Surface-coupled Metal Nanoparticle Arrays
Amitabh Ghoshal and Pieter G. Kik
CREOL, The College of Optics and Photonics, UCF, Orlando, FL

University of Central Florida – Outgrowing Google Maps
Founded in 1968
> 50,000 students
2nd largest in USA
> 1200 faculty
> 180,000 degrees awarded

CREOL: always evolving
Periodic arrays on or near metals – large scale plasmonic antennas

- Enhanced optical transmission

- Enhanced solar cell response
  - Atwater, Polman, Nat. Mater. 9, 205 (2010)

- Enhanced biosensing
  - Adata, Altug, PNAS 106, 19227 (2009)

- Beam collimation in QCL
  - Yu et al., Nat. Photon. 2, 564 (2008)

Controlled excitation of propagating SPPs – miniature plasmon launch pad?
Near-field surface plasmon excitation

**Approach:** utilize **local fields** around nanostructures

Normal incidence illumination ⇒ localized fields (here: ~dipole)
Field localized in space ⇒ **k-vector ill-defined**

For optimum SPP excitation: maximize local field strength

Resonant enhancement of near fields

**Approach:** use **resonant nanostructures** for near-field excitation

Resonant excitation, enhanced local fields ⇒ larger SP amplitude

Further enhancement: add contribution from multiple particles
Constructive interference of locally excited surface plasmons

**Approach:** match inter-particle spacing to SP wavelength

**Constructive** addition of SPP excitation under **normal incidence illumination**

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**Prediction:** surface plasmon excitation using resonant metal particles can be used to construct **miniature couplers**

Nanoparticles enable **engineering of coupling** through **size** or **shape**

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Simulated field distribution under normal incidence illumination

**Nanoparticle mediated SPP excitation:**
- Dipolar field distribution near particle (local fields)
- Periodicity of SPP matches grating period

**Plasmons excited; frequency dependence?**

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Silver NP
AR = 3.5
h = 80 nm
L_x = 440 nm
L_y = 100 nm
f = 4.255 x 10^{14} Hz
Local field evolution

Frequency domain response shows:
- broad nanoparticle resonance
- narrow grating resonance (SPPs) at predicted frequency

Optimize coupling – adjust particle AR to match grating resonance

Surface plasmon amplitude vs. particle shape

Anti-crossing ⇒ strong coupling; weak SPP excitation near crossing
Nature of Eigenmodes at anti-crossing

Coupled LSP + SPP modes

At Eigenfrequencies: large field at NP location ⇒ large damping?

If damping is origin of reduced SPP amplitude ⇒ modify NP volume

Volume dependent study of three aspect ratios

Change NP volume, monitor max SPP amplitude and linewidth at grating resonance
Amplitude and linewidth vs. particles size

SPP amplitude increases until **NP-induced damping** becomes significant

Analytical model of NP induced surface plasmon damping

Find **nonradiative** and **radiative** NP damping rates using analytical cross-sections $\sigma_{\text{abs}}$ and $\sigma_{\text{scatt}}$ and equivalent ‘SPP irradiance’ $\frac{1}{2} n c \epsilon_0 E_{\text{SP,loc}}^2$

$\Rightarrow$ **Nanoparticle induced damping affects total linewidth and SPP amplitude**
Sample fabrication

Fabrication: e-beam lithography, gold particles

- Au, 34nm
- Cr, 6nm
- SiO₂, 65nm
- Au, 200nm
- Cr, 20nm
- Si substrate

Resulting patterns:
Regular, well-defined aspect ratio

APL 94, 171108 (2009)

First studies: vary inter-particle spacing, monitor SPP excitation

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Reflectivity vs. illumination numerical aperture

Narrow grating resonance, broad NP resonance and small narrow grating resonance due to weak z-polarization contribution

Next: Vary grating spacing to verify strong coupling
Reflection spectra vs. inter-particle spacing

Anti-crossing of LSP and SPP resonances, no anti-crossing of z-mode

Compare with normal incidence grating equation:

\[ k_{SPP}(\omega) = n \times G \]

Location of minima vs. grating constant

Reflection minima from z-mode follow SPP dispersion relation
Grating resonance follows SPP dispersion, except when NPs affect SPPs
SPP excitation observed indirectly - Next: direct SPP imaging
Leakage radiation experiments

Fabricate arrays on Au film on transparent substrate

Normal incidence illumination excites LSPs and SPPs. SPPs radiate into substrate, radiation collected with oil immersion objective.

Outline

Transmission microscopy image ‘from below’: faint contrast from array
Block direct transmission (‘spatial filter’ for low-k): SPP radiation
Leakage radiation spectroscopy

LR image → into monochr. → spectrally dispersed

Selective area leakage radiation spectroscopy

Observe SPP spectrum within and just outside coupler structure

SPP excitation efficiency

Leakage radiation spectrum just outside array

SPP excitation efficiency

\[ \eta = \frac{P_{SP\text{-rad}}}{P_{inc}} \left(1 + \frac{\Gamma_i}{\Gamma_{rad}}\right) \]

Measure
Calculate

PSS RRL 4, 280 (2010)

Low efficiency due to
- Large NA excitation
- LSP mismatch

Features in leakage radiation spectrum match well to reflection spectrum

Low frequency NP resonance absorbs strongly, but weakly excites SPP
SPP excitation vs. array size

Prepare different arrays, vary number of grating periods, measure LR spectrum

Single row of metal NP: LSP weakly excites SPPs at one main resonance freq.
Additional rows increase SPP strength, coupled modes develop

Integrated SPP amplitude outside array

SPP amplitude increases linearly with N, then saturates at N~8
Competition between SPP re-radiation and SPP excitation
⇒ Miniature SPP coupling device (size ~4 um)
Conclusions

LSP mediated SPP excitation

Strong coupling

Frequency selective excitation

Controlled interaction

Miniature devices