Georgia Institute of Technology

School of
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Nanoplasmonic Waveguides: Optical Interconnects, Lasers, and Near-Field Probes

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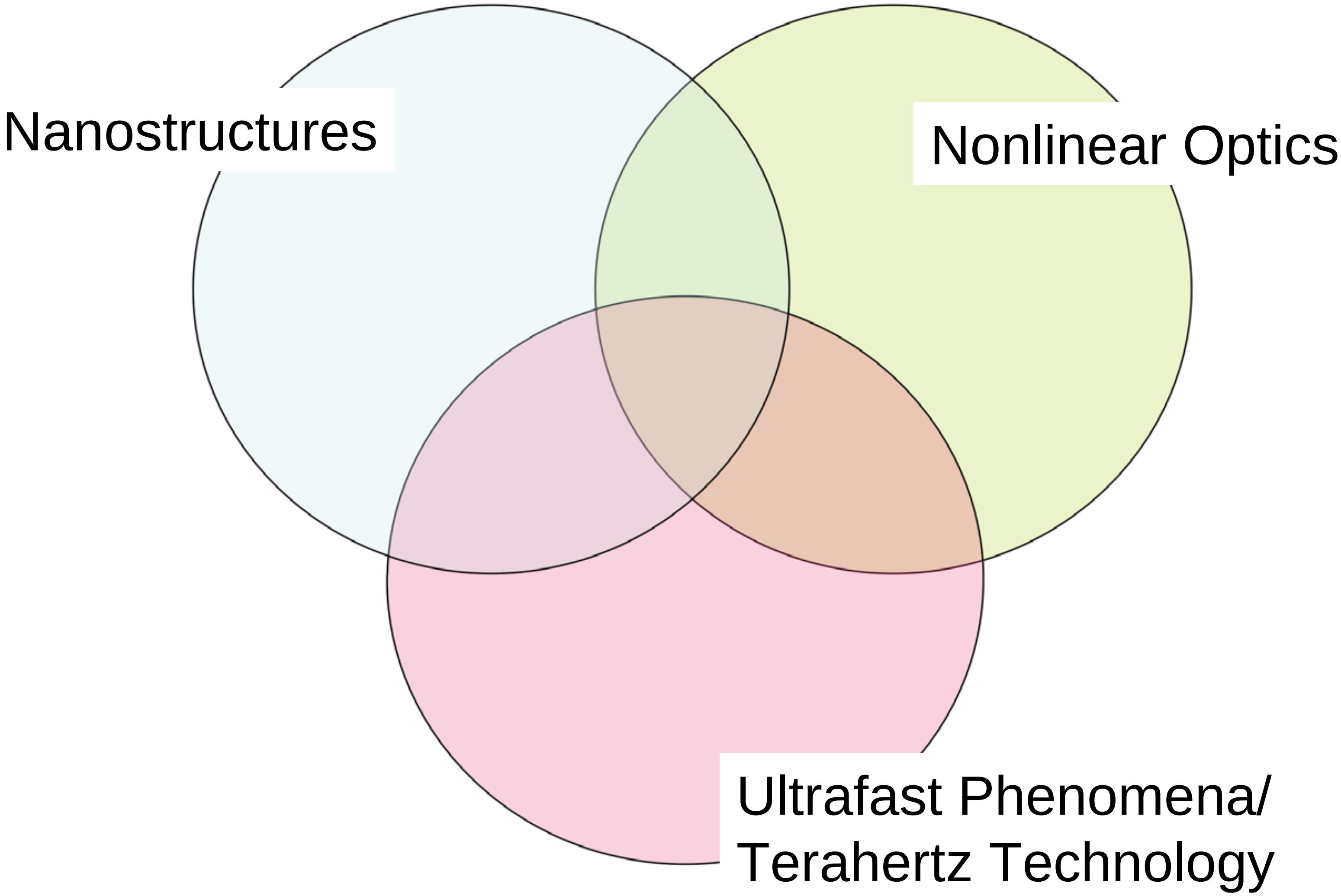
Outline

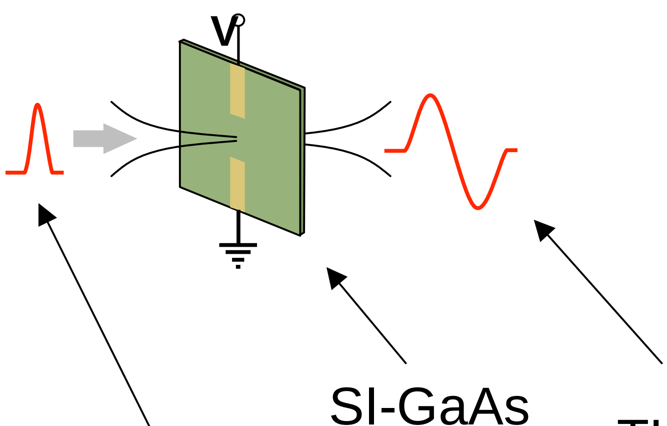
- Research Overview
- Metal nanoparticle arrays
  - Nanoplasmonics
- Conclusions

Research Overview



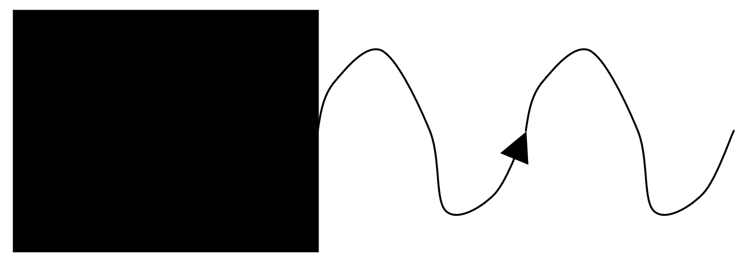
THz Sources

Photoconductive THz Generation



S. E. Ralph, D. Denison-Georgia Tech

UC Santa Barbara Free-Electron Laser

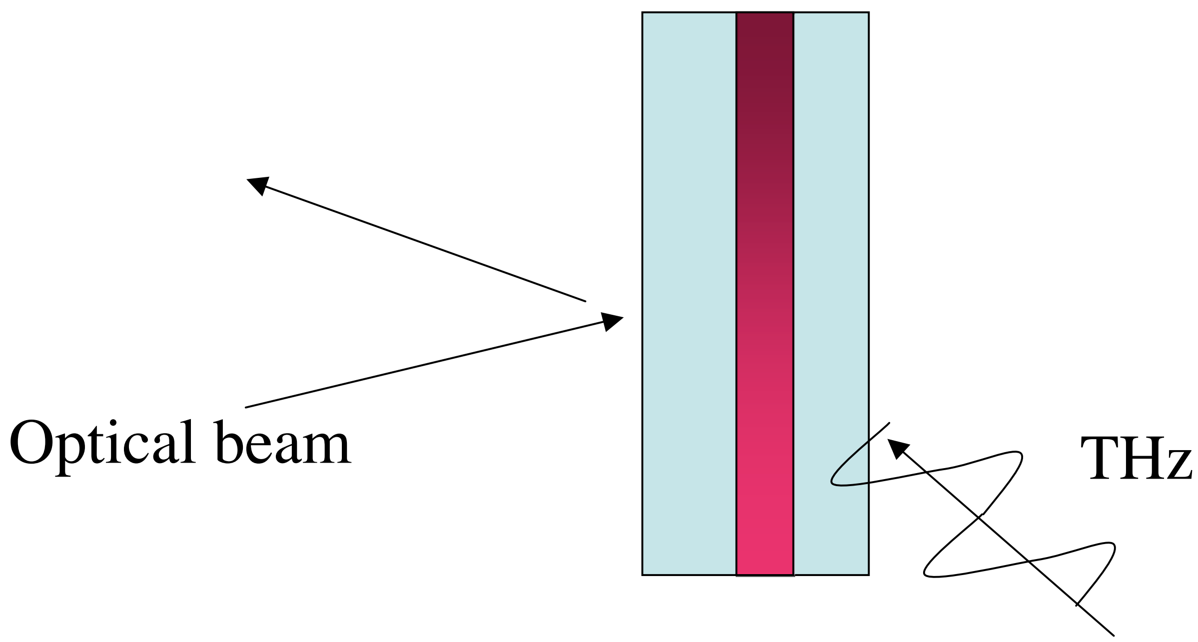


M. S. Sherwin-UCSB

and various other approaches

Nonlinear Optics

THz/Optical Nonlinearities in Semiconductors



Outline

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  - Nanoplasmonics
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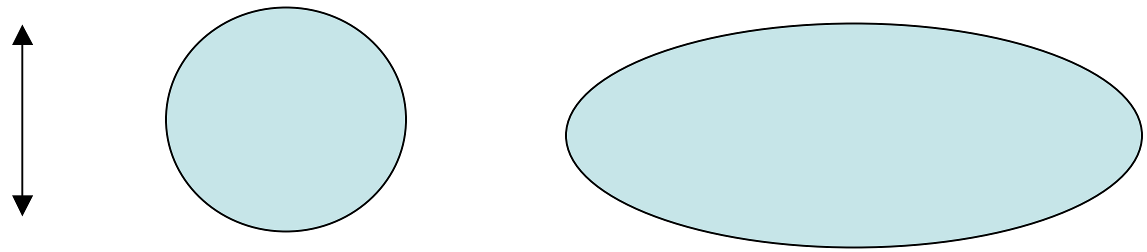
The Lycurgus Cup (glass; British Museum; 4th century A. D.)

When illuminated from outside, it appears green. However, when Illuminated from within the cup, it glows red. Red color is due to very small amounts of gold powder (about 40 parts per million)

Metal Nanoparticles

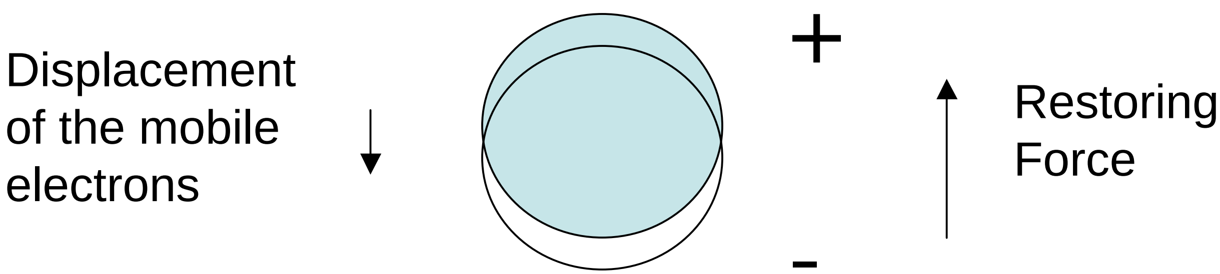
2-200 nm



Au, Ag,…

Other shapes
(cups, rods, wires,
core-shell structures,…)

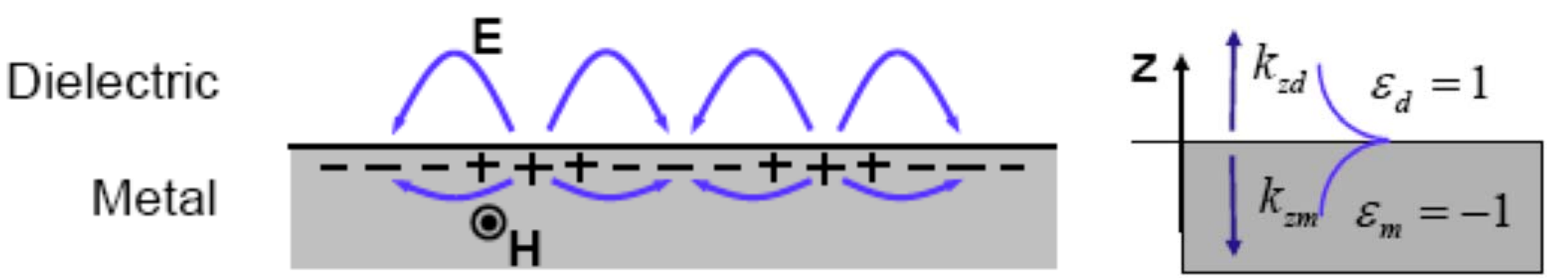
Metal Nanoparticle Surface Plasmons



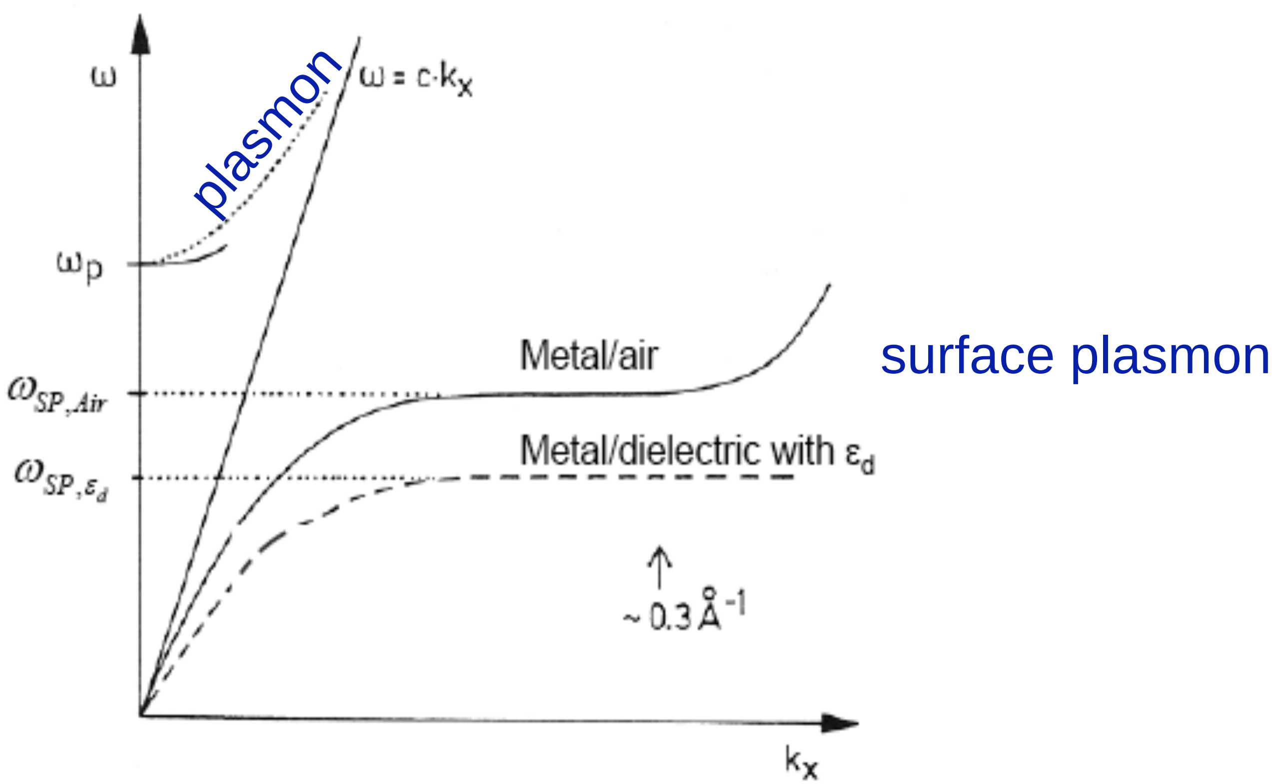
Surface Plasmons: Periodic (but damped) charge oscillations

Q~10

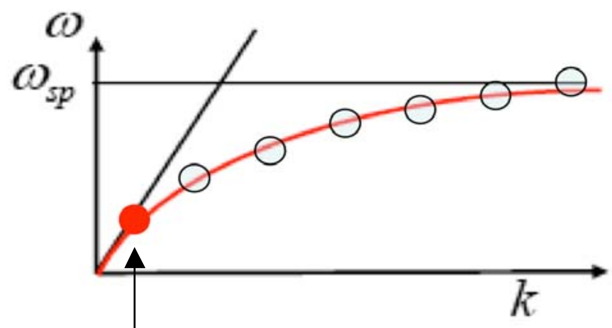
Surface Plasmon at Dielectric-Metal Interface



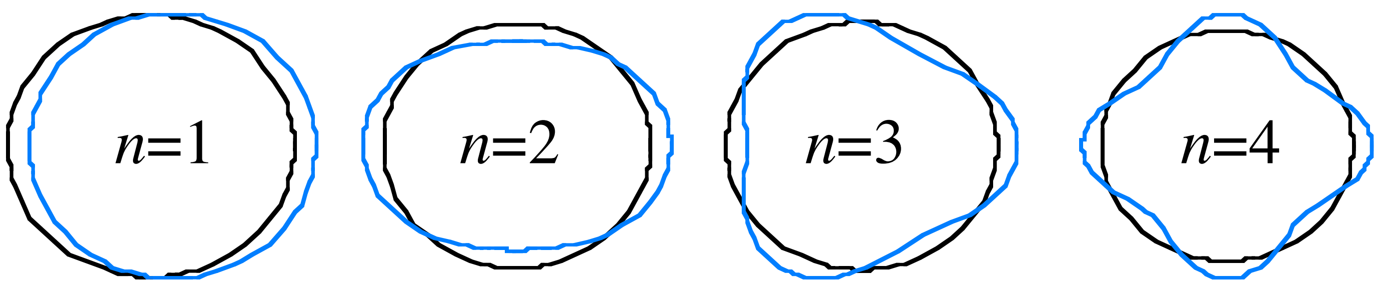
Dispersion Relation for Surface Plasmon



Boundary Conditions Result in Discrete SP Modes



Optically important n=1 mode
Electric-dipole mode



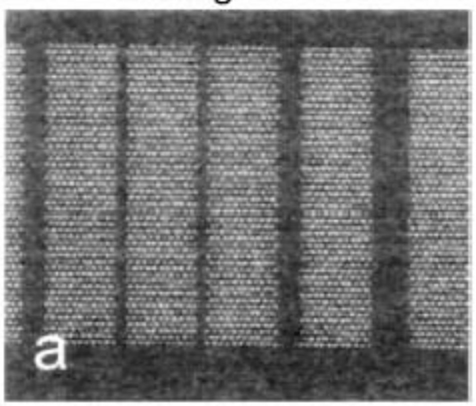
Can be obtained from Mie theory

Guiding SPPs in 2D metallo-dielectric Photonic Crystals

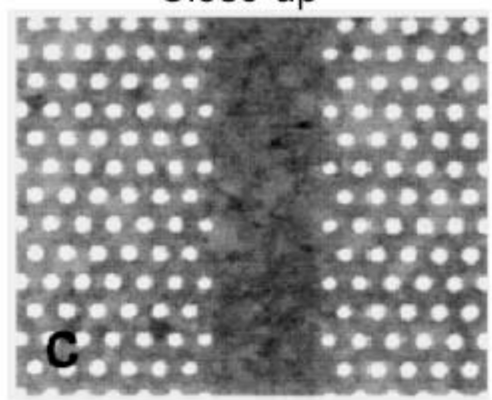
Guiding along line defects in hexagonal arrays of metallic dots (period 400 nm)

- Scanning electron microscopy images

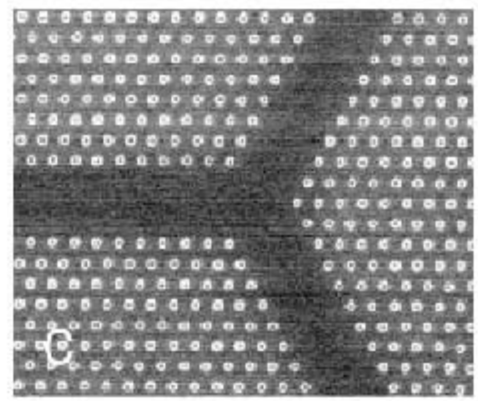
Linear guides



Close-up

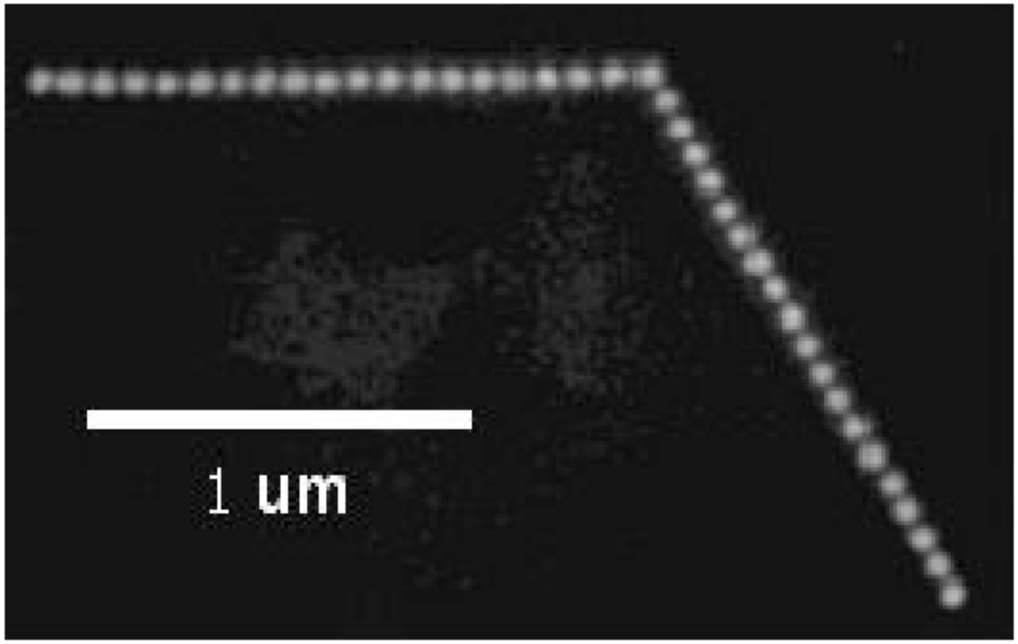


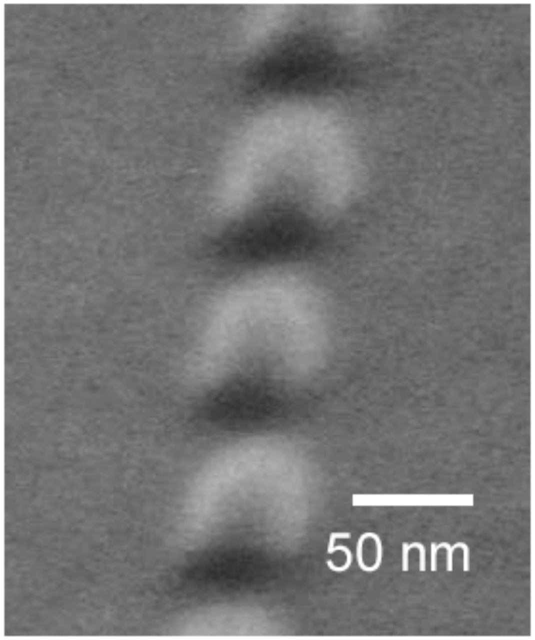
Y-Splitter



- SPP is confined to the plane
- Full photonic bandgap confines SPP to the line defect created in the array

S.I. Bozhevolnyi, Phys Rev Lett. ***86***, *3008 (2001)*

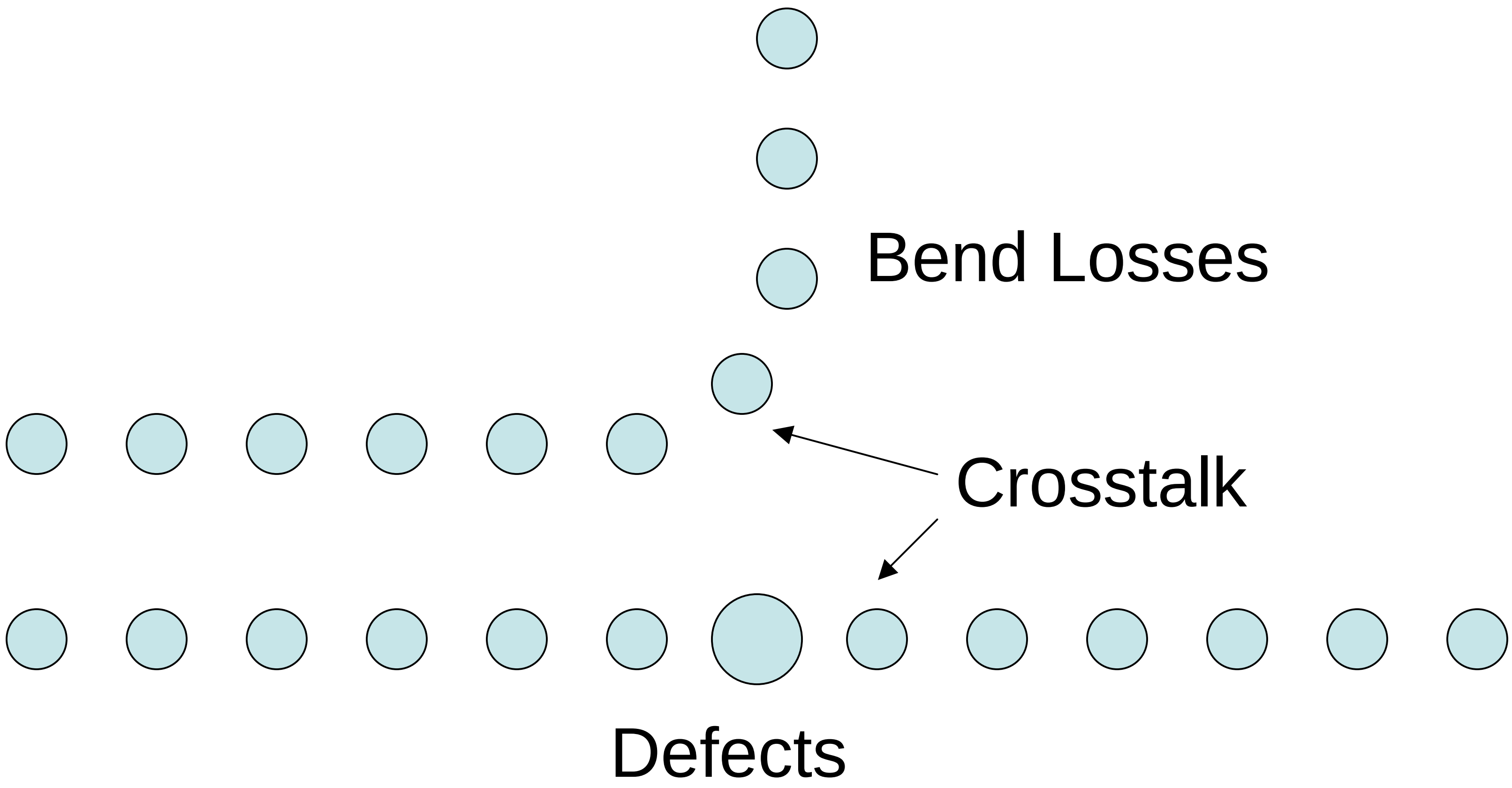




- Array of 50 nanometer diameter Au particles spaced by 75 nanometer
- Guides electromagnetic energy at optical frequency below the diffraction limit
- Enables communication between nanoscale devices
- Information transport at speeds and densities exceeding current electronics

M.L. Brongersma, et al., Phys. Rev. B ***62****, R16356 (2000)*
S.A. Maier et al., Advanced materials ***13****, 1501 (2001)*

Metal Nanoparticle Chains



Metal Nanoparticle Chains

- Potential: Fabricate optical waveguides with lateral dimensions << l --**Nano-optical Interconnects, near-field optical probes**

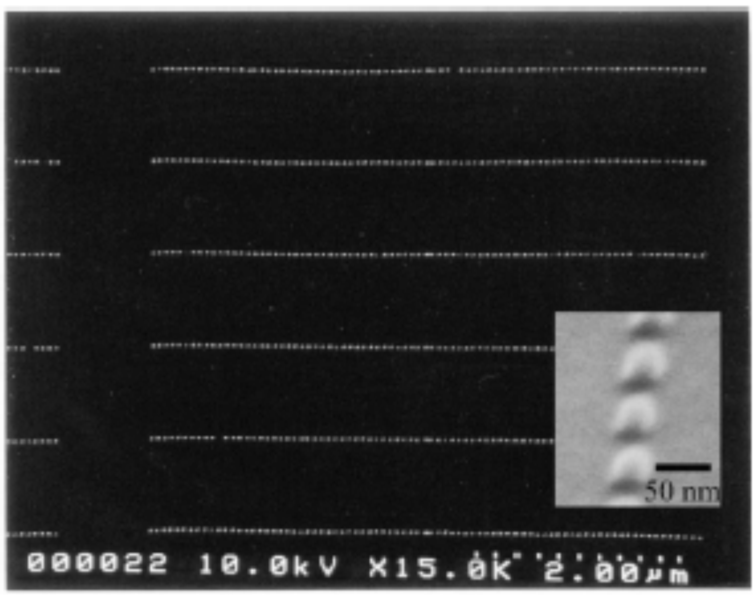
- Challenges: Control attenuation!

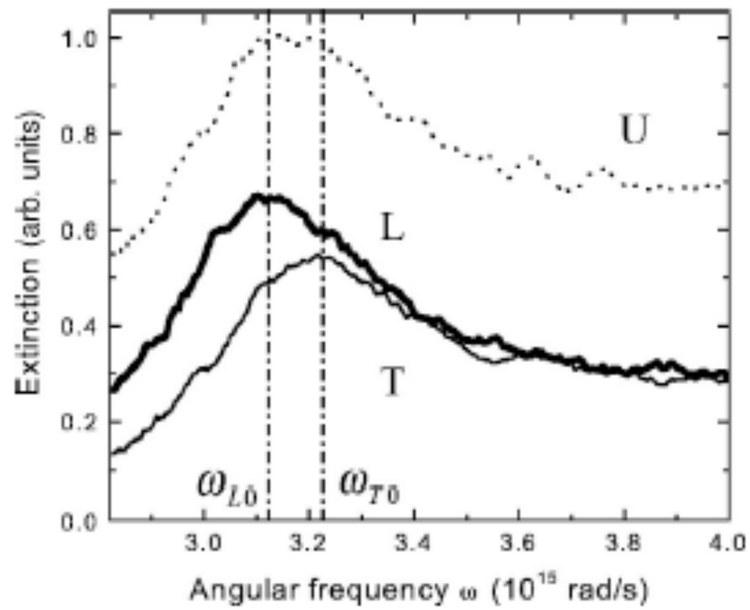
Metal Nanoparticle Chains

- 40-100 nm radius Au/Ag nanoparticles on glass/semiconductor substrate; chains with 75-300 nm period
- Single nanoparticles: broad plasmon resonance
- Optical propagation along chains measured (indirectly)

Electron micrograph

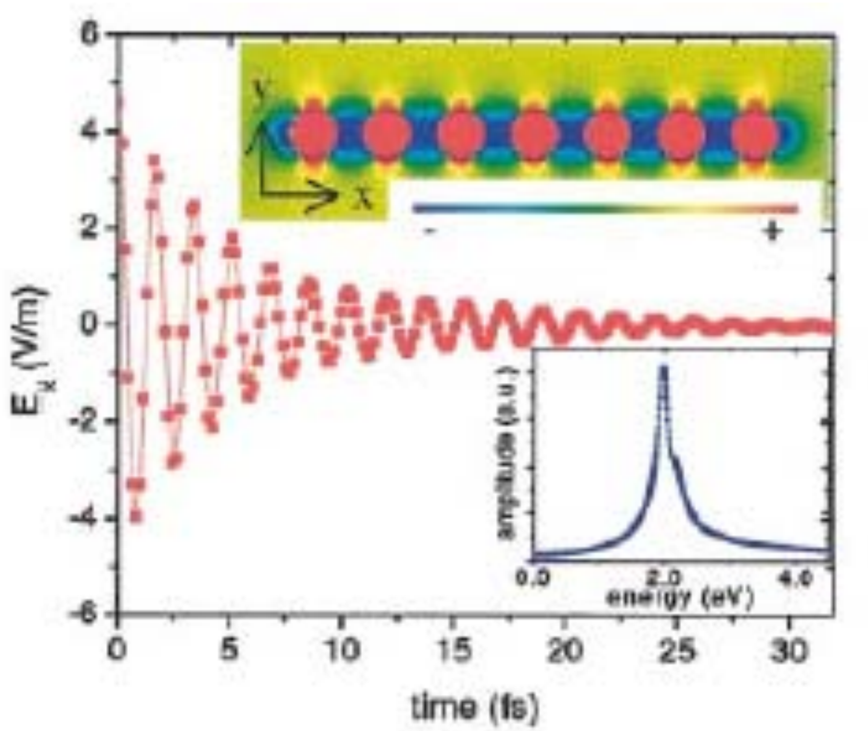
Optical Extinction





Stefan A. Maier, Mark L. Brongersma, Pieter G. Kik, and Harry A. Atwater* PHYSICAL REVIEW B, VOLUME 65, 193408

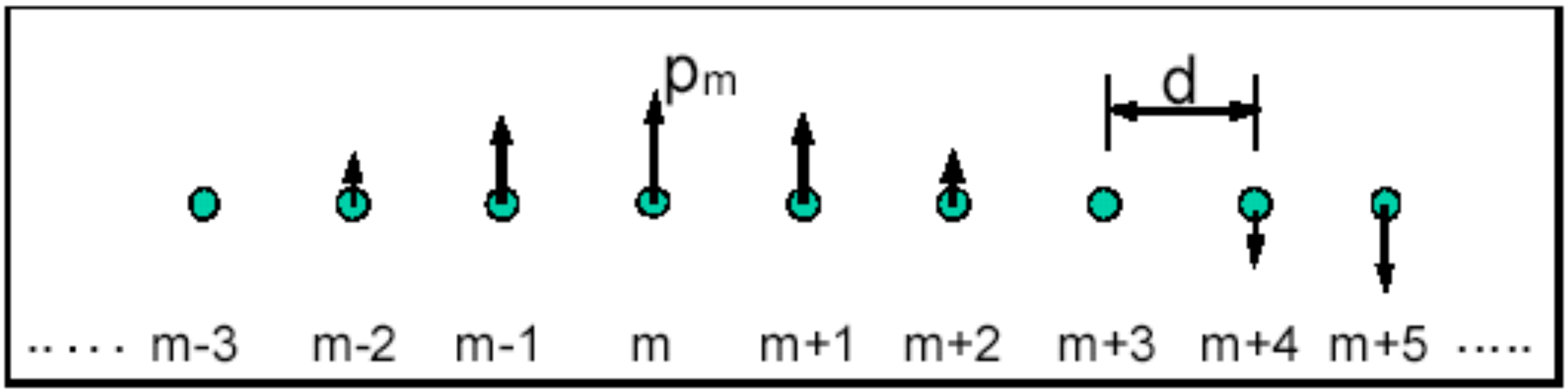
2D FDTD Calculation of Electromagnetic Propagation in Metal Nanoparticle Chains



Stefan A. Maier,[a] Pieter G. Kik, and Harry A. Atwater

APPLIED PHYSICS LETTERS VOLUME 81, NUMBER 9 26 AUGUST 2002

Metal Nanoparticle Chains



Nanoparticle surface plasmons modeled as static point dipoles with nearest-neighbor coupling, PhD Thesis, S. A. Maier

Effects of Higher Multipoles

- Distortion of dispersion relation, compared to retaining only dipole-dipole interaction--effect most pronounced when particles approach contact

But Hard to Incorporate!

What we do: only keep electric dipole moment; correctly account for retardation

Excellent account of optical properties provided spacing is not too small (G. Schatz)

Plasmon-Polariton Dispersion Relation

Complex!

$$w(q)- w_p-S[w(q),q]=0$$

$$q=2p/l$$

Self-Energy:

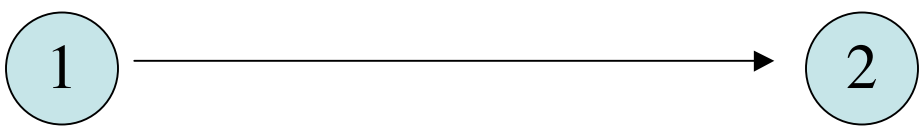
Real part: mode frequency

Imaginary part: radiative loss

Self-Energy:Retarded Dipole-Dipole Energy

$$S(w, \mathbf{r}_{12}) = E\,(\mathbf{r}_{12}, t_{ret}) \cdot d_2$$

$d_2, \mathbf{r}_{12}$



Retarded dipole-dipole coupling:

- Polarization perpendicular to $\mathbf{r}_{12}$: $\mathbf{r}_{12}^{-1}$, $\mathbf{r}_{12}^{-2}$, $\mathbf{r}_{12}^{-3}$
- Polarization parallel to $\mathbf{r}_{12}$:

$$\mathbf{r}_{12}^{-2},\ \mathbf{r}_{12}^{-3}$$

$\rightarrow$ Long-range coupling only for perpendicular polarization

- Fourier transform $\mathbf{r}_{12}$ --> q
- Express excitation wavelength and optical wavelength in dimensionless units

$k=qd$, $\mathrm{c}=\mathrm{k}d$

$\mathrm{k}=\mathrm{we}^{1/2}/c$

- Write S in units of single nanoparticle radiative width

Dispersion and Radiative Width in Infinite Chains

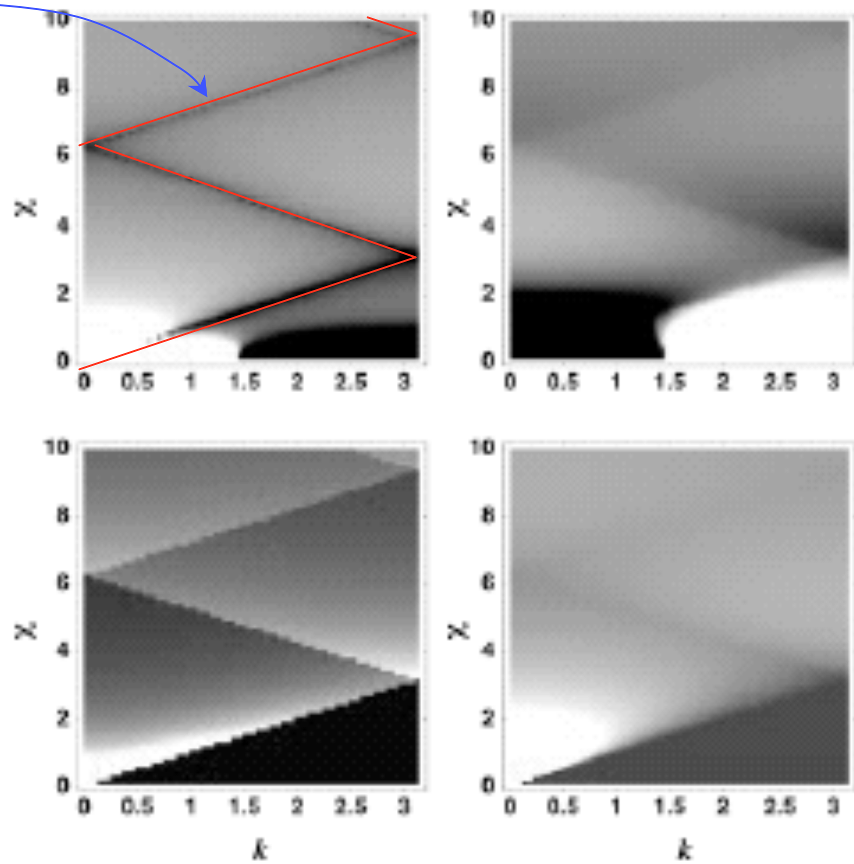
Close Spacing

Zone-folded light line

T-modes

L-modes

Optical Wavevector



Excitation wavevector

Dispersion
Re $S(k,\chi)$

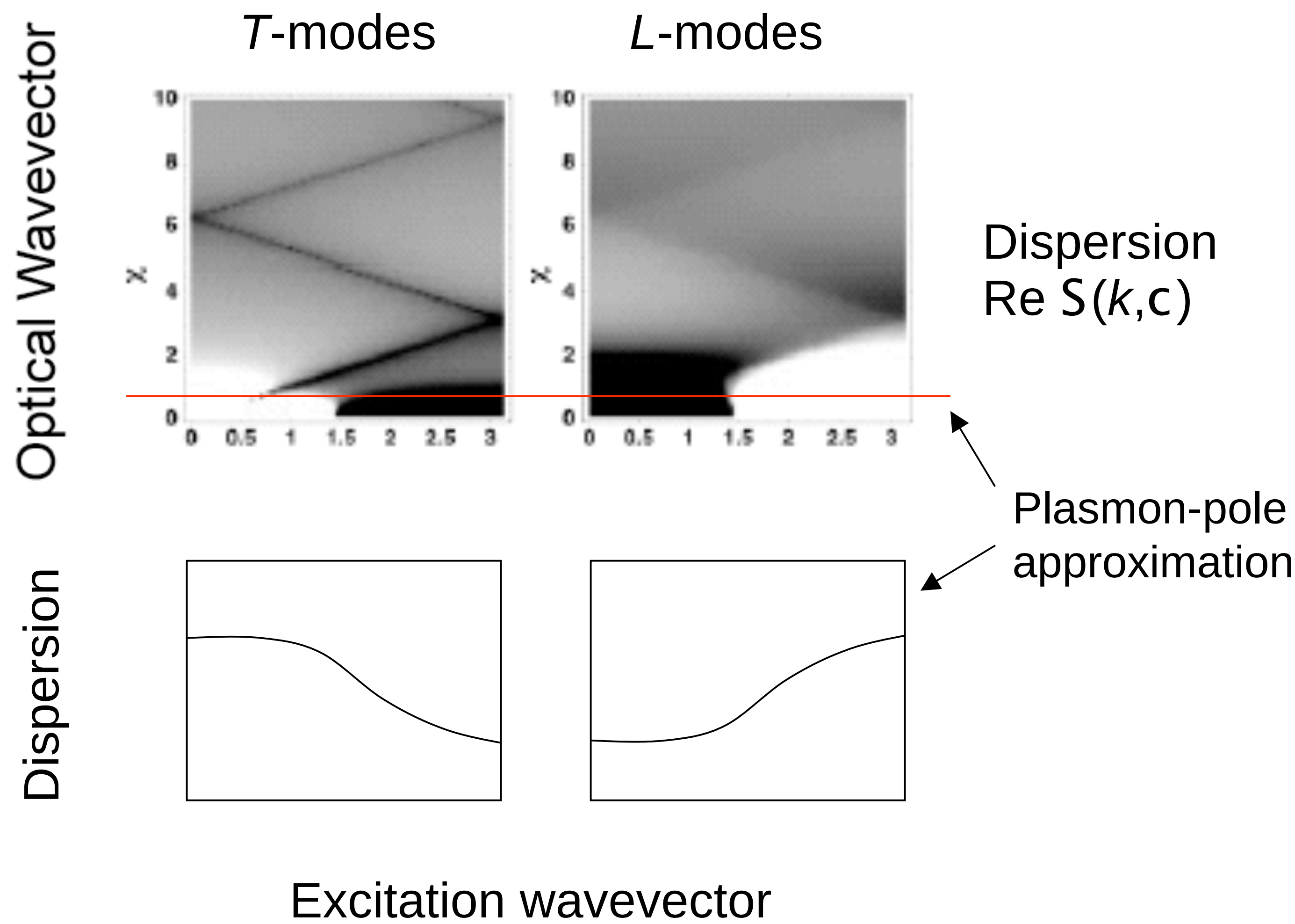
Radiative Width
-Im $S(k,\chi)$

$k=qd$, $\chi=\kappa d$

D. S. Citrin,Nano Lett. **4**, 1561 (2004).

Nano Lett.

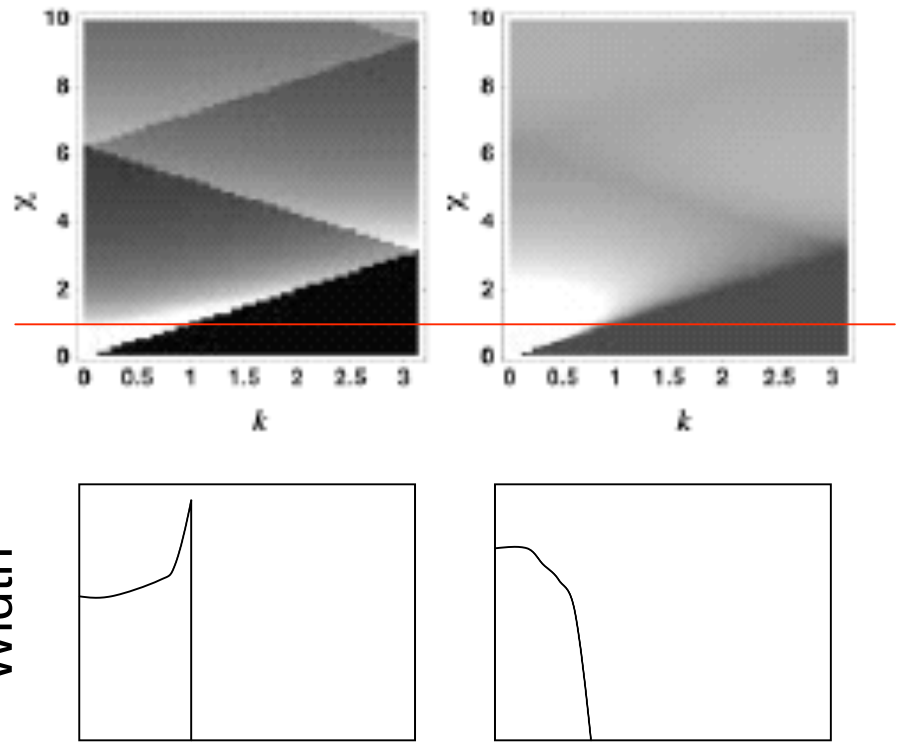
Dispersion in Infinite Chains



Radiative Width in Infinite Chains

T-modes *L*-modes

Optical Wavevector

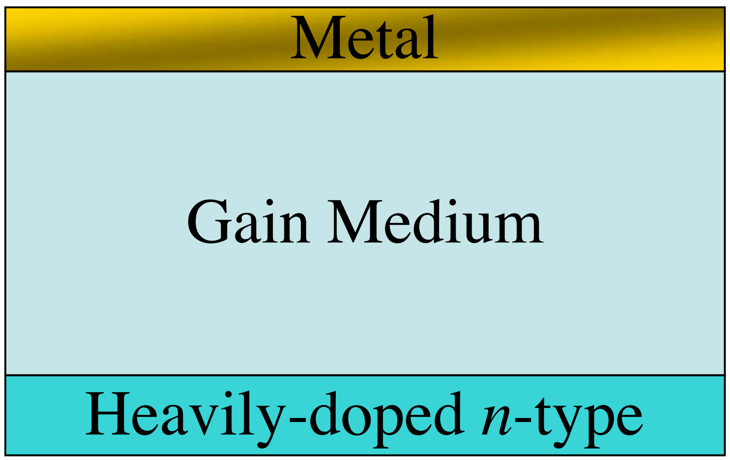


Radiative Width
-Im S(k,c)

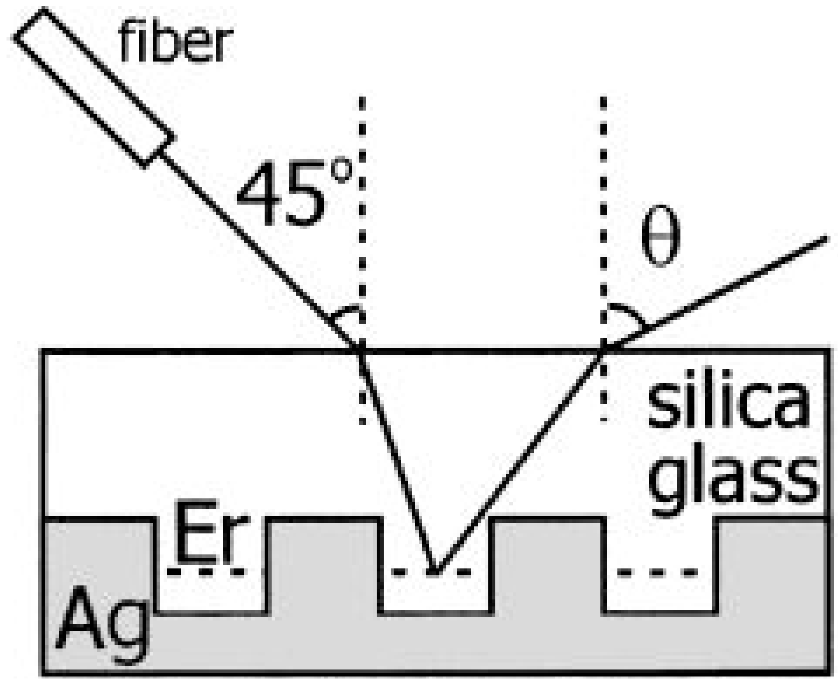
Radiative Width

Excitation wavevector

Surface-Plasmon Laser



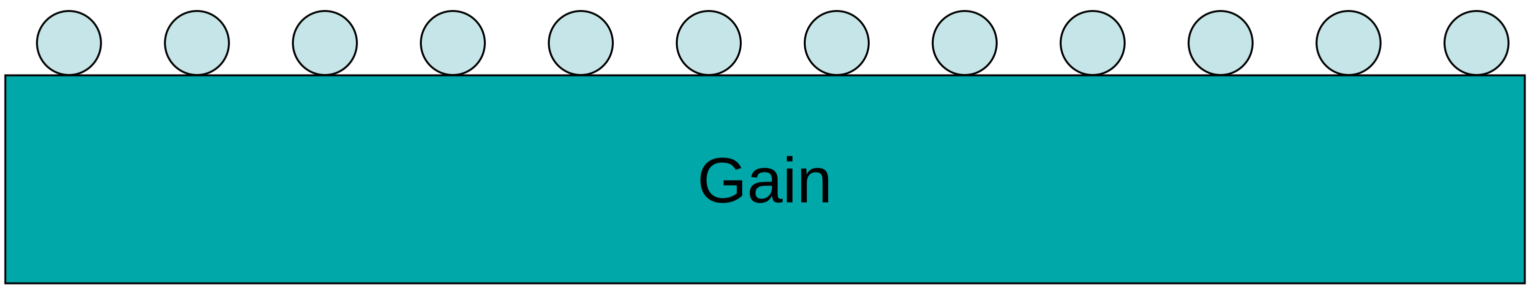
MIR and FIR QCL



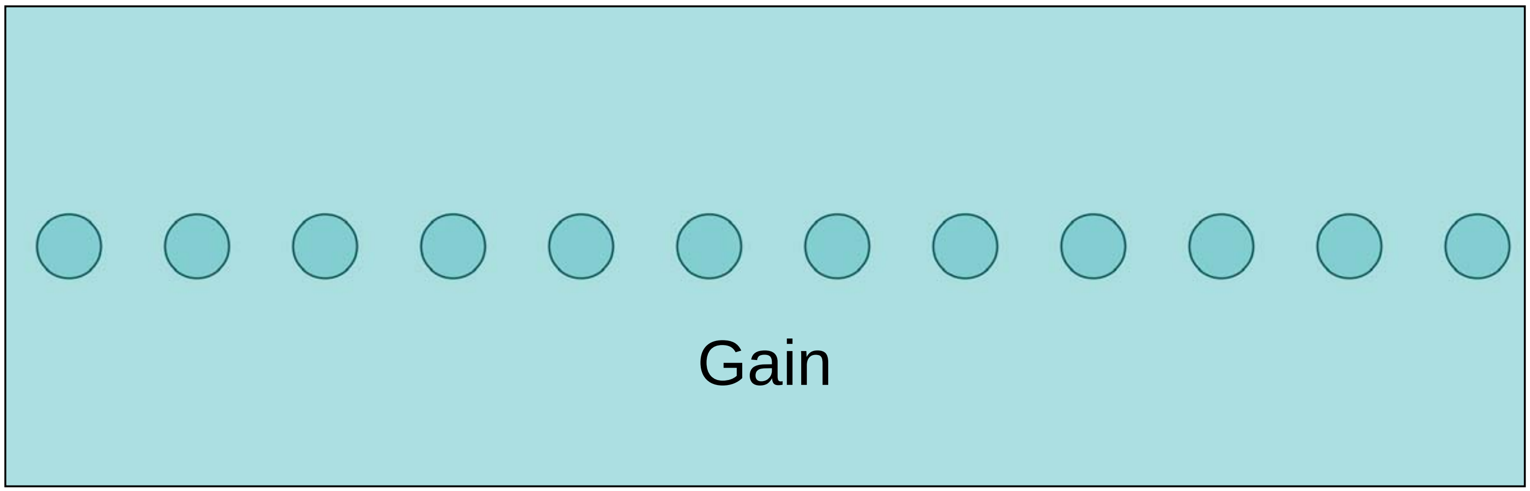
A. Tredicucci *et al.*,
Appl. Phys. Lett. **76**, 2164 (2000).

J. Kalkman *et al.*,
Appl. Phys. Lett. **83**, 30 (2003).

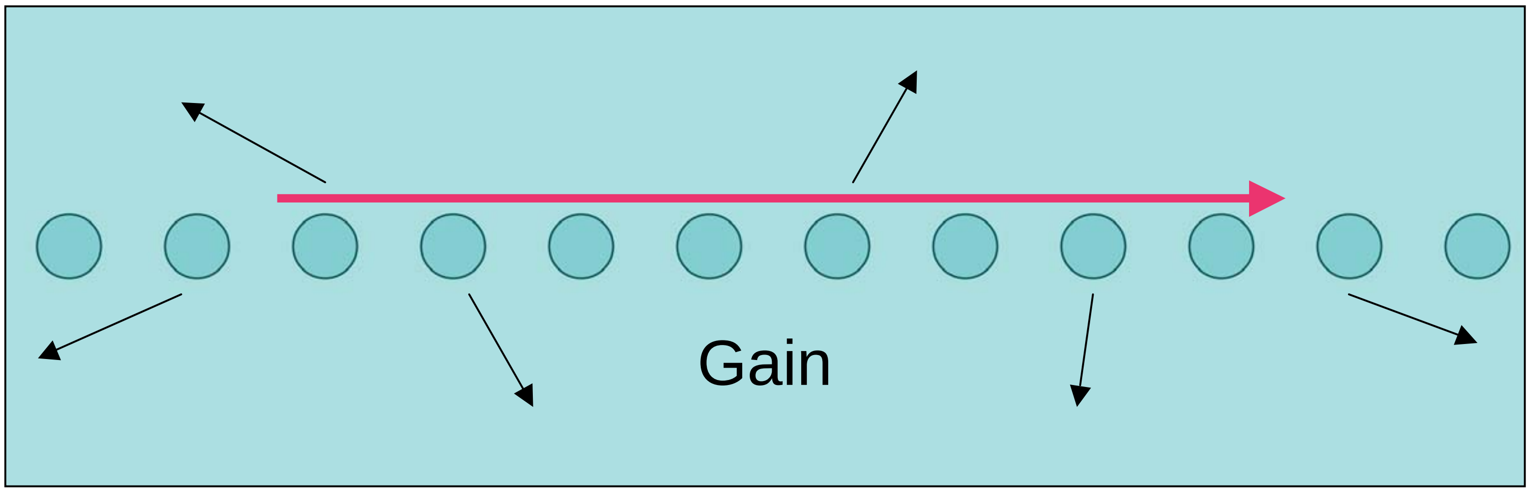
Attenuation Management via a Gain Medium



Attenuation Management via a Gain Medium



Attenuation Management via a Gain Medium

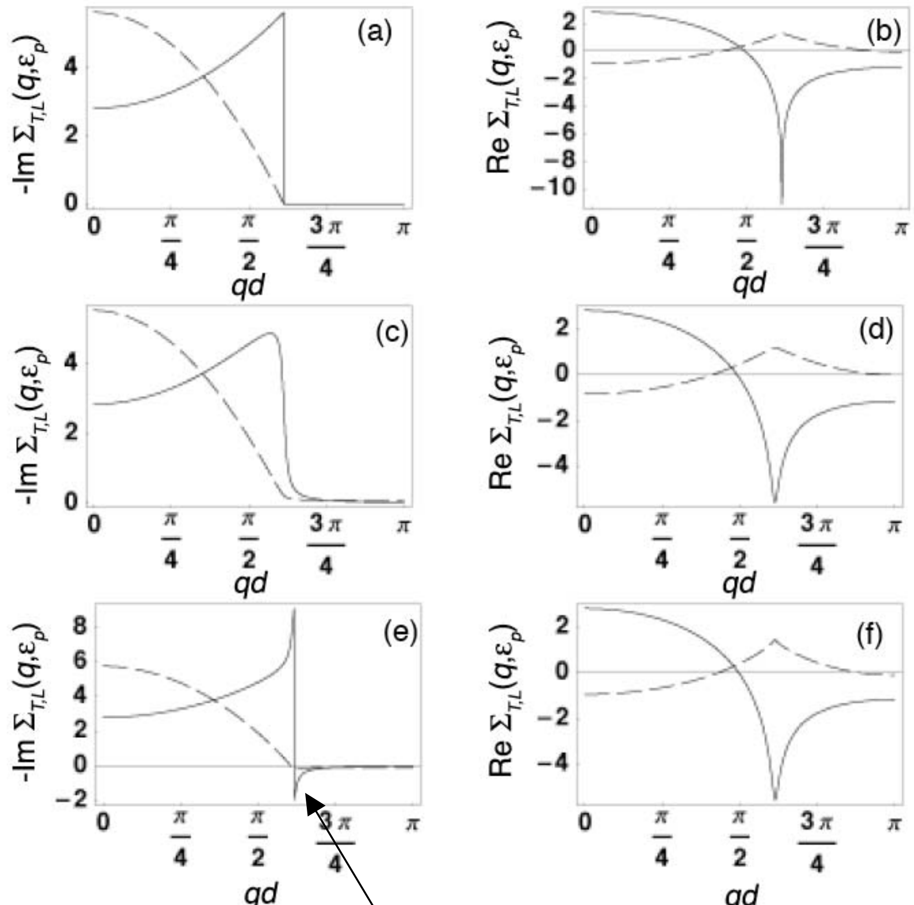


Surface plasmon polaritons benefit from gain; radiative Plasmon polaritons do not!

Perfect dielectric

Loss

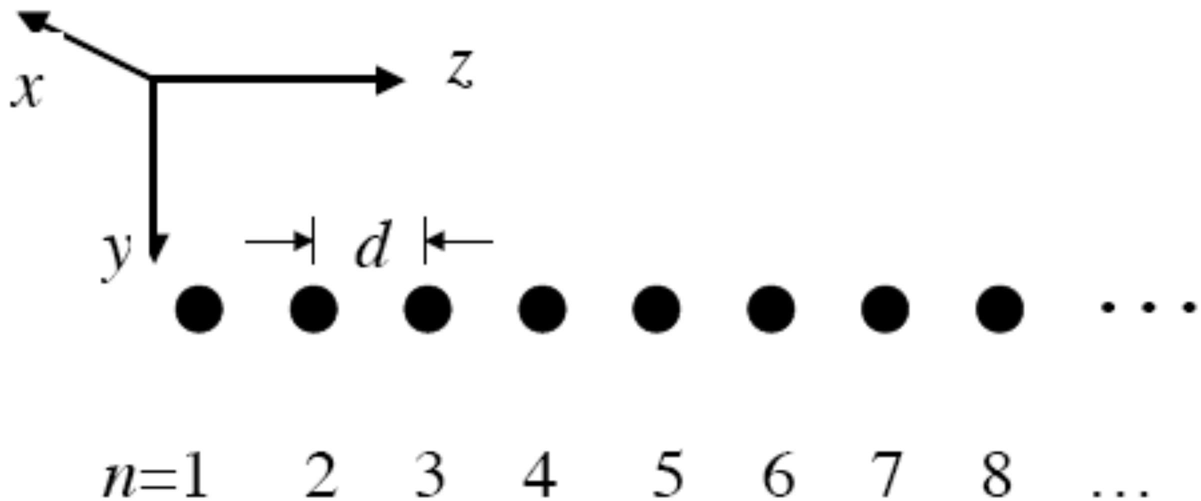
Gain



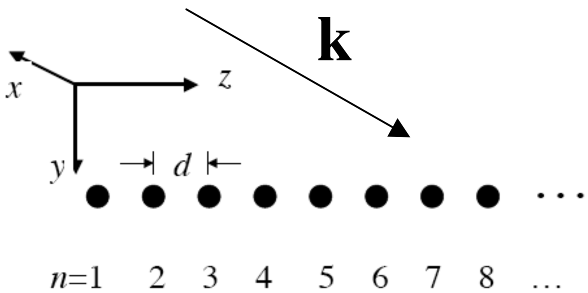
Radiative decay rate goes negative for surface plasmon polaritons!

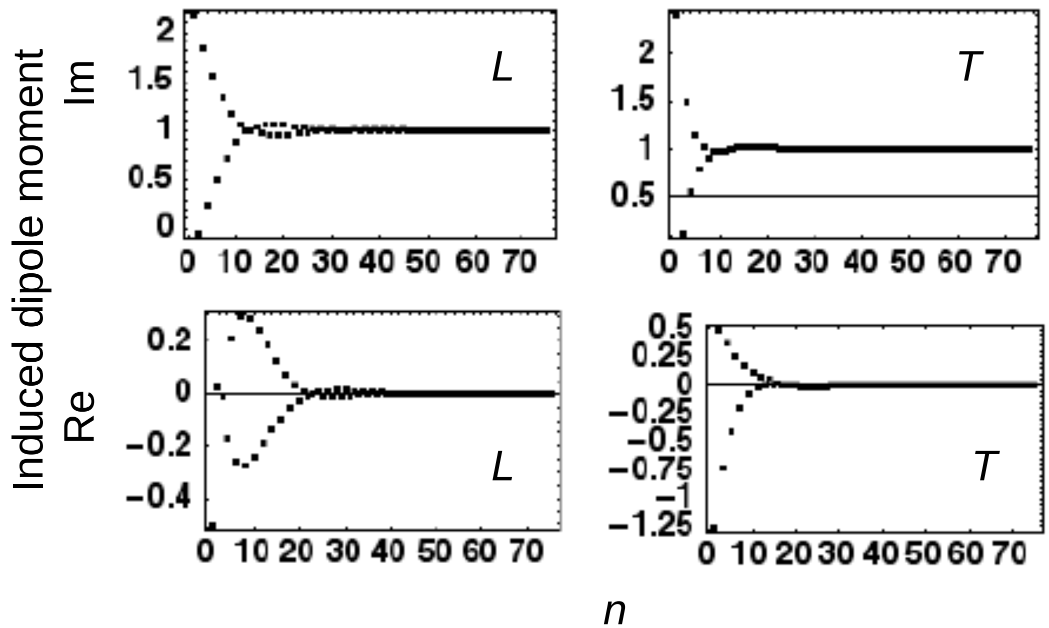
D. S. Citrin, Opt. Lett., in press.

In-Coupling to and Out-Coupling from Semi-Infinite Nanoparticle Chains: Far-Field Coupling



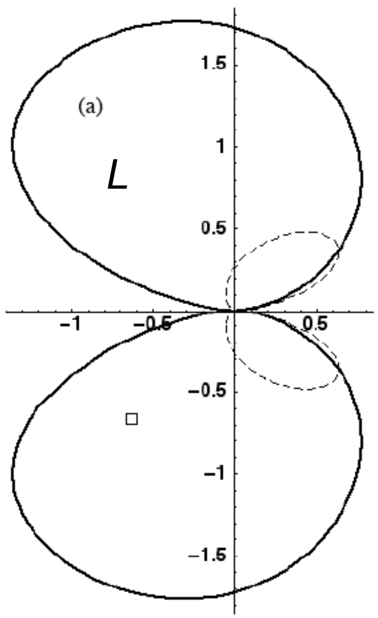
In-Coupling to Semi-Infinite Nanoparticle Chains: Far-Field Coupling



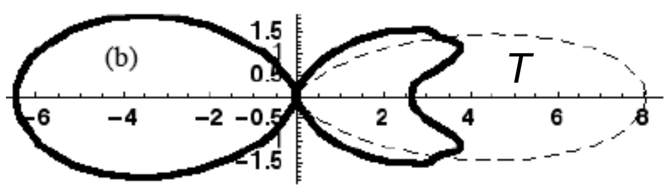


Conclusion: Dipole distribution only modified within ~10 nanoparticles nearest chain termination.

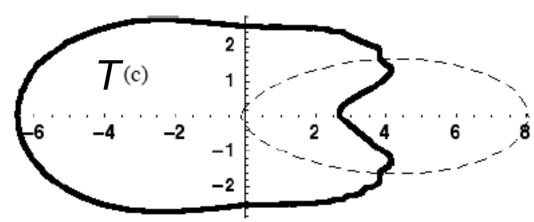
In-Coupling to Semi-Infinite Nanoparticle Chains: Far-Field Radiation Patterns



In plane of polarization



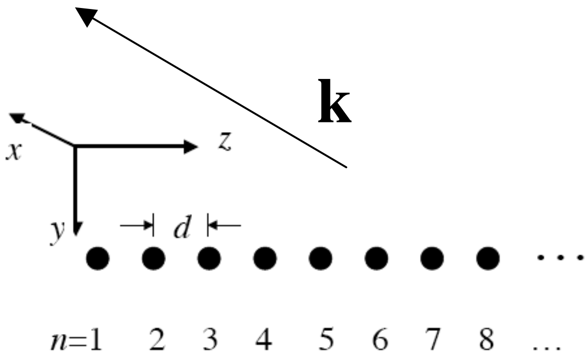
In plane perpendicular to polarization

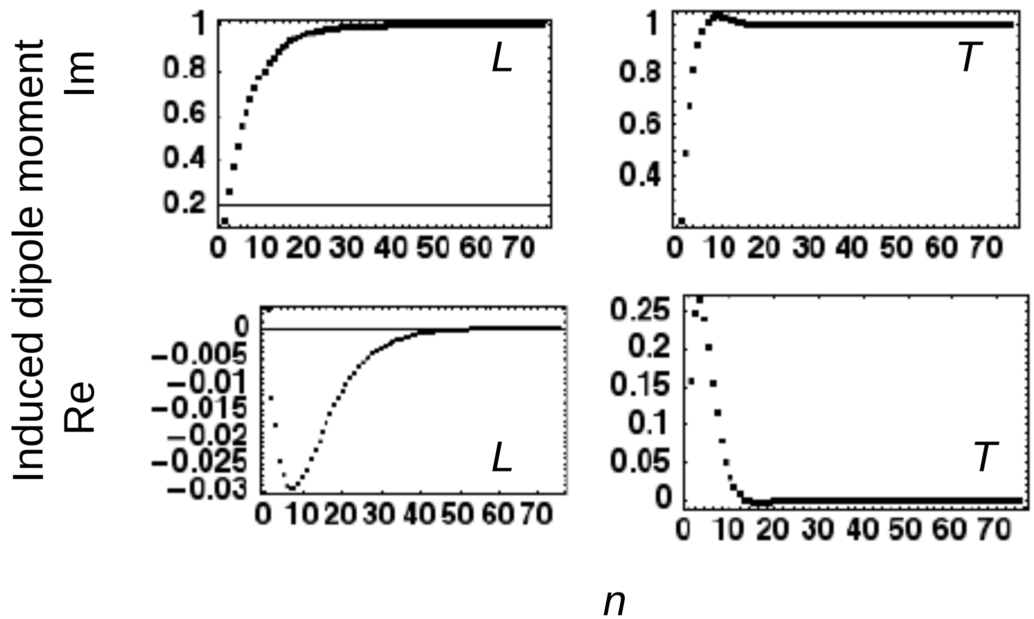


Dashed lines are the radiation distributions in the Kirchhoff approximation

Conclusion: Kirchhoff approximation is lousy.

Out-Coupling to Semi-Infinite Nanoparticle Chains: Far-Field Coupling





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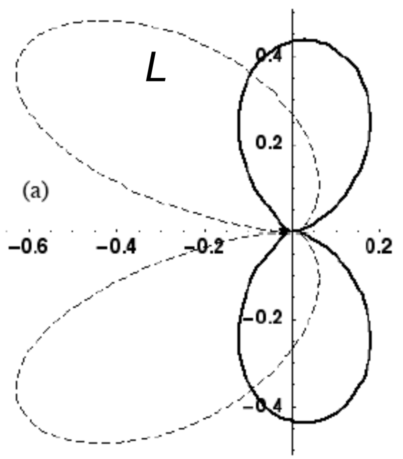
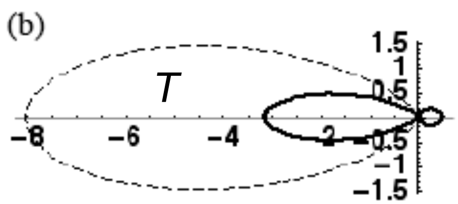
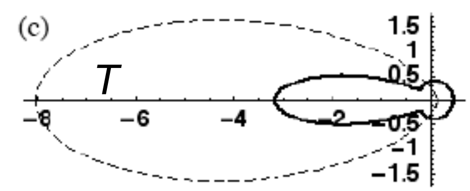
In-Coupling to Semi-Infinite Nanoparticle Chains: Far-Field Radiation Patterns



In plane of polarization



In plane perpendicular to polarization



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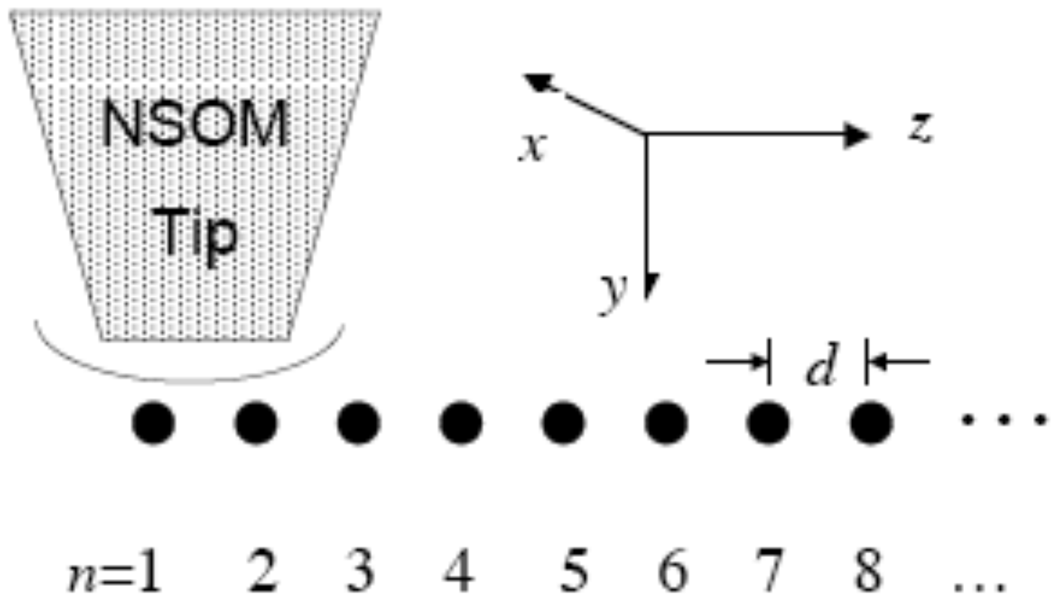
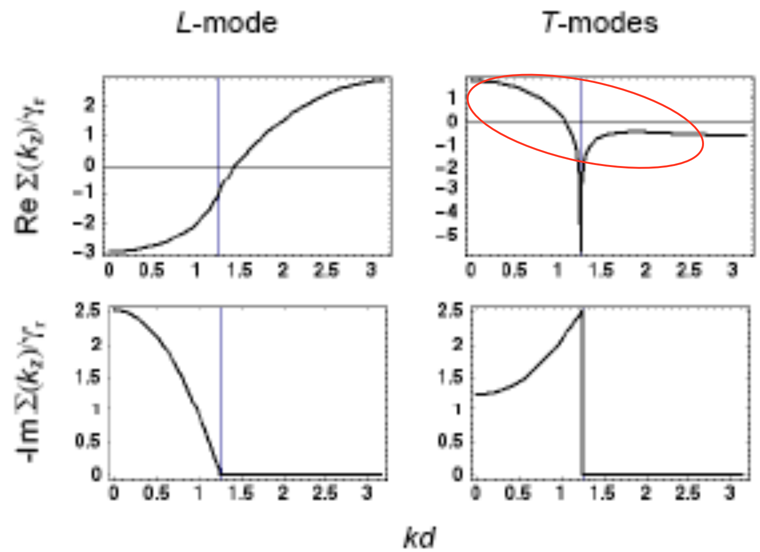
Near-Field Coupling to Semi-Infinite Nanoparticle Chains

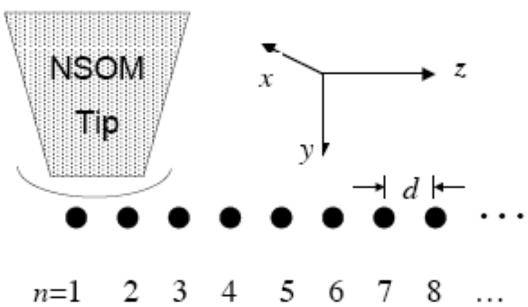


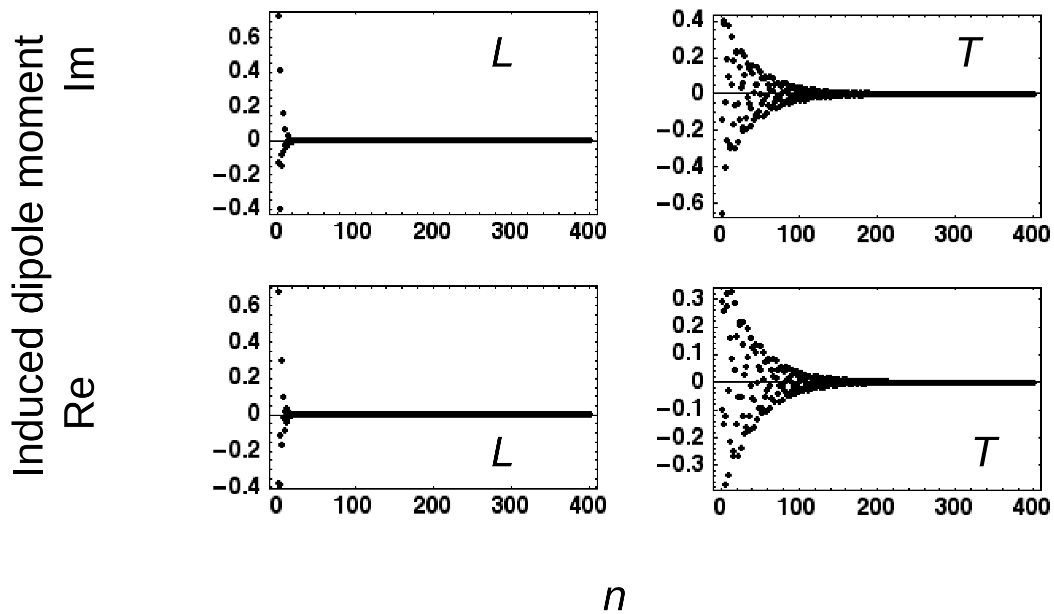
Near-Field Coupling to Semi-Infinite Nanoparticle Chains

Recall: Dispersion of T-modes on nanoparticle chain exhibits negative group velocity

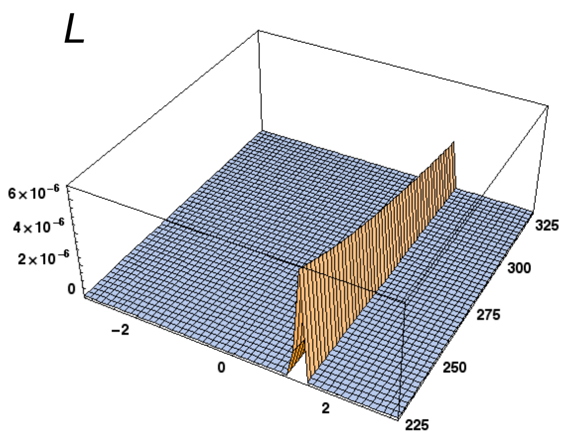


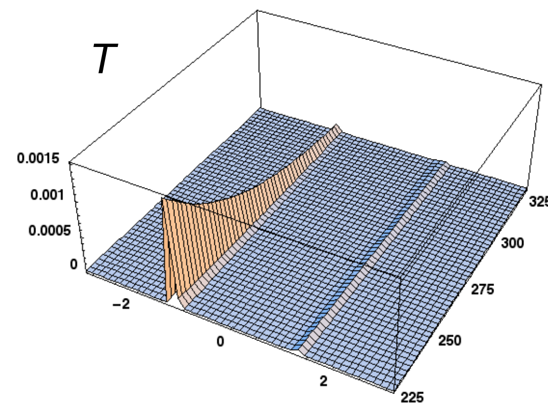
Near-Field Coupling to Semi-Infinite Nanoparticle Chains





Near-Field Coupling to Semi-Infinite Nanoparticle Chains

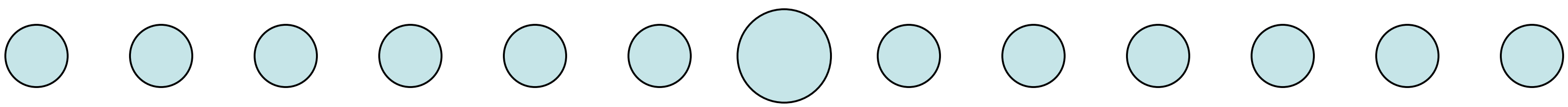




Local spatial phase is positive: Phase velocity *away* from termination/excitation

Local spatial phase is (mostly) negative: Phase velocity *toward* termination/excitation

Defects in Nanoparticle Chains



Substitutional Impurity

Vacancy

Defects in Nanoparticle Chains

Off-diagonal disorder

$$
\begin{aligned}
D^{+\,-1}_{nm} &= \mathcal{D}^{-1}_{nm} - V\delta_{n0}\delta_{0m}, \\
\mathcal{D}^{-1}_{nm} &= D^{(0)\,-1}_{nm} + (\delta_{n0} + \delta_{0m})\Sigma_{nm}, \\
V &= D^{(0)\,-1}_{00} - \frac{\varepsilon^2 - \varepsilon'^2}{2\varepsilon'} - i0^+ + 2\Sigma_{00}.
\end{aligned}
$$

Diagonal disorder

Exact inversion of D^{+-1}_{nm}
Two-step approach

- Diagonal term using standard approach
- Off-diagonal term

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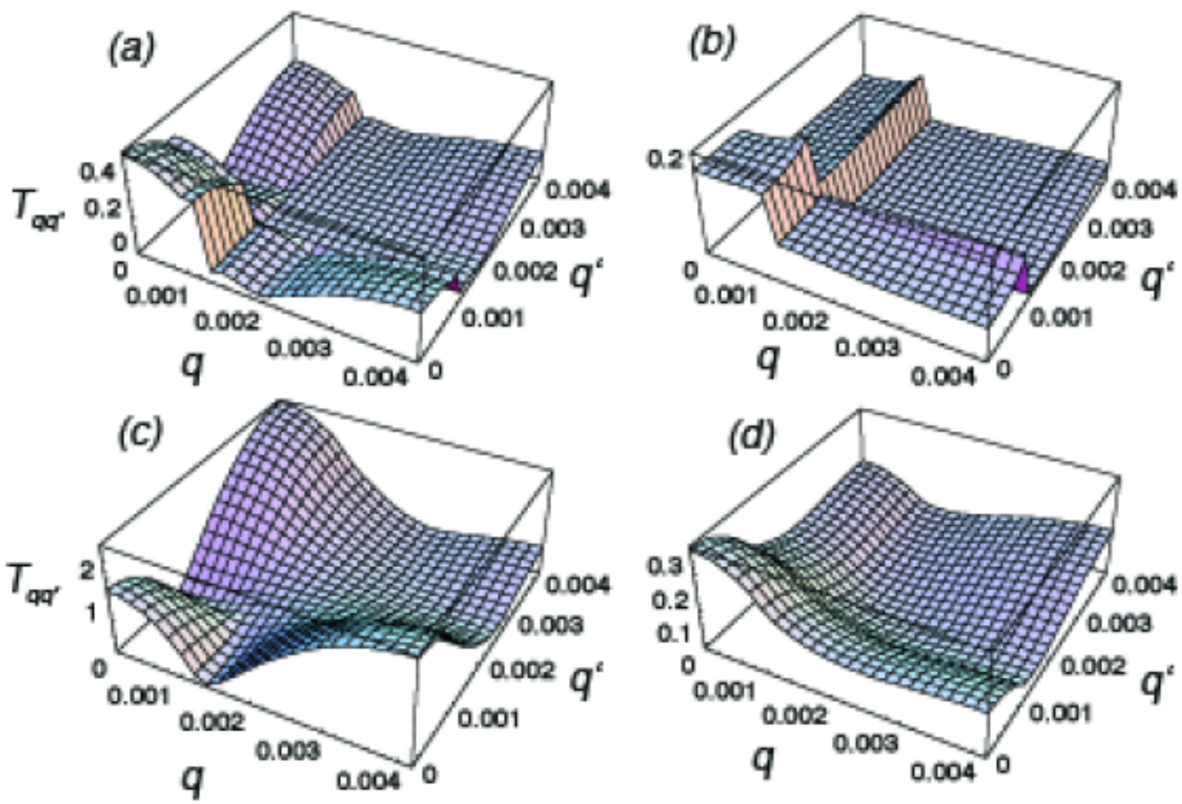
School of
Electrical and Computer Engineering

Exact T-matrix $T_{qq'}$: Describes the vacancy-induced scattering of plasmon polaritons

T-modes



L-modes

Other Topics Investigated

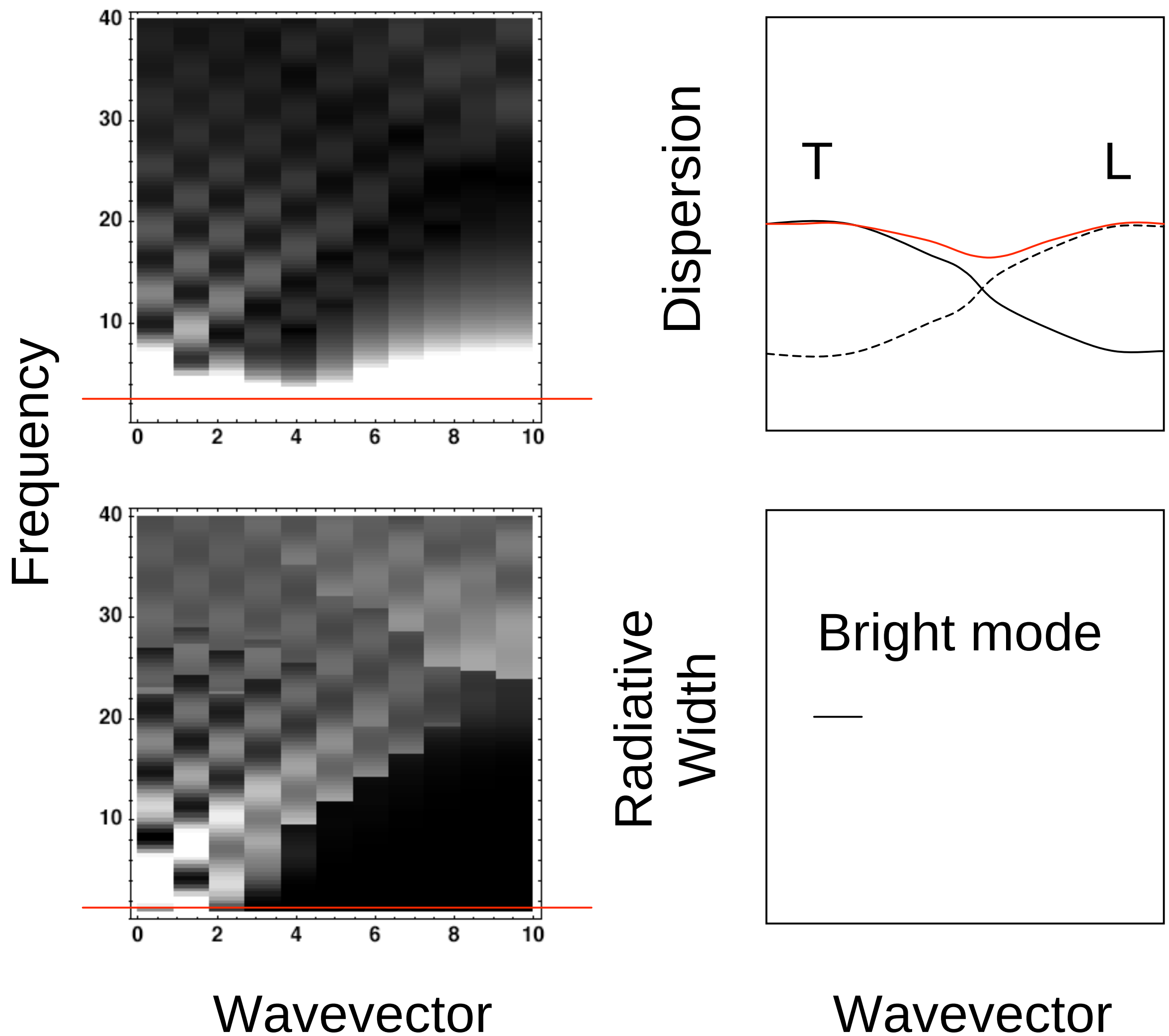
- Finite length chains (D. S. Citrin, Nano Lett. **5**, 985 (2005).

Nanoparticle Ring

Nano-optical resonator
Nano-optical corral
Nano-antenna
Nano-optical trap…

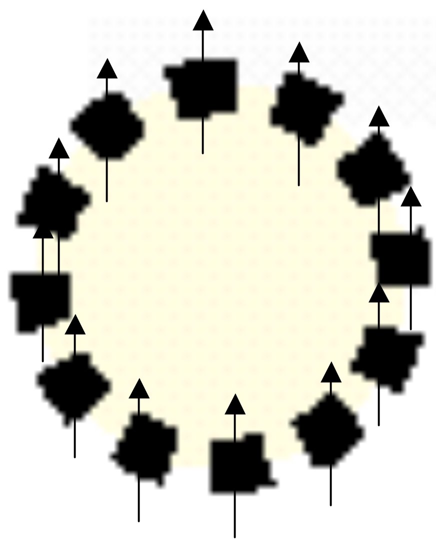
Re S

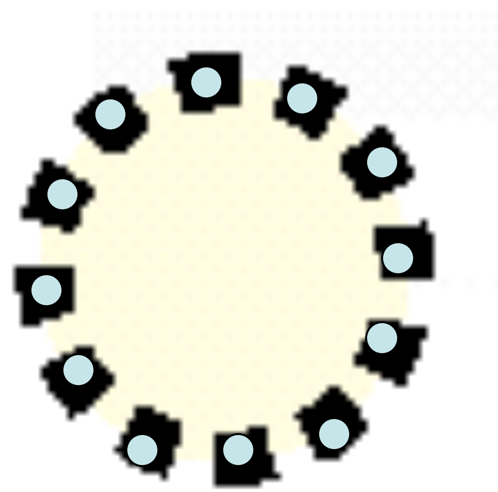
-Im S



D. S. Citrin, J. Opt. Soc. Am. B **22**, 1763 (2005).

What are the bright modes?

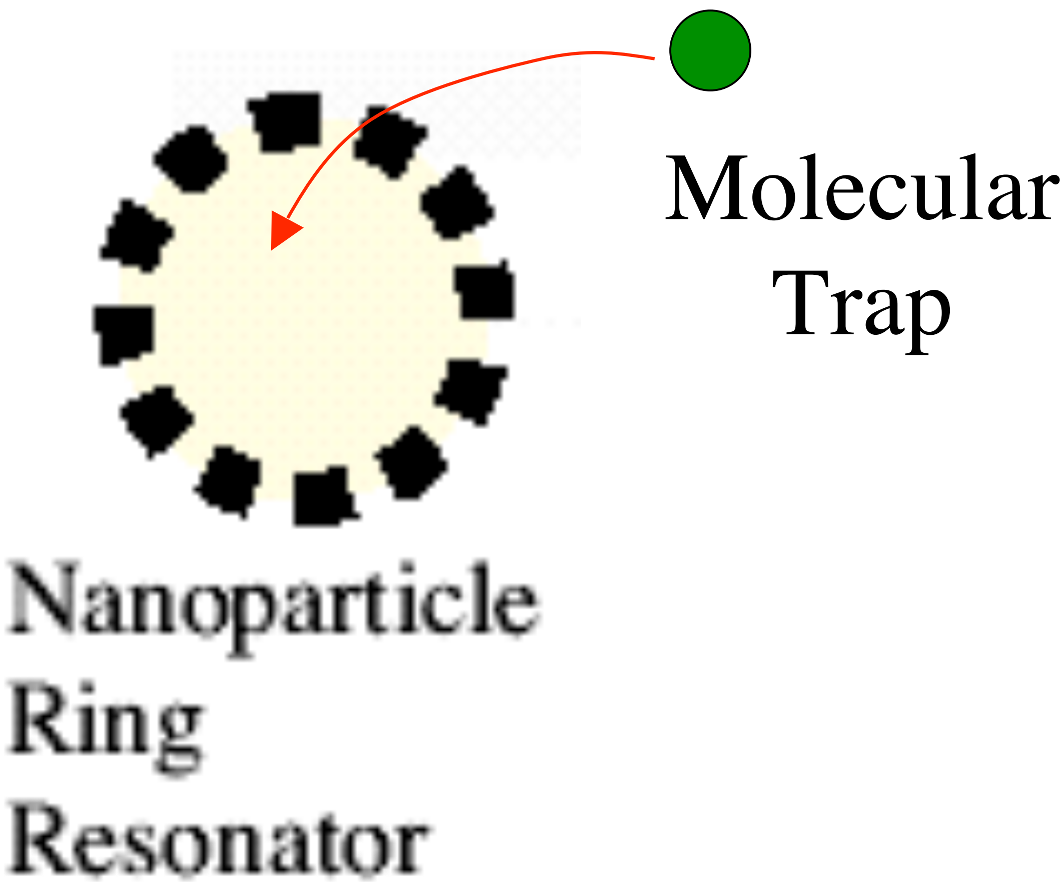




Wavevector: n=1 n=0

Nanoantenna

Nanoparticle
Ring
Resonator


Molecular
Trap
Nanoparticle
Ring
Resonator

Conclusions

- Optical propagation on nanoparticle chains involves interplay of long/short-range coupling, polarization effects, radiative decay,…
- Attenuation is severe, but there might be strategies for its management.
- A nascent understanding of in- and out-coupling to nanoparticle chains is emerging.
- Nanoparticle rings might form subwavelength optical resonators.