Coherent Far-Field Excitation of Surface Plasmons Using Resonantly Tuned Metal Nanoparticle Arrays

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Introduction

Surface plasmons: charge density waves at the surface of conductors

Main features

- have shorter wavelength than light
- confined to the metal surface ⇒ small mode size possible
- may propagate up to hundreds of microns

Problem: Light-line does not intersect with SP mode. Difficult to excite!

Solution: Smaller periodicity in E-field
Introduction: Methods of Coupling

Prism coupling: Coherent excitation

- Incident light
- θ
- Reflected light
- SPs excited by evanescent field

Grating coupling: Coherent excitation

- Ditlbacher, Efficiency of local light-plasmon coupling, 2003

Nanostructure mediated: Local excitation

- Schematic of NSOM tip exciting SP
- NSOM image of SP

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No coherent excitation necessary

Ditlbacher, Efficiency of local light-plasmon coupling, 2003

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Coherent Excitation

Proposed structure

Plan:
Use nanoparticle resonance to create enhanced near-field
Space the nanoparticles to coherently excite SPs

Design parameters:
Design frequency: $2.78 \times 10^{15}$ rads/s ($\lambda_0 = 676\text{nm}$)
SP wavelength at Ag-SiO$_2$ interface: 440 nm
Propagation distance: 32 $\mu$m
Preliminary Parameters

Dispersion: Ag – SiO$_2$.

\[ k_{\text{design}} = 1.43 \times 10^7 \text{ m}^{-1} \rightarrow \lambda_{sp} = 440\text{nm} \]

decreasing aspect ratio \(\rightarrow\) increasing resonance frequency

Aspect ratio at design frequency: 3.5
Simulation Details

**Boundaries:**
Periodic in x and y ⇒ infinite array

**Excitation signal:**
Gaussian plane wave pulse
\[ f_{\text{center}} = 4.43 \times 10^{14} \text{ Hz}, \]  
bandwidth ±30%

**Structure Parameters:**
- Inter-particle spacing, \( L \approx \lambda_{sp} \approx 440\text{nm} \)
- Particle distance from film surface, \( d = 70\text{nm} \)
- Lateral particle separation, \( w = 3 \times (\text{particle width}) \approx 100\text{nm} \)
- Particle Aspect Ratio, \( \text{AR} 1.0 \text{ to } 4.0 \)

**Simulation:**
Finite Integration Technique  
800,000 mesh cells  
Ag – Drude model  
SiO\(_2\) – refractive index 1.44
SP Strength Determination

Normal incidence illumination, but dipole-like field

Field distribution indicative of SP, but excitation signal present

Plot clearly implies charge distribution of SP

⇒ $E_z$ due to SPs (and particle)

⇒ $E_z$ is large at charge locations
Signal peaks after excitation
Oscillations continue after excitation signal has stopped

Energy is stored in the system

Peak in amplitude implies maximum SP excitation
Particle Aspect Ratio Variation. AR = 1.0

SP amplitude dominated by coupler periodicity
Caused by nanoparticle, but resonance effect negligible

Predicted particle resonance frequency

\[ \frac{E_z}{E_{in}} \]

Frequency (\(10^{14}\) Hz)
Particle Aspect Ratio Variation. AR = 2.0

- Increase in SP strength
- Red-shift in particle resonance frequency
- Predicted particle resonance frequency
- Observed particle resonance frequency
- Design frequency
Particle Aspect Ratio Variation, AR = 2.5

Further increase in SP strength

Design frequency

Predicted particle resonance frequency

\[ E_z/E_{\text{in}} \]

Frequency (\(10^{14}\) Hz)
Particle Aspect Ratio Variation: AR = 3.0

Maximum in SP strength at AR of 3.0, near predicted 3.5

Design frequency

Predicted particle resonance frequency

Frequency ($10^{14}$ Hz)

$E_z/E_{in}$
Particle Aspect Ratio Variation, AR = 3.5

- Decrease in SP strength
- Observed particle resonance frequency
- Predicted particle resonance frequency
- Design frequency

\[ E_z/E_{in} \]

Frequency (\(10^{14} \text{ Hz}\))

Particle Aspect Ratio Variation. AR = 4.0

Design frequency

Even lower SP strength

Observed particle resonance frequency

Predicted particle resonance frequency

Even lower SP strength
Conclusion

Modeled SP excitation by a resonant Ag nanoparticle under normal illumination

Periodicity and nanoparticle shape affect SP excitation

Future Work:

• Investigate effects of particle-surface distance, $d$, particle spacing, $L$, lateral spacing, $w$

• Fabricate coupler structures and measure efficiency experimentally