Anomalous Surface Plasmon Dispersion in Metallodielectric Multilayers

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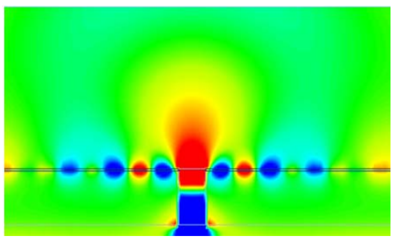
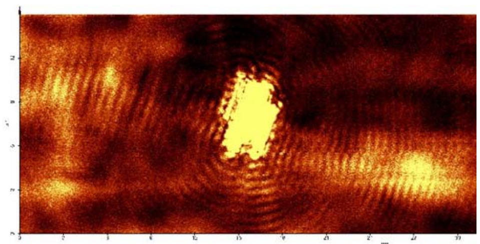


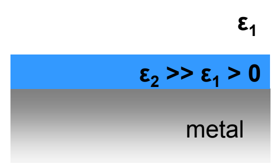


Introduction

Surface plasmons can provide highly confined modes at optical frequencies

Short wavelength plasmons have several applications:

- *Nanolithography*
- *Densely integrated optical circuits*
- *High resolution optical microscopy*



Prediction by Karalis et al. : A. Karalis et al., Phys. Rev. Lett. **95**, 063901 (2005)

A thin high refractive index film on can give rise to unusual type of <u>strongly confined plasmon with negative group velocity</u>

Theoretical study by Stockman : M.I. Stockman, Nano Lett., **6** (11), 2604 -2608, (2006)

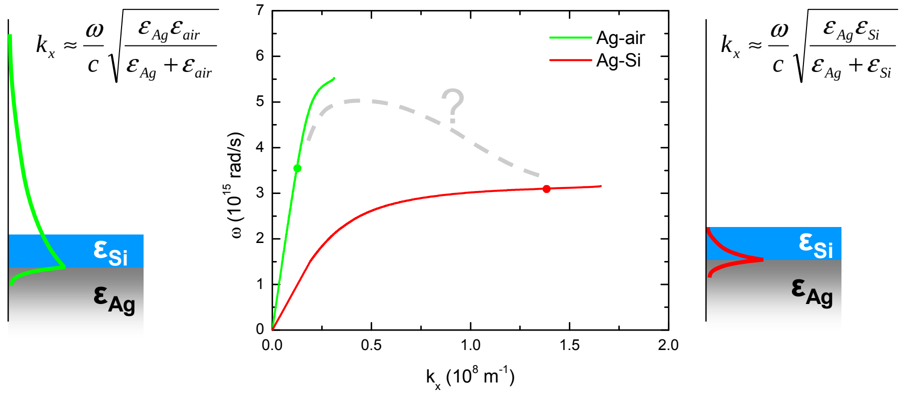
Negative group velocity modes are highly damped! **<u>Question: observable?</u>**

1. Calculate multilayer plasmon dispersion of real materials
2. Simulate to evaluate feasibility of experimental demonstration

Intuitive picture : origin of anomalous dispersion

SP confinement depends on ω - low ω: extended mode ; high ω: confined mode

$$k_x \approx \frac{\omega}{c}\sqrt{\frac{\varepsilon_{Ag}\varepsilon_{air}}{\varepsilon_{Ag}+\varepsilon_{air}}} \qquad k_x \approx \frac{\omega}{c}\sqrt{\frac{\varepsilon_{Ag}\varepsilon_{Si}}{\varepsilon_{Ag}+\varepsilon_{Si}}}$$



Low ω: extended mode, little overlap with Si: 'air like dispersion'

High ω: highly confined mode, large overlap with Si, 'silicon like dispersion'

Question: how do these limiting cases connect?

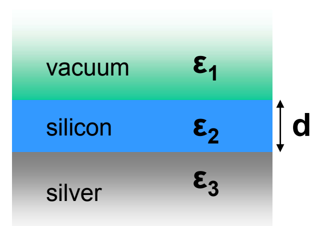
Calculation of surface plasmon dispersion relation

Experimentally realizable system: **silver substrate**, **thin silicon cover layer**

Calculate SP dispersion relation in three layer system

Bound surface plasmon modes can exist when:

$$\begin{vmatrix} 1 & -1 & -1 & 0 \\ \frac{k_{z_1}}{\varepsilon_1} & -\frac{k_{z_2}}{\varepsilon_2} & \frac{k_{z_2}}{\varepsilon_2} & 0 \\ 0 & e^{ik_{z_2}d} & e^{-ik_{z_2}d} & -e^{-ik_{z_3}d} \\ 0 & \frac{k_{z_2}}{\varepsilon_2}e^{ik_{z_2}d} & -\frac{k_{z_2}}{\varepsilon_2}e^{-ik_{z_2}d} & \frac{k_{z_3}}{\varepsilon_3}e^{-ik_{z_3}d} \end{vmatrix} = 0$$



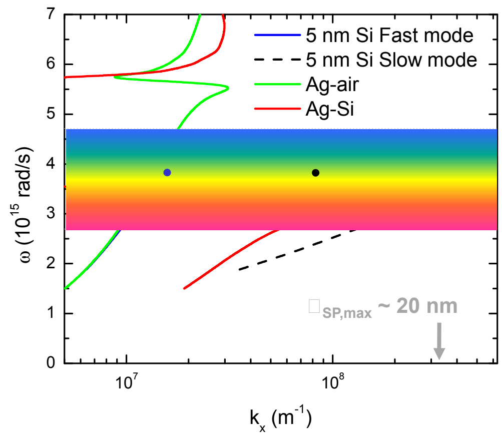
with ε_i the dielectric function of layer i, and

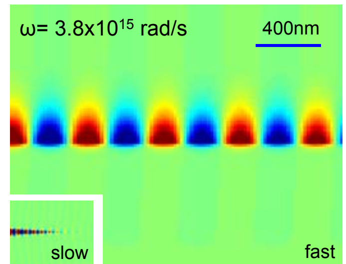
k_z the wavevector normal to the film surface: $k_{z_i} = \sqrt{k_x^2 - \frac{\omega^2}{c^2}\varepsilon_i}$

For fixed **d** find zeros of the determinant using literature dielectric functions

⇒ Complex k_x and complex k_z

Surface plasmon dispersion : 5nm Si on Ag





Note: modes to scale

Color scale shows H_y

Dispersion relation in layered system 'in between' Ag-air and Ag-Si dispersion

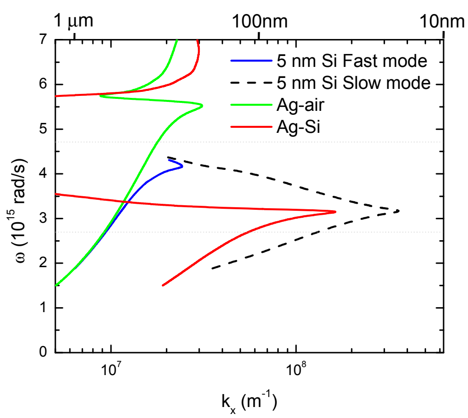
Observation of **fast mode** (high v_g) and **slow mode** (low and negative v_g)

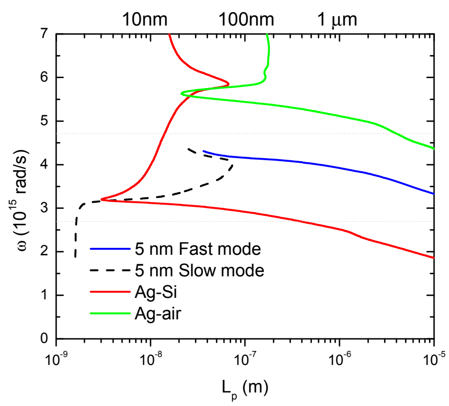
Plasmon wavelength of ~20nm at visible frequencies ! (~□/20, red light)

Single frequency: two modes possible, very different level of confinement

Surface plasmon dispersion : 5nm Si on Ag

Determine propagation length from imaginary part of k_x



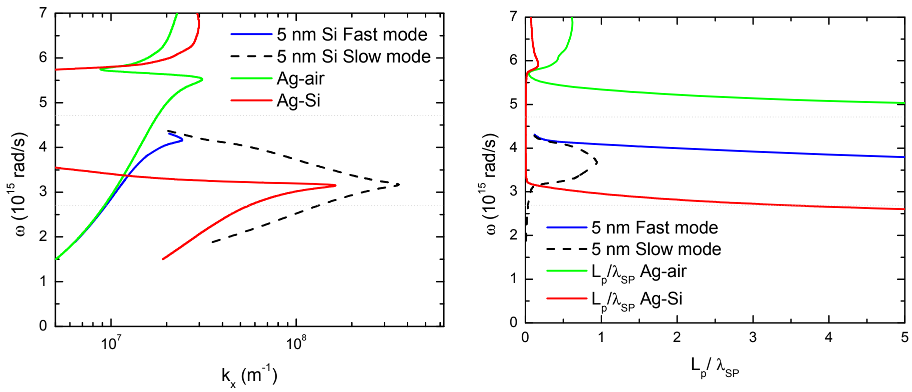


Max. propagation length of slow mode for d=5nm ~100nm

Question: is this sufficient to observe oscillatory nature of SP modes?

Surface plasmon dispersion : 5nm Si on Ag

Plot propagation length in terms of SP wavelength: L_p/□$_{SP}$

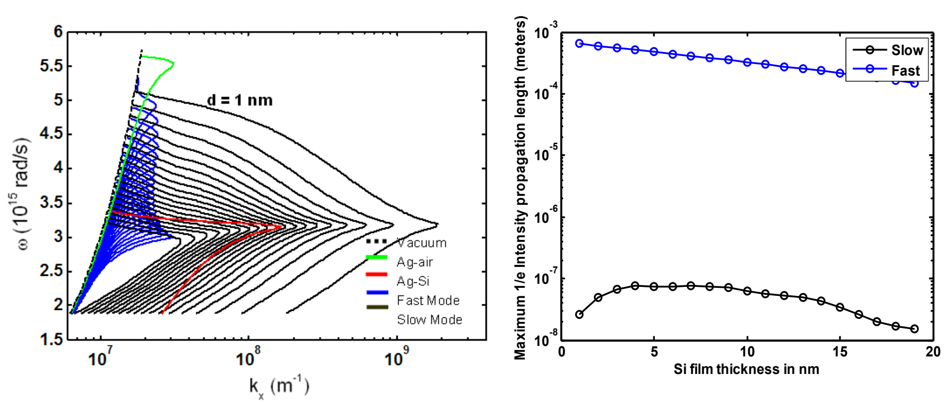


Maximum 1/e slow mode propagation length for this thickness: one wavelength

Next: Find maximum propagation length of slow mode vs. Si thickness

Surface plasmon dispersion : 5nm Si on Ag

Repeat calculation for range of Si thicknesses



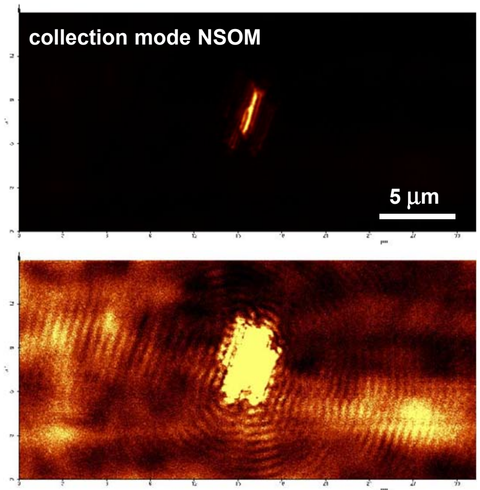
Conclusion: maximum propagation length of slow mode ~100nm at d_{Si}=4nm

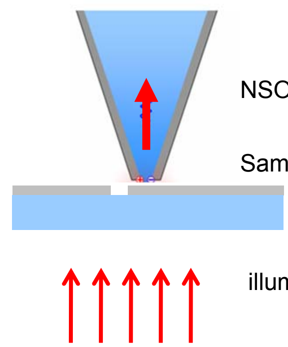
Simulate this system to evaluate feasibility of experimental demonstration

Slow plasmon excitation through slit

Part II: evaluate viability of experimental observation

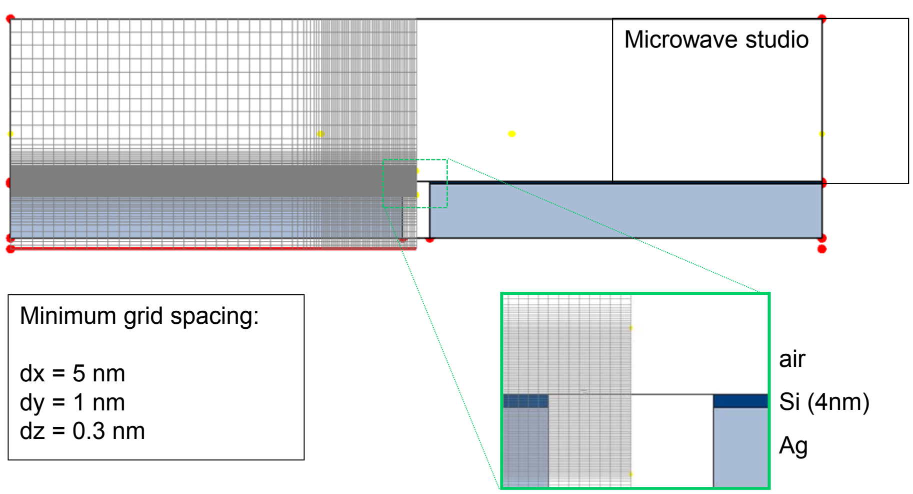
Example system: slit in silver film on glass





Simulate slow plasmon excitation using illumination through slit

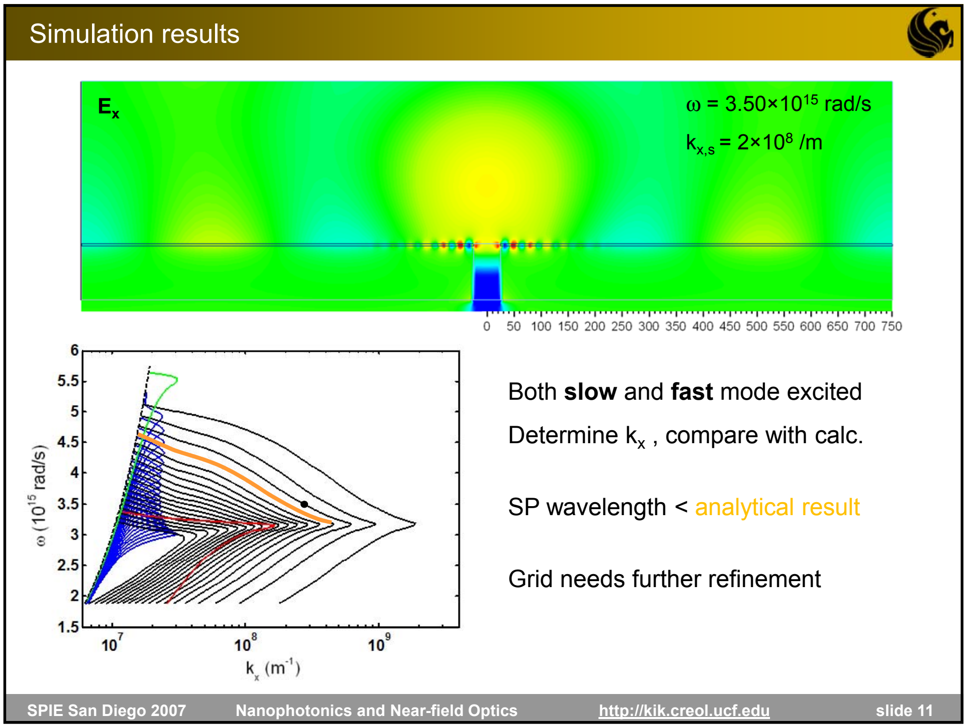
Frequency domain simulations



Two dimensional frequency domain simulation

Fine grid needed at sharp corners (edge of slit) and near Si film

Boundary conditions simulate array of infinite slits $\Rightarrow$ may see standing waves


Simulation results
E_x
$\omega = 3.50\times10^{15}$ rad/s
$k_{x,s} = 2\times10^{8}$ /m
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750
ω (10^{15} rad/s)
k_x (m^{-1})
Both **slow** and **fast** mode excited
Determine k_x , compare with calc.
SP wavelength < analytical result
Grid needs further refinement
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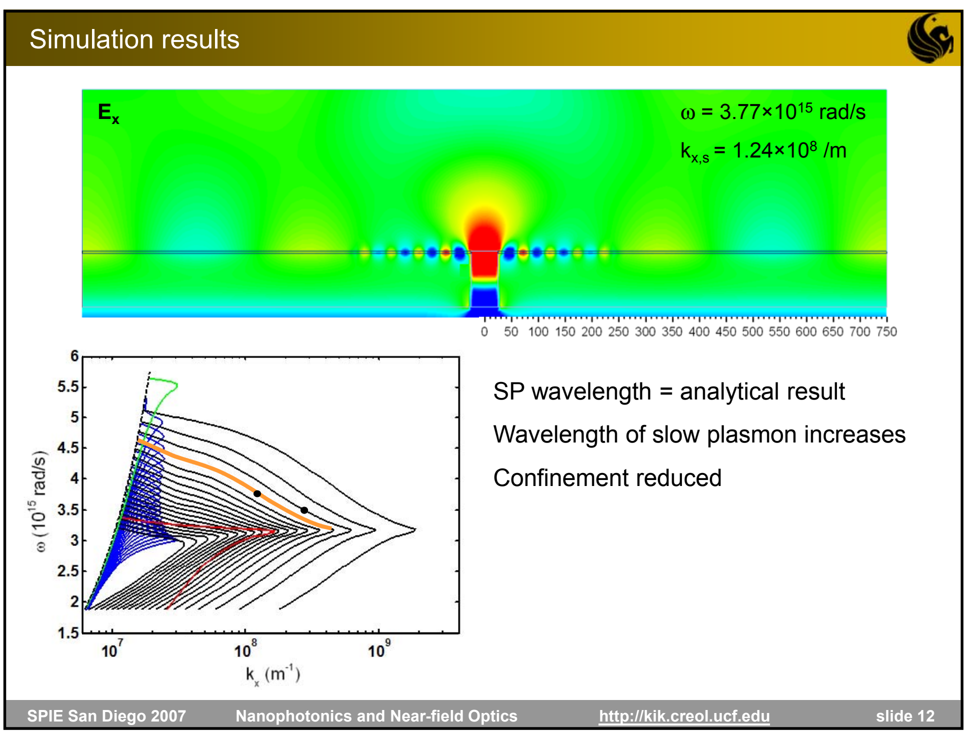
Simulation results
E_x
$\omega = 3.77\times10^{15}$ rad/s
$k_{x,s} = 1.24\times10^{8}$ /m
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750
ω (10^{15} rad/s)
k_x (m^{-1})
SP wavelength = analytical result
Wavelength of slow plasmon increases
Confinement reduced
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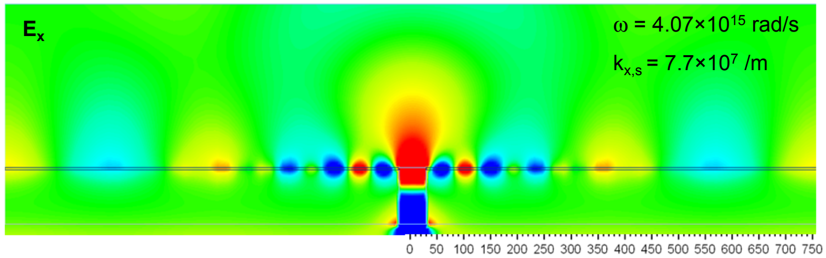
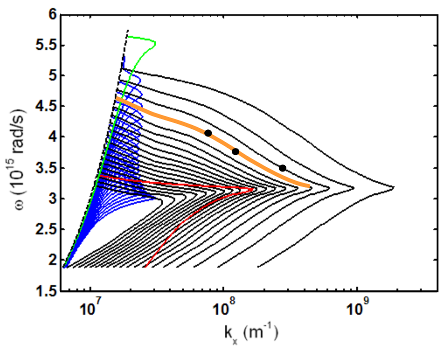
Simulation results





SP wavelength = analytical result

$\square_{SP}$ further increased

confinement further reduced

Fast mode has noticeably shorter $\square_{SP}$

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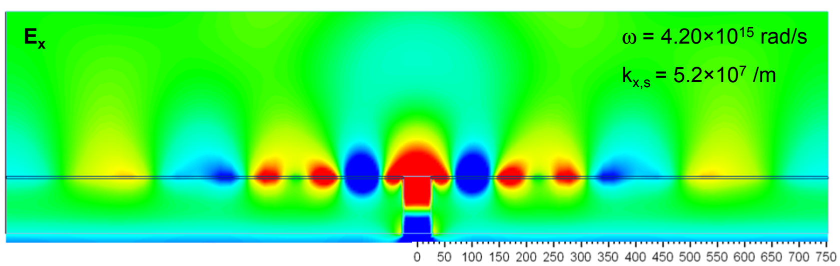
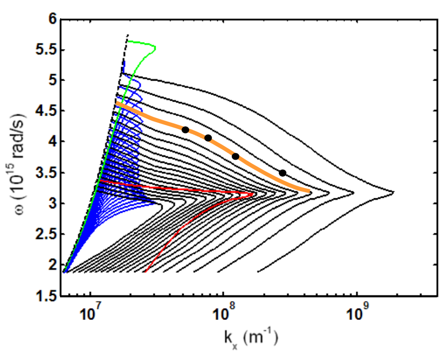
Simulation results





Fast and slow mode ~similar wavelength

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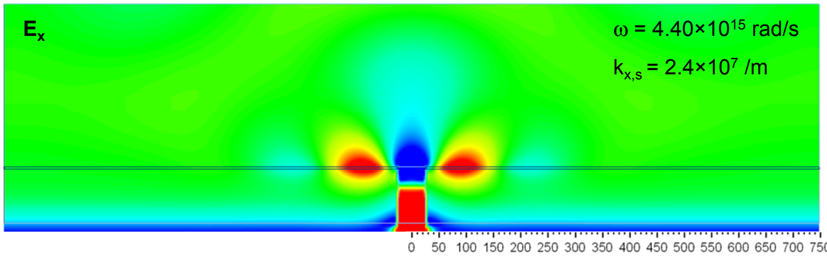
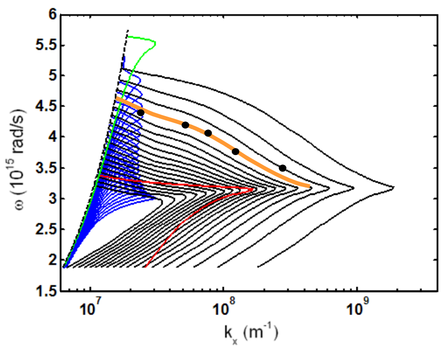
Simulation results





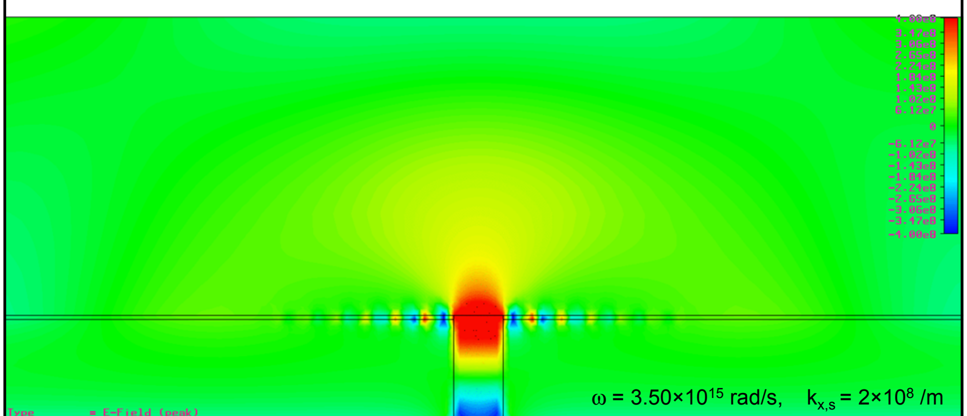
High frequency ⇒

Excitation near 'turning point'

⇒ Fast and slow mode:
- Similar k_x
- Group velocity ~0
- Localized mode near slit

Negative group velocity?

Observation of negative phase velocity



Phase = 0 degrees

Fast SPP creates standing wave, Slow SPP exhibits negative phase velocity

Conclusions

Analytical calculations

- Ag-Si system can lead to anomalous dispersion
- Strongly confined slow plasmon predicted at visible frequencies
- Maximum propagation length of slow plasmon < 100nm for d_{Si} = 4nm

Numerical simulations

- Illumination through slit leads to simultaneous slow and fast plasmon excitation
- Presence of slow plasmons with wavelength ~□/20 observed
- Experimental observation seems challenging, but feasible

Future work

- Evaluate slow plasmon excitation efficiency vs. slit geometry
- Attempt experimental demonstration of slow plasmons on silver