Surface-coupled Metal Nanoparticle Arrays

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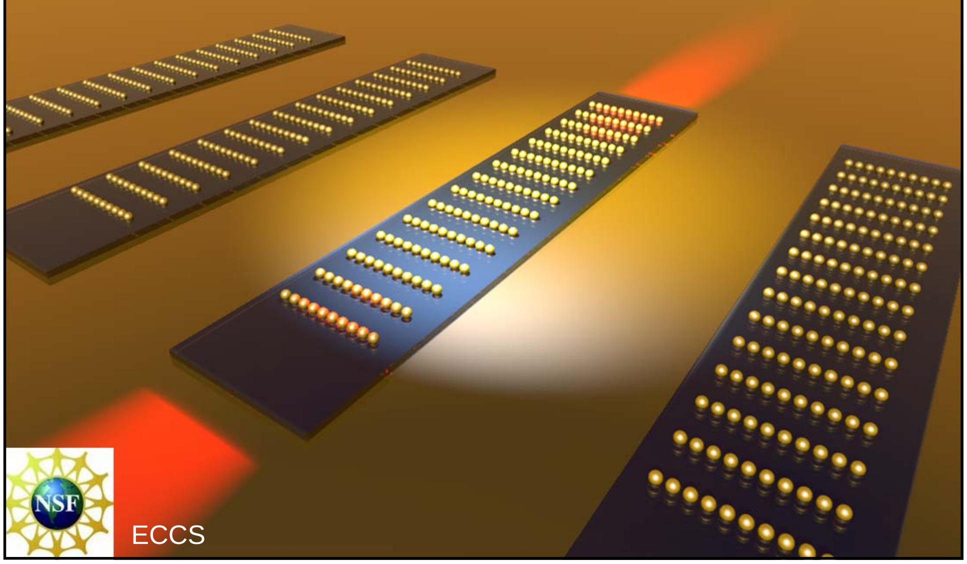


ECCS

University of Central Florida – Outgrowing Google Maps

Founded in **1968**

> 50,000 students

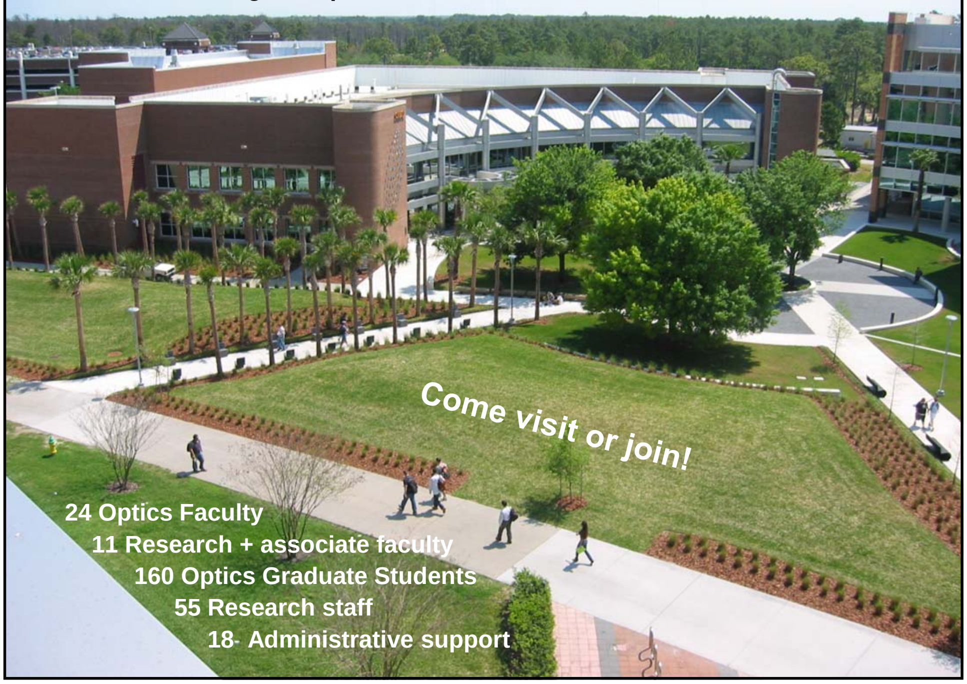
2nd largest in USA

> 1200 faculty

> 180,000 degrees awarded

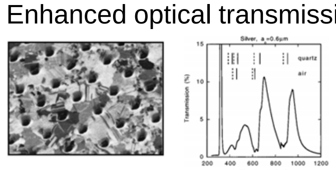
CREOL: always evolving

CREOL, The College of Optics and Photonics - Dean: Bahaa Saleh



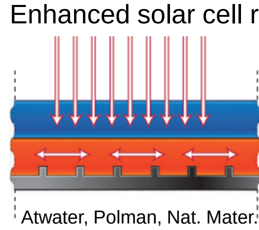
Periodic arrays on or near metals – large scale plasmonic antennas

Enhanced optical transmission



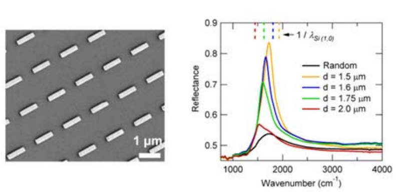
Gaemi et al. Phys. Rev. B **58**, 6779 (1998)

Enhanced solar cell response



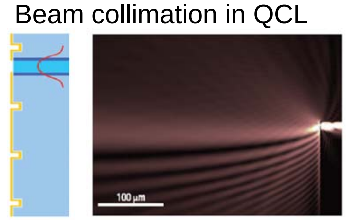
Atwater, Polman, Nat. Mater. 9, 205 (2010)

Enhanced biosensing



Adata, Altug, PNAS 106, 19227 (2009)

Beam collimation in QCL



Yu et al., Nat. Photon. 2, 564 (2008)

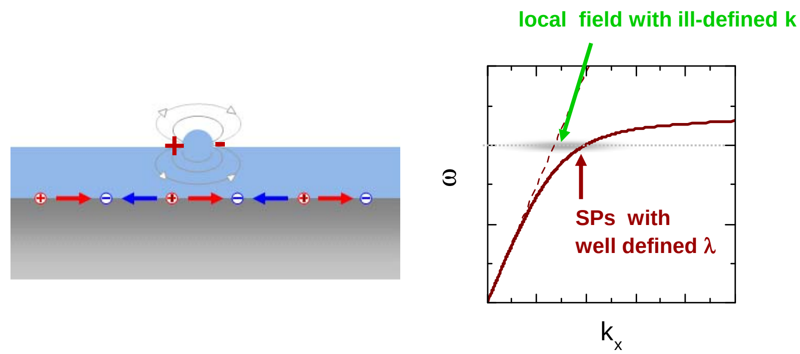
Controlled excitation of propagating SPPs – miniature plasmon launch pad?

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

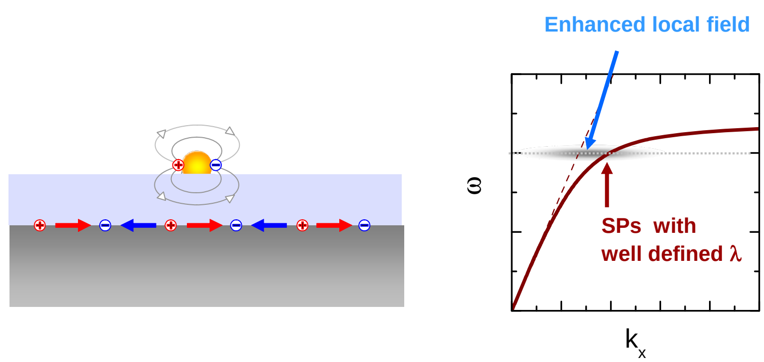


For optimum SPP excitation: maximize local field strength

Resonant enhancement of near fields

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

Resonant excitation, enhanced local fields ⇒ larger SP amplitude

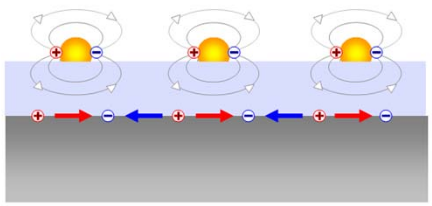


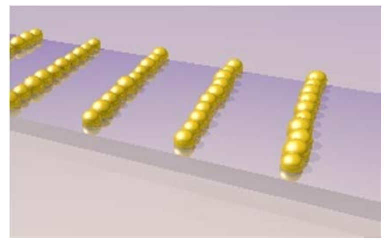
Further enhancement: add contribution from multiple particles

Constructive interference of locally excited surface plasmons

Approach: match inter-particle spacing to SP wavelength

Constructive addition of SPP excitation under normal incidence illumination





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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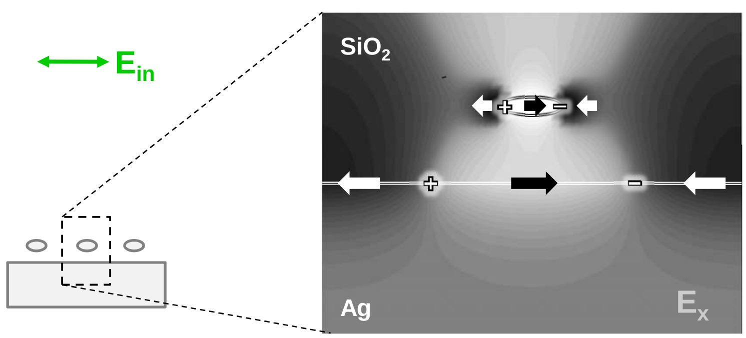
Simulated field distribution under normal incidence illumination



Nanoparticle mediated SPP excitation :

- Dipolar field distribution near particle (local fields)
- Periodicity of SPP matches grating period

Plasmons excited; **frequency dependence?**

Silver NP
AR = 3.5
h = 80 nm
L_x = 440 nm
L_y = 100 nm
$f = 4.255\times10^{14}$ Hz

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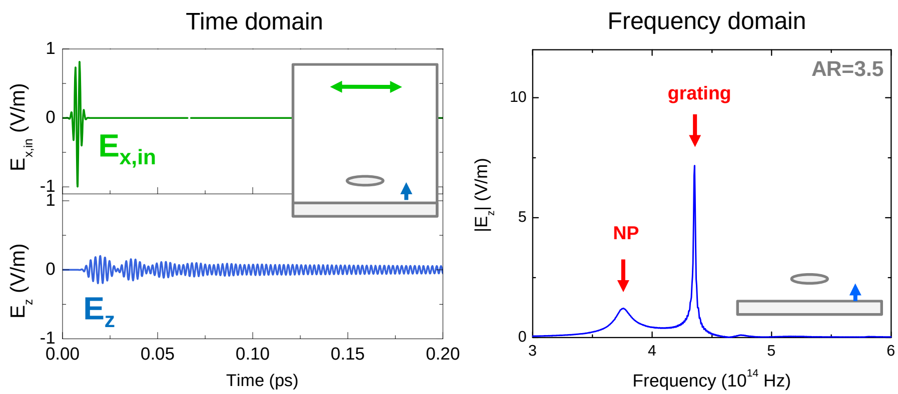
Local field evolution



Ghoshal et al. JAP **103**, 113111 (2008)

Frequency domain response shows

- broad nanoparticle resonance
- narrow grating resonance (SPPs) at predicted frequency

Optimize coupling – adjust particle AR to match grating resonance

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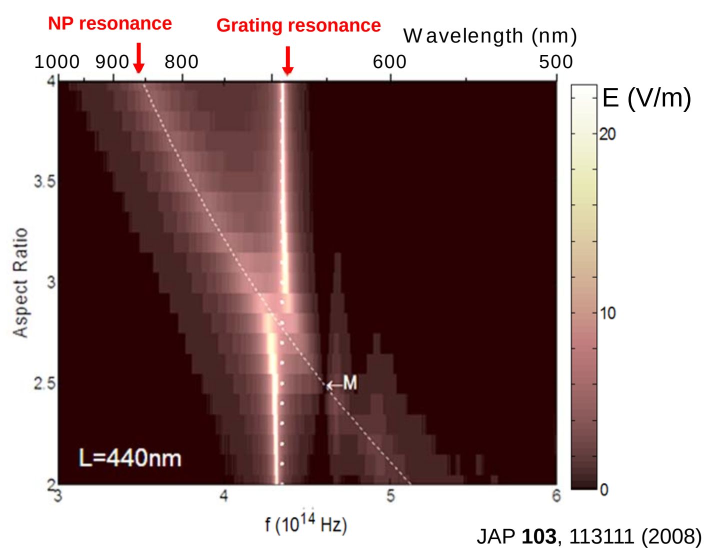
Surface plasmon amplitude vs. particle shape



JAP **103**, 113111 (2008)

Anti-crossing ⇒ strong coupling; weak SPP excitation near crossing

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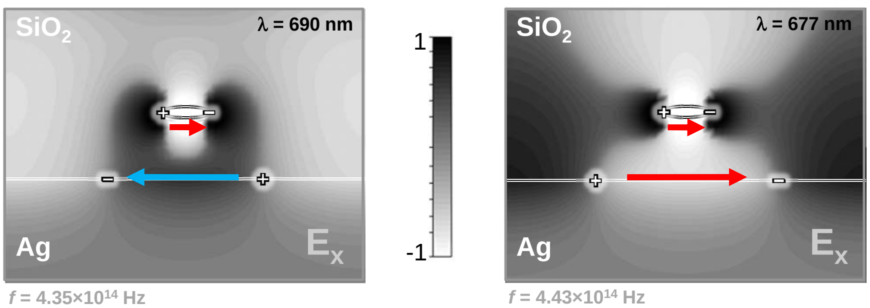
Nature of Eigenmodes at anti-crossing



Coupled LSP + SPP modes

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

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

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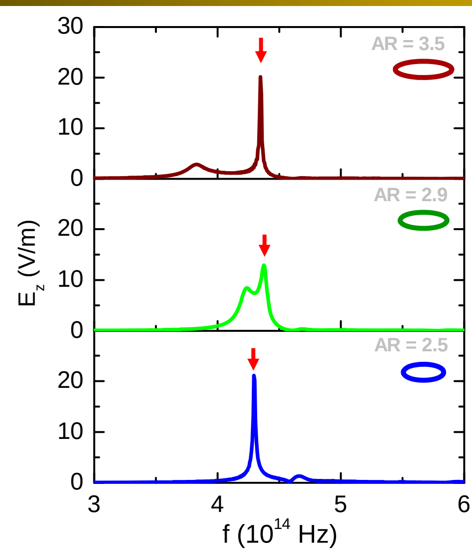
Volume dependent study of three aspect ratios



APL **94**, 251102 (2009)

Change **NP volume**, monitor **max SPP amplitude** and **linewidth** at grating resonance

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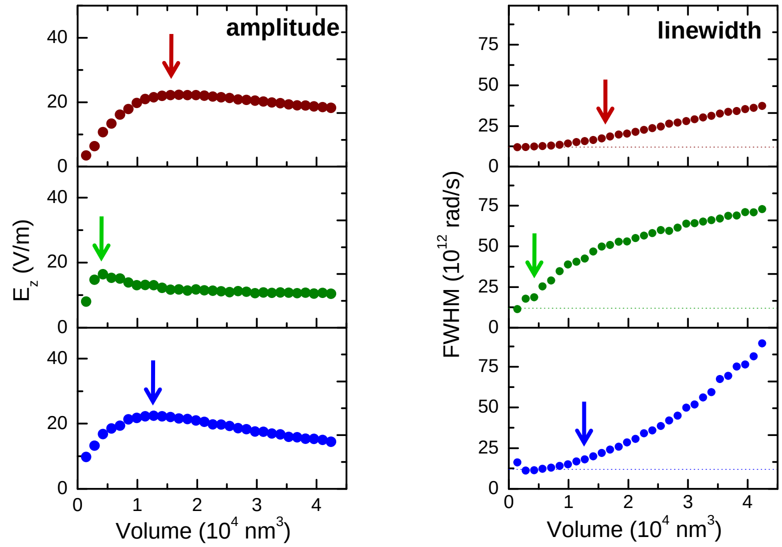
Amplitude and linewidth vs. particles size



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

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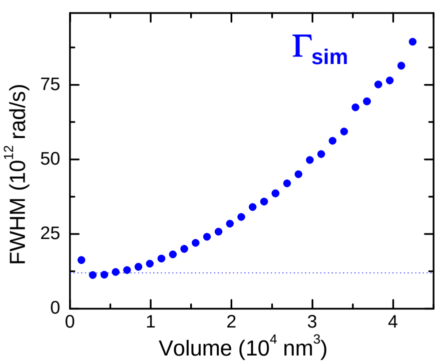
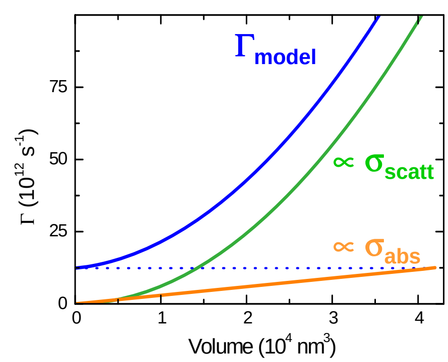
Analytical model of NP induced surface plasmon damping

Find nonradiative and radiative NP damping rates using analytical cross-sections σ_{abs} and σ_{scatt} and equivalent 'SPP irradiance' $\frac{1}{2} n c \varepsilon_0 E_{SP,loc}^2$





APL **94**, 251102 (2009)

⇒ Nanoparticle induced damping affects total linewidth and SPP amplitude

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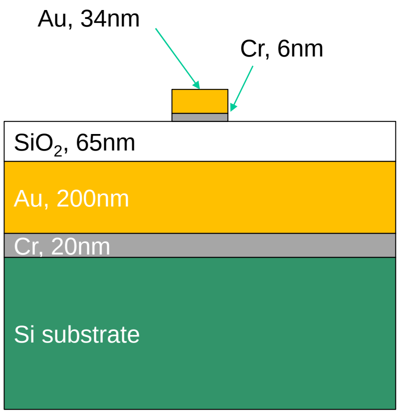
Sample fabrication

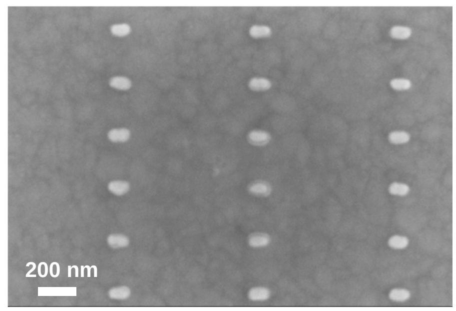
Fabrication : e-beam lithography, **gold** particles



APL **94**, 171108 (2009)

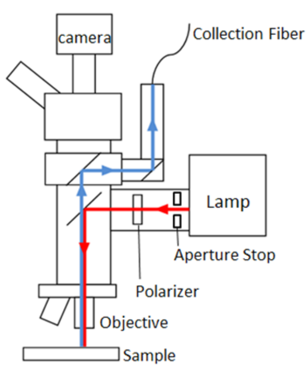
Resulting patterns:

Regular, well-defined aspect ratio

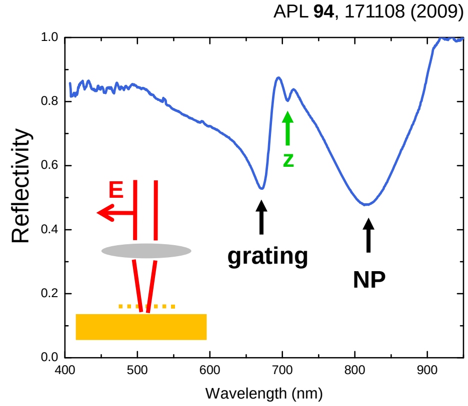


First studies: vary inter-particle spacing, monitor SPP excitation

Reflectivity vs. illumination numerical aperture



APL **94**, 171108 (2009)



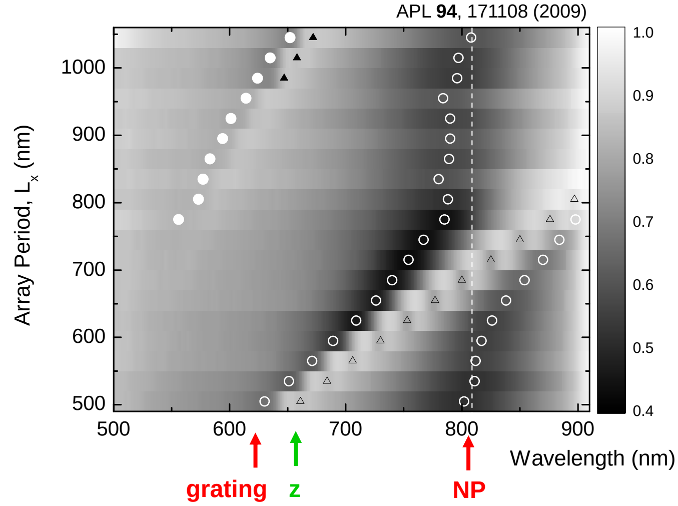
Narrow **grating resonance**, broad **NP resonance**

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

APL **94**, 171108 (2009)



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

Compare with normal incidence grating equation: $\mathbf{k_{SPP}(\omega) = n \times G}$

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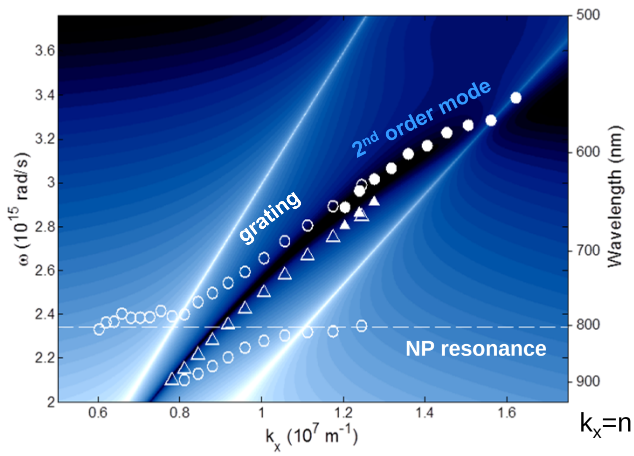
Location of minima vs. grating constant



$k_x = n \times 2\pi/L_x$

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

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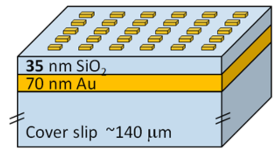
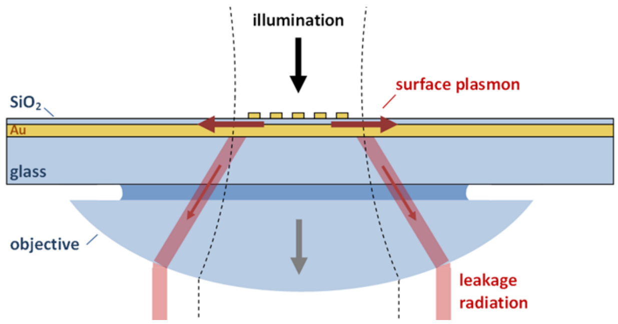
Leakage radiation experiments

Fabricate arrays on Au film on transparent substrate



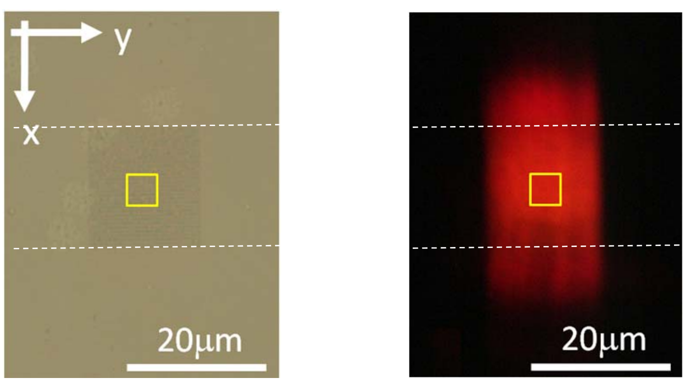


Phys. Stat. Sol. RRL **4**, 280 (2010)

Normal incidence illumination excites **LSPs** and **SPPs**

SPPs radiate into substrate, **radiation** collected with oil immersion objective

Outline



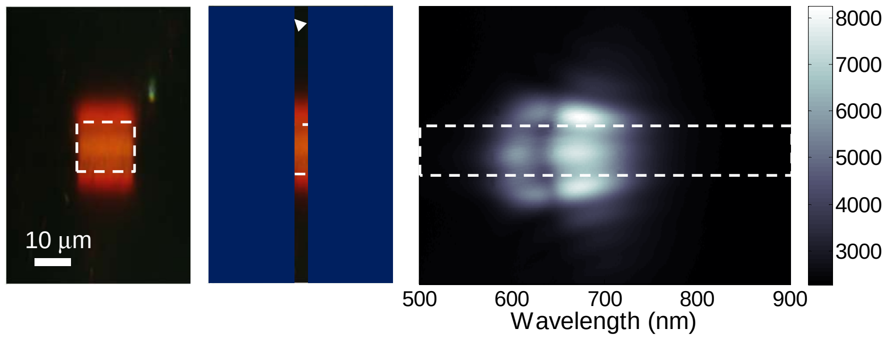
Phys. Stat. Sol. RRL **4**, 280 (2010)

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

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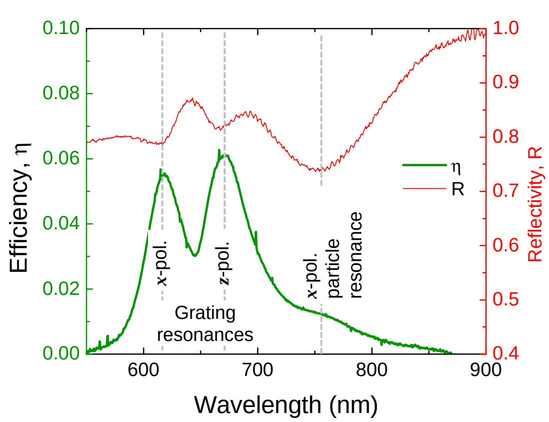
SPP excitation efficiency

Leakage radiation spectrum just outside array



SPP excitation efficiency

$$\eta = \frac{P_{SP,rad}}{P_{inc}} \cdot \left(1 + \left(\frac{\Gamma_i}{\Gamma_{rad}}\right)\right)$$

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

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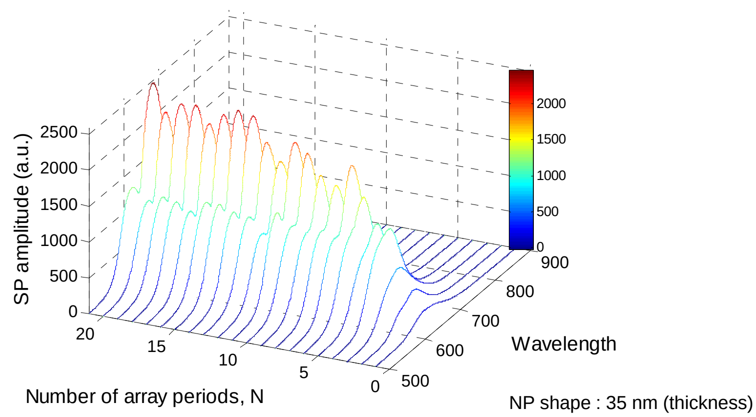
SPP excitation vs. array size

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

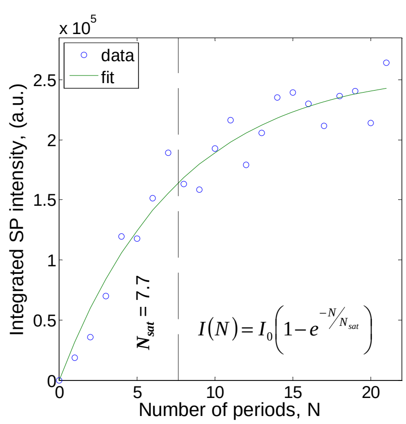


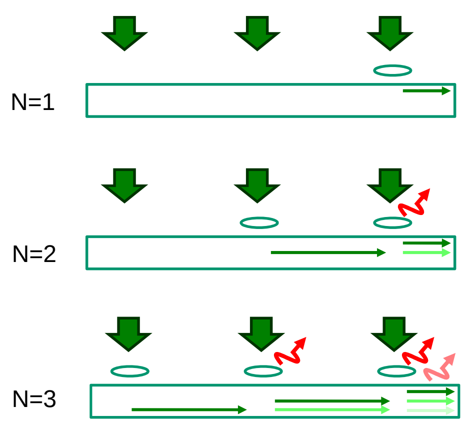
NP shape : 35 nm (thickness) x 100nm x 70nm

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

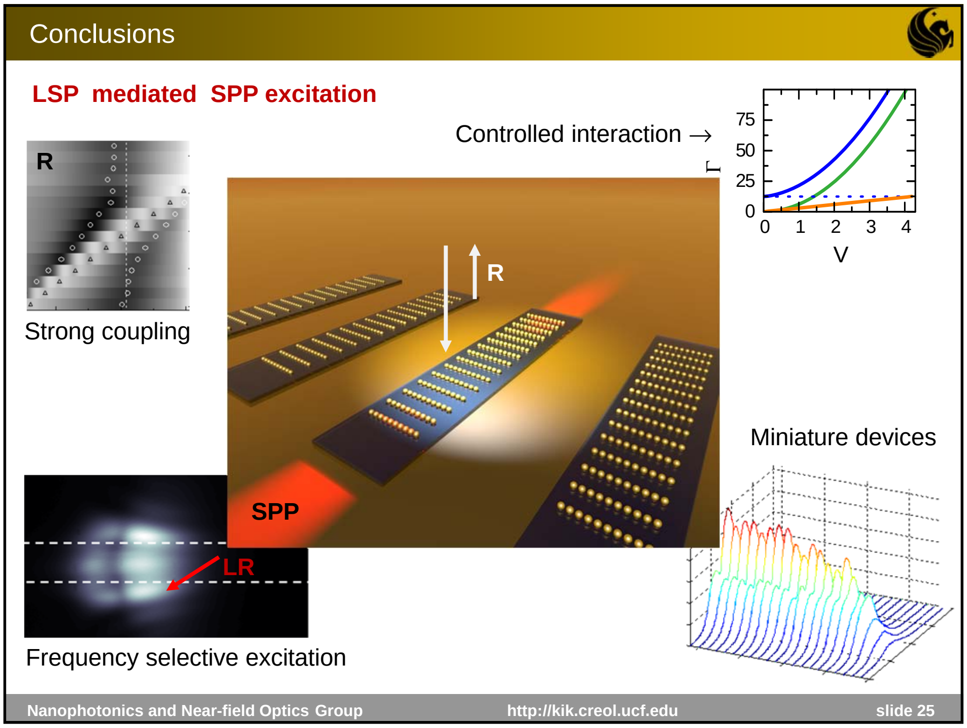




SPP amplitude increases linearly with N, then saturates at N~8

Competition between SPP re-radiation and SPP excitation

⇒ Miniature SPP coupling device (size ~4 um)


Conclusions
LSP mediated SPP excitation
R
Strong coupling
Controlled interaction →
Γ
75
50
25
0
0 1 2 3 4
V
R
SPP
LR
Frequency selective excitation
Miniature devices
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