Lecture 9: Surface Plasmon Excitation

5 nm
Summary

The dispersion relation for surface plasmons

• Useful for describing plasmon excitation & propagation

This lecture:

Coupling light to surface plasmon-polaritons

• Using high energy electrons (EELS)
• Kretchman geometry

$$k_{//,SiO_2} = \sqrt{\varepsilon_d \frac{\omega}{c}} \sin \theta = k_{sp}$$

• Grating coupling
• Coupling using subwavelength features
• A diversity of guiding geometries
Dispersion Relation Surface-Plasmon Polaritons

Plot of the dispersion relation

- Last page: 
  \[ k_x = \frac{\omega}{c} \left( \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \right)^{1/2} \]

- Plot of the dielectric constants:

- Note: 
  \[ k_x \to \infty \text{ when } \varepsilon_m = -\varepsilon_d \]

- Define: \[ \omega = \omega_{sp} \text{ when } \varepsilon_m = -\varepsilon_d \]

- Low \( \omega \): 
  \[ k_x = \frac{\omega}{c} \lim_{\varepsilon_m \to -\infty} \left( \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \right)^{1/2} \approx \frac{\omega}{c} \sqrt{\varepsilon_d} \]

- Solutions lie below the light line! (guided modes)
Note: Higher index medium on metal results in lower $\omega_{sp}$

$$\omega = \omega_{sp} \text{ when: } \epsilon_m = 1 - \frac{\omega_p^2}{\omega^2} = -\epsilon_d$$

$$\omega^2 - \omega_p^2 = -\epsilon_d \omega^2$$

$$\omega^2 = \frac{\omega_p^2}{1 + \epsilon_d}$$

$$\omega = \frac{\omega_p}{\sqrt{1 + \epsilon_d}}$$
Excitation Surface-Plasmon Polaritons (SPPs) with Light

Problem SPP modes lie below the light line
• No coupling of SPP modes to far field and vice versa (reciprocity theorem)
• Need a “trick” to excite modes below the light line

Trick 1: Excitation from a high index medium
• Excitation SPP at a metal/air interface from a high index medium $n = n_h$

- SPP at metal/air interface can be excited from a high index medium!
- How does this work in practice?
Excitation Surface-Plasmon Polaritons with Light

Kretschmann geometry (Trick 1)

• Makes use of SiO₂ prism
• Create evanescent wave by TIR
• Strong coupling when \( k_{\parallel, SiO₂} \) to \( k_{sp} \)
• Reflected wave reduced in intensity

Note: we are matching energy and momentum
Surface-Plasmon is Excited at the Metal/Air Interface

Kretschmann geometry

- Makes use of SiO₂ prism
- Enables excitation surface plasmons at the Air/Metal interface
- Surface plasmons at the metal/glass interface can not be excited!

\[ k_{\parallel, SiO_2} = \sqrt{\varepsilon_d \frac{\omega}{c}} \sin \theta = k_{sp} \]
Quantitative Description of the Coupling to SPP’s

Calculation of reflection coefficient

- Solve Maxwell’s equations for
- Assume plane polarized light
- Find case of no reflection

\[ R = \left| \frac{E_r^p}{E_0^p} \right|^2 = \frac{r_{01}^p + r_{12}^p \exp(2ik_{z1}d)}{1 + r_{01}^p r_{12}^p \exp(2ik_{z1}d)} \]

Where \( r_{ik}^p \) are the amplitude reflection coefficients

\[ r_{ik}^p = \left( \frac{k_{zi}}{\varepsilon_i} - \frac{k_{zk}}{\varepsilon_k} \right) \left/ \left( \frac{k_{zi}}{\varepsilon_i} + \frac{k_{zk}}{\varepsilon_k} \right) \right. \]

Also known as Fresnel coefficients (p 95 optics, by Hecht)

Notes: Light intensity reflected from the back surface depends on the film thickness
There exists a film thickness for perfect coupling (destructive interference between two refl. beams)
When light coupled in perfectly, all the EM energy dissipated in the film)
Dependence on Film Thickness

- Width resonance related to damping of the SPP
- Light escapes prism below critical angle for total internal reflection
- Technique can be used to determine the thickness of metallic thin films

Raether, “Surface plasmons”
Quantitative Description of the Coupling to SPP’s

Intuitive picture: A resonating system

- When \( |\varepsilon_m'| > > 1 \) …well below \( \omega_{sp} \):
  - and \( |\varepsilon_m''| << |\varepsilon_m'| \) …low loss…

Reflection coefficient has Lorentzian line shape (characteristic of resonators)

\[
R = 1 - \frac{4\Gamma_i\Gamma_{rad}}{\left[\left(k_x - k_x^0\right)^2 + (\Gamma_i + \Gamma_{rad})^2\right]}
\]

Where
- \( \Gamma_i \): Damping due to resistive heating
- \( \Gamma_{rad} \): Damping due to re-radiation into the prism
- \( k_x^0 \): The resonance wave vector (maximum coupling)

Note: \( R \) goes to zero when \( \Gamma_i = \Gamma_{rad} \)
Current Use of the Surface Plasmon Resonance Technique

Determination film thickness of deposited films

• Example: Investigation Langmuir-Blodget-Kuhn (LBK) films

![Graph showing reflectance vs. incident angle]

- Coupling angle strongly dependent on the film thickness of the LBK film
- Detection of just a few LBK layers is feasible

Hiroshi Kano, “Near-field optics and Surface plasmon Polaritons”, Springer Verlag
Surface Plasmon Sensors

Advantages
- Evanescent field interacts with adsorbed molecules only
- Coupling angle strongly depends on $\varepsilon_d$
- Use of well-established surface chemistry for Au (thiol chemistry)

http://chem.ch.huji.ac.il/~eugeniik/spr.htm#reviews
Imaging SPP waves

- Near-field optics is essential
- Tip “taps” into the near-field
Direct Measurement of the Attenuation of SPP’s

• Local excitation using Kretschmann geometry

• Imaging of the (decay length of the) SPP

• Width resonance peak gives same result
Grating coupling geometry (trick 2)

• Bloch: Periodic dielectric constant couples waves for which the k-vectors differ by a reciprocal lattice vector $G$

• Strong coupling occurs when

$$k_{\parallel, SiO_2} = k_{sp} \pm mG$$

where:

$$k_{\parallel, SiO_2} = \left| k_e \right| = \sqrt{\varepsilon_d} \frac{\omega}{c} \sin \theta$$

$$k_{sp} = \frac{\omega}{c} \left( \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \right)^{1/2}$$

$$|G| = 2\pi/P$$

• Graphic representation
Excitation Surface-Plasmon Polaritons with Dots (Trick 3)

• Strong coupling: \( k_{\parallel, SiO_2} = k_{sp} \pm \Delta k_{dot} \)

Spatial Fourier transform of the dot contains significant contributions of \( \Delta k_{dot} \) values up to \( 2\pi/d \)


• Dipole radiation in direction of charge oscillation!
• Reason: Plasmon wave is longitudinal
Other Excitation Geometries

- Radiation pattern more directional
- Divergence angle determined by spot size
- Illumination whole line $\perp$ to line
- Pattern results from interference 2 dipoles

Excitation Surface-Plasmon Polaritons from a Scattering Particle

**Atomic Force Microscopy Image**

- Scattering site created by local metal ablation with a 248 nm Excimer laser (P=200 GW/m²)

**Near-field Optical Microscopy Image**

- Scattering site brakes translational symmetry
- Enables coupling to SPP at non-resonant angles

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Excitation SPPs on stripes with $d < \lambda$

Excitation using a launch pad

Atomic Force Microscopy image

Near Field Optical Microscopy image

Note oscillations

Excitation SPPs on stripes with $d < \lambda$

Atomic Force Microscopy image

Near Field Optical Microscopy image

Note oscillations

End stripe

Note: Oscillations are due to backreflection
2D Metallo-dielectric Photonic Crystals

Full photonic bandgap for SPPs

- Hexagonal array of metallic dots

![](image)

- Array causes coupling between waves for which:

  \[ k_{sp} = \pi / P \] or \[ \lambda_{sp} = 2\pi / k_{sp} = 2P \]

- Gap opens up at the zone boundary

\[ \omega / k = c \]

\[ \omega_s \]

\[ \omega_e \]

\[ \text{Gap} \]

\[ \text{Gap} \]

Guiding SPPs in 2D metallo-dielectric Photonic Crystals

Guiding along line defects in hexagonal arrays of metallic dots (period 400 nm)

- Scanning electron microscopy images

- SPP is confined to the plane

- Full photonic bandgap confines SPP to the line defect created in the array

S.I. Bozhevolnyi, Phys Rev Lett. 86, 3008 (2001)
Guiding SPPs in 2D metallo-dielectric Photonic Crystals

First results

- Scanning electron microscopy images

Dot spacing: \( d = 380 \text{ nm} \)
Excitation: \( \lambda_e = 725 \text{ nm} \)
SPP: \( \lambda_{sp} = 760 \text{ nm} = 2d \)

S.I. Bozhevolnyi, Phys Rev Lett. 86, 3008 (2001)
Summary

Coupling light to surface plasmon-polaritons

- **Kretschman geometry**

  \[ k_{\parallel, SiO_2} = \sqrt{\varepsilon_d \frac{\omega}{c}} \sin \theta = k_{sp} \]

- **Grating coupling**

  \[ k_{\parallel, Air} = k_{sp} \pm mG \]

- **Coupling using a metal dot (sub-\(\lambda\) structure)**

Guiding geometries

- **Stripes and wires**

- **Line defects in hexagonal arrays (2d photonic crystals)**