Chapter 16

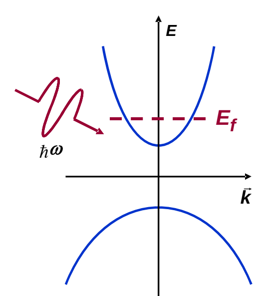
Plasmonics

In this lecture you will learn:

- Plasmons in Metals
- Surface Plasmons in Metals
- Surface Plasmons in Metal Nano-Dots
- Nanocavity Lasers

High Frequency Dielectric Constant: Case of Non-Zero Conductivity

We had obtained an expression for the dielectric constant that incorporated a non-zero conductivity:



Start from Maxwell equations:

$$\nabla \times \vec{E}(\vec{r},\omega) = i\omega\,\mu_o \vec{H}(\vec{r},\omega) \qquad \text{Faraday's Law}$$

$$\nabla \times \vec{H}(\vec{r},\omega) = \vec{J}(\omega) - i\omega\,\varepsilon(\omega)\,\vec{E}(\vec{r},\omega) \qquad \text{Ampere's Law}$$

New term (current density due to electrons or holes or both)

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

$$\Rightarrow \nabla \times \vec{H}(\vec{r},\omega) = \sigma(\omega)\,\vec{E}(\omega) - i\omega\,\varepsilon(\omega)\,\vec{E}(\vec{r},\omega)$$

$$\Rightarrow \nabla \times \vec{H}(\vec{r},\omega) = -i\omega\,\varepsilon_{total}(\omega)\,\vec{E}(\vec{r},\omega)$$

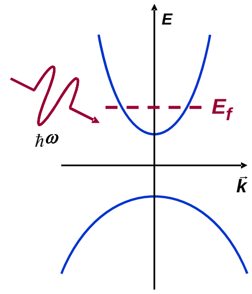
Where:

$$\varepsilon_{total}(\omega) = \varepsilon(\omega) + i\,\frac{\sigma(\omega)}{\omega}$$

High Frequency Dielectric Constant: Drude Model for Conductivity

We have:

$$\varepsilon_{total}(\omega) = \varepsilon(\omega) + i\,\frac{\sigma(\omega)}{\omega}$$



Drude model for the frequency dependent conductivity:

The equation for the electron velocity is (assuming parabolic/isotropic bands in 3D):

$$m_e \frac{d\vec{v}}{dt} + \frac{m_e \vec{v}}{\tau} = -q\,\vec{E}$$

In phasor notation (assuming a sinusoidal electric field):

$$\vec{v}(\omega) = -\frac{q\tau_e / m_e}{1 - i\omega\tau}\,\vec{E}(\omega)$$

The current density is:

$$\vec{J}(\omega) = n\,(-q)\,\vec{v}(\omega) = \sigma(\omega)\,\vec{E}(\omega)$$

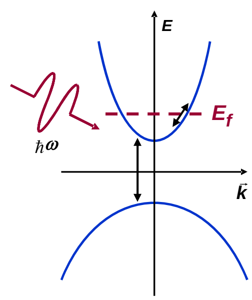
Where:

$$\sigma(\omega) = \frac{n\,q^2\tau / m_e}{1 - i\omega\tau}$$ (Drude model)

High Frequency Dielectric Constant : Non-Zero Conductivity

Assuming a metal with an electron density n :

$$\sigma(\omega) = \frac{n\,q^2\tau_e / m_e}{1 - i\omega\tau}$$



We have:

$$\varepsilon_{total}(\omega) = \varepsilon(\omega) + i\,\frac{\sigma(\omega)}{\omega}$$

Therefore:

$$\varepsilon_{total}(\omega) = \underbrace{\varepsilon(\omega)}_{\text{Interband optical processes}} + i\,\underbrace{\frac{nq^2\tau / m_e}{\omega(1 - i\omega\tau)}}_{\text{Intraband optical processes}}$$

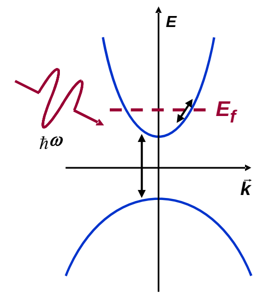
Interband optical processes

Intraband optical processes

The Plasma Frequency

Suppose that:

$$\omega\tau >> 1$$
$$\hbar\omega << E_g$$



Then we have:

$$\varepsilon_{total}(\omega) = \varepsilon(\omega) + i\,\frac{nq^2\tau/m_e}{\omega(1-i\omega\tau)}$$
$$= \varepsilon + i\,\frac{nq^2\tau/m_e}{\omega(1-i\omega\tau)} \approx \varepsilon - \frac{nq^2/m_e}{\omega^2}$$
$$= \varepsilon\left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

Where the plasma frequency is defined as:

$$\omega_p = \sqrt{\frac{nq^2}{\varepsilon\, m_e}}$$

For metals:

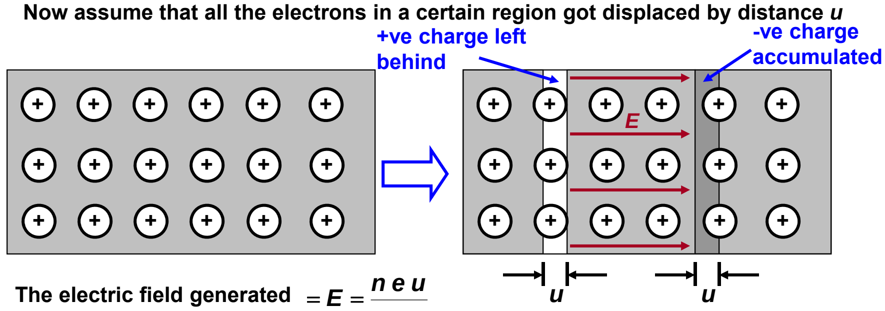
$\omega_p/2\pi \sim 4\times10^{15}$ Hz **(UV-blue light frequency)**

For n-doped semiconductors:

$\omega_p/2\pi \sim 10^{11} - 10^{13}$ Hz **(Terahertz frequency)**

Plasma Oscillations in Metals

Consider a metal with electron density *n*
Now assume that all the electrons in a certain region got displaced by distance *u*



The electric field generated $= E = \dfrac{n\,e\,u}{\varepsilon}$

Force on the electrons $= F = -eE = -\dfrac{n\,e^2\,u}{\varepsilon}$

As a results of this force electron displacement *u* will obey Newton's second law:

$$m\frac{d^2u(t)}{dt^2} = F = -eE = -\frac{n\,e^2\,u(t)}{\varepsilon} \quad\Rightarrow\quad \frac{d^2u(t)}{dt^2} = -\omega_p^2\,u(t)$$

← **second order system**

Solution is: $u(t) = A\cos(\omega_p t) + B\sin(\omega_p t)$

Plasma oscillations are charge density oscillations

Plasma Oscillations in Metals – with Scattering

From Drude model, we know that in the presence of scattering we have:

$$\frac{d\vec{p}(t)}{dt} = -e\,\vec{E}(t) - \frac{\vec{p}(t)}{\tau} \quad \Rightarrow \quad m\frac{d^2u(t)}{dt^2} = -e\,E(t) - \frac{m}{\tau}\frac{du(t)}{dt} \longrightarrow \text{(1)}$$

As before, the electric field generated $= E(t) = \dfrac{n\,e\,u(t)}{\varepsilon} \longrightarrow$ **(2)**

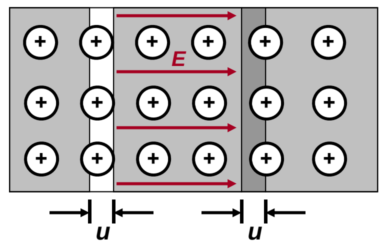
Combining (2) with (1) we get the differential equation:

$$\frac{d^2u(t)}{dt^2} = -\omega_p^2\,u(t) - \frac{1}{\tau}\frac{du(t)}{dt}$$

Or:

$$\frac{d^2u(t)}{dt^2} + \frac{1}{\tau}\frac{du(t)}{dt} + \omega_p^2\,u(t) = 0$$

second order system with damping



Plasma Oscillations in Metals – with Scattering

Case I (underdamped case): $\omega_p > \dfrac{1}{2\tau}$

Solution is:

$$u(t) = e^{-t/2\tau}\left[A\cos(\Omega_p t) + B\sin(\Omega_p t)\right] \longleftarrow \textbf{Damped plasma oscillations}$$

Where:

$$\Omega_p = \sqrt{\omega_p^2 - \left(\frac{1}{2\tau}\right)^2}$$

Case II (overdamped case): $\omega_p < \dfrac{1}{2\tau}$

Solution is:

$$u(t) = A\,e^{-\gamma_1 t} + B\,e^{-\gamma_2 t} \longleftarrow \textbf{No oscillations}$$

Where:

$$\gamma_1 = \frac{1}{2\tau} + \sqrt{\frac{1}{4\tau^2} - \omega_p^2} \qquad \gamma_1 = \frac{1}{2\tau} - \sqrt{\frac{1}{4\tau^2} - \omega_p^2}$$

Maxwell's Equations for Polarizable Media

For any medium, Maxwell's equations are:

$$\vec{D} = \varepsilon_o \vec{E} + \vec{P} = \varepsilon_{total}(\omega)\vec{E}$$

$$\nabla.\vec{E} = \frac{\rho_u + \rho_p}{\varepsilon_o}$$

$$\nabla.\vec{D} = \frac{\rho_u}{\varepsilon_o}$$

$$\rho_p = -\nabla.\vec{P}$$

$\rho_p =$ Charge density due to material polarization (paired charge density)

$\rho_u =$ Charge density due to free unpaired charges

When a medium polarizes and charge dipoles are created then the charge density associated with these dipoles is described by ρ_p

External charge placed inside a medium is described by ρ_u

Plasmons in Bulk Metals: Another Approach

Suppose the E-field of the plasmon wave has the form:

$$\vec{E} = \hat{n} E_o e^{i\vec{k}.\vec{r} - i\omega t}$$

The D-field is given as:

$$\vec{D} = \varepsilon_o \vec{E} + \vec{P} = \varepsilon_{total}(\omega)\vec{E}$$

For bulk plasmons we must have:

$$\nabla.\vec{E} \neq 0$$

$$\nabla.\vec{D} = \varepsilon_{total}(\omega)\nabla.\vec{E} = 0$$

$\{ \nabla.\vec{E} \neq 0 \quad \Rightarrow \quad \vec{k}.\hat{n} \neq 0$

→ Because there are no unpaired charges

The only way that both the above equations can hold is if the frequency of the wave is such that at that frequency:

$$\varepsilon_{total}(\omega) = 0$$

The above equation gives the frequency of the bulk plasmons:

$$\varepsilon_{total}(\omega) = \varepsilon\left[1 - \frac{\omega_p^2}{\omega^2}\frac{i\omega\tau}{(i\omega\tau - 1)}\right] = 0 \longrightarrow \omega = -\frac{i}{2\tau} \pm \sqrt{\omega_p^2 - \left(\frac{1}{2\tau}\right)^2}$$

E&M Wave Propagation in Metals

Suppose the E-field of an E&M wave travelling in a metal has the form:

$$\vec{E}(\omega) = \hat{n}E_o e^{i\vec{k}.\vec{r}-i\omega t} \qquad \left\{ \nabla.\vec{E} = 0 \quad \Rightarrow \quad \vec{k}.\hat{n} = 0 \right.$$

The D-field is given as:

$$\vec{D}(\omega) = \varepsilon_o \vec{E}(\omega) + \vec{P}(\omega) = \varepsilon_{total}(\omega)\vec{E}(\omega)$$

For transverse electromagnetic waves, we must have:

$$\nabla.\vec{E} = \nabla.\vec{D} = 0$$

The electromagnetic wave equation when $\nabla.\vec{E} = 0$ is:

$$\nabla \times \nabla \times \vec{E} = \omega^2 \mu_o \varepsilon_{total}(\omega)\vec{E}$$

$$\Rightarrow \nabla\left(\nabla.\vec{E}\right) - \nabla^2\vec{E} = \omega^2 \mu_o \varepsilon_{total}(\omega)\vec{E} \quad (\nabla.\vec{E} = 0)$$

$$\Rightarrow -\nabla^2\vec{E} = \omega^2 \mu_o \varepsilon_{total}(\omega)\vec{E}$$

The plane wave is a solution of the wave equation if:

$$\omega^2 \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = k^2 c^2$$

The above equation gives the dispersion of the wave in a metal

E&M Wave Propagation in Metals

Consider a conducting medium (like gold, silver) whose dielectric constant is approximately,

$$\varepsilon_{total}(\omega) = \varepsilon + i\frac{\sigma(\omega)}{\omega} = \varepsilon + i\frac{ne^2\tau/m_e}{\omega(1-i\omega\tau)} \approx \varepsilon\left(1 - \frac{\omega_p^2}{\omega^2}\right) \qquad \begin{cases} \hbar\omega < E_g \\ \omega\tau >> 1 \end{cases}$$

→ **No loss**

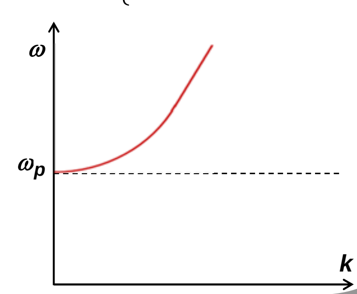
The wave dispersion relation: $\omega^2 \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = k^2 c^2$

can be simplified as:

$$\omega^2 = \omega_p^2 + k^2 c^2 \frac{\varepsilon_o}{\varepsilon} \qquad \left\{ \omega_p = \sqrt{\frac{ne^2}{\varepsilon\, m_e}} \right.$$

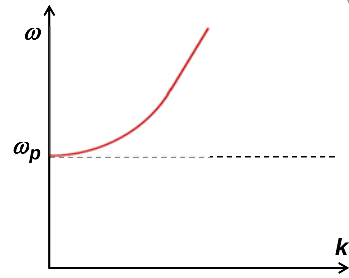
The resulting dispersion relation is plotted in the Figure

Note that no transverse electromagnetic wave can propagate in the medium with a frequency smaller than the plasma frequency



E&M Wave Incident on a Metal below the Plasma Frequency

Suppose: $\omega < \omega_p$



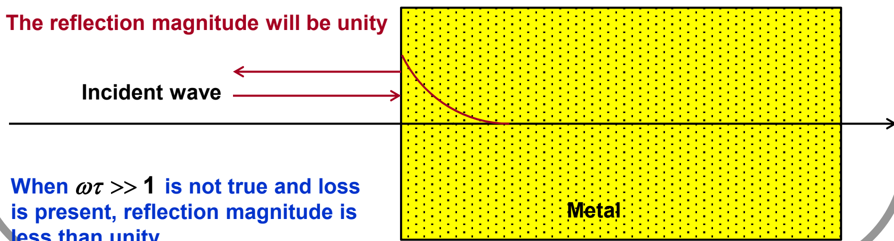
We have: $\omega^2 = \omega_p^2 + k^2 c^2 \dfrac{\varepsilon_o}{\varepsilon}$

$$\Rightarrow k = i\sqrt{\mu\varepsilon}\sqrt{\omega_p^2 - \omega^2} \quad \text{Imaginary!}$$

The wave decays exponentially inside the medium

The wave will decay exponentially inside the medium (without oscillations) since the wavevector is completely imaginary

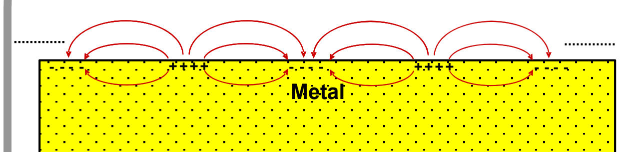
The reflection magnitude will be unity



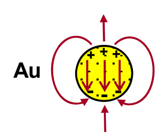
When $\omega\tau >> 1$ is not true and loss is present, reflection magnitude is less than unity

Surface Plasmons in Metals

Electromagnetic waves can propagate/exist on the surface of metals:



Propagating Surface Plasmon Mode



Confined Surface Plasmon Mode on a Metal Nano-Dot

Dispersion relation for an E&M wave outside the metal is:

$$\omega^2 = |\vec{k}|^2 c^2$$

Dispersion relation inside the metal is:

$$\omega^2 \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = |\vec{k}|^2 c^2$$

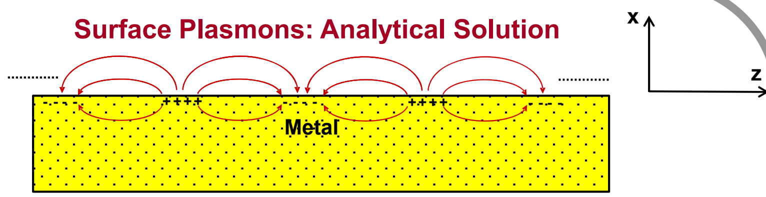
Actual dielectric constant (loss is present)

$$\varepsilon_{total}(\omega) = \varepsilon\left[1 - \frac{\omega_p^2}{\omega^2}\frac{i\omega\tau}{(i\omega\tau - 1)}\right]$$

Simpler dielectric constant (assumes no loss)

$$\varepsilon_{total}(\omega) = \varepsilon\left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

Surface Plasmons: Analytical Solution



Assume the wave outside the metal is (exponentially decaying away from the metal-air interface):

$$\vec{E}^{out} = \left(\hat{z}E_z^{out} + \hat{x}E_x^{out}\right)e^{-\alpha x}e^{ikz - i\omega t} \longrightarrow \omega^2 = \left(k^2 - \alpha^2\right)c^2$$

Assume the wave inside the metal is:

$$\vec{E}^{in} = \left(\hat{z}E_z^{in} + \hat{x}E_x^{in}\right)e^{\beta x}e^{ikz - i\omega t} \longrightarrow \omega^2 \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = \left(k^2 - \beta^2\right)c^2$$

Boundary conditions at x=0:

$$E_z^{in} = E_z^{out}$$

$$\varepsilon_{total}(\omega)E_x^{in} = \varepsilon_o E_x^{out}$$

Simpler dielectric constant (assumes no loss)

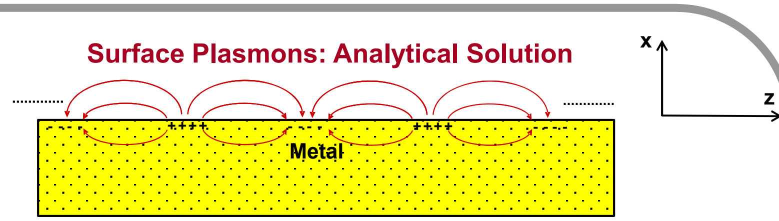
$$\varepsilon_{total}(\omega) = \varepsilon\left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

We must also have:

$$\nabla.\vec{E}^{out} = 0$$

$$\nabla.\vec{E}^{in} = 0$$

Surface Plasmons: Analytical Solution



$$\nabla.\vec{E}^{out} = 0 \qquad \nabla.\vec{E}^{in} = 0$$

$$\frac{E_x^{out}}{E_z^{out}} = \frac{ik}{\alpha} \qquad \frac{E_x^{in}}{E_z^{in}} = -\frac{ik}{\beta}$$

Use the boundary condition at x=0:

$$E_z^{in} = E_z^{out}$$

$$\frac{E_x^{out}}{E_x^{in}} = -\frac{\beta}{\alpha}$$

But we already have:

$$\frac{E_x^{out}}{E_x^{in}} = \frac{\varepsilon_{total}(\omega)}{\varepsilon_o}$$

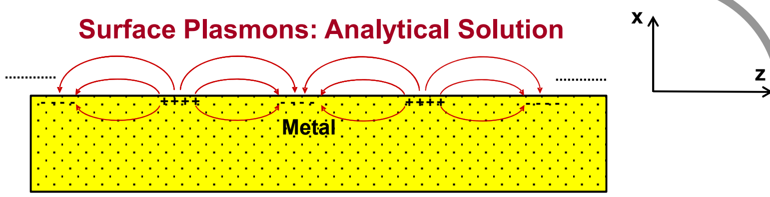
Therefore, a wave solution is possible provided:

$$\frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = -\frac{\beta}{\alpha}$$

$$\omega^2 = \left(k^2 - \alpha^2\right)c^2$$

$$\omega^2 \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = \left(k^2 - \beta^2\right)c^2$$

Surface Plasmons: Analytical Solution



A wave solution is possible provided:

$$\frac{\varepsilon_{total}(\omega)}{\varepsilon_o} = -\frac{\beta}{\alpha}$$

$$\Rightarrow k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{total}(\omega)/\varepsilon_o}{1+\varepsilon_{total}(\omega)/\varepsilon_o}}$$

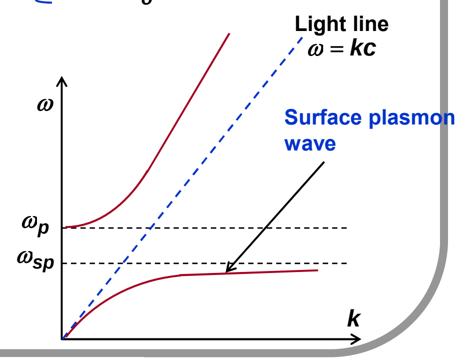
$$\begin{cases} \omega^2 = (k^2 - \alpha^2)c^2 \\ \omega^2 \dfrac{\varepsilon_{total}(\omega)}{\varepsilon_o} = (k^2 - \beta^2)c^2 \end{cases}$$

The frequency ω_p is determined, as before, by:

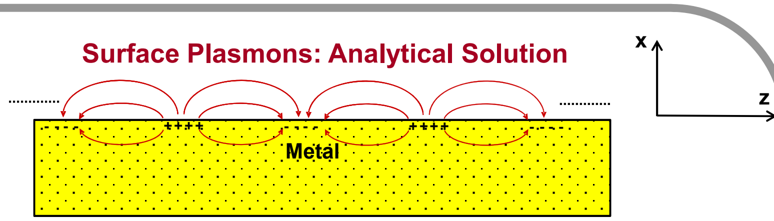
$$\varepsilon_{total}(\omega) = 0$$

The frequency ω_{sp} is determined by:

$$\varepsilon_{total}(\omega) + \varepsilon_o = 0 \longrightarrow \omega_{sp} = \frac{\omega_p}{1+\varepsilon_o/\varepsilon}$$



Surface Plasmons: Analytical Solution



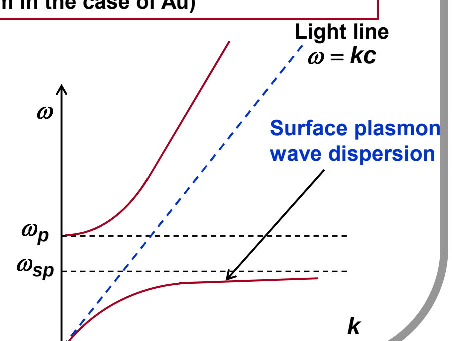
$$k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{total}(\omega)/\varepsilon_o}{1+\varepsilon_{total}(\omega)/\varepsilon_o}}$$

$$\alpha = \frac{\omega}{c}\sqrt{\frac{-1}{1+\varepsilon_{total}(\omega)/\varepsilon_o}}$$

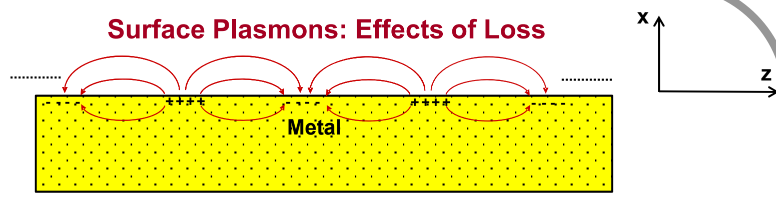
$$\beta = -\frac{\varepsilon_{total}(\omega)}{\varepsilon_o}\alpha$$

$$= \frac{\omega}{c}\left(-\frac{\varepsilon_{total}(\omega)}{\varepsilon_o}\right)\sqrt{\frac{-1}{1+\varepsilon_{total}(\omega)/\varepsilon_o}}$$

As $\frac{\varepsilon_{total}(\omega)}{\varepsilon_o} \to -1$ and $\omega \to \omega_{sp}$, all k, α, β $\to 0$
The wave becomes tightly confined to the metal (within ~10-20 nm in the case of Au)



Surface Plasmons: Effects of Loss



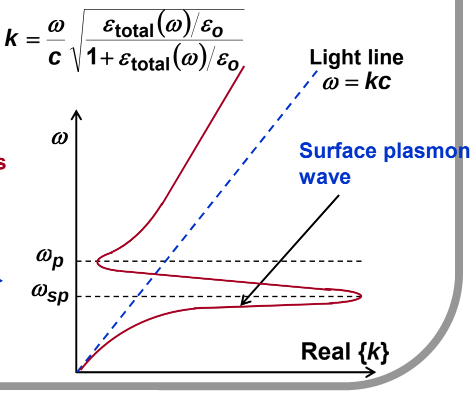
If loss were included:

$$\varepsilon_{total}(\omega) = \varepsilon\left[1 - \frac{\omega_p^2}{\omega^2}\frac{i\omega\tau}{(i\omega\tau - 1)}\right] \longrightarrow k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{total}(\omega)/\varepsilon_o}{1+\varepsilon_{total}(\omega)/\varepsilon_o}}$$

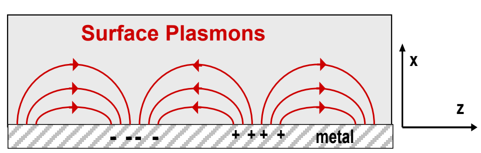
The wavevector *k* would become imaginary
The imaginary part is pretty large!!
The plasmon wave will decay as it propagates

The dispersion would be as shown

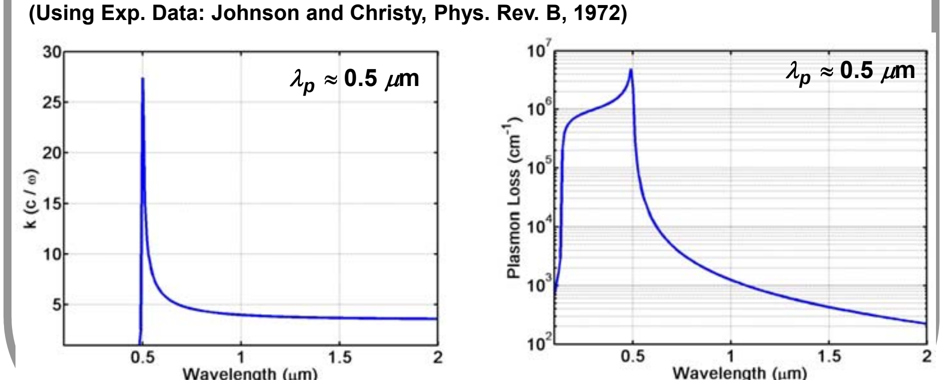
Region of negative group velocity



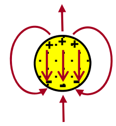
Surface Plasmons in Silver: Effects of Loss



Dispersion of Plasmons on Silver/Semiconductor Interface
(Using Exp. Data: Johnson and Christy, Phys. Rev. B, 1972)



Surface Plasmons in Metal Nano-Dots



Au

Metal Nano-Dot

Consider a small metal nano-dot of radius *R* such that:

$$kR = \frac{\omega}{c} R = 2\pi \frac{R}{\lambda} << 1$$

Wave equation outside is:

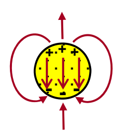
$$-\nabla^2 \vec{E} = \frac{\omega^2}{c^2} \vec{E}$$

Wave equation inside is:

$$-\nabla^2 \vec{E} = \frac{\omega^2}{c^2} \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} \vec{E}$$

Surface Plasmons in Metal Nano-Dots

Metal Nano-Dot



Wave equation outside is:

$$-\nabla^2 \vec{E} = \frac{\omega^2}{c^2} \vec{E}$$

Solution outside should look like that of a radiating charge dipole (it is not a confined solution – it radiates):

$$\vec{E}^{out}(\vec{r}) = \frac{A}{r} e^{ikr} \left\{ \hat{r} \left[-\frac{1}{ikr} + \left(\frac{1}{ikr}\right)^2 \right] 2\cos(\theta) + \hat{\theta} \left[1 - \frac{1}{ikr} + \left(\frac{1}{ikr}\right)^2 \right] \sin(\theta) \right\}$$

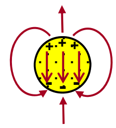
$$\left\{ \begin{array}{l} \omega^2 = k^2 c^2 \\ kR << 1 \end{array} \right.$$

$$\vec{E}^{out}(\vec{r}) \approx \frac{C}{r^3} \{ \hat{r} \; 2\cos(\theta) + \hat{\theta} \sin(\theta) \}$$

For: $kr << 1$

Surface Plasmons in Metal Nano-Dots

Metal Nano-Dot



Wave equation inside is:

$$-\nabla^2 \vec{E} = \frac{\omega^2}{c^2} \frac{\varepsilon_{total}(\omega)}{\varepsilon_o} \vec{E}$$

Solution should look like that of a charge dipole:

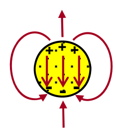
$$\vec{E}^{in}(\vec{r}) \approx \hat{z}B = B\left[\hat{r}\cos(\theta) - \hat{\theta}\sin(\theta)\right]$$

$kR << 1$

This is not an exact solution of the wave equation but it is a very good approximate solution if *kR* << 1

Surface Plasmons in Metal Nano-Dots

Metal Nano-Dot



Match the boundary conditions:

$$E_\theta^{in}(r = R) = E_\theta^{out}(r = R)$$

$$\varepsilon_{total}(\omega) E_r^{in}(r = R) = \varepsilon_o E_r^{out}(r = R)$$

This gives the condition that a solution exists provided:

$$\varepsilon_{total}(\omega) + 2\varepsilon_o = 0$$

The frequency ω_{sp} is then:

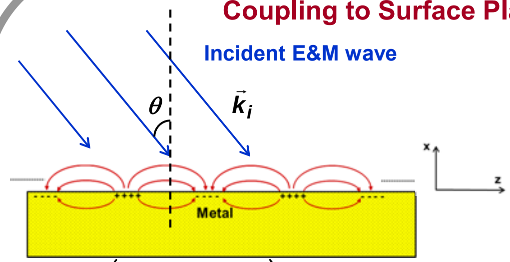
$$\omega_{sp} = \frac{\omega_p}{1 + 2\varepsilon_o/\varepsilon}$$

Compare to the propagating surface plasmon frequency for a plane surface as $k \rightarrow \infty$:

$$\varepsilon_{total}(\omega) + \varepsilon_o = 0$$

$$\Rightarrow \omega_{sp} = \frac{\omega_p}{1 + \varepsilon_o/\varepsilon}$$

Coupling to Surface Plasmon Modes



$$\vec{E}^{out} = \left(\hat{z}E_z^{out} + \hat{x}E_x^{out}\right)e^{-\alpha x}e^{ik_{sp}z - i\omega t}$$

Phase matching condition:

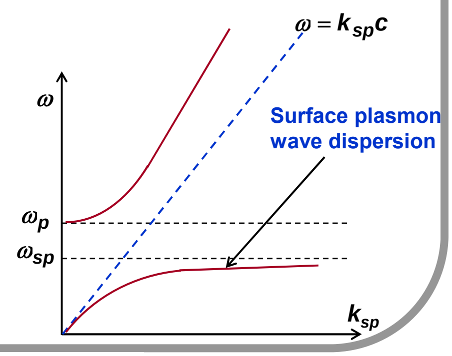
$$\vec{k}_{iz} = k_i \sin\theta = k_{sp}$$

$$\Rightarrow k_{sp} = \frac{\omega}{c}\sin\theta$$

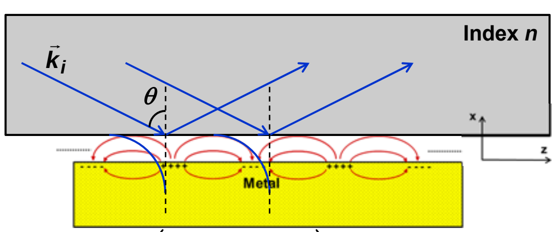
But plasmon dispersion below shows that:

$$k_{sp} > \frac{\omega}{c}$$

Therefore, radiation incident from free-space cannot excite surface plasmons using this scheme



Coupling to Surface Plasmon Modes



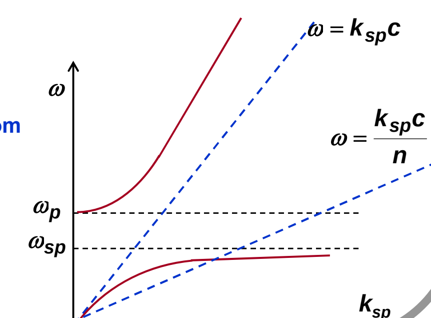
$$\vec{E}^{out} = \left(\hat{z}E_z^{out} + \hat{x}E_x^{out}\right)e^{-\alpha x}e^{ik_{sp}z - i\omega t}$$

Evanescent wave coupling:

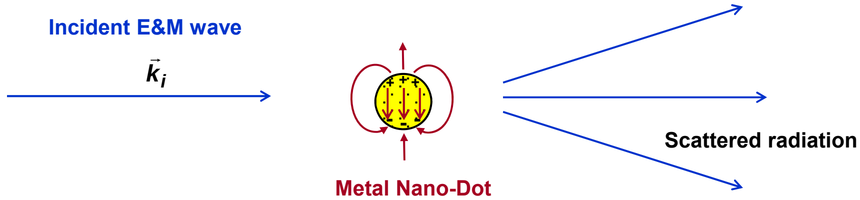
$$\vec{k}_{iz} = k_i \sin\theta = k_{sp}$$

$$\Rightarrow k_{sp} = \frac{\omega}{c}n\sin\theta$$

Therefore, evanescent radiation incident from a high index medium can couple to the surface plasmons



Coupling to Confined Surface Plasmon Modes

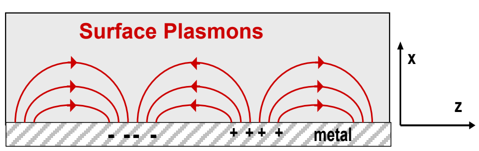


The confined surface plasmon mode can couple to incident radiation

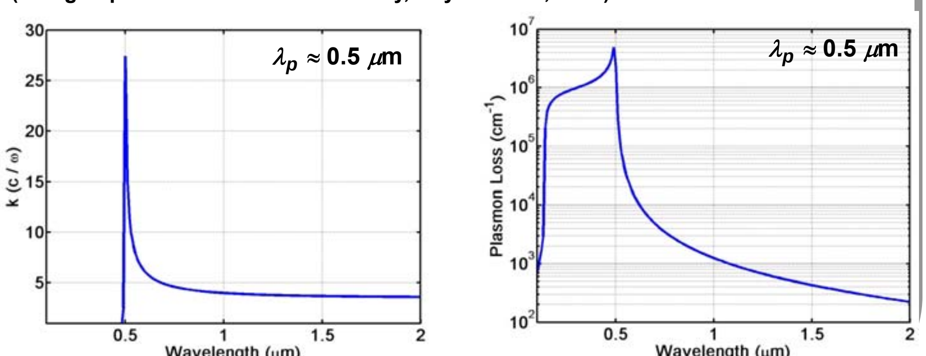
Surface plasmon mode of metal nanoparticles can be probed by free-space radiation

The scattered radiation spectra will show energy absorption by the confined surface plasmon mode

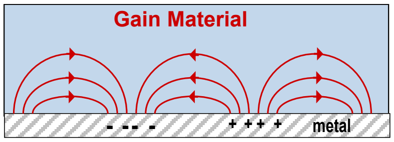
Surface Plasmons in Silver: Effects of Loss



Dispersion of Plasmons on Silver/Semiconductor Interface
(Using Exp. Data: Johnson and Christy, Phys. Rev. B, 1972)



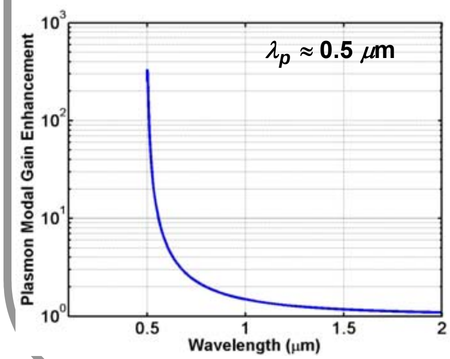
Gain in Plasmonics

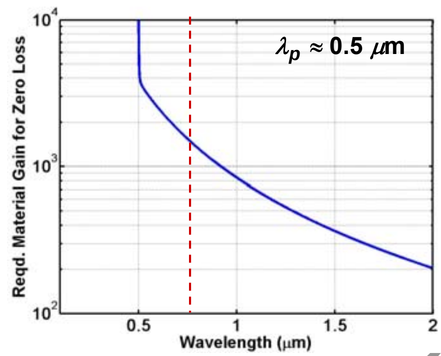


Plasmon Modal Gain Enhancement:

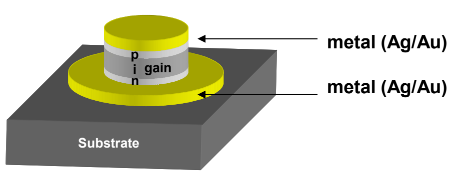
$$= \frac{\text{Plasmon Modal Gain}}{\text{Semiconductor Material Gain}}$$

- Small group velocity of plasmons enhances plasmon modal gain
- But losses are also similarly enhanced

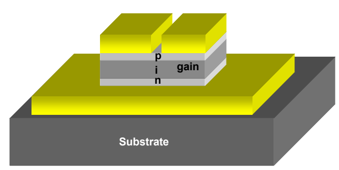




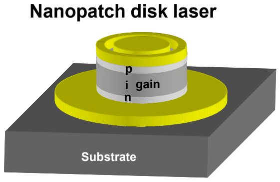
Plasmon Lasers: Nano-patch Lasers



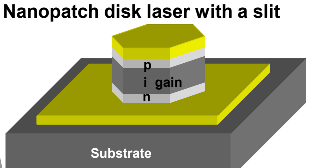
Nanopatch disk laser



Rectangular nanopatch laser with a slit



Nanopatch disk laser with a slit



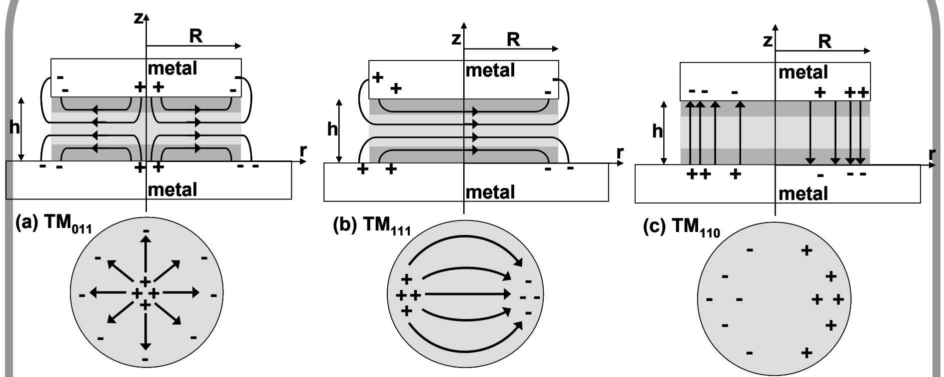
Hexagonal nanopatch laser

Key Characteristics:

- SNLs are a family of nanoscale lasers
- SNLs are similar to microstrip patch antennas used at microwave frequencies
- Mode confined by surface-plasmons in the dual-metal structures
- Efficient surface-normal emission in a single-lobe beam
- Ultrawide 75-150 GHz relaxation oscillation frequencies

C. Manolatou, F. Rana et. al., IEEE JQE (2008)

Plasmon Lasers: Nano-patch Lasers



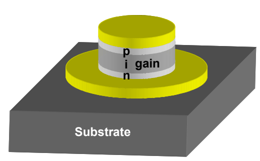
Requires larger cavity dimensions then the TM_{111} mode

Preferred choice for lasing in optical cavities

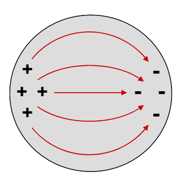
High radiation losses, low radiation-Q, good for RF antennas

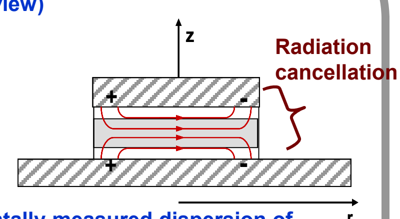
Plasmon Lasers: Nano-patch Lasers

Circular nanopatch laser example: m=1 dipole-like mode (TM_{111})

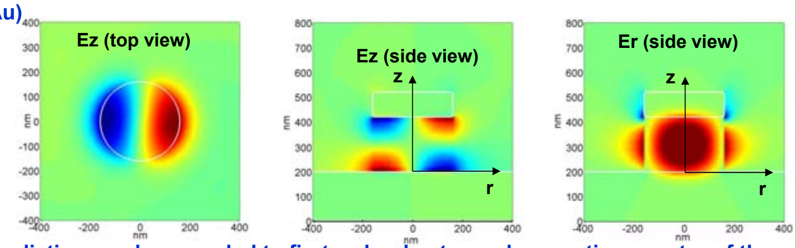


Field Lines (top view)





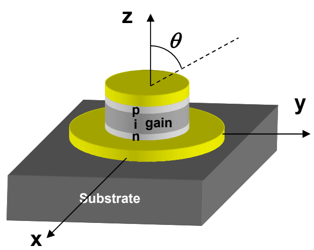
Full-vector 3D-FDTD simulations using the experimentally measured dispersion of metals (Ag/Au)



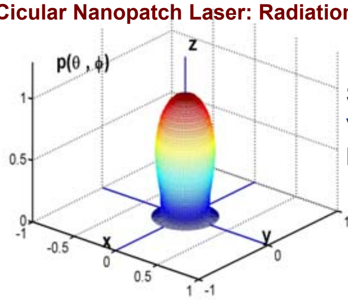
- Outgoing radiation can be canceled to first order due to up-down anti-symmetry of the mode
- Large mode overlap with the gain region (~75% mode confinement in the gain region)

Plasmon Lasers: Nano-patch Lasers

Circular Nanopatch Laser

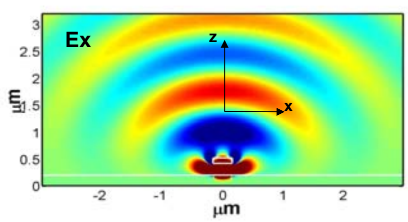


Cicular Nanopatch Laser: Radiation Pattern

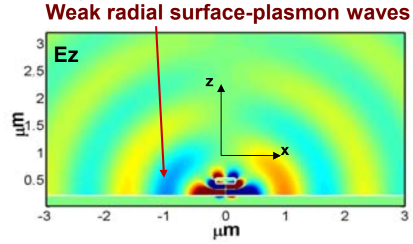


SNLs are optical versions of microwave patch antennas

Surface-normal emission

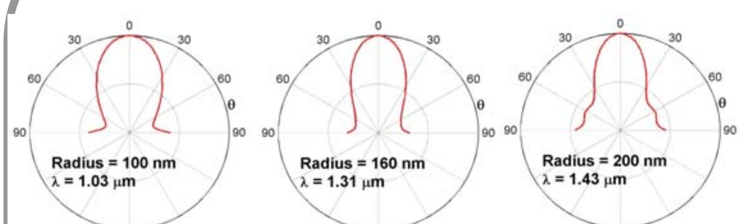


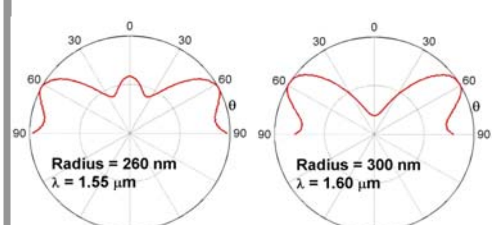
Weak radial surface-plasmon waves



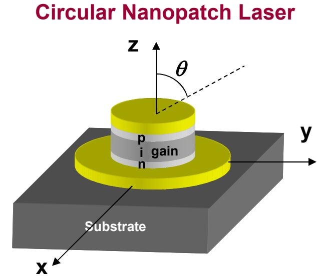
C. Manolatou, F. Rana et. al., IEEE JQE (2008)

Plasmon Lasers: Nano-patch Lasers





Circular Nanopatch Laser



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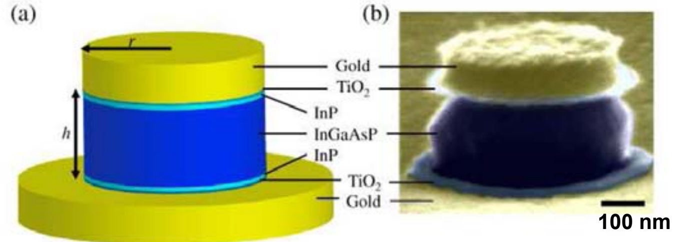
Plasmon Lasers: Nano-patch Lasers



Ming C. Wu, Optics Express, Vol. 18, Issue 9, pp. 8790-8799 (2010)