2022 FIRST ACM/IEEE NEXT G SUMMIT

Design and Development of Optical Antennas for Wireless Communication

Presented

By

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Motivation

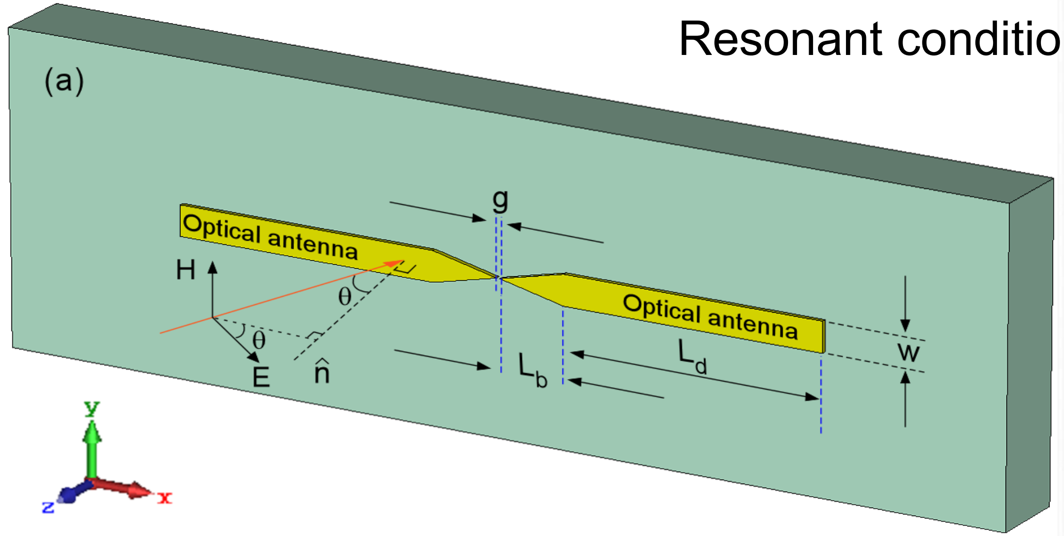
- Investigate antenna theories (e.g. gain, receiving patterns, polarization, etc.) in the optical frequency regimes (10THz - 300THz).
- Develop efficient light collection and strong optical confinement in subwavelength region for dynamic polarimetric infrared (IR) imaging
- Plasmonic optical antennas (POA) with engineerable polarization and receiving patterns.
- Strong SPR surface confinement enhanced photodetection at the subwavelength region.
- Plasmonic cavity with perfect absorption.

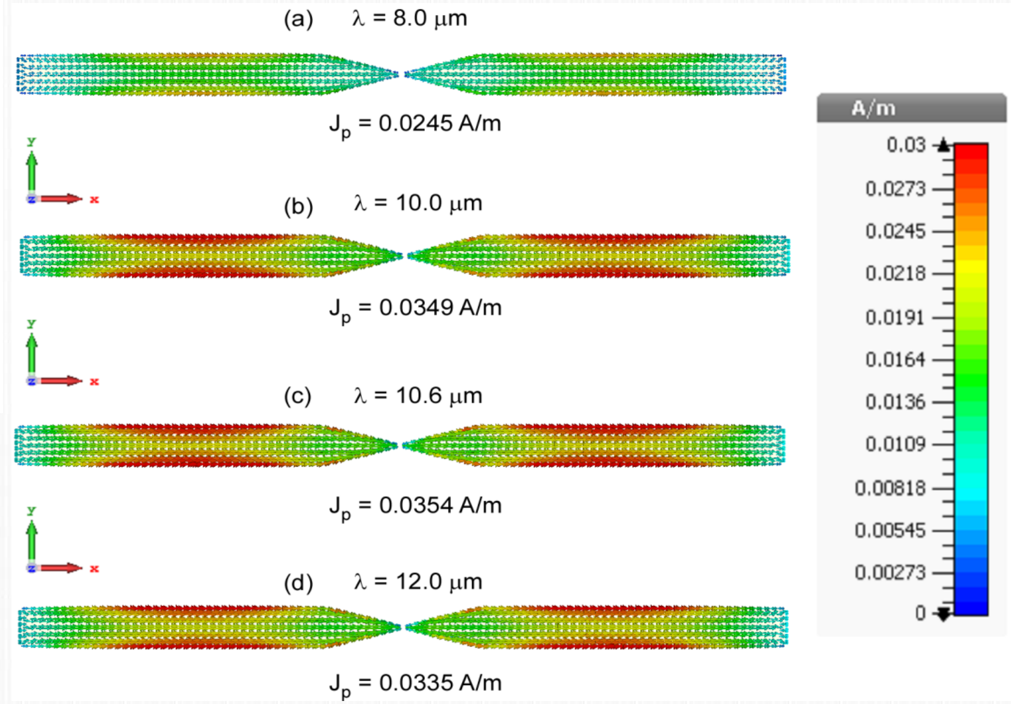
OBJECTIVE

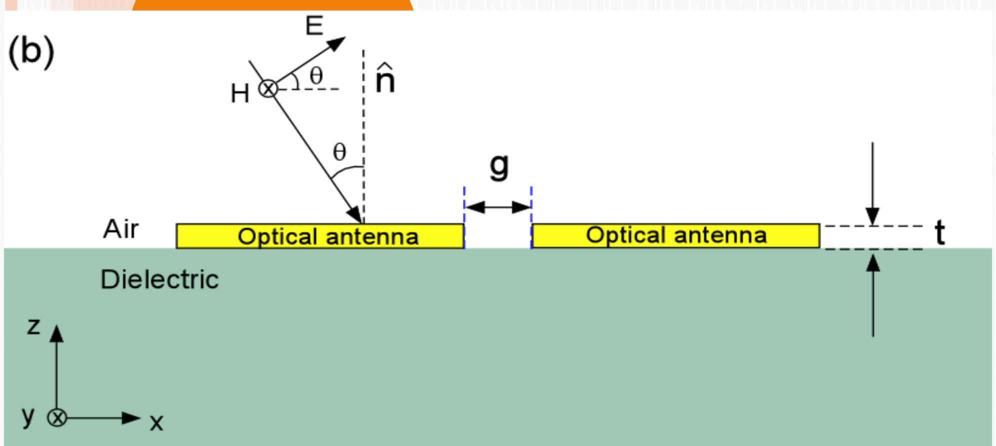
- Key elements in transmitting and receiving signals in RF microwave spectral regimes.
- Engineerable antenna gains and receiving patterns.
- Pioneered by Lukas Novotny, etc., extensively researched recently.
- Much higher frequency (10THz - 300THz).
- Wavelength scaling, µm to nm antenna dimensions.

Pointed Dipole POA

Resonant condition: $k_{sp} L = \pi$ $\qquad k_{sp} = \frac{2\pi}{\lambda_0} \mathrm{Re}\left\{ \left[\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \right]^{1/2} \right\}$





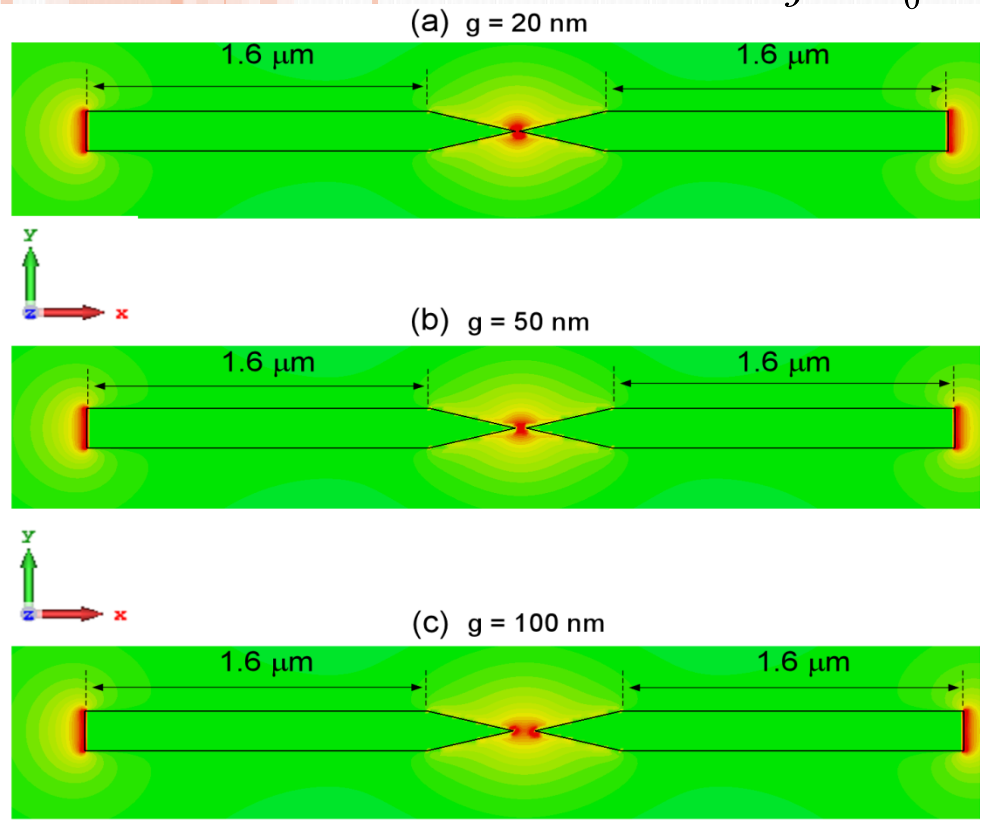


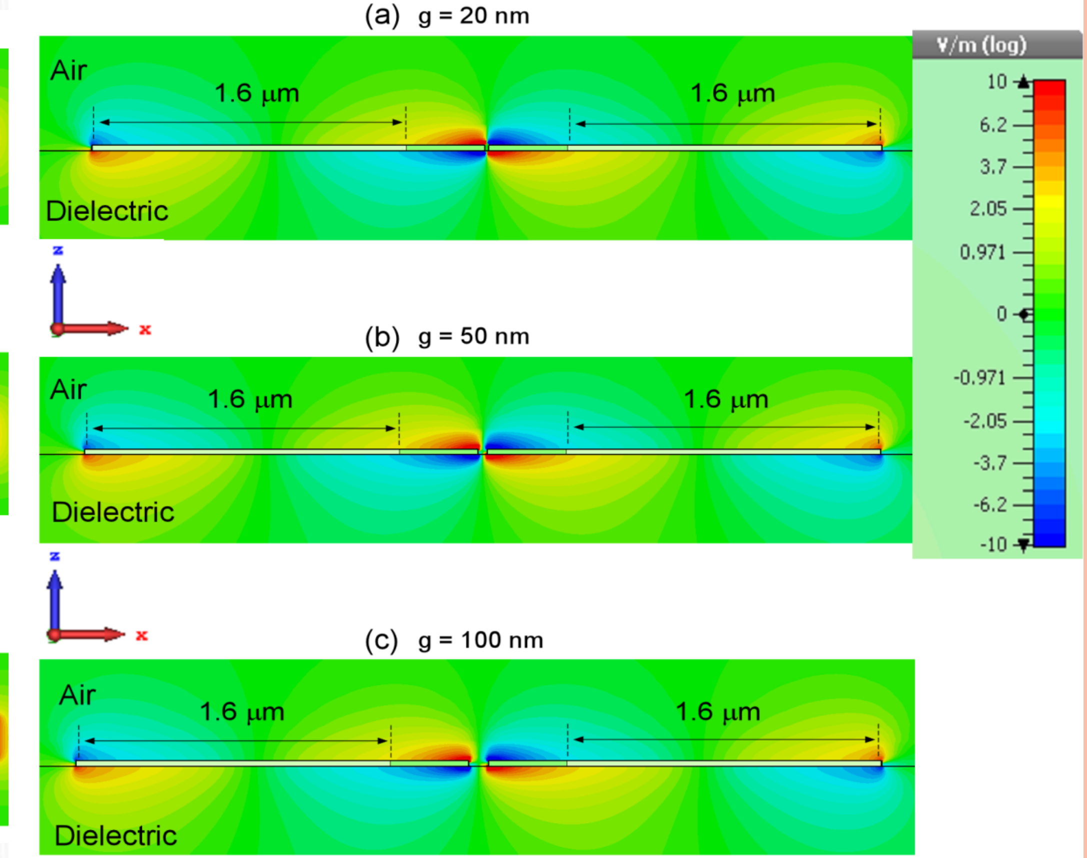
- Collect free-space propagation light.
- Convert it to surface current in POA.

Pointed Dipole POA

Near field profiles

$$\vec{E} = \frac{1}{j\omega\varepsilon\varepsilon_0 R^3}\left[3R(R\cdot\vec{p}) - \vec{p}\right]$$





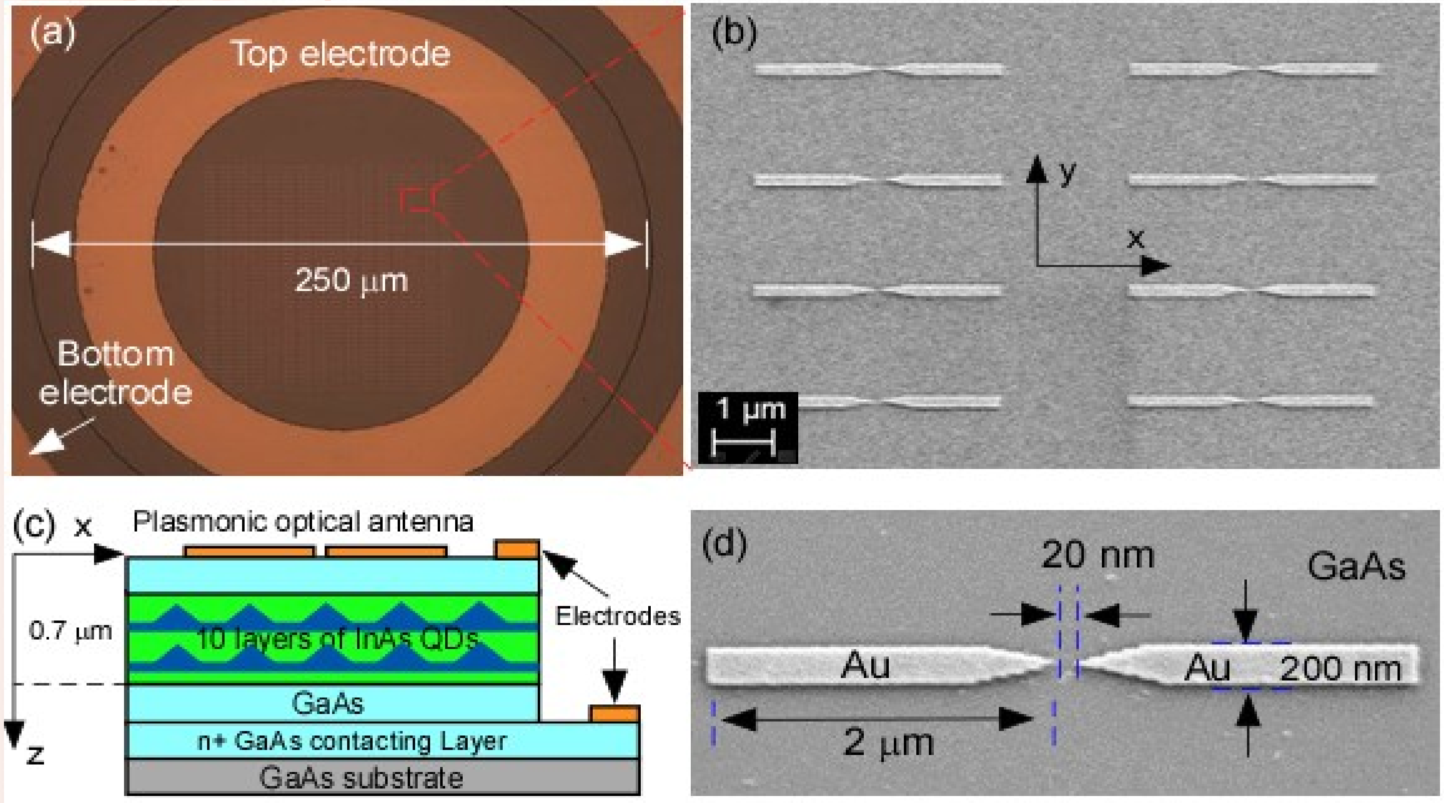
Near field current relation:

$$I = \int J dy = j\omega\varepsilon_{r,eff}\varepsilon_0 \iint |E| ds$$

- Surface current generates the near-field.

Pointed Dipole POA

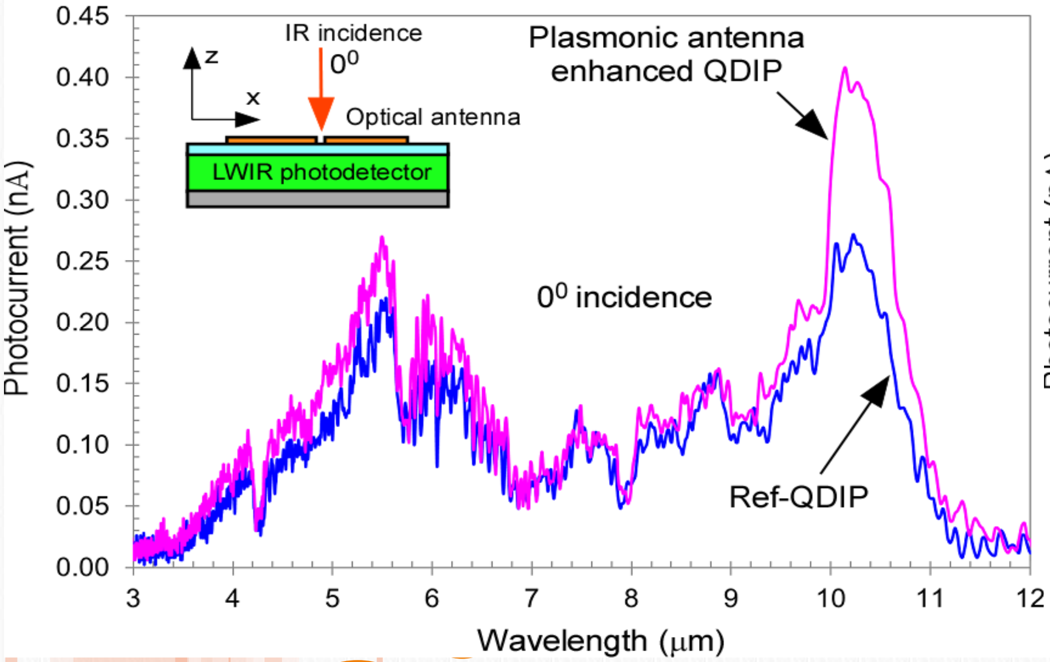
Pointed dipole POA enhanced LWIR photodetector

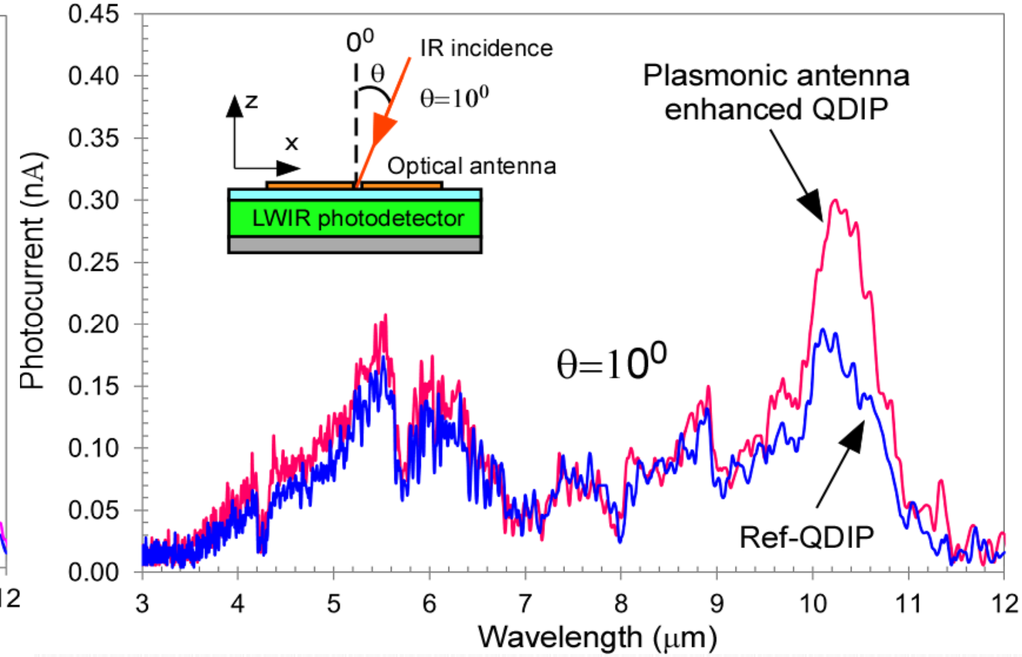


- Direct integration on an LWIR photodetector.
- Surface confinement induced enhancement.

Pointed dipole POA

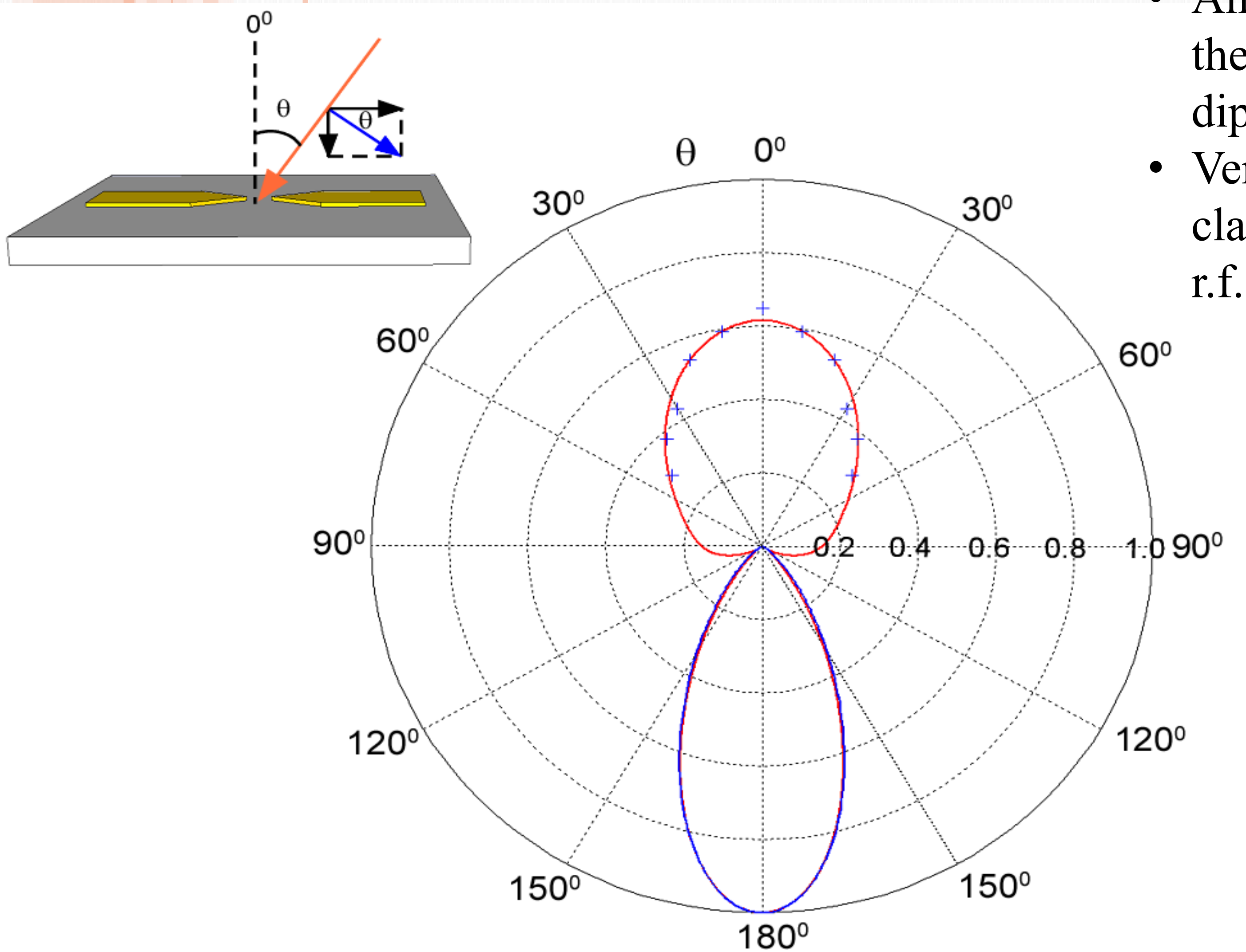
Angular dependence and receiving patterns





Pointed Dipole POA

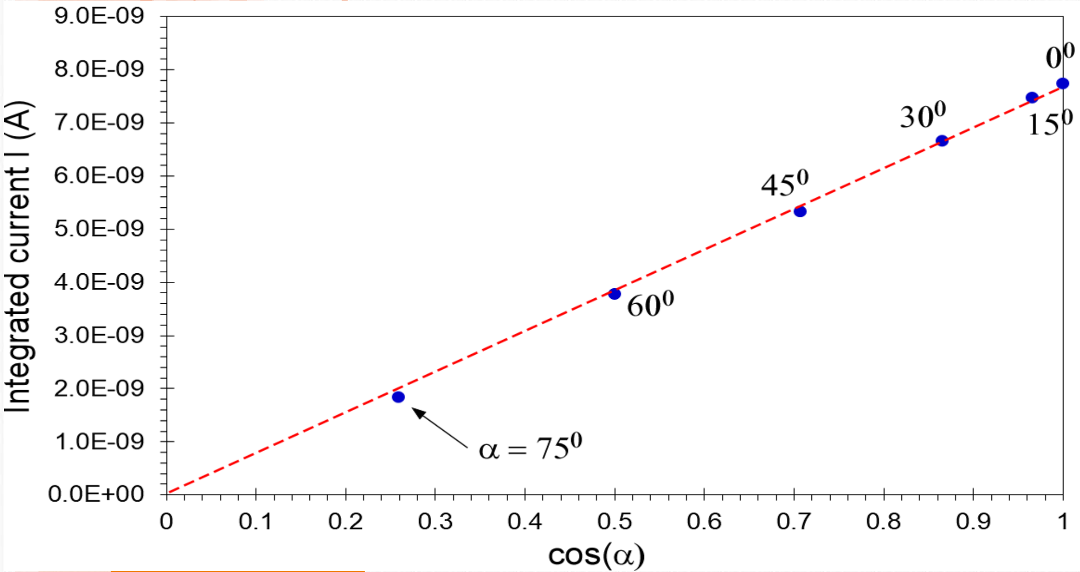
Angular dependence and receiving patterns

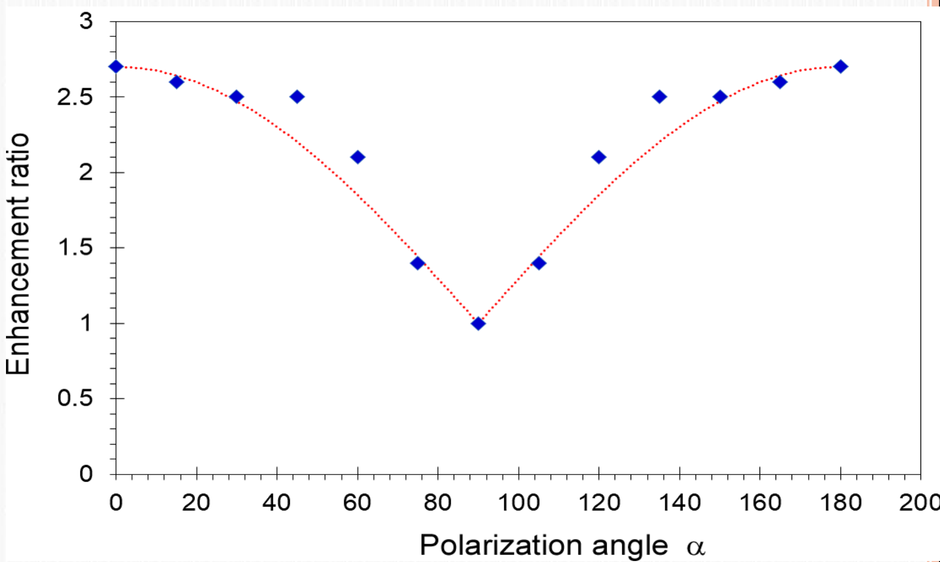


- Antenna receiving patterns are the same as the full wave dipole antenna.
- Verified the POA follows the classical antenna theory in the r.f. frequency regimes.

Pointed dipole POA

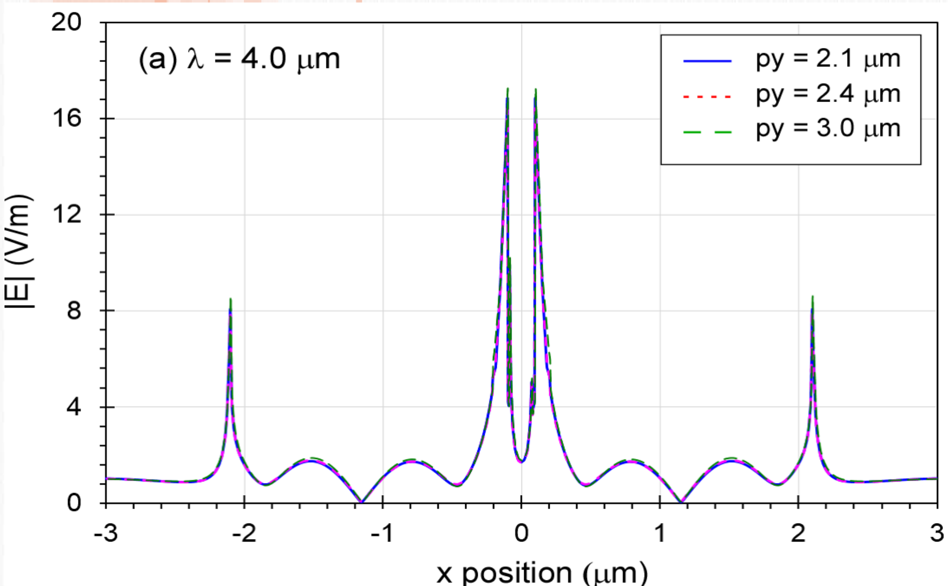
Polarization dependence

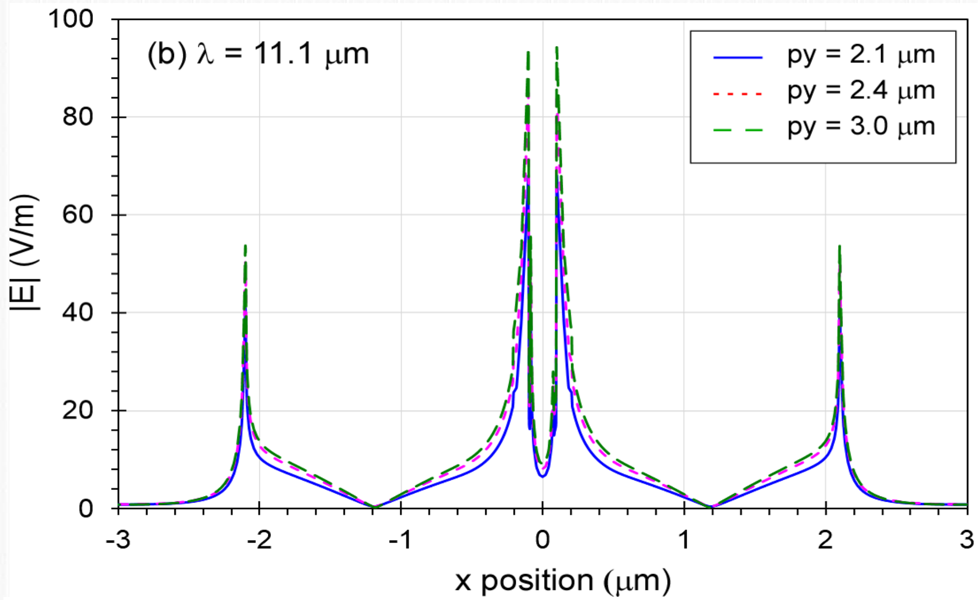


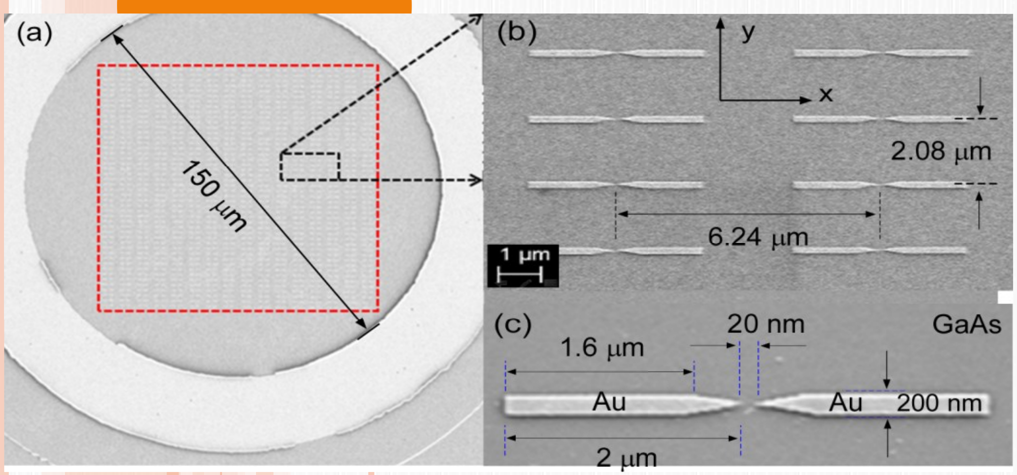


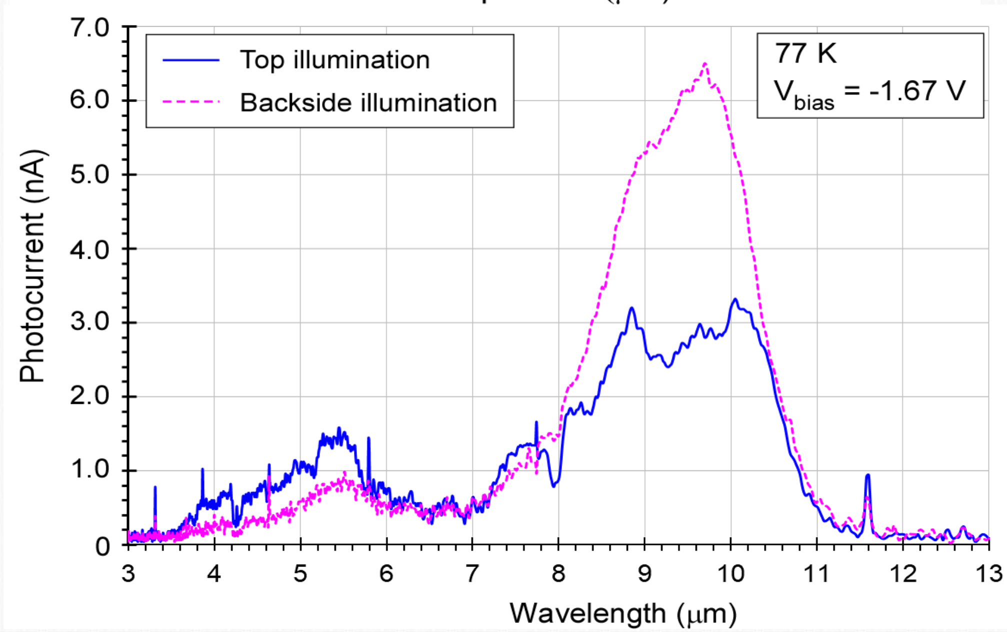
- The polarization dependence follows the cosα relation defined by the classical antenna theory.

Reflective POA



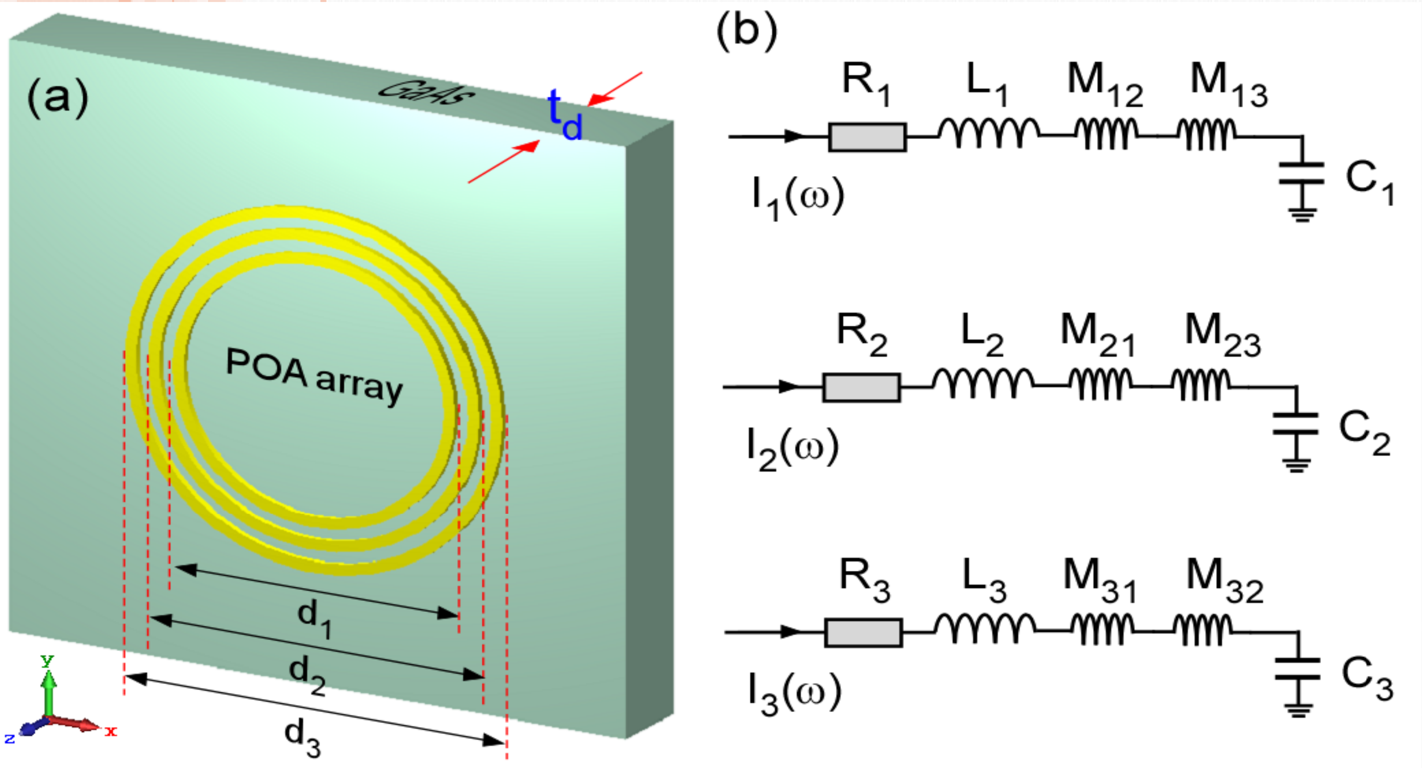






Multispectral Circular POA

- Multispectral enhancement due to the different resonant wavelengths.
- Compact and polarization independent device structure for multispectral detectors.
- Ideal platform for mutual coupling in POA elements.



Multispectral Circular POA

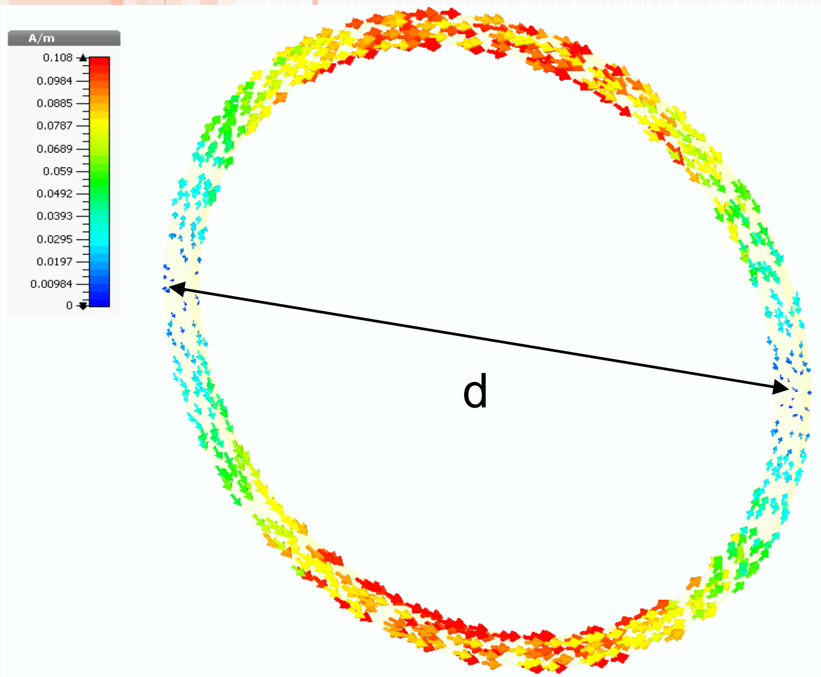
- Standing wave in circular ring.
- Resonant condition: $k_{sp}\dfrac{\pi d}{2}=\pi$

$$I(\omega)=\frac{V_0}{R+j\omega L+\dfrac{1}{j\omega C}}$$

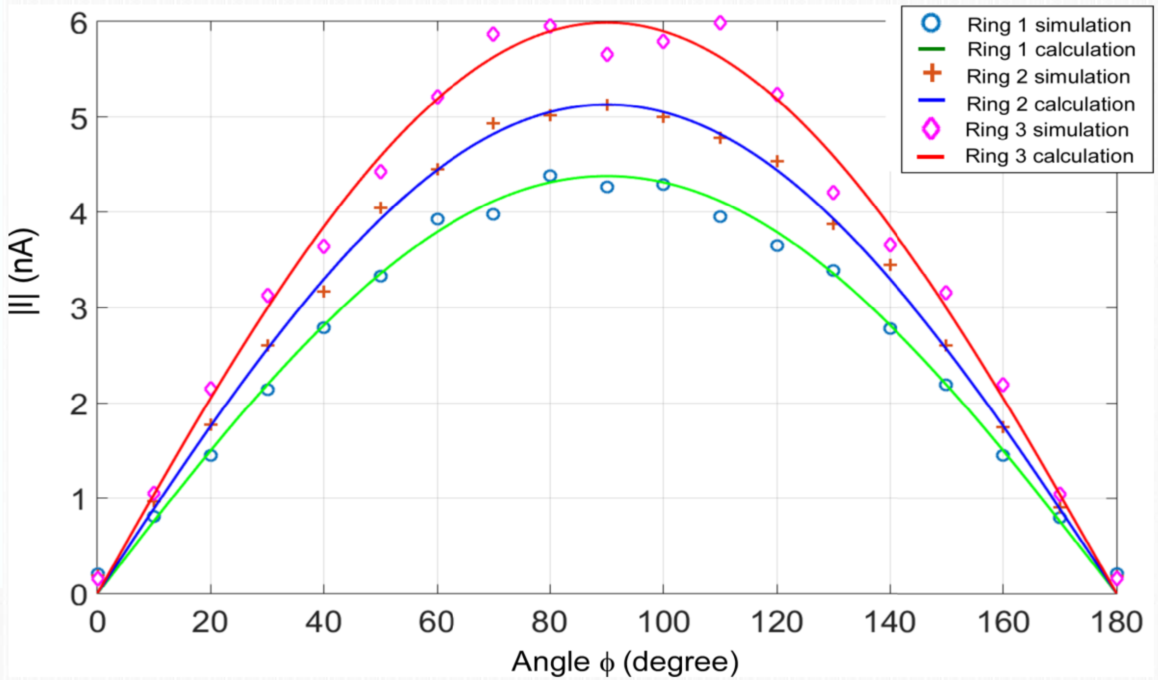
$$L=0.002\pi^2\left(\frac{2R}{t_m}\right)\frac{RK'}{2}$$

$$R=\rho\frac{\pi\left(R_{in}+R_{out}\right)/2}{\sqrt{2}Wt_{m,sk}}$$

K’ values are given by F. W. Grover. Etc., Tables for the calculation of the inductance of circular coils of rectangular cross section.



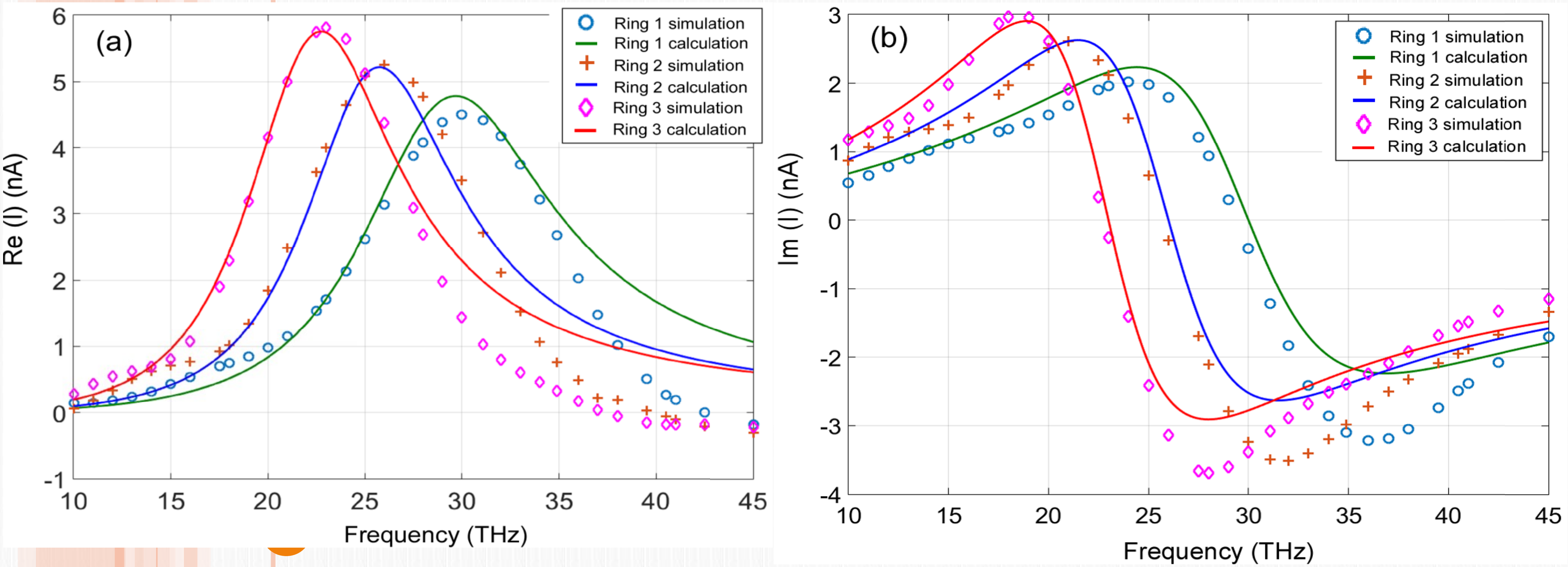
$$I=I_0\sin(\phi)$$



Multispectral Circular POA

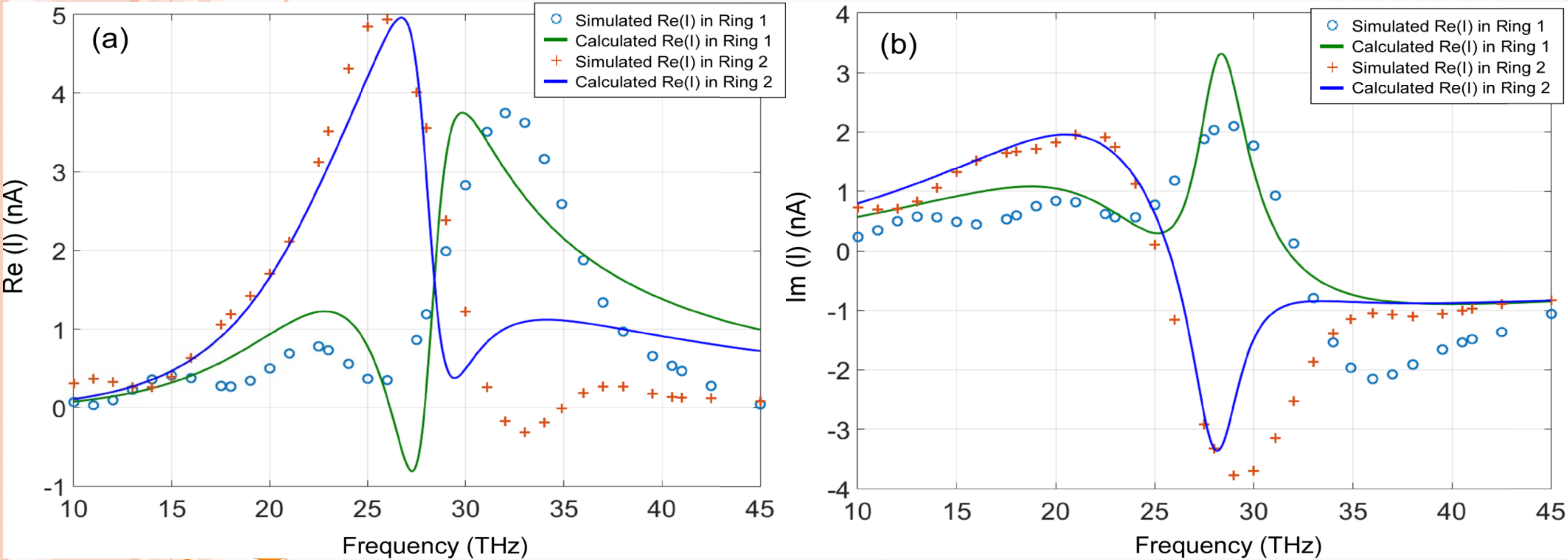
- Individual rings without coupling.
- The RLC model fits in the simulation very well.

$$C = \frac{Q}{V_0} = \frac{\int_0^{T/2} I dt}{V_0}$$

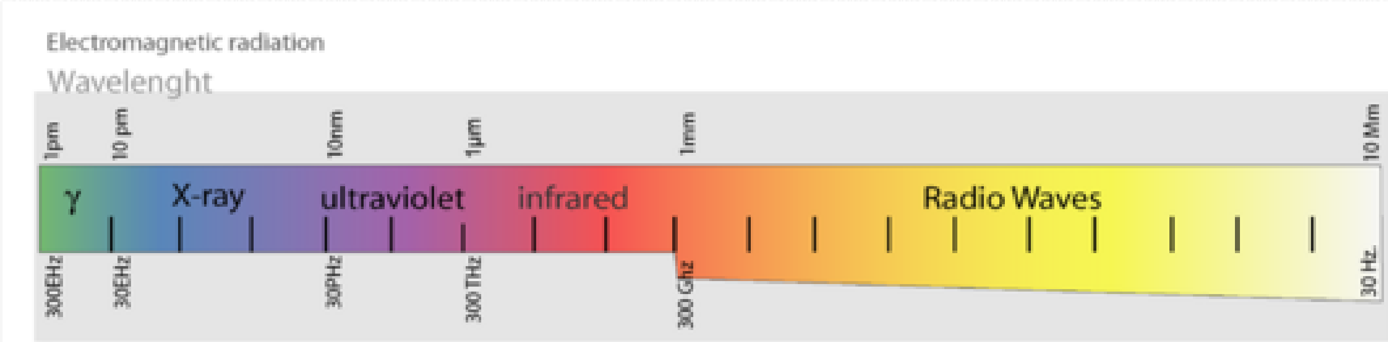


Multispectral Circular POA

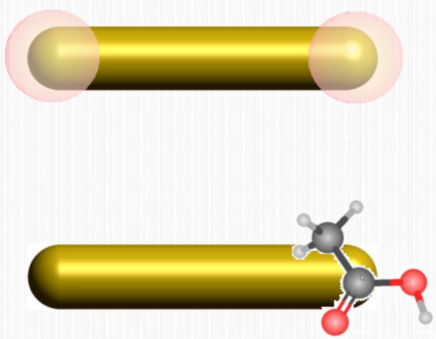
- Comparison with simulation
- Two coupled rings

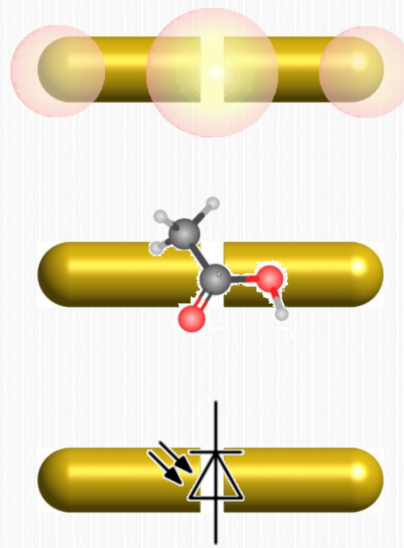


Scaling down in size ← Scaling down in wavelength

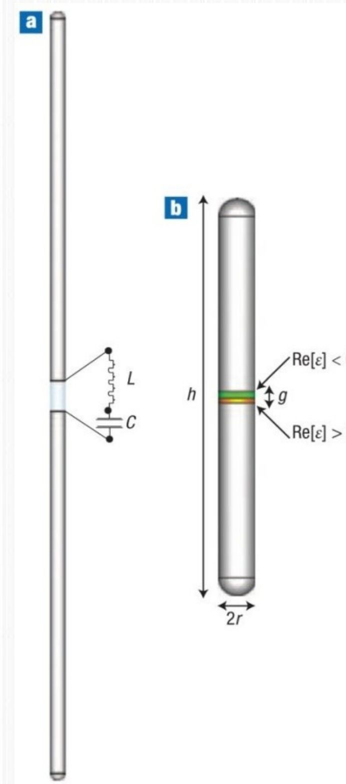


Visible light ⇔ Optical antenna ⇔ Nanoantenna



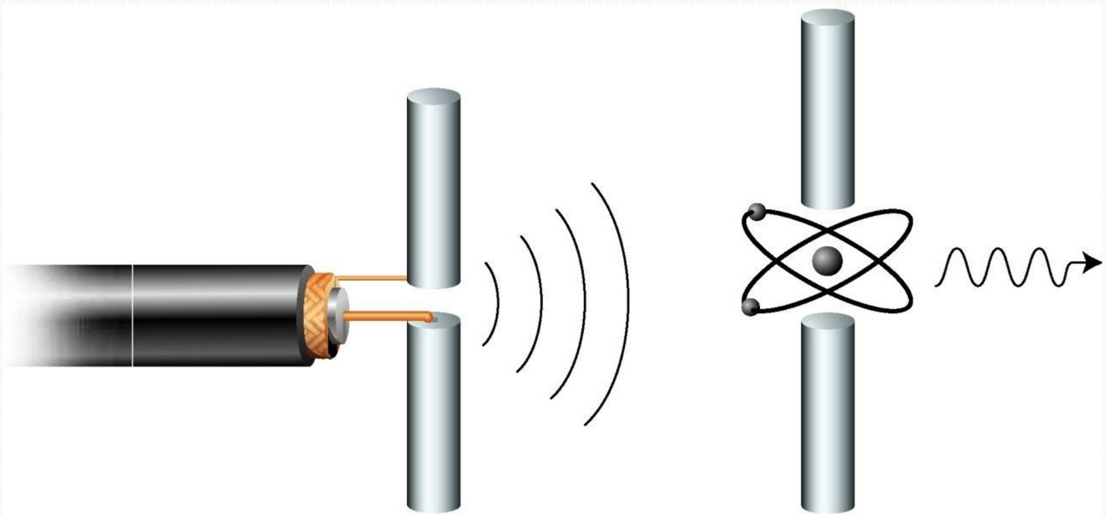


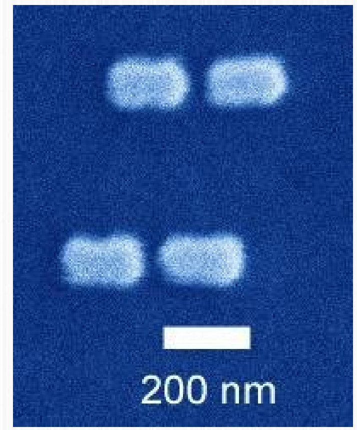
λ/2 nanoantenna



OPTICAL NANOANTENNAS

- Design of plasmonic nanoparticles: size, shape, interactions, ...



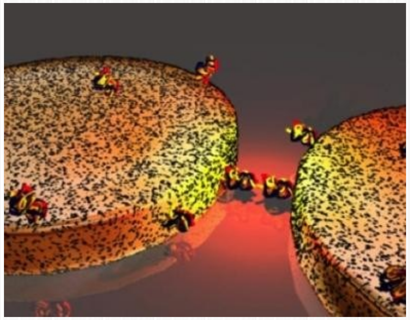


Analogy with radio-wave antennas

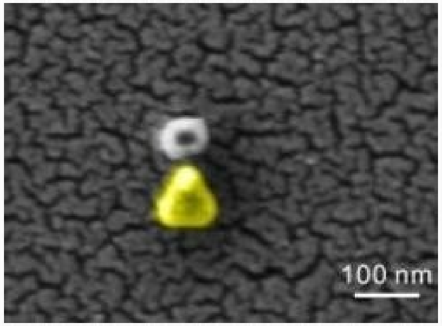
Mühlschlegel et al. Science 308, 1607 (2005)

OPTICAL NANOANTENNAS

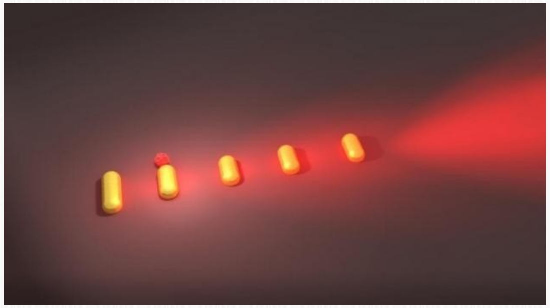
- Applications: biosensing, nonlinear optics / SERS, fluorescence, quantum optics,...



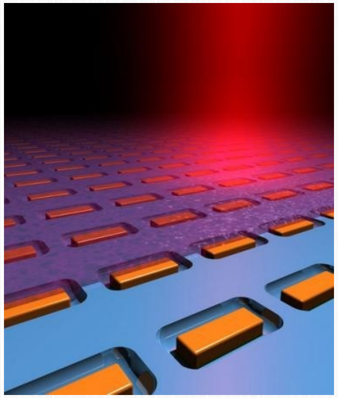
Quidant, ICFO
Antenna-gap sensing



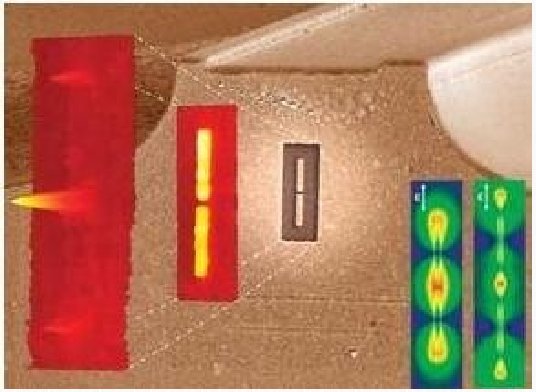
Alivisatos, Giessen
Pd-antenna sensor



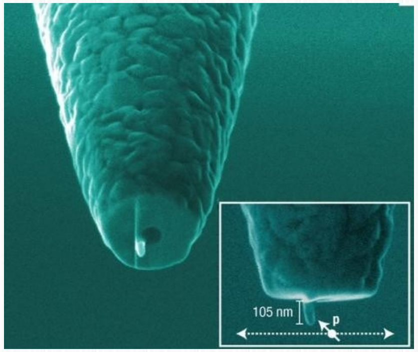
Van Hulst, ICFO - Single molecule, scanning probe



Halas, Nordlander
Plasmonic photodetector



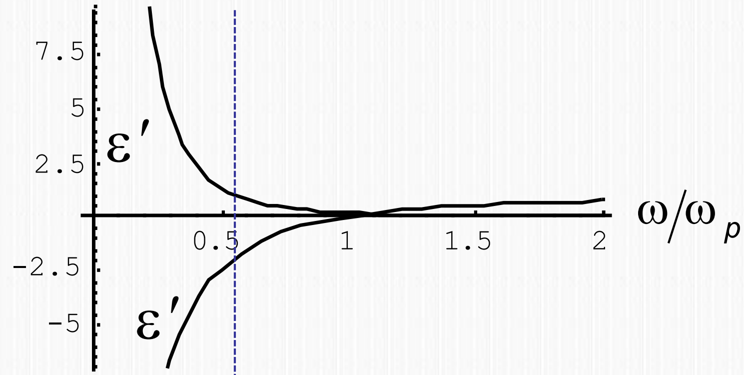
Capasso
Antenna QCL

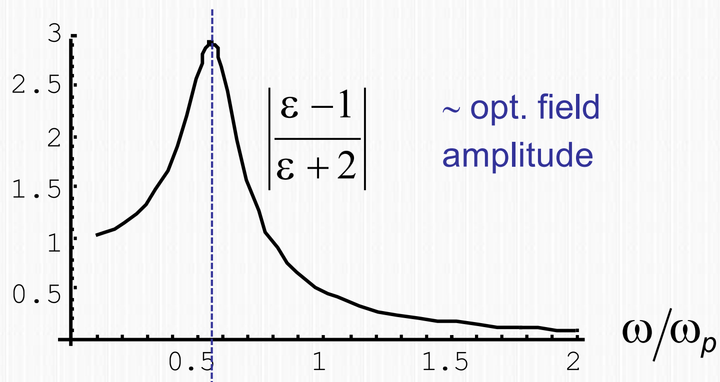


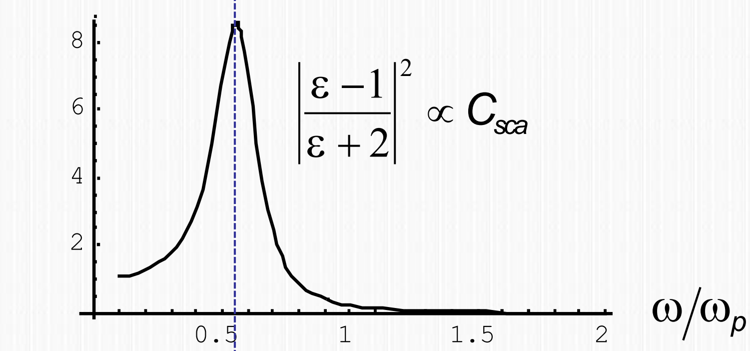
Optical cross sections of small spheres

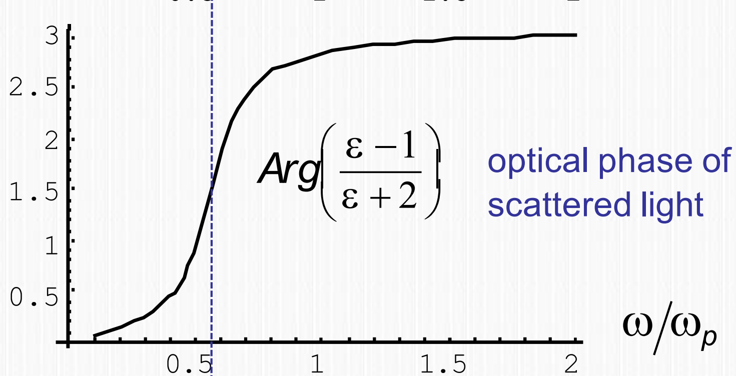
Drude model

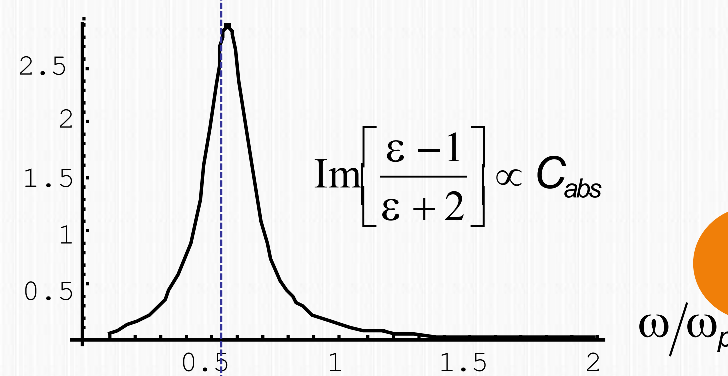
$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2 + 0.2 i\omega}$$





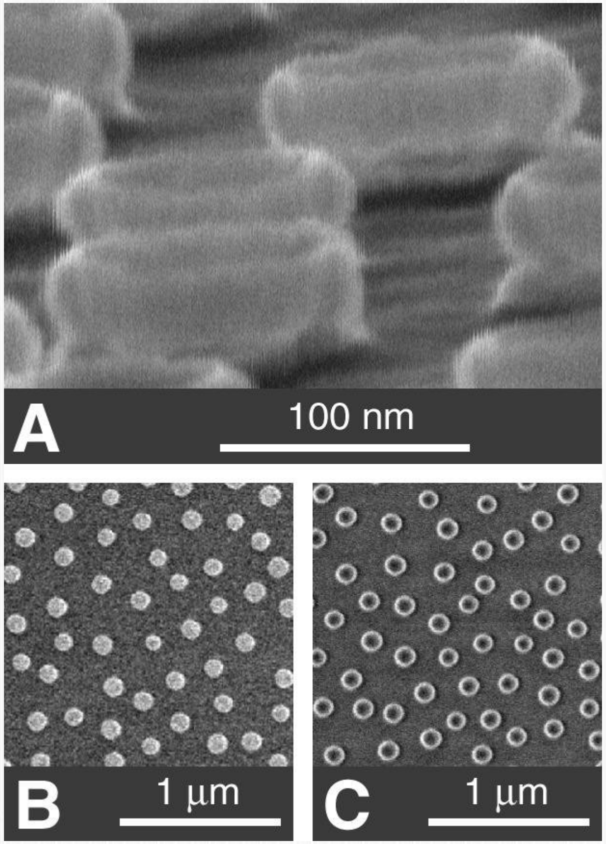




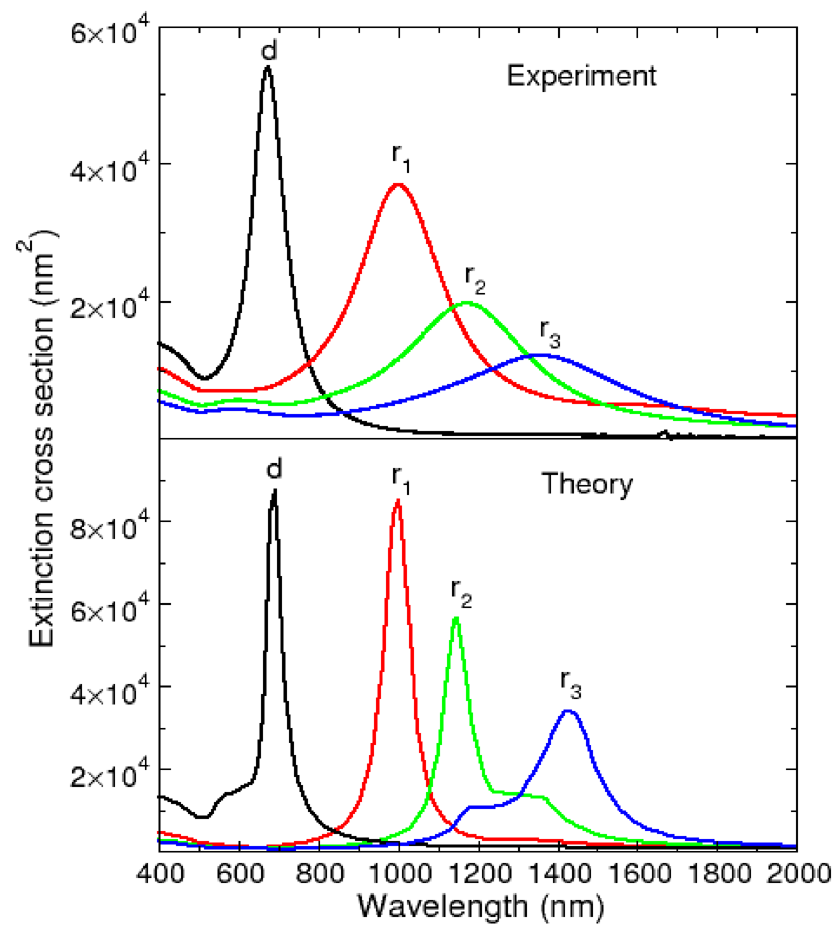


An Example of Optical Antenna:

Optical properties of metallic nanorings

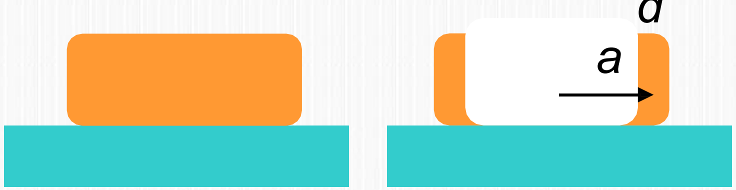


d/a smaller -> red shift

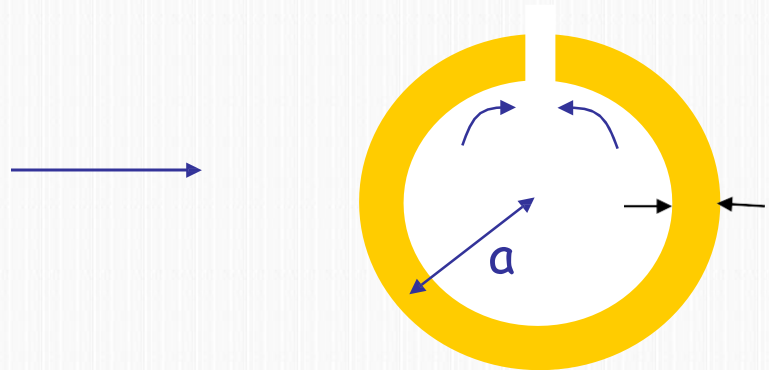


Disk

Nanoring

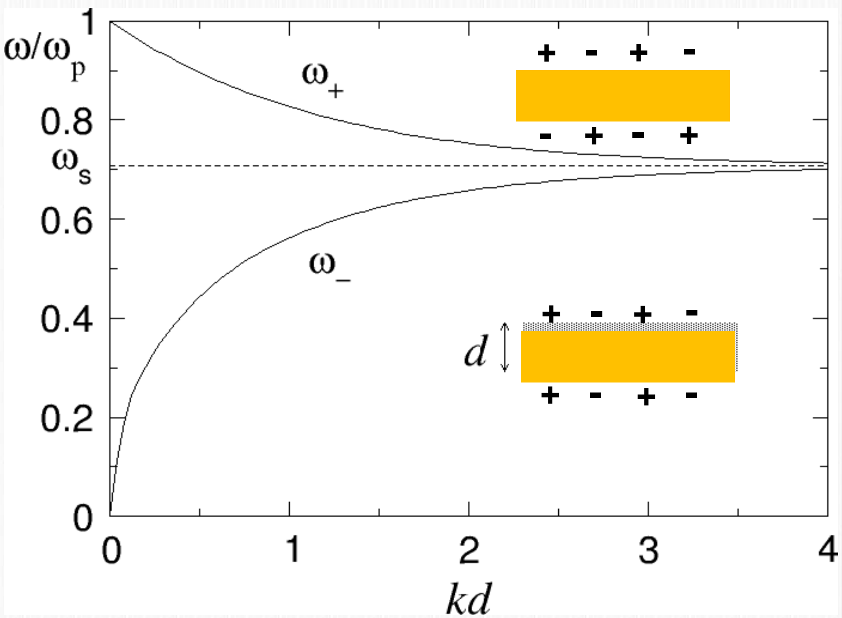


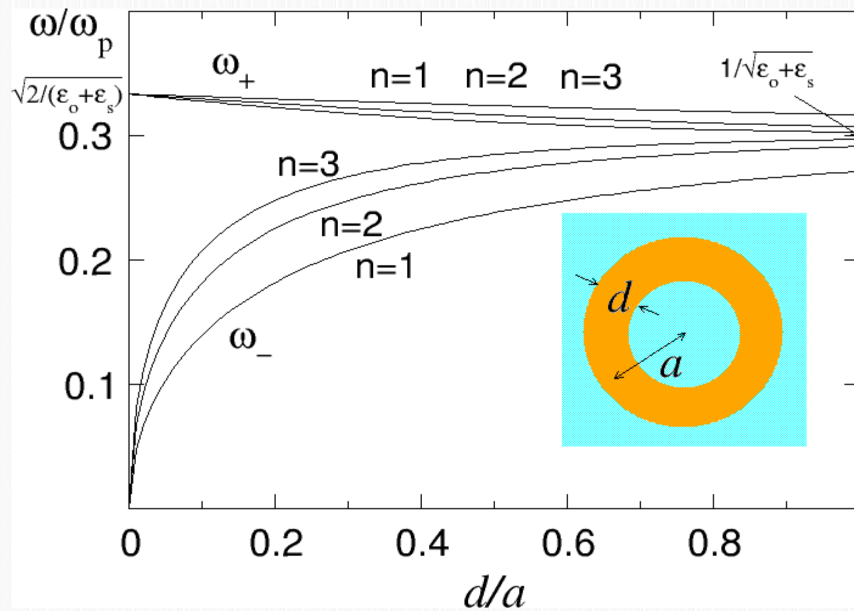
MODES IN A NANORING. THE TWISTED SLAB



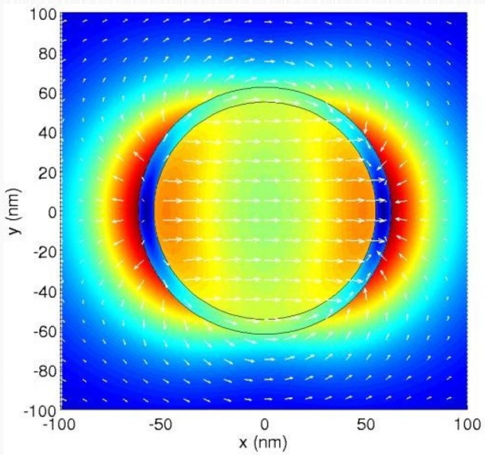
$$\omega_\pm = \omega_s(1 \pm e^{-kd})^{1/2}$$

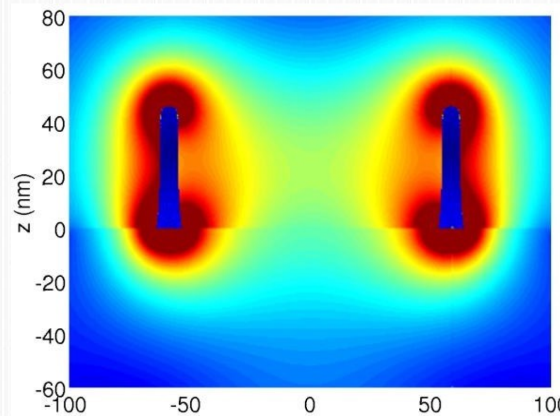
$$kd = n\frac{2\pi}{L}d = n\frac{d}{a}$$

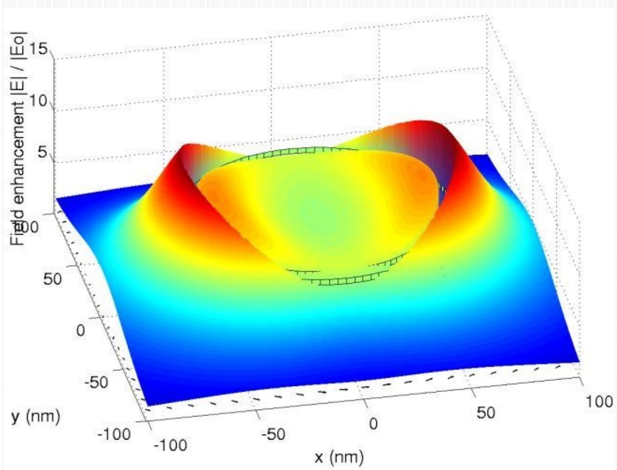


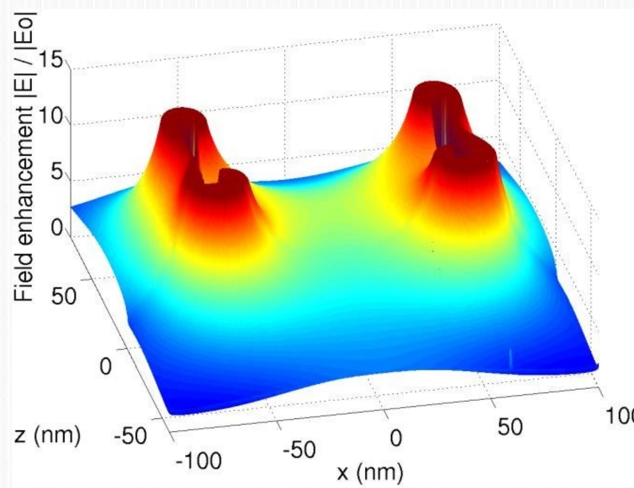


Field-enhancement in a nanoring



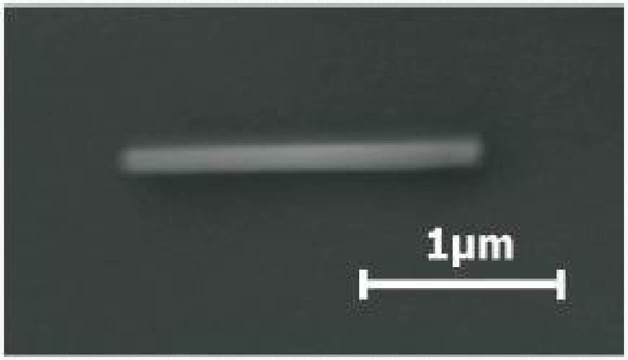


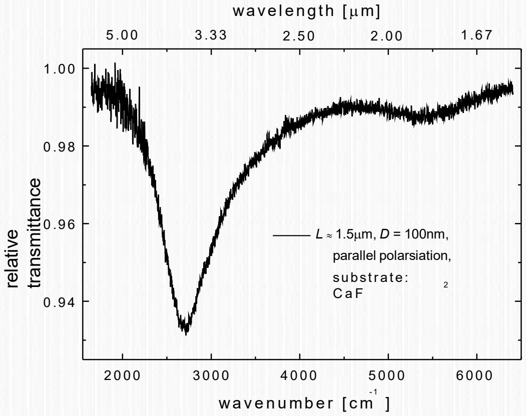




λ/2

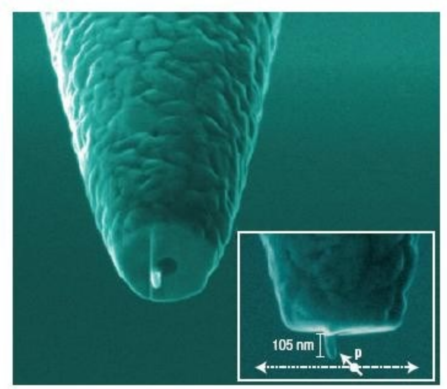
NANOANTENNA

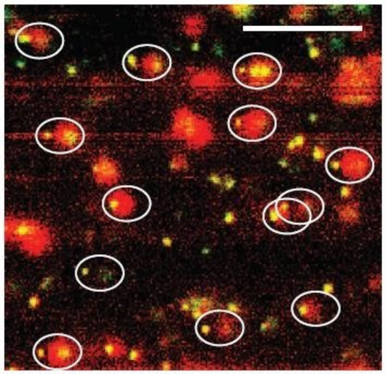




Neubrech *et al.*,
App. Phys. Lett. 89, 253104 (2006)

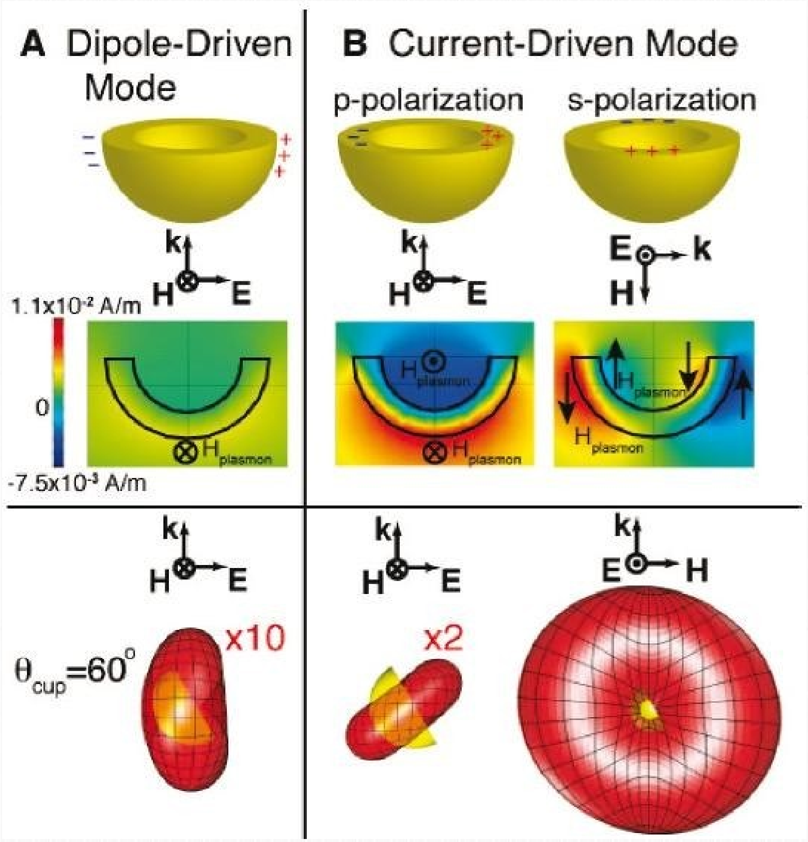
λ/4 optical antenna

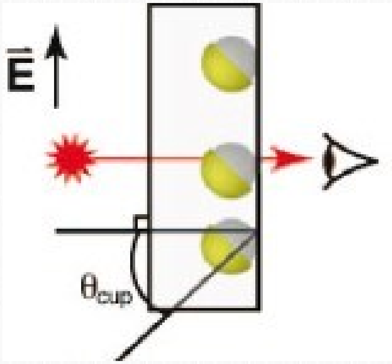




Taminiau *et al.*,
Nature Photonics 2, 234 (2008)

PARABOLIC-LIKE OPTICAL NANOANTENNAS





N. Mirin and N. Halas, Nano Letters 9, 1255 (2009)

Resonant Optical Antennas

P. Mühlschlegel,[1] H.-J. Eisler,[1] O. J. F. Martin,[2] B. Hecht,[1*]
D. W. Pohl[1]

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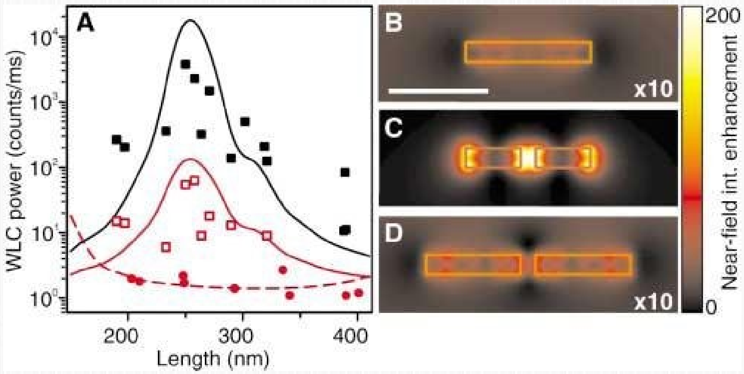
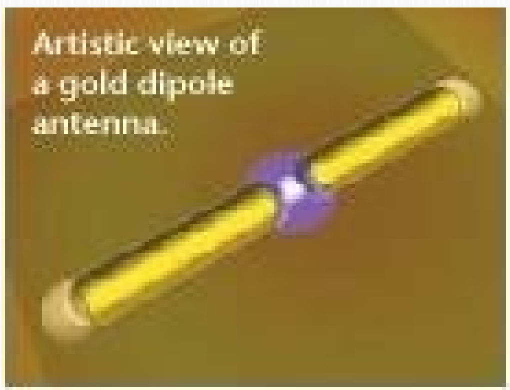
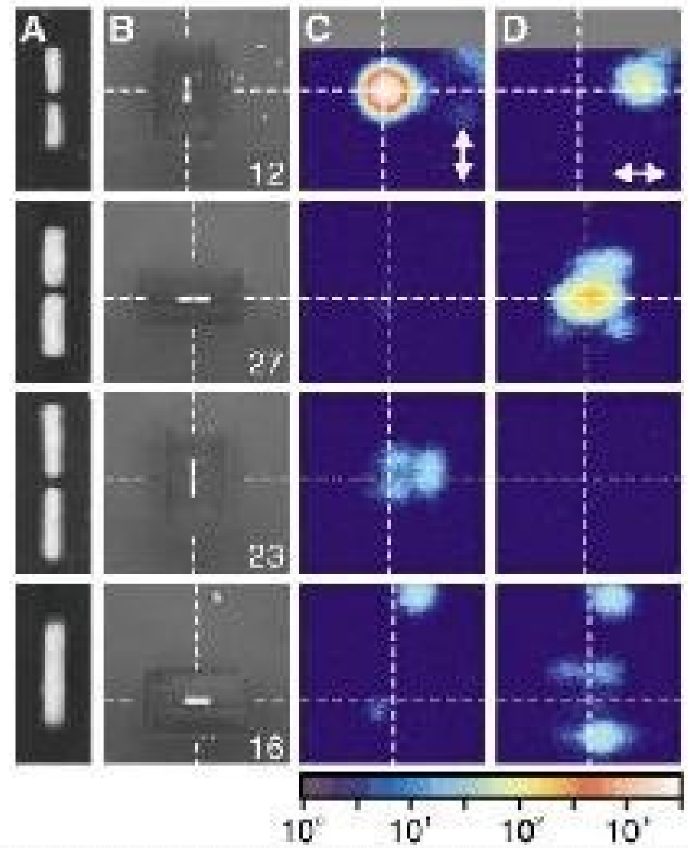
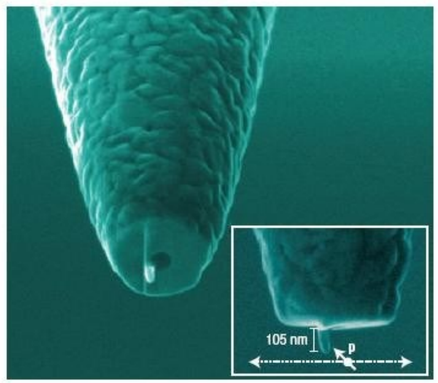
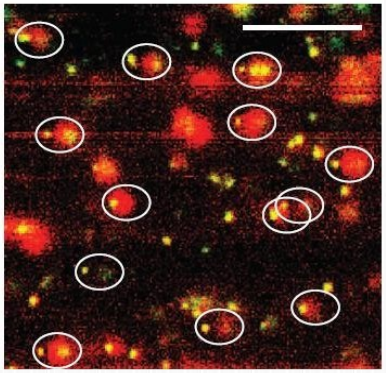






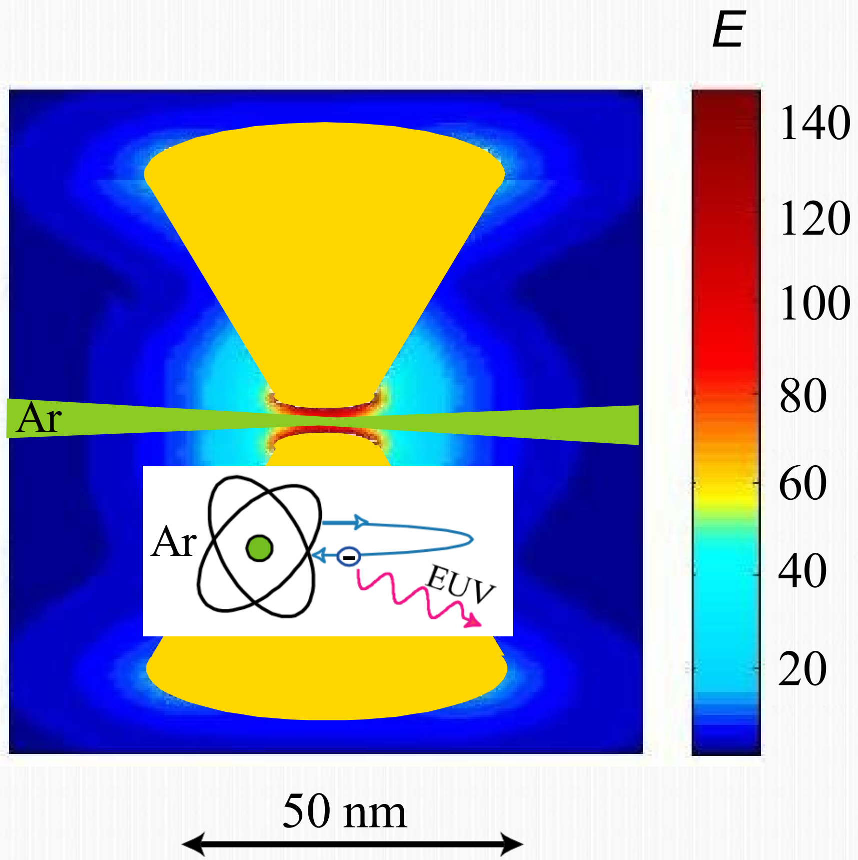
λ/4 OPTICAL ANTENNA





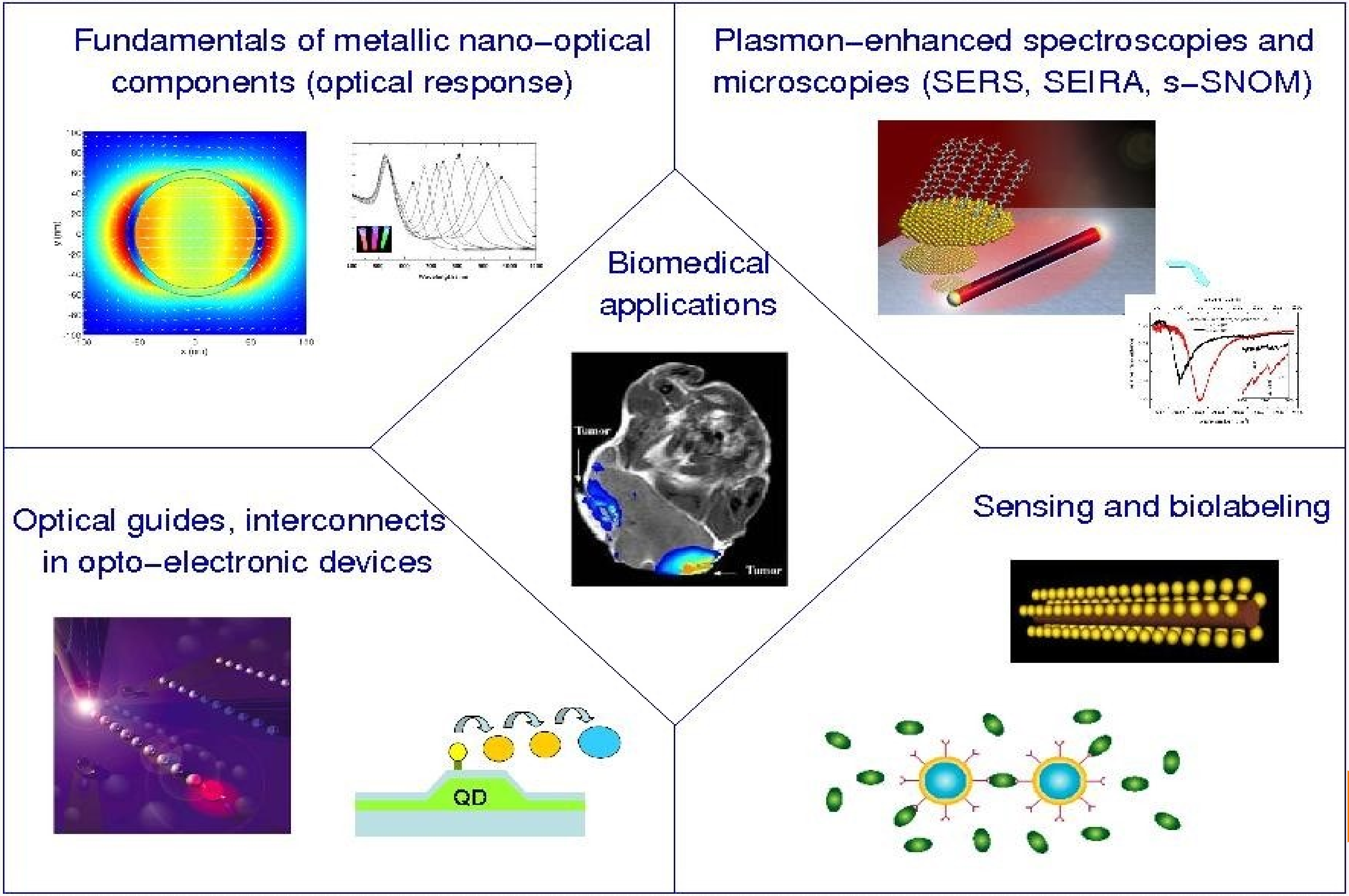
Taminiau ***et al.***,
Nature Photonics 2, 234 (2008)

Bowtie antennas

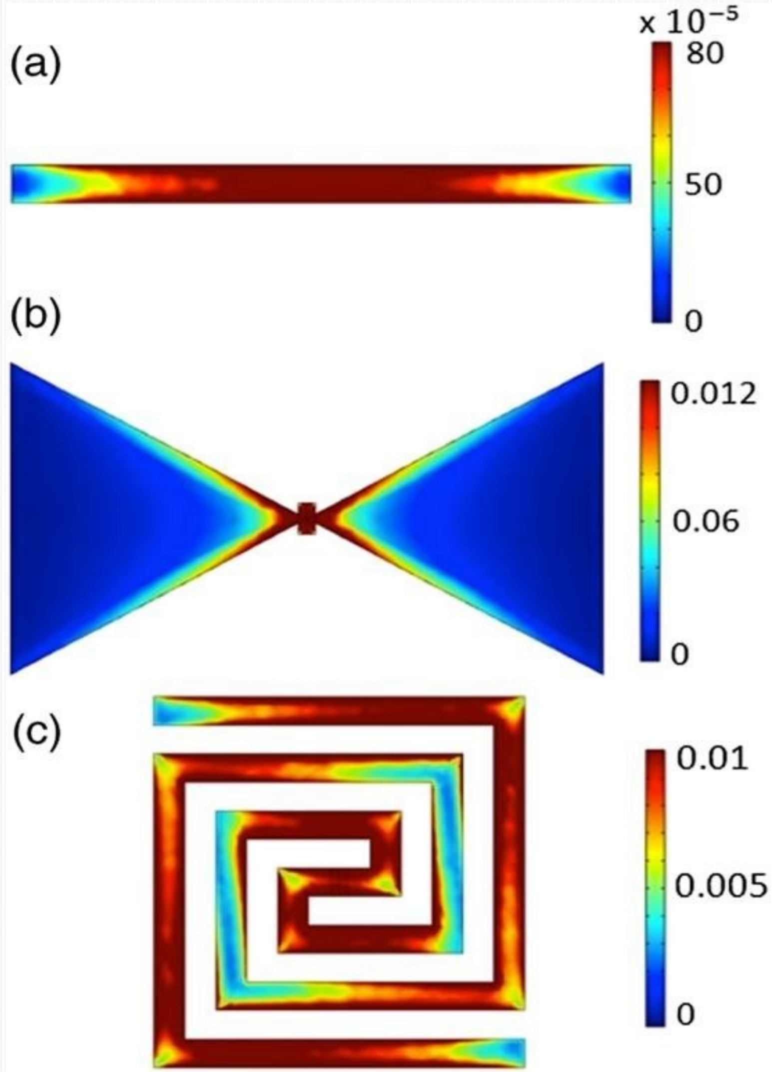


Nature 453, 731 (2008)

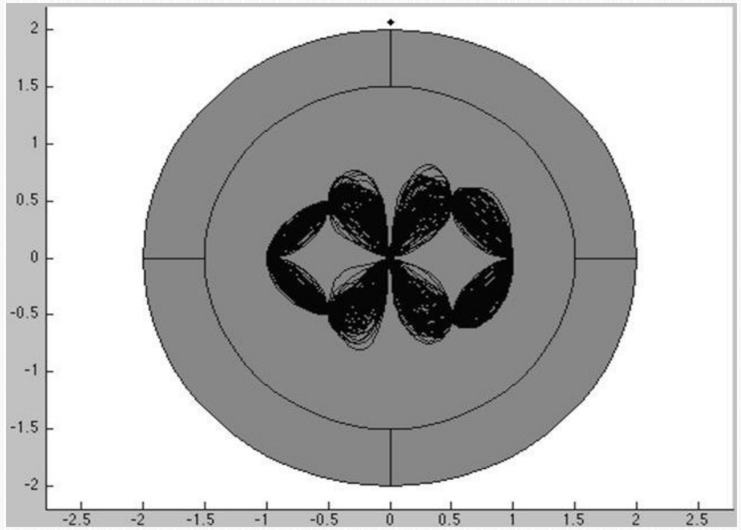
PLASMONIC ANTENNAS

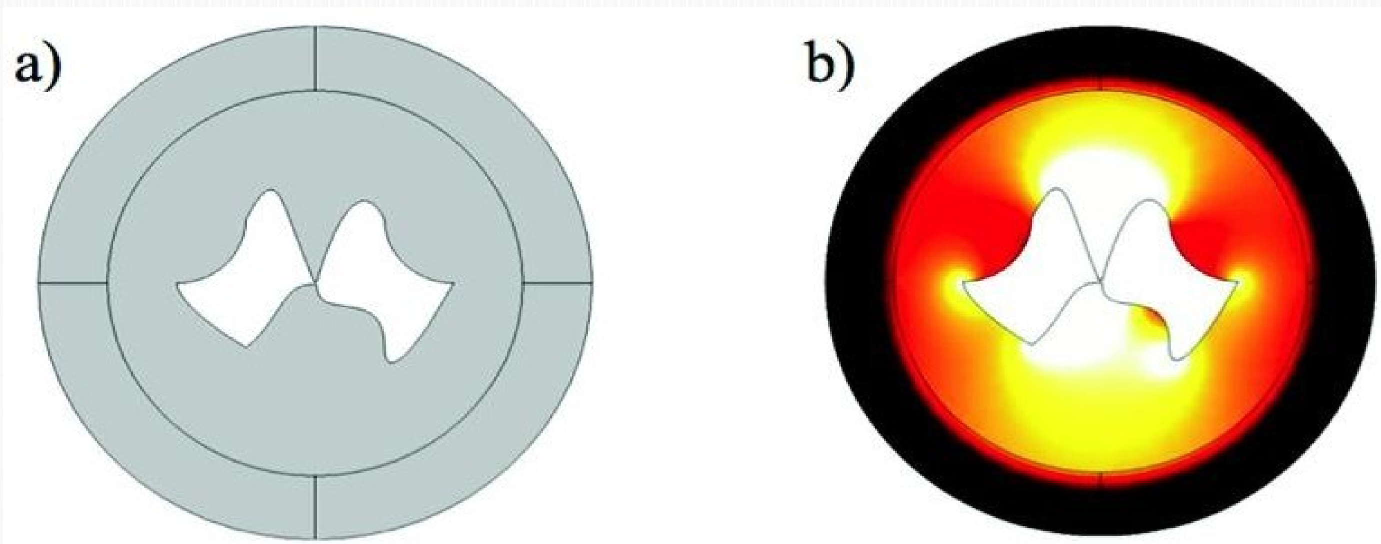


RF GEOMETRIES USED IN OPTICAL ANTENNA DESIGNS

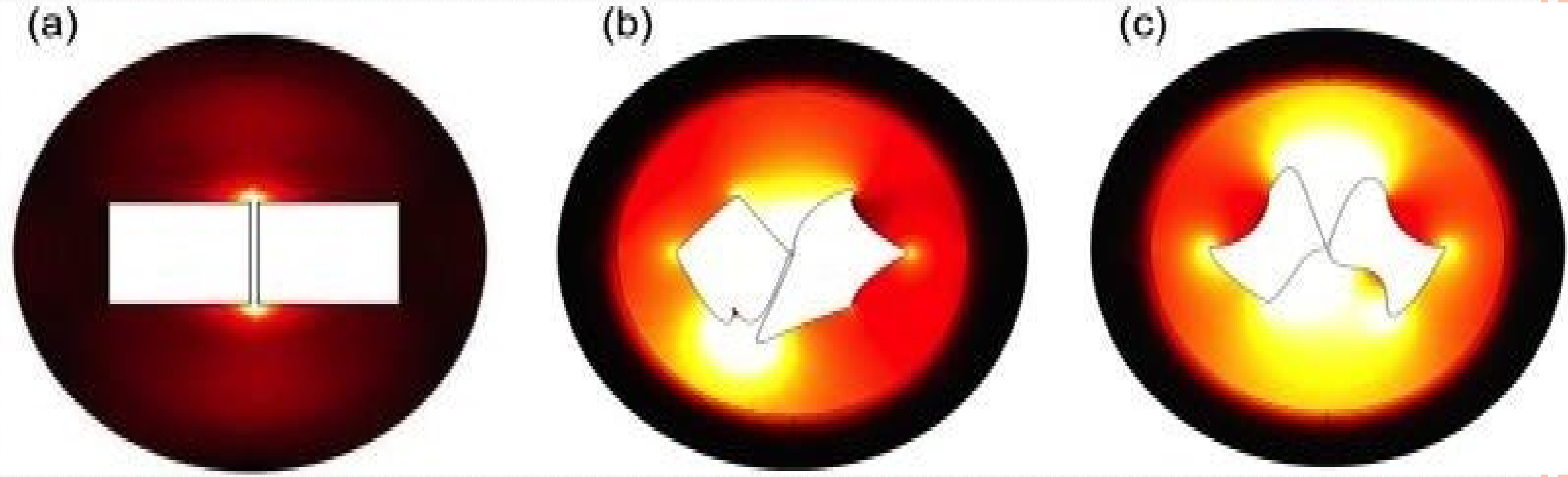


Results

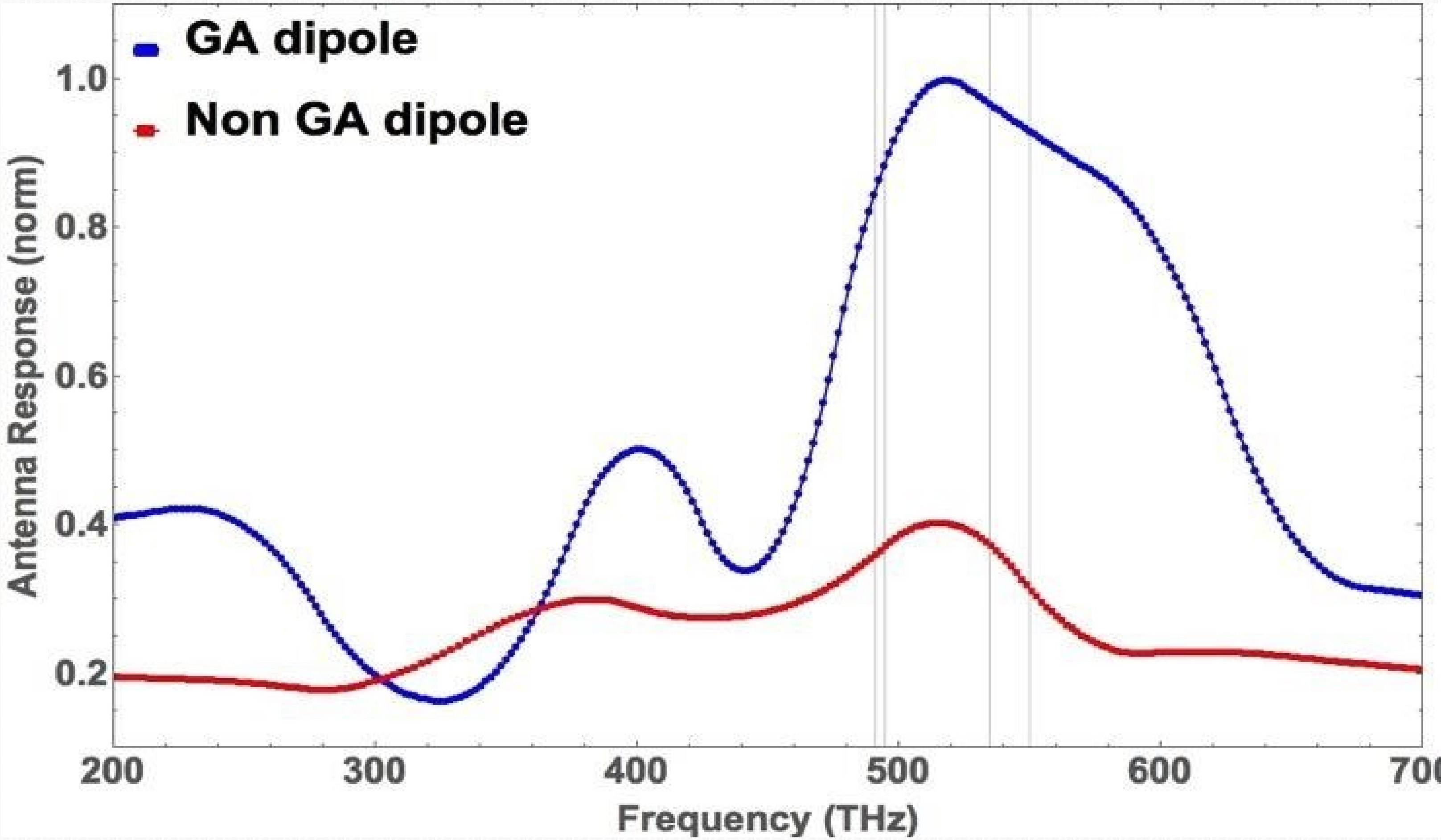




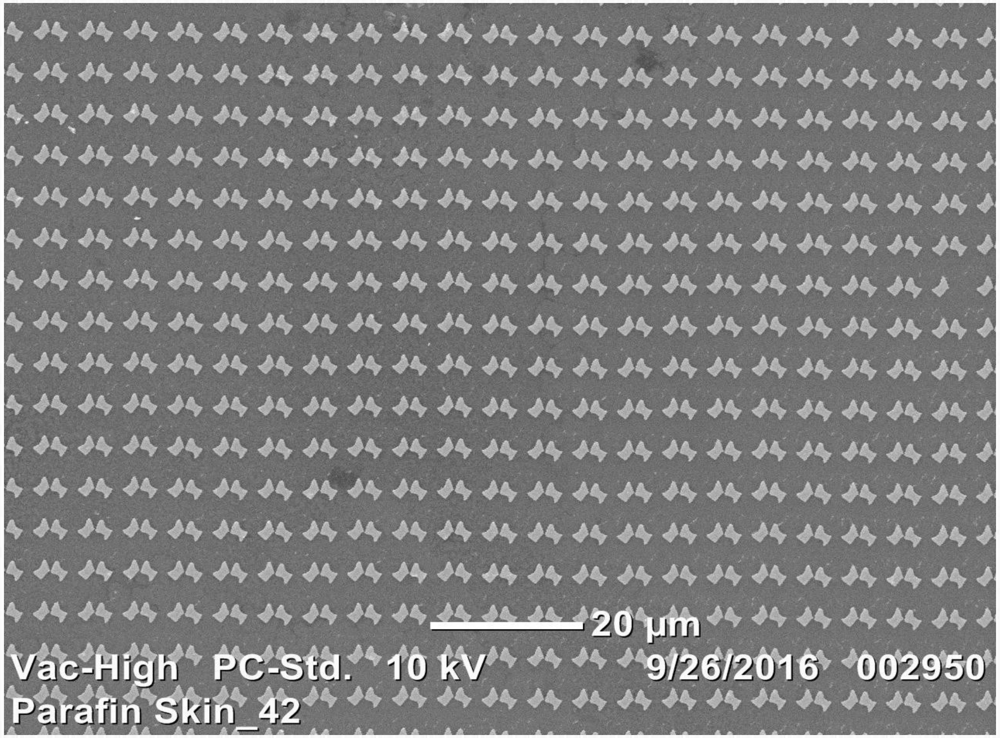
CONCLUSIONS

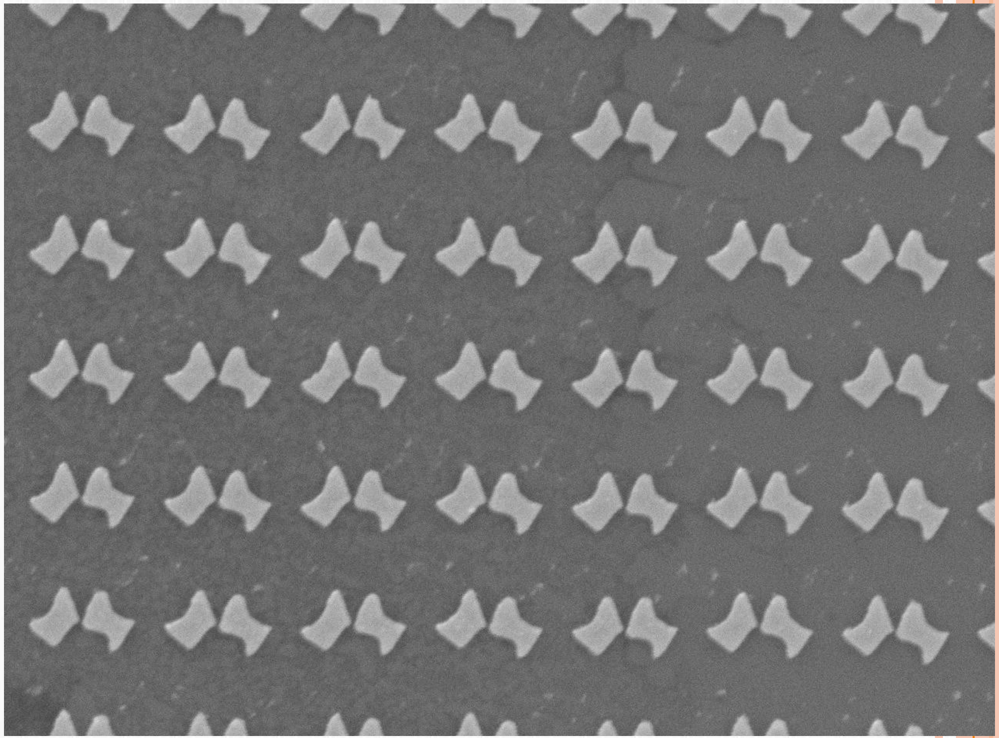


CONCLUSIONS



Work in progress





CONCLUSION AND FUTURE WORK

- Investigated antennas in the optical spectral regimes and compared with the classical RF antenna theory. The POA optical antennas can still be described using the classical RF antenna theory.
- Investigated various POA structures and develop efficient light collection and polarization and receiving pattern control.
- Developped optical confinement POAs in subwavelength region for strong plasmonic enhancement and high QE MWIR/LWIR sensing and imaging.
- Plan to integrate POA with the perfect absorber cavity for further understanding of plasmonic cavity and material interaction.
- Plan to integrate plasmonic enhanced nonlinear EO effect in a strongly confined subwavelength region with low dimensional materials (QD, coupled QW, etc.)


Thank You For Your Attention

Any Question/ Query?

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