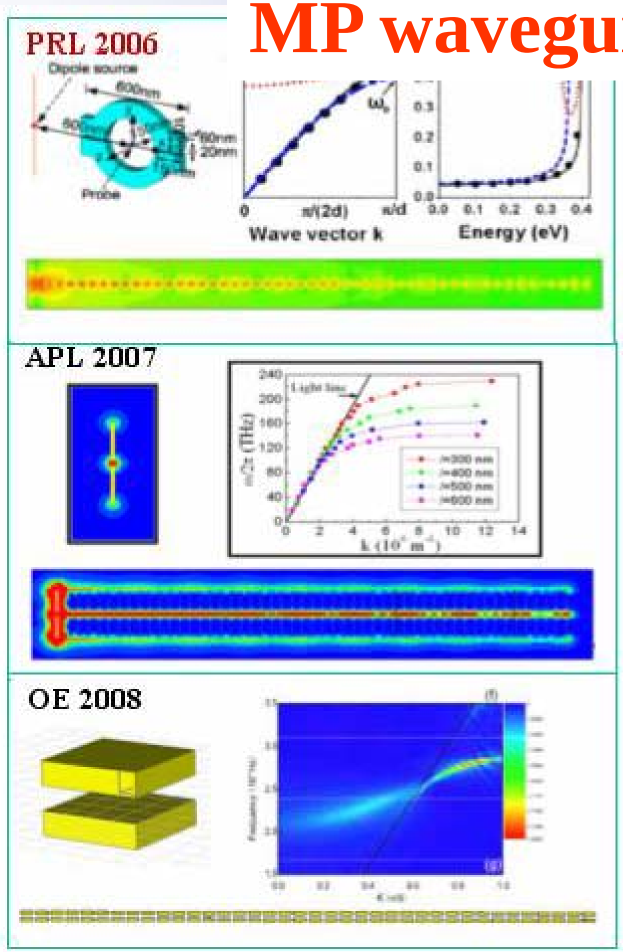
APL 92, 064101 (2008)

fishnet

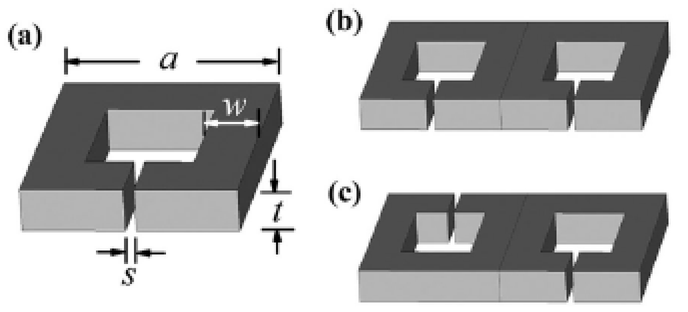


APL 90, 251112 (2008)

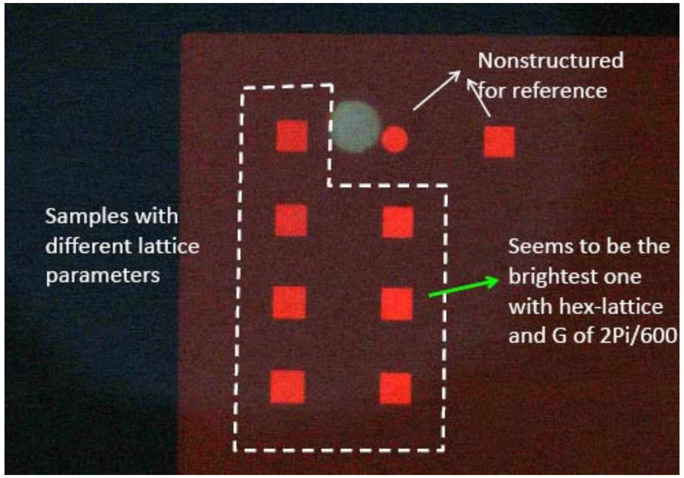
MP waveguide



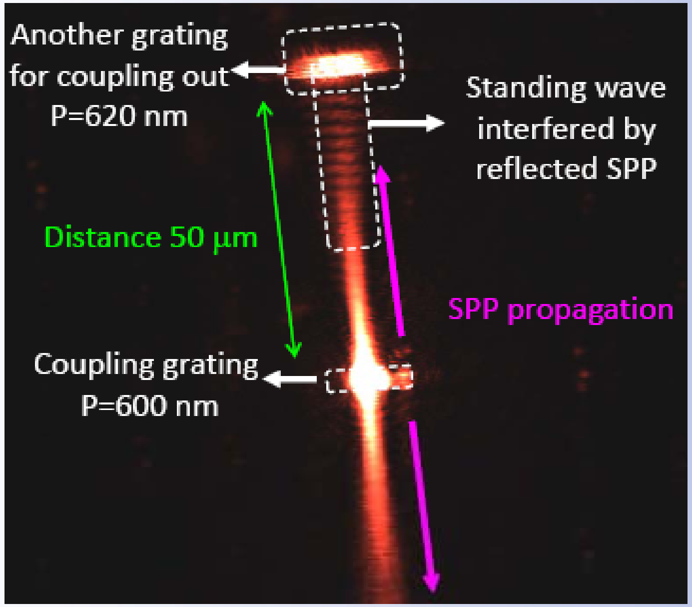
My recent approaches



(a) Coupled metamaterial



(b) Plasmonic electro-optics



(c) SPP propagation modulation and integration

Summary

It is a very fascinating research area, Opportunities and Challenges are fronted, welcome to join us!

Thank you!