Nanoplasmonics

Enhancement of optical processes is severely limited by the metal loss

Why do we need metals in nanophotonics?
How does the metal loss limit the nanoplasmonic enhancement?
Can one compensate the SPP loss with gain?
Can light flow down on the surface like a water drop?

**Water drop**

- gravity
- Surface tension

**SPP (surface plasmon-polariton)**

- Light drop
- Electromagnetic force

**Diagram details:**
- Liquid/substrate
- EM frequency/metal
- TM pol.
Surface plasmons

Definitions: collective excitation of the free electrons in a metal
- Can be excited by light: photon-electron coupling (polariton)
- Thin metal films or metal nanoparticles
- Bound to the interface (exponentially decaying along the normal)
- Longitudinal surface wave in metal films
- Propagates along the interface anywhere from a few microns to several millimeters (long range plasmon) or can be extremely confined in nanostructures (localized plasmon)

Surface plasmon-polaritons (SPP) = SPs + photons

(Gary Wiederrecht, Purdue University)
Why do we need metals in photonics?

How does the propagation loss (Ohmic damping) limit nanoplasmonic enhancement?

- SPP-LEDs, SPP-solar cells, SPP-sensors

Can one compensate the SPP loss with gain?

- SPP nanocavity lasers
Plasmonics: the next chip-scale technology

Plasmonic devices, therefore, might interface naturally with similar speed photonic devices and similar size electronic components. For these reasons, plasmonics may well serve as the missing link between the two device technologies that currently have a difficult time communicating. By increasing the synergy between these technologies, plasmonics may be able to unleash the full potential of nanoscale functionality and become the next wave of chip-scale technology.

Why metals?

Plasmonics
Metals can support a guided mode with x-ray wavelength at optical frequencies

Dispersion relation of SPP: \[ k_{SPP} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \]

SP resonance when \( \varepsilon_m(\omega) + \varepsilon_d = 0 \)

\[ \omega_{SP} = \frac{\omega_p}{\sqrt{1 + \varepsilon_d}} \]

Therefore we need a metal with negative permittivity

\[ \varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} < -\varepsilon_d \]
Metals

Silver

Permittivity ($\varepsilon$)

Dispersion relation

Propagation length

Gold

Copper

Permittivity ($\varepsilon$) Dispersion relation Propagation length Metals
Fundamental parameters of SPP modes

1. Propagation and Absorption Indices:
   complex effective index
   \[ \tilde{n}_{\text{SP}} = k_{\text{SP}} / k_0 = \sqrt{\frac{\varepsilon_{\text{metal}}}{1+\varepsilon_{\text{metal}}}} = n_{\text{SP}} + i\kappa_{\text{SP}} \]

2. Propagation length:
   \[ L_{\text{SP}} = \left( \frac{\lambda}{2\pi} \right) \kappa_{\text{SP}} \quad (\lambda: \text{wavelength}) \]

3. Effective number of oscillations (ohmic Q-factor):
   \[ Q_{\text{SP}} = L_{\text{SP}} / \lambda_{\text{SP}} = n_{\text{SP}} L_{\text{SP}} \quad (\lambda_{\text{SP}} = \lambda / n_{\text{SP}}) \]
   \[ \ll 1 \quad \text{for a good resonance mode} \]

4. Mode size (range of evanescent field tail):
   \[ D_{\text{SP}} = \frac{\lambda}{2\pi \sqrt{n_{\text{SP}}^2 - 1}} \]
Aluminum looks good for plasmonics in visible range, better than gold in some senses!
Guiding and focusing of SPPs using metal tips


Guiding of a one-dimensional optical beam with nanometer diameter

Junichi Takahara, Suguru Yamagishi, Hiroaki Taki, Akihiro Morimoto, and Tetsuro Kobayashi
Department of Electrical Engineering, Faculty of Engineering Science, Osaka University, Toyonaka, Osaka 560, Japan
Dispersion relation of metal nanotips

$$\varepsilon_m I_1(k_0 \kappa_m R) + \varepsilon_d K_1(k_0 \kappa_d R) = 0$$

$$\kappa_m = \sqrt{n^2 - \varepsilon_m}$$

$$\kappa_d = \sqrt{n^2 - \varepsilon_d}$$

For a thin, nanoscale-radius wire $|k_y R| \ll 1$ (corresponding to large $|\varepsilon_2/\varepsilon_1|$).

$$\frac{\varepsilon_2}{\varepsilon_1} = \frac{2}{(\gamma - \log 2 + \log C)(C)^2}, \quad k_y = n k_0$$

$$n(R) \approx \frac{1}{k_0 R \sqrt{\frac{4 \varepsilon_m}{\varepsilon_d} - \gamma}}$$

$\gamma = 0.577$ is Euler’s constant.

For $k_0 R \rightarrow 0$, the phase velocity $v_p = c/n(z) \rightarrow 0$ and the group velocity $v_g = c/[d(n \omega)/d \omega] \rightarrow 0$.

The time to reach the point $R = 0$ (or $z = 0$) $\propto \int n(R) dR \propto -\ln(k_0 R) \rightarrow \infty$.
Why are the velocities so slow?

**Dielectric** \( \varepsilon > 0 \)

**Metal** \( \varepsilon < 0 \)

Total Energy Flux: \( \vec{p} = \vec{p}_1 + \vec{p}_2 \)

Medium 1: \( \vec{p}_1 = \int_{-\infty}^{0} dz \vec{W}_1(z) = \frac{\psi_0^2}{4 \omega} \frac{1}{\varepsilon_1} \sqrt{\frac{f}{f - \varepsilon_1 \mu_1}} \hat{x} \)

Medium 2: \( \vec{p}_2 = \int_{0}^{+\infty} dz \vec{W}_2(z) = \frac{\psi_0^2}{4 \omega} \frac{1}{\varepsilon_2} \sqrt{\frac{f}{f - \varepsilon_2 \mu_2}} \hat{x} \)

\( (f = \beta / k_0) \)

Always opposite to each other by the surface confinement condition
Apllications

Permittivity of a metal

\[ \varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} + i \frac{\omega_p^2}{\omega^2 + \gamma^2} \left( \frac{\gamma}{\omega} \right) \]

\[ \approx 1 - \frac{\omega_p^2}{\omega^2} \]

Dispersion relations

\[ k_{SPP} = \frac{\omega}{c} \left( \frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m} \right)^{1/2} \]
Type-A: low k

Type-A

- Low frequency region (IR)
- Weak field-confinement
- Most of energy is guided in clad
- Low propagation loss

► clad sensitive (sensor) applications
► SPP waveguides applications

Type-A: Plasmonic waveguides for interconnections


14 nm-thick, 2.5 μm-wide gold stripes

0.6 dB/cm: World best record in propagation loss.
(Previous world record: 3.2 dB/cm by Berini, 2006)
Double-electrode metal waveguides: S-band, Y-branch

Song, Long-range surface plasmon-polaritons on asymmetric double-electrode structures, APL, 2008.
Type-A: SPP sensors

SPR (surface plasmon resonance) on metal-coated prism

Metal SPP waveguide

Reference arm Sensing arm

Output signal

Sensorgram
LRSSP waveguides sensors with a \( \mu \)-fluidic channel
But, dielectric GMR sensors are also excellent.

Fast - instant results
Outstanding accuracy – cross referenced data
High sensitivity – detection of small molecules to large bacteria
High resolution – sharp detection peaks, high signal to noise
Mass producible – high density formats

Initial market applications in drug discovery and proteomics:
• Antigen-antibody assays, peptides and cell-based assays, DNA arrays

http://www.resonantsensors.com/
Type-B: middle k

**Type-B**

- Visible-light frequency region
- Coupling of localized field and propagation field
- Moderated field enhancement
- **Sensors, display applications**
- **Extraordinary transmission of light**
Type-B: Color filters using EOT

![Type-B: Color filters using EOT](image1)

- **R**
- **G**
- **B**

![Graphs and diagrams](image2)

- **T** (%)
- **Wavelength (nm)**
- **R, A (%)**

**Equation:**

\[ \rho(D) = \frac{1}{n} \]

**Diagram:**

- **FDTD Analytic model**
- **Glass-side incidence**
- **Air-side incidence**

**Wavelength (nm):**

790, 795, 800, 805, 810, 815

**Temperature (°C):**

0, 20, 40, 60, 80, 100
Type-C : high k

Type-C

- UV frequency region
- Strong field confinement
- Very-low group velocity
  ► Nano-focusing, Nano-lithography
  ► SP-enhanced LEDs, solar cells
**Type-C : SP Nano Lithography**

**Plasmonic nanolithography**

W. Srituravanich, N. Fang, C. Sun, Q. Luo, and X. Zhang,

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**Superlens-based nanopatterning**

- A flat plane of NRM behaves as superlens and amplifies evanescent waves in near-field through a series of plasmon resonances.
- This allows super-resolutions below diffraction limit.
- Experimentally achieved improvements in UV range: 5-10x beyond the operating wavelength
- Applicable for direct imaging of evanescent modes, thus for immediate recognition of analytes
- Also applicable for nanopatterning through subwavelength contact lithography

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**Sub-Diffraction-Limited Optical Imaging with a Silver Superlens**

Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang*

*Science* VOL 308 22 April 2005 535

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- UV illumination
- Quartz
- Metal spacer
- Resist
- Mask

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**Photoresist**

<table>
<thead>
<tr>
<th>Ag 35 nm</th>
<th>PMMA 40 nm</th>
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**Cr 50 nm mask with inscribed objects**

**Quartz support**

**UV exposure (365nm)**

**Thin silver film**
Plasmonic structures can offer at least three ways of reducing the physical thickness of the photovoltaic absorber layers while keeping their optical thickness constant.


Type-C: SP solar cells

- **a**: Metal nanoparticles at the surface of the solar cell. Light is preferentially scattered and trapped into the semiconductor thin film.

- **b**: Metal nanoparticles embedded in the semiconductor. Light trapping by the excitation of localized surface plasmons.

- **c**: Corrugated metallic film on the back surface of a thin photovoltaic absorber layer. Light trapping by the excitation of surface plasmon polaritons at the metal/semiconductor interface.
Why do we need metal?

How does the propagation loss limit the nanoplasmonic enhancement? 
: SPP-LEDs, SPP-solar cells, SPP-sensors

Can one compensate the SPP loss with gain? 
: SPP nano-cavity lasers
Consider a Type-C application: SPP-assisted LEDs

### Conventional LED

\[ \eta_0 = \frac{E_0 R_0}{R_{nr} + R_0} \]

### SP enhanced LED

\[ \eta_{SP} = \frac{E_0 R_0 + E_{SP} R_{SP}}{R_{nr} + R_0 + R_{SP}} \]
Purcell enhancement factor of surface plasmon-polaritons

SE Rate: \[ R = \frac{1}{\tau(\omega)} = \frac{1}{2\varepsilon_0 \hbar} |\langle f | p \cdot E | i \rangle|^2 \rho(\omega) \]

Dipole moment of the radiating source
Electric field strength of half photon (vacuum fluctuation)

Photon DOS (Density of States)

Purcell Factor:

\[ F_p = \frac{R_0 + R_{SP}}{R_0} = 1 + \frac{1}{2\pi} \frac{1}{L/\lambda} \frac{(k_{SP} / k_0)}{(v_{SP} / c)} \]

We need a slow and tightly confined mode

[Graph showing Purcell Factor vs. Propagation Constant]
Purcell factor

The gap separation less than 20 nm is required for $F_P > 10$. 

\[ F_P = 1 + \varepsilon_0 \frac{k_{SP}}{k_0} \frac{|E_{SP}(a)|^2}{V_{SP}/c'} k_0 U_{SP} \]
But, the metal loss is severe in such a small separation.

At $a = 20$ nm,
- A: 25.1%
- B: 55.9%
- C: 19%

High nonradiative recombination rate due to the metal loss.
The SP approach was started for organic LEDs

- ITO glass (anode)
- Organic molecules
- Cathode & Mirror

SPP quenching (~40%)

Nanostructures on metal mirror

Direct coupling

SPP band gap

$(\Lambda \sim \pi / k_{SPP})$

SPP cross-coupling

$(\Lambda = \pi / [k_{SPP1} - k_{SPP2}])$

Metallic thin film

Strongly coupled to SPPs

Main issue: SPP $\Rightarrow$ Radiation coupling
Cross-Coupled vs Coupled SPP

Surface plasmon-polariton mediated light emission through thin metal films

Stephen Wedge and W. L. Barnes

Thin Films Photonics Group, School of Physics, Stocker Road, University of Exeter, Exeter, EX4 4QL, UK

g.wedge@exeter.ac.uk
Surface Plasmon Enhanced Light-Emitting Diode

Jelena Vučković, Marko Lončar, and Axel Scherer

(c) 480nm period (2nd order coupling)
(d) 250nm period (1st order coupling)
(160nm gap)
Green LEDs might be possible.
Grating on p-GaN

- Little damage to p-GaN
- Enlarged surface area for low contact resistance
Wafer-scale fabrication of ~ 100 nm patterns

- Laser ($\lambda = 266$ nm)
- Pinhole
- Objective Lens
- Shutter
- Mirror
- Photoresist
- Aperture
- Wafer holder with $\phi$ rotator

Rotation stage

$\theta$

$x$

$y$

$z$

$\theta$ rotator

$\phi$ rotator

Wafer

NANO EGGBOX
EL measurement of the fabricated SPP-LED

- p-GaN 40nm, Bias=0V
- p-GaN 40nm, Bias=3V
- p-GaN 40nm, Bias=5V
- p-GaN 20nm, Bias=5V
An Optimistic Estimation of SP-enhanced LEDs

At green (530 nm) with a 1st order grating

(Bare-chip LED with 8 % extraction)  ➞  (82 % / 8 %) x 2.3  ~  24 times Brighter

( Optimized LED with 50 % extraction)  ➞  (82 % / 50 %) x 2.3  ~  4 times Brighter
Extraction efficiency of highly confined surface plasmon-polaritons to far-field radiation: an upper limit


\[ F_{SP} = \frac{\eta_{SP}}{\eta_0} = 1 + \frac{R_{SP}}{R_{total}} \left( \frac{E_{SP}}{\eta_0} - 1 \right) = \frac{E_{SP} + (1 - E_{SP})F_P^{-1}}{\eta_0 + (1 - \eta_0)F_P^{-1}} \]

\[ F_{SP} \leq \frac{E_{SP}}{\eta_0} \text{ even if } F_P \rightarrow \infty \]

\[ E_{SP} > \eta_0 \text{ to get } F_{SP} > 1 \]

\( \Rightarrow \) We need an efficient grating coupler

\[
E_{SP} = \lim_{\Gamma \rightarrow 0} \gamma_q \frac{[e_i(\Gamma)]}{\gamma_q [e_i(r)]}
\]

\( \Lambda = 632.8 \text{ nm.} \)
But, for a reasonable $F_P < 10$:

\[
F_{SP} = \frac{\eta_{SP}}{\eta_0} = 1 + \frac{R_{SP}}{R_{total}} \left( \frac{E_{SP}}{\eta_0} - 1 \right) = \frac{E_{SP} + (1 - E_{SP})F_P^{-1}}{\eta_0 + (1 - \eta_0)F_P^{-1}}
\]


Substantial improvement can be achieved only for very inefficient emitters with $\eta_0 < 1\%$. 

For 1-dim. Grating structure
SPP enhancement of spontaneous radiation is most noticeable only if the original radiative efficiency of the emitter is very small, far less than 1%. For this reason it does not appear that SPP offers any advantage for LEDs. The only possibly exception is Si emitters whose original radiative efficiency is very low. The main application of SPP enhancement should remain as improving the efficiency of weak photoluminescence and nonlinear processes.
Why do we need metal?
How does the propagation loss limit nanoplasmionic enhancement?
⇒ Can one compensate the SPP loss with gain?  SPP nano-cavity lasers

![Spaser design](image1)


(Jacob B. Khurgin)

Rate equation for the number of electrons in the SPP mode

\[
\frac{dn_{SPP}}{dt} = g(n_{SPP} + 1) - \gamma n_{SPP}
\]

When the modal gain \( g \) is close to compensating the loss \( \gamma \),

\[
(dn_{SPP} / dt) \sim \gamma \sim 10^{14} / s
\]

\[i_{inj} \sim e\gamma \sim 10 \mu A \text{ for } \lambda^2 \text{-scale}
\]

\[J = 10^6 A/cm^2 \text{ for (50 nm)$^2$-area} !!!!!!

In the figure, the spaser design is shown, indicating dye molecules throughout the silica shell. The transmission electron microscope image of Au core, scanning electron microscope image of Au/silica/dye core–shell nanoparticles, and the spaser mode are also depicted.
Challenges of SPPs


“Some of the challenges that face plasmonics research in the coming years are ..”

(i) demonstrate optical frequency subwavelength metallic wired circuits with a propagation loss that is comparable to conventional optical waveguides;
   → Too lossy.

(ii) develop highly efficient plasmonic organic and inorganic LEDs with tunable radiation properties;
    → Not efficient.

(iii) achieve active control of plasmonic signals by implementing electro-optic, all-optical, and piezoelectric modulation and gain mechanisms to plasmonic structures;
    → Not enough gain.

(iv) demonstrate 2D plasmonic optical components, including lenses and grating couplers, that can couple single mode fiber directly to plasmonic circuits;
    → Long-range SPPs only on Ag or Au, not Cu or Al.

(v) develop deep subwavelength plasmonic nanolithography over large surfaces.
    → ??

→ 2nd and 3rd Nonlinearity (SHG, SERS), Nano antennas (guiding and focusing), Sensors,.....

→ Ultrafast processing by the enhanced SE rate.
How about another polaritons: **SMPs**, instead of SPPs?

**Surface Magnetic(magneton)-Polaritons**

**Surface Magnetic Polariton (SMP)**

Coupling to TE-pol. light

Normalized energy flow densities