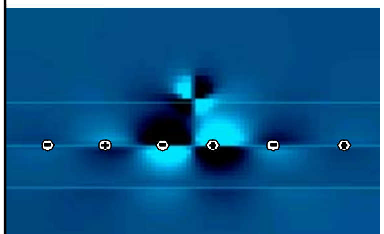
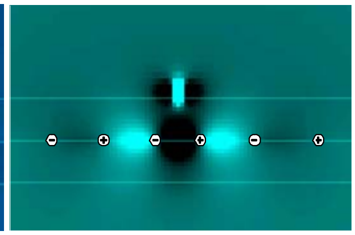
Experimental study of the perfect lens

Pieter G. Kik

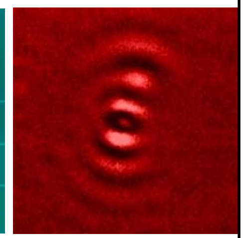
CREOL, The College of Optics and Photonics
University of Central Florida, Orlando, FL



simulation…



simulation…

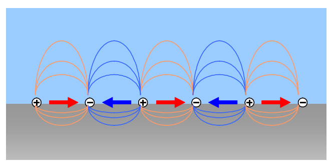


experiment!

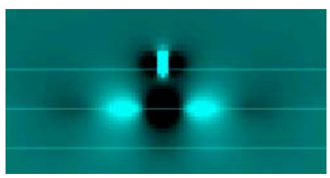
Key idea: surface plasmons can achieve *focusing on sub-wavelength scale*

Outline

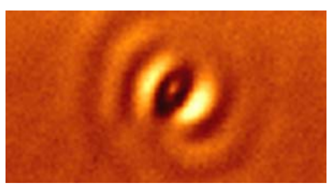
1. **Introduction**:
   - what is the near field
   - what are surface plasmons
   - what is the 'perfect lens'

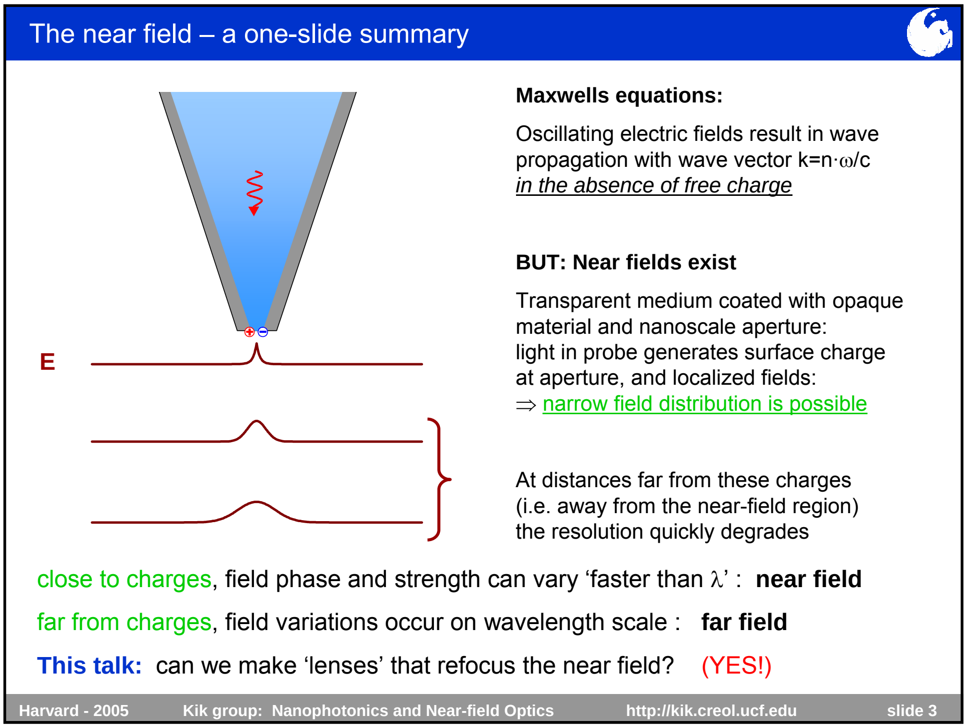


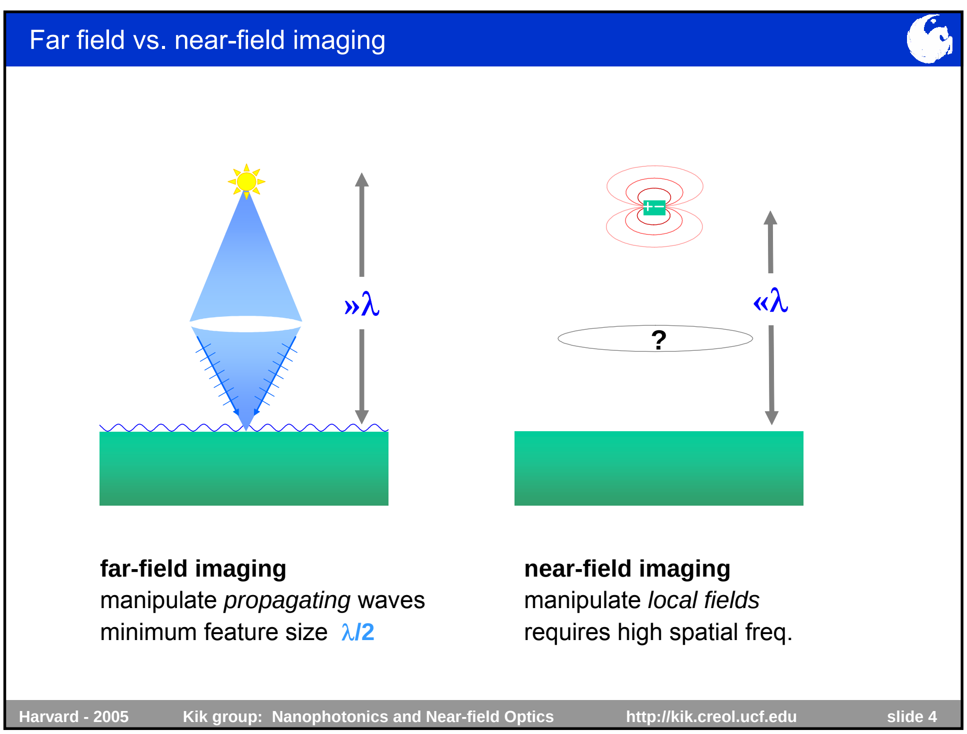
2. **Simulations** (Caltech)
   - finite element calculations
   - demonstration of focusing



3. **Experiments** (UCF)
   - near-field scanning optical microscopy
   - demonstration of focusing

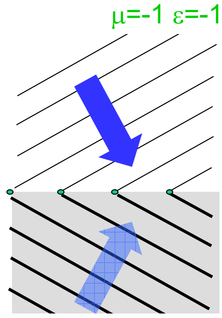



The near field – a one-slide summary
E
Maxwells equations:
Oscillating electric fields result in wave propagation with wave vector k=n·ω/c
in the absence of free charge
BUT: Near fields exist
Transparent medium coated with opaque material and nanoscale aperture:
light in probe generates surface charge at aperture, and localized fields:
⇒ narrow field distribution is possible
At distances far from these charges (i.e. away from the near-field region) the resolution quickly degrades
close to charges, field phase and strength can vary 'faster than λ' : near field
far from charges, field variations occur on wavelength scale : far field
This talk: can we make 'lenses' that refocus the near field? (YES!)
Harvard - 2005
Kik group: Nanophotonics and Near-field Optics
http://kik.creol.ucf.edu
slide 3

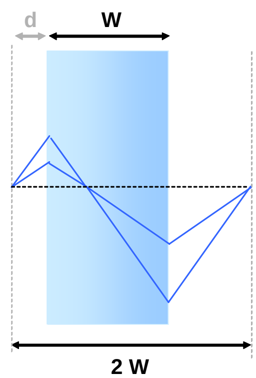

Far field vs. near-field imaging
»λ
«λ
?
far-field imaging
manipulate propagating waves
minimum feature size λ/2
near-field imaging
manipulate local fields
requires high spatial freq.
Harvard - 2005
Kik group: Nanophotonics and Near-field Optics
http://kik.creol.ucf.edu
slide 4

Negative refraction and imaging

left-handed media (LHM)

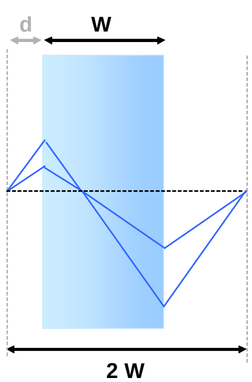


imaging with LHM slab



- V. G. Veselago, "*The electrodynamics of substances with simultaneously negative values of ε and μ*", Sov. Phys. Usp. **10**, 509 (1968)

Sub-diffraction limit focusing



General for LHM:

- Focusing if $n_{film} = - n_{surroundings}$ and d<W
- No unique 'optical axis' ⇒ no magnification
- For **ideal** (lossless) materials focusing occurs for all spatial frequencies, including non-radiating components ($k<2\pi/\lambda_{free}$)

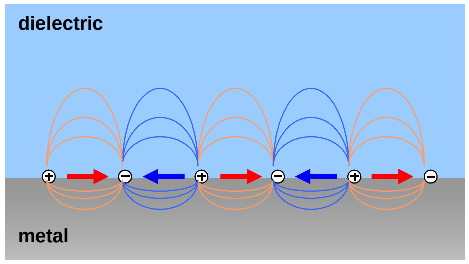
Specific for thin films: **(W « λ)**

- Focusing if $\varepsilon_{film} = - \varepsilon_{surroundings}$ ($E_{//}$ only)
- Loss/absorption limits resolution

- J. B. Pendry, "*Negative Refraction Makes a Perfect Lens*", Phys. Rev. Lett. **85**, 3966 (2000)

Surface plasmons

Surface plasmons: charge density waves at the surface of conductors

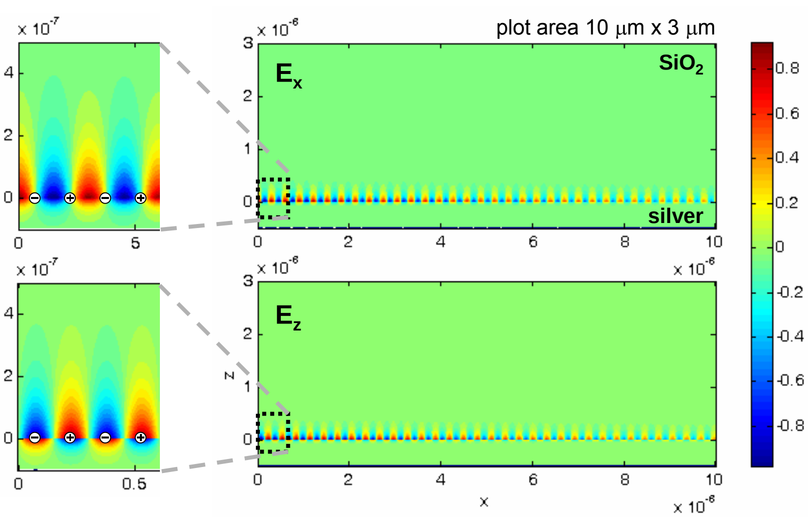


Main features

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

Surface plasmons – field distribution

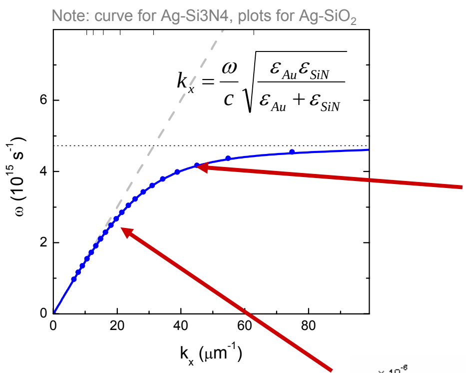
Example: surface plasmons on silver in SiO_2 surroundings, λ=500 nm



Note: mode strongly confined around interface

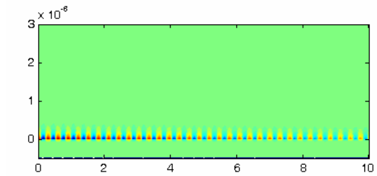
Surface plasmon dispersion relation

Surface plasmons at metal surfaces show unusual frequency dependence



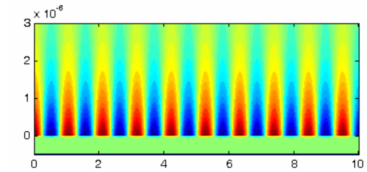
High frequency

- wavelength << λ free space
- tightly confined (small mode)
- short (1-10 μm) propagation



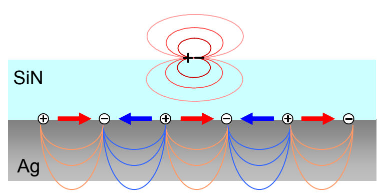
Low frequency

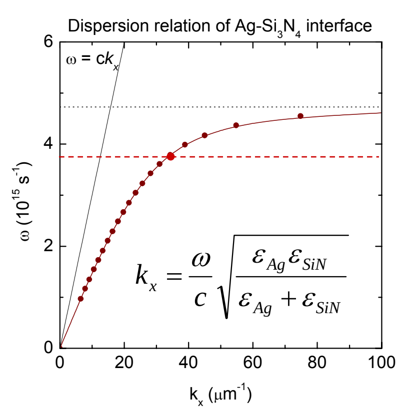
- wavelength ~ λ free space
- weakly confined (large mode)
- long (>100 μm) propagation



Near-field excitation of surface plasmons

surface plasmons can be locally ***excited*** and ***detected***





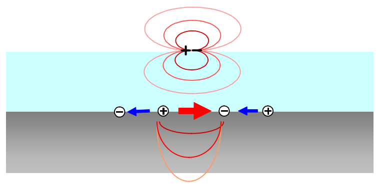
for a given ω, the plasmon **k** is higher than that of propagating light

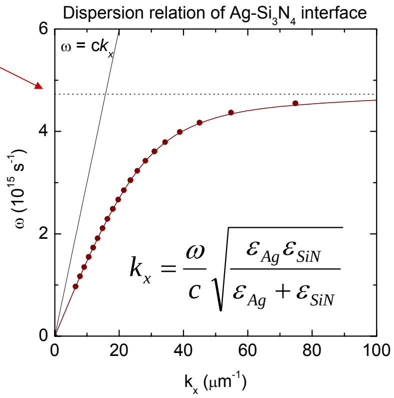
for a single frequency, a single k is excited (except when…)

Building a localized image – a ‘simple’ picture of the perfect lens

ω_{SP} when $\varepsilon_{Ag} = - \varepsilon_{surroundings}$

Excite many **high k** plasmon modes to make up *localized ‘wave packet’*

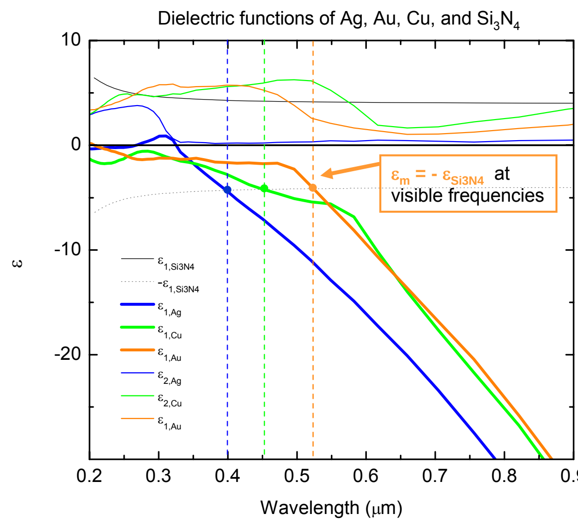




$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{Ag}\varepsilon_{SiN}}{\varepsilon_{Ag}+\varepsilon_{SiN}}}$$

SPs are the ’building blocks’ for sub-diffraction limit images in the near-field

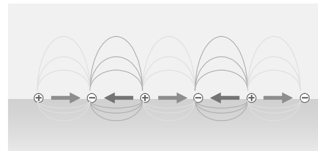
Imaging condition at metal-Si_3N_4 interfaces



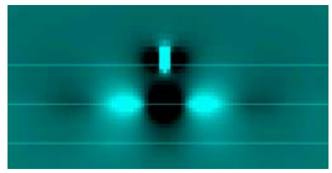
Condition for near-field in metal-Si_3N_4 system focusing occurs at visible frequencies

Outline

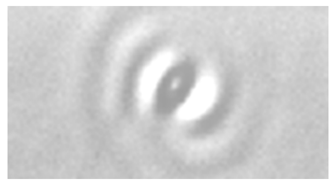
1. **Introduction**:
   - what is the near field
   - what are surface plasmons
   - what is the 'perfect lens'



2. **Simulations** (Caltech)
   - finite element calculations
   - demonstration of focusing



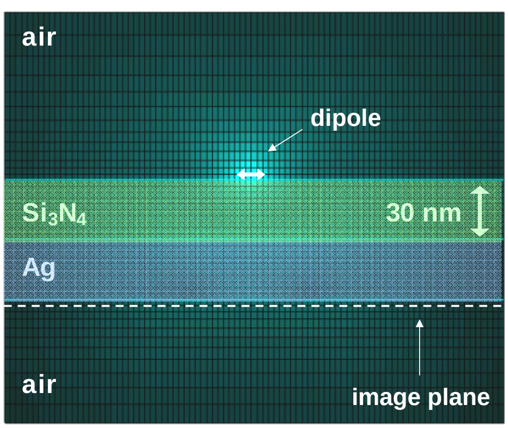
3. **Experiments** (UCF)
   - near-field scanning optical microscopy
   - demonstration of focusing



Harvard - 2005 Kik group: Nanophotonics and Near-field Optics http://kik.creol.ucf.edu slide 13

3D Finite Integration Technique (FIT) simulations

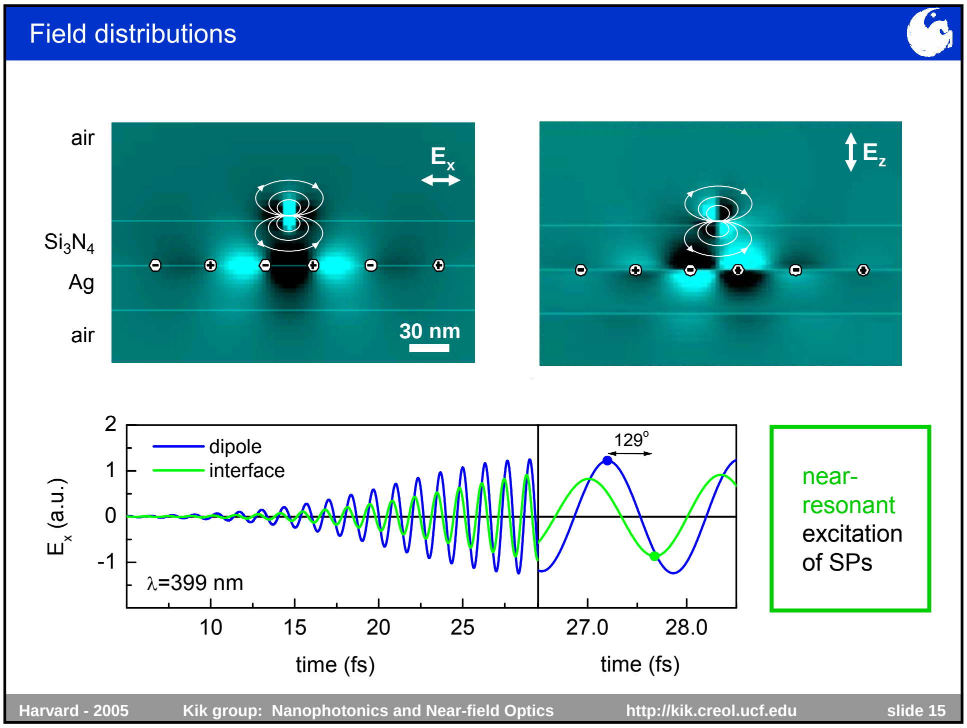
Kik, Maier, Atwater, Phys. Rev. B **69**, 045418 (2004)

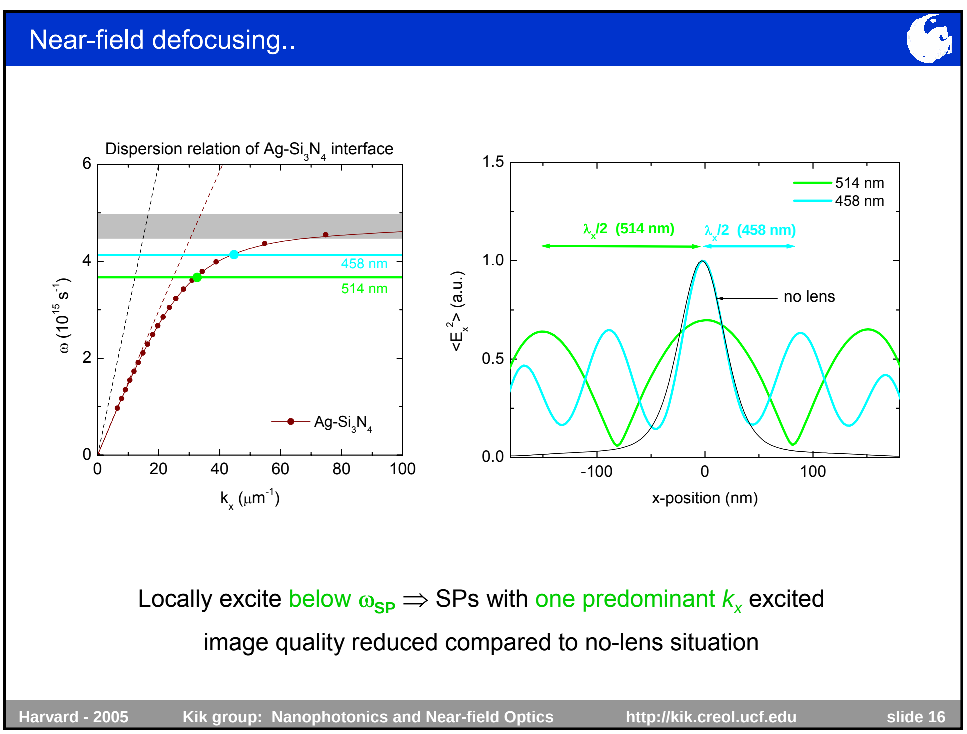


Cells	**10^6**
Steps	**300/cycle**
Cell size	**$(3\ nm)^3$**
Length	**~20 cycles**
Volume	**$(500\ nm)^3$**
$\Delta\omega$	**0.10 ω_c**

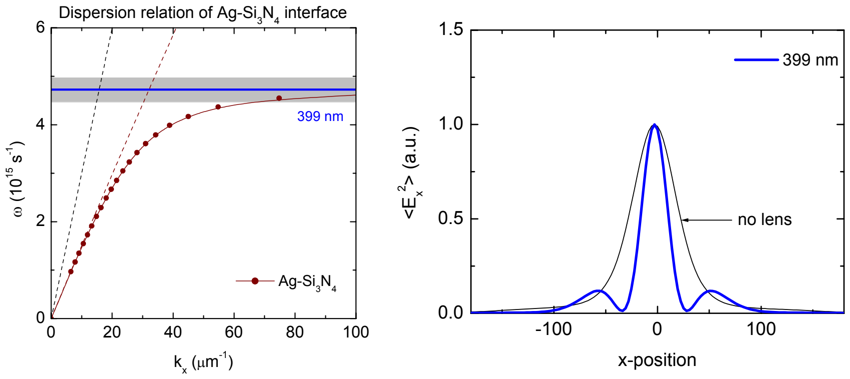
Finite bandwidth oscillating dipole near ω_{SP} in realistic materials system

Harvard - 2005 Kik group: Nanophotonics and Near-field Optics http://kik.creol.ucf.edu slide 14


Field distributions
air
Si3N4
Ag
air
Ex
Ez
30 nm
2
1
0
-1
Ex (a.u.)
dipole
interface
λ=399 nm
129°
10
15
20
25
27.0
28.0
time (fs)
time (fs)
near-resonant excitation of SPs
Harvard - 2005
Kik group: Nanophotonics and Near-field Optics
http://kik.creol.ucf.edu
slide 15


Near-field defocusing..
Dispersion relation of Ag-Si3N4 interface
ω (10^15 s^-1)
kx (μm^-1)
458 nm
514 nm
Ag-Si3N4
0
20
40
60
80
100
0
2
4
6
<Ex^2> (a.u.)
x-position (nm)
514 nm
458 nm
λx/2 (514 nm)
λx/2 (458 nm)
no lens
0.0
0.5
1.0
1.5
-100
0
100
Locally excite below ωSP ⇒ SPs with one predominant kx excited
image quality reduced compared to no-lens situation
Harvard - 2005
Kik group: Nanophotonics and Near-field Optics
http://kik.creol.ucf.edu
slide 16

Near-field focusing!

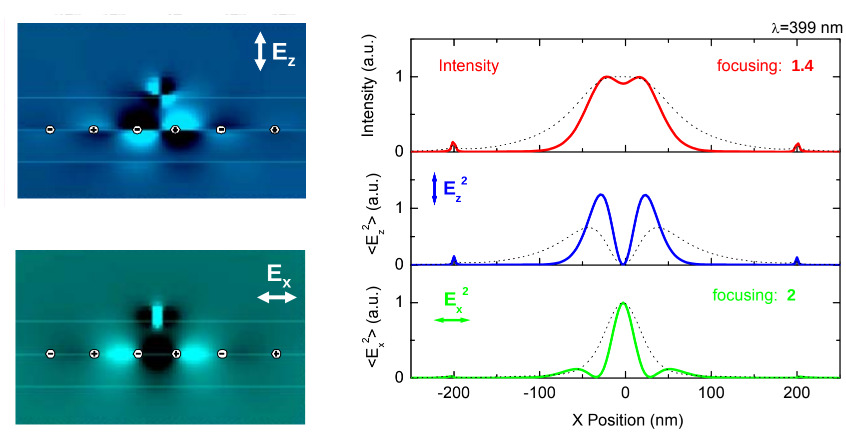


Locally excite **at ω_{SP}** ⇒ SPs with high k_x excited

image width reduced by factor ***2*** compared to no-lens situation

Harvard - 2005 Kik group: Nanophotonics and Near-field Optics http://kik.creol.ucf.edu slide 17

Numerical calculations – summary



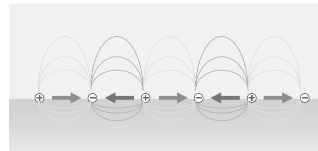
In order to obtain localized E_x, localized E_z necessary

⇒ **intensity** focusing impeded by normal fields

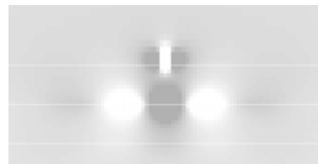
Harvard - 2005 Kik group: Nanophotonics and Near-field Optics http://kik.creol.ucf.edu slide 18

Outline

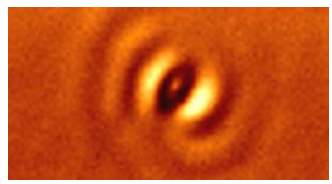
1. **Introduction**:
   - what is the near field
   - what are surface plasmons
   - what is the 'perfect lens'



2. **Simulations** (at Caltech)
   - finite element calculations
   - demonstration of focusing



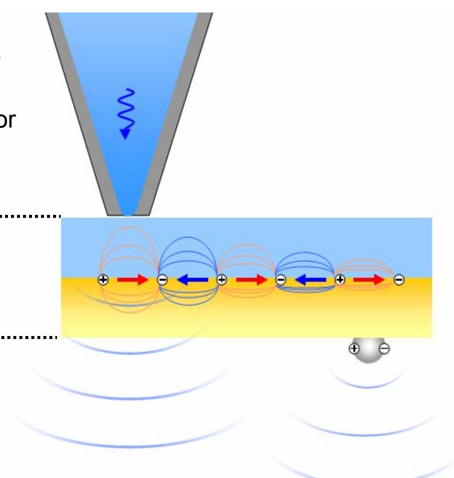
3. **Experiments** (at UCF)
   - near-field scanning optical microscopy
   - demonstration of focusing



Experimental approach to far field detection of super resolution

Proposed in Kik, Maier, Atwater, Phys. Rev. B **69**, 045418 (2004)

Requirements:
1) Near-field source
2) Near-field lens
3) Near-field detector



NSOM tip
(50-100nm ∅)

- SP excitation
- dipole radiation

Surface plasmons

Confined;
no radiation

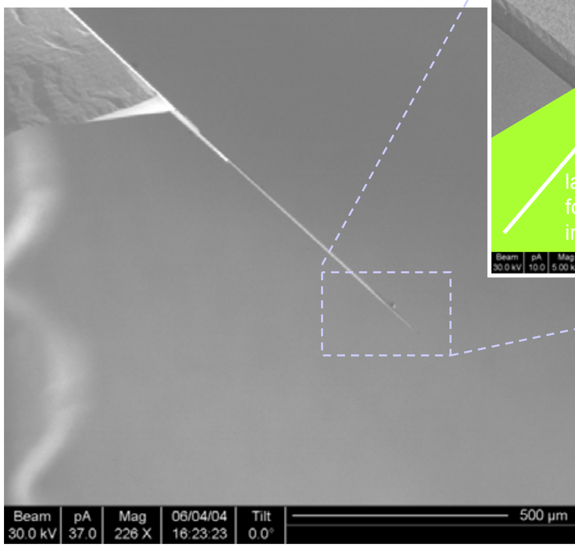
Pt nanoparticle

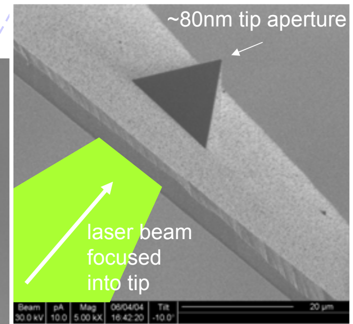
- Scattering element

Collecting the total far-field intensity will reveal presence and spatial extent of SP-related fields near 'image plane'

Local source – microfabricated NSOM tip

Al-coated tip, aperture 50-100nm





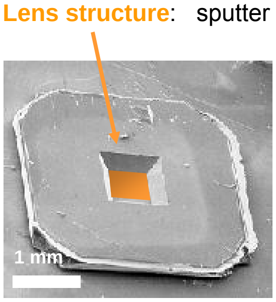
FIB image of an NSOM tip

Near-field microscope used in our nanophotonics lab: The Witec AlphaSNOM

WITec focus innovations

Lens structure - Si_3N_4 / Au film

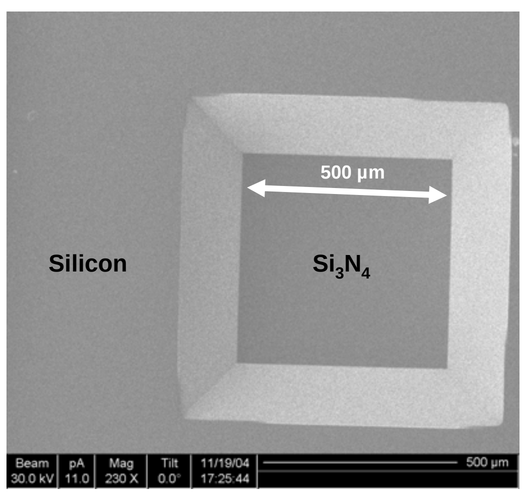
Lens structure: sputter deposit 50 nm Au onto 50 nm Si_3N_4 TEM window



Membrane : 50 nm Si_3N_4

Si_3N_4
Au

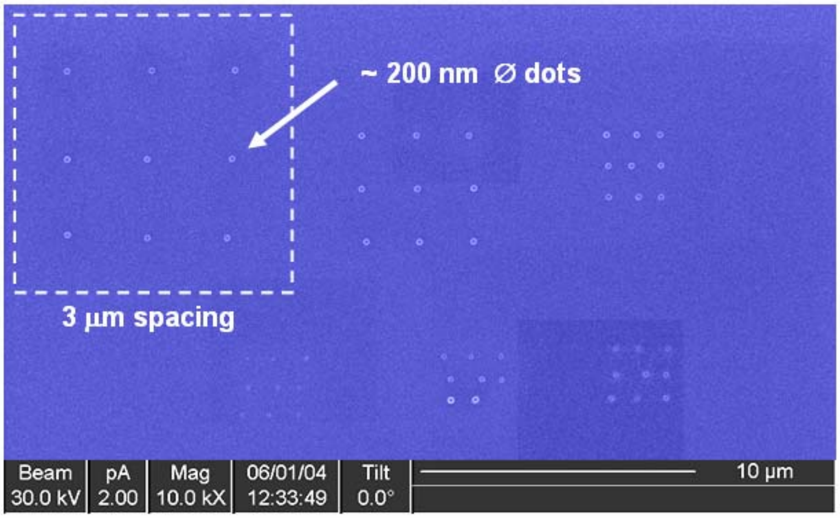
- Au more stable than Ag
- Visible frequency operation λ_{SP} ~ 530nm



Looking down into the window aperture

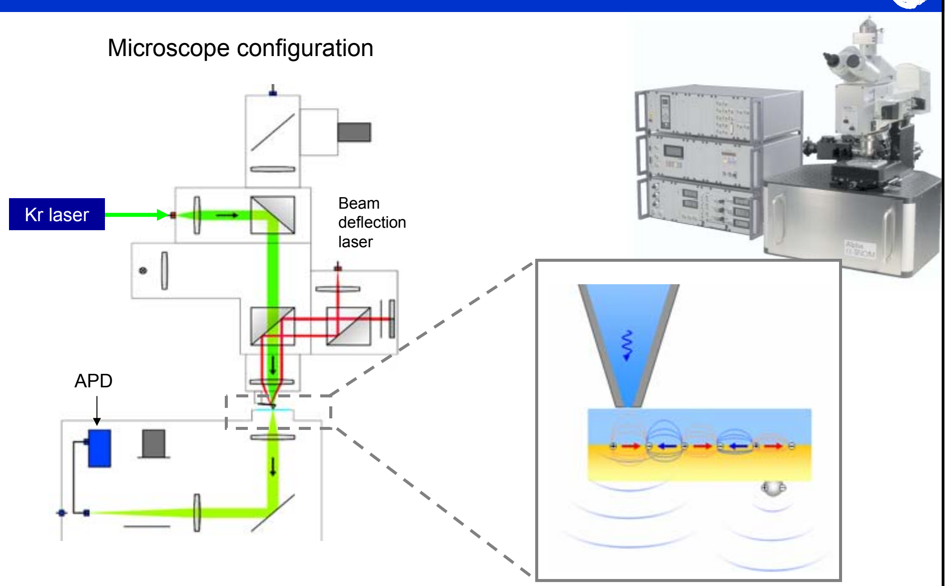
Near-field scatterer

Use Focused Ion Beam (FIB) to deposit **Pt dots** on Au layer



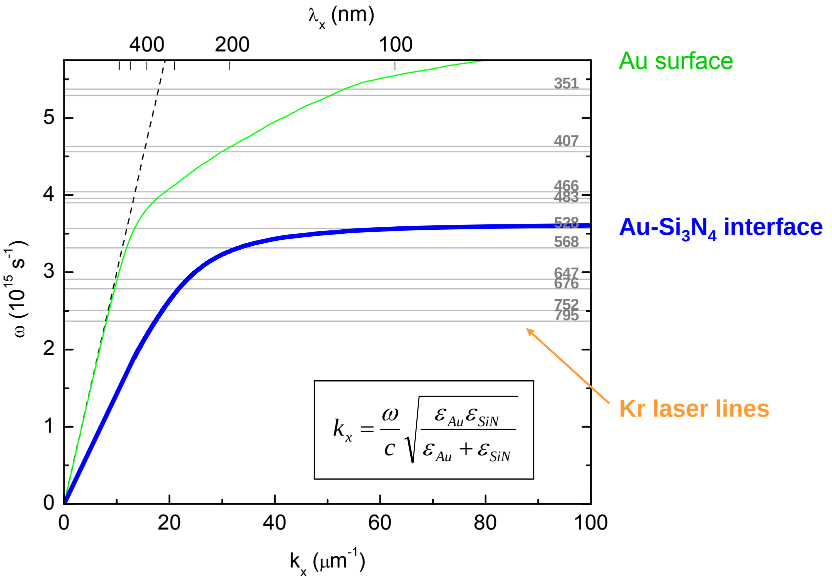
Experimental setup

Microscope configuration

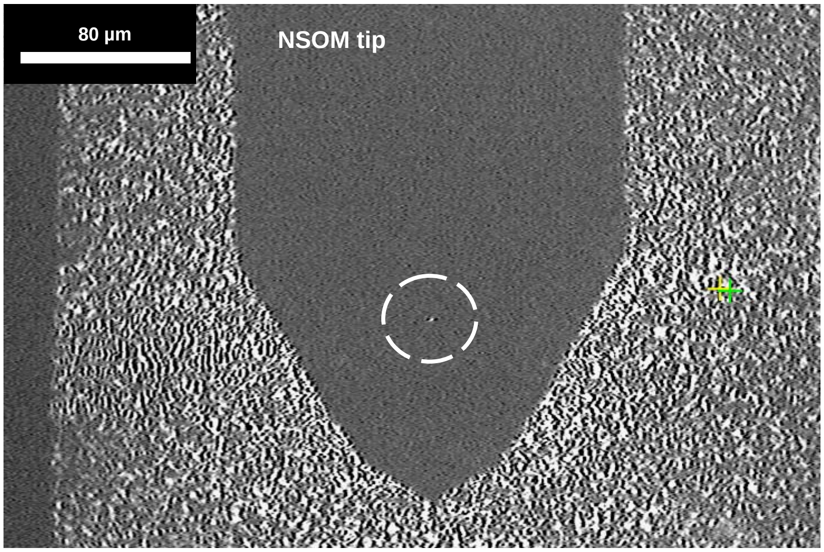


Far-field detection of near-field interference (lateral field components only)

Surface plasmon dispersion of Au-Si_3N_4 interface



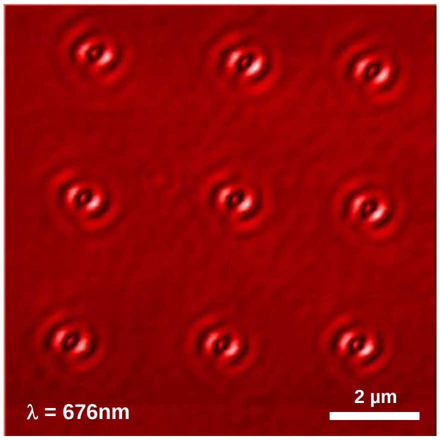
View through bottom microscope

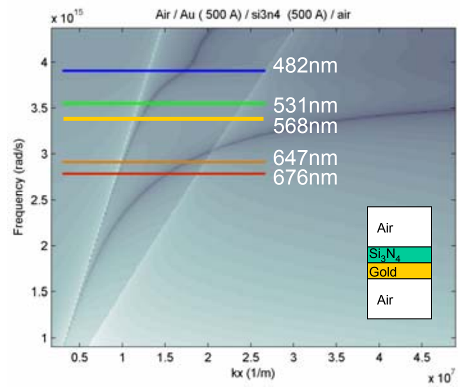


NSOM tip with laser illuminated aperture viewed from the lower microscope objective, **through** the plasmonic lens.

Near-field scanning microscopy 1/5

Grady Webb-Wood, Amitabh Ghoshal, and Pieter G. Kik, Appl. Phys. Lett. 89, 193110 (2006)





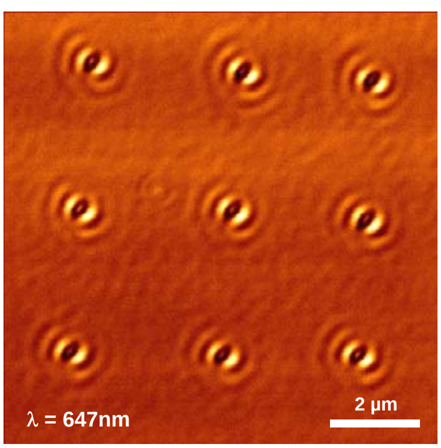
Calculated multilayer dispersion curve and excitation laser wavelengths

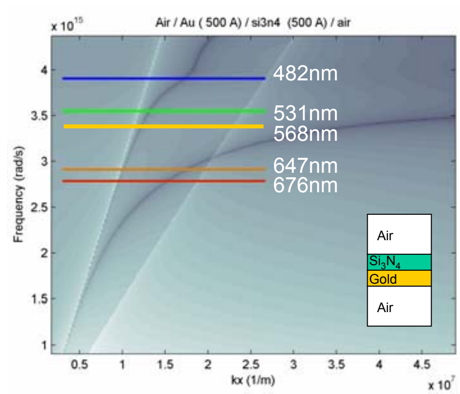
Dipolar field pattern, extended waves: **surface plasmons**

Small contrast ripple - caused by nanoscale film roughness on back surface

Harvard - 2005 Kik group: Nanophotonics and Near-field Optics http://kik.creol.ucf.edu slide 27

Near-field scanning microscopy 2/5





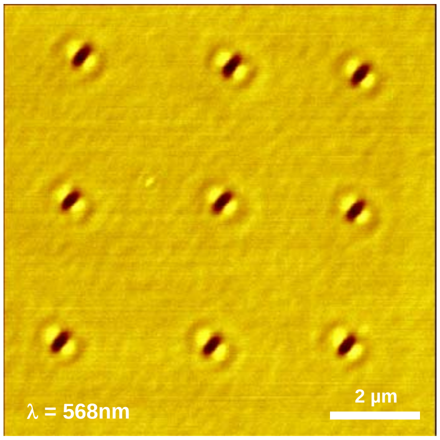
Calculated multilayer dispersion curve and excitation laser wavelengths

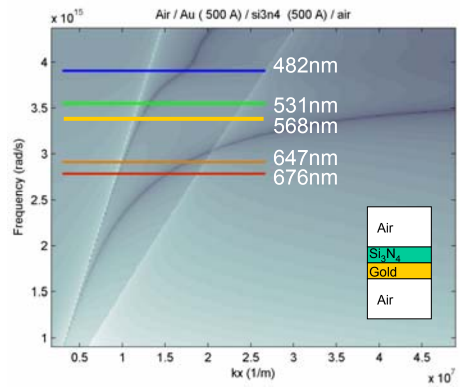
Higher frequency ⇒ shorter SP wavelength

Nanoscale roughness more clearly visible

Harvard - 2005 Kik group: Nanophotonics and Near-field Optics http://kik.creol.ucf.edu slide 28

Near-field scanning microscopy 3/5

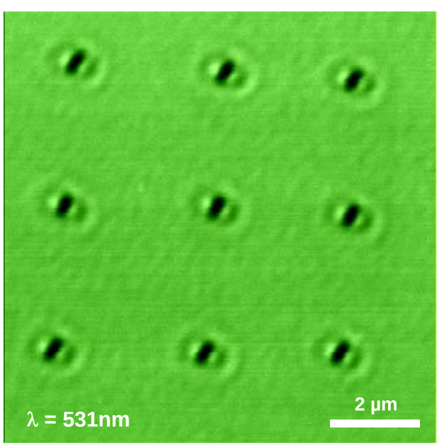


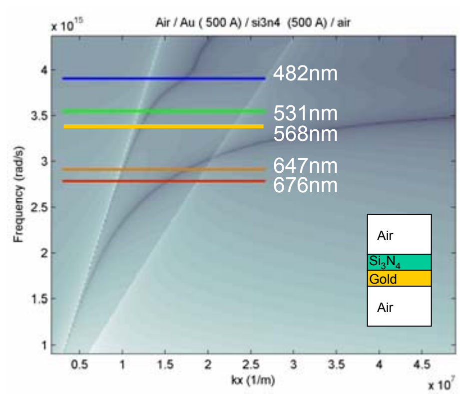


Calculated multilayer dispersion curve and excitation laser wavelengths

Frequency close to imaging condition ⇒ localized dipole imaged
Nanoscale roughness clearly evident

Near-field scanning microscopy 4/5

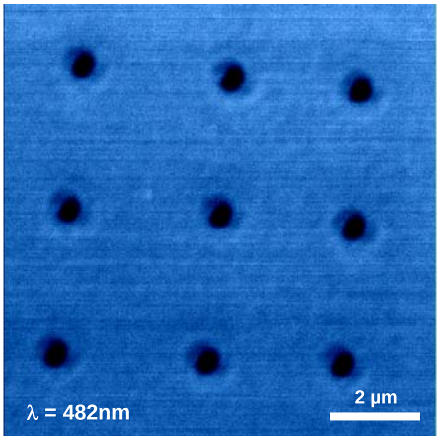


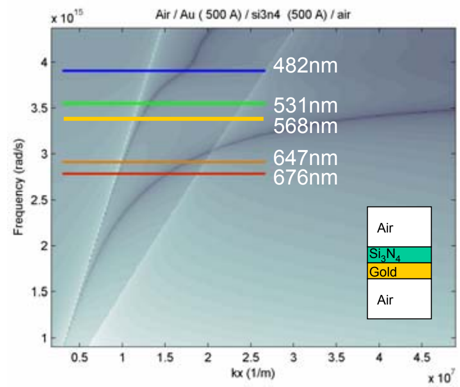


Calculated multilayer dispersion curve and excitation laser wavelengths

Frequency near or slightly above imaging condition, localized dipole still visible
Nanoscale roughness still noticable

Near-field scanning microscopy 5/5

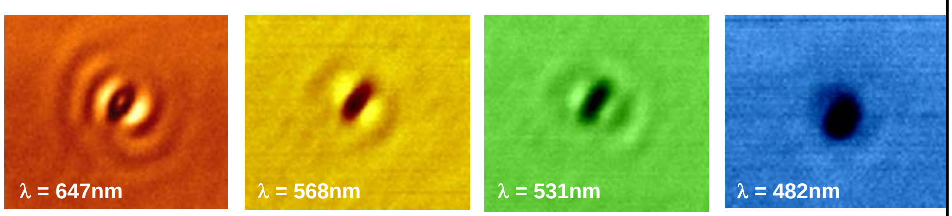




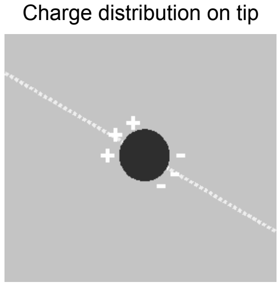
Calculated multilayer dispersion curve and excitation laser wavelengths

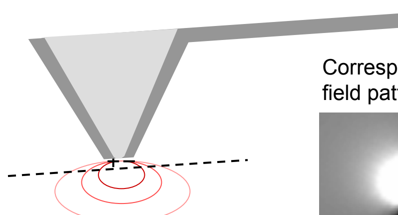
Frequency well above imaging condition ⇒ no clear dipolar image
Nanoscale roughness no longer visible

Field patterns

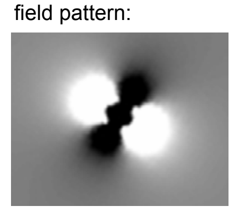


Charge distribution on tip



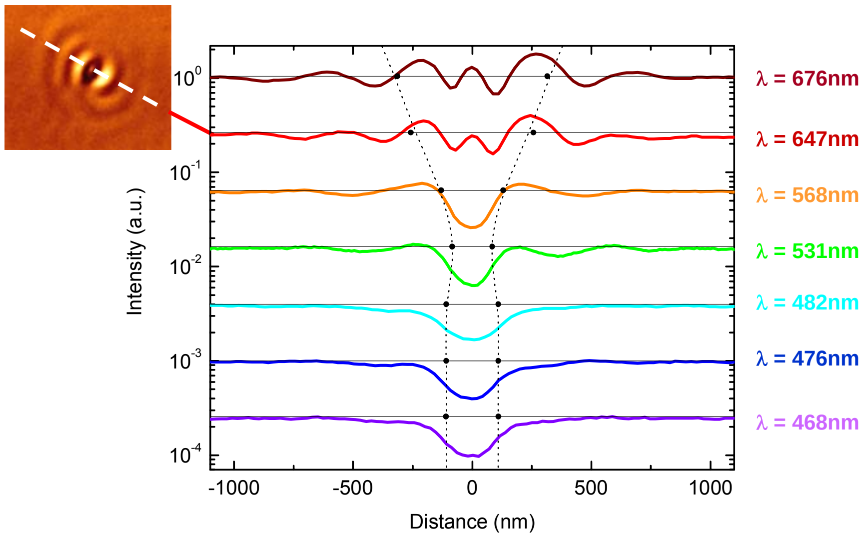


Corresponding lateral field pattern:



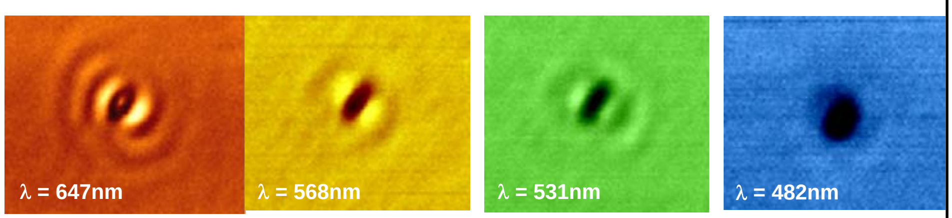
Detected image at optimum frequency resembles E_x pattern of dipole

Line cuts for resolution measurement



Minimum image width observed near the predicted optimum imaging wavelength

Conclusions



Experimental demonstration of frequency dependent focusing in the near-field using surface plasmons in a ‘perfect lens’ structure

Resolution ~180nm, currently limited by size of scatterer

Control over surface plasmon dispersion enables near-field resolution control

Future work

- Investigate silver superlens in different dielectric media
- Explore plasmon dispersion manipulation for further image enhancement