The Abdus Salam
International Centre for Theoretical Physics

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2328-18

Preparatory School to the Winter College on Optics and the Winter College on Optics: Advances in Nano-Optics and Plasmonics

30 January - 17 February, 2012

Plasmonic nanorod metamaterials

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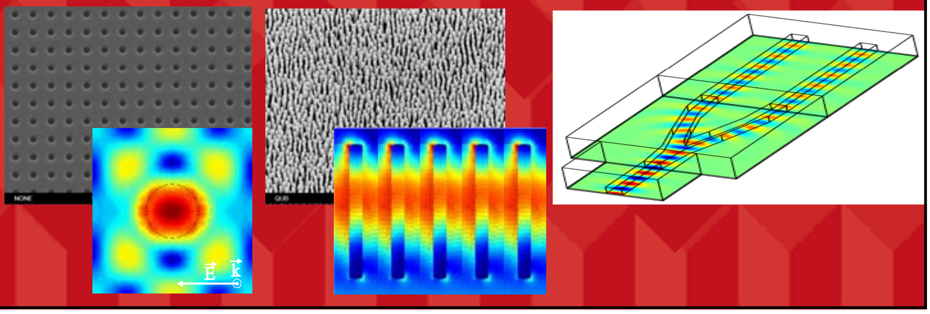
The Queen's University of Belfast
U.K.

Plasmonic nanorod metamaterials

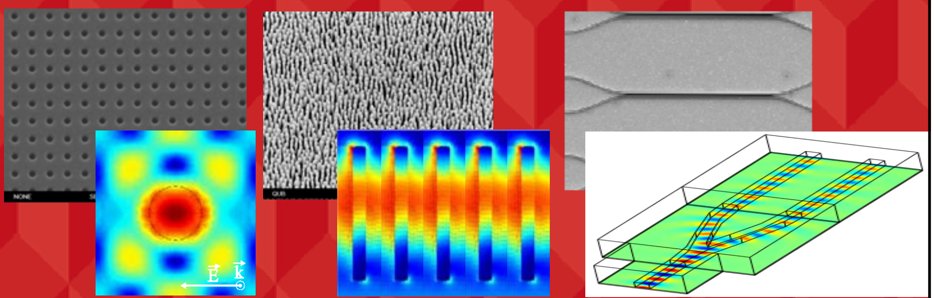
Anatoly V Zayats

Nano-optics and Near-field Spectroscopy Group

www.nano-optics.org.uk

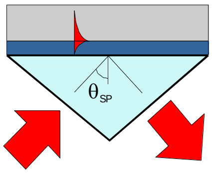


Plasmonic platforms

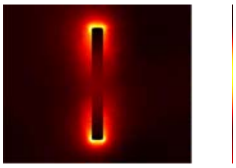


- field enhancement
- dispersion engineering
- sensitivity to surroundings=active functions

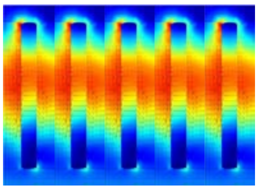
Plasmonic resonances



$$k_{SPP} = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$$



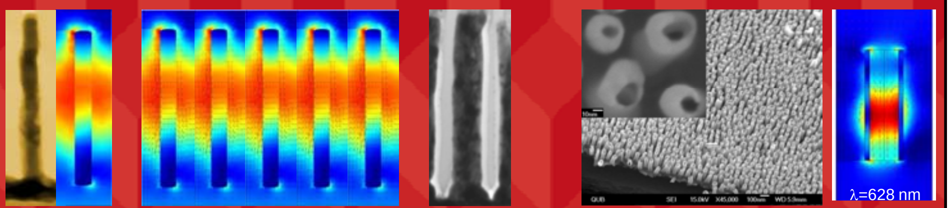
$$\omega_{LSP} = f(a, \varepsilon_m, \varepsilon_d)$$



$$\omega_{meta} = f(a, d, \varepsilon_m, \varepsilon_d)$$

Plasmonic nanorod metamaterials

- Plasmonic nanorod arrays
- Plasmonic nanorod arrays for nanophotonics



Plasmonic nanorod metamaterials

- Engineering spectral response and spatial field distribution
- Super- and hyperlenses, cloaking, ENZ metamaterials, bio- and chemo-sensing
- Metamaterials with (all-optically) tuneable photonics properties, modulation/switching applications

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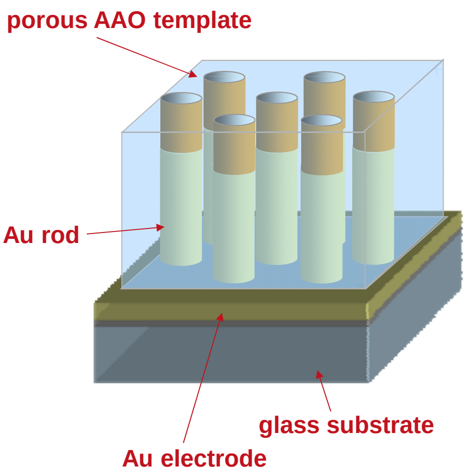
Plasmonic nanorod arrays



free standing nanorods
diameter 20—50 nm
length 20—500 nm
separation 20—50 nm
periodicity: almost
area up to N cm^2

APL 89, 231117 (2006).

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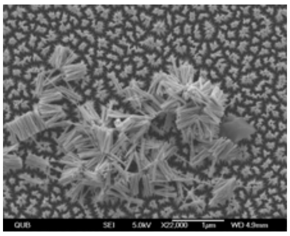
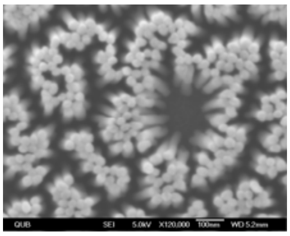
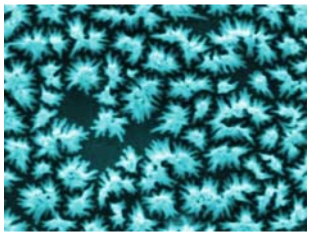
Plasmonic nanorod arrays

If something goes wrong ….

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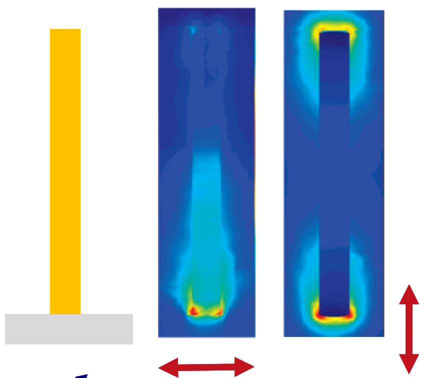
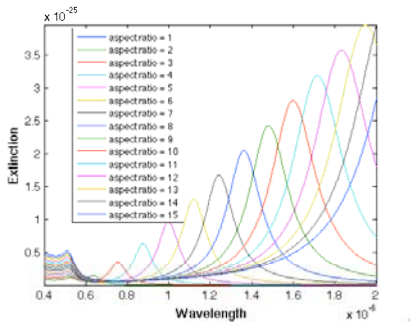
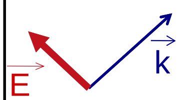
Plasmonic nanorod







~ 520 nm ~ 1.6 μm
aspect ratio 10

$$\alpha = 4\pi\varepsilon_0 a_1 a_2 a_3 \frac{\varepsilon_1(\omega)-\varepsilon_2}{3\varepsilon_2 + 3L_i(\varepsilon_1(\omega)-\varepsilon_2)}$$

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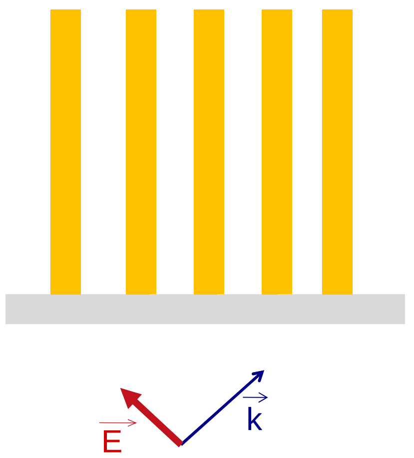
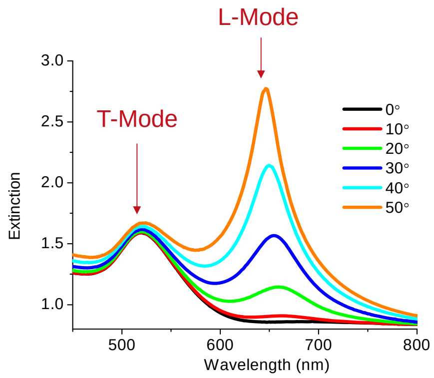
Optical properties





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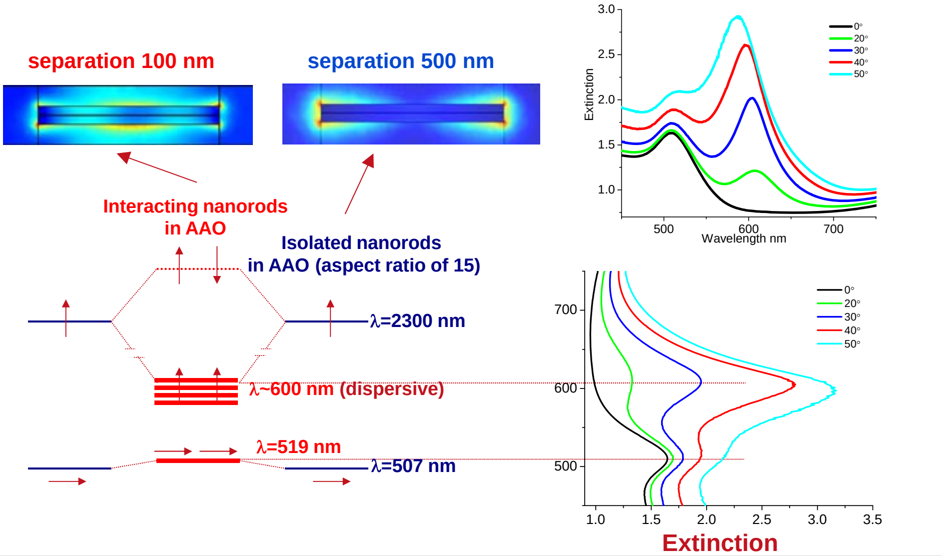
Plasmonic nanorod arrays



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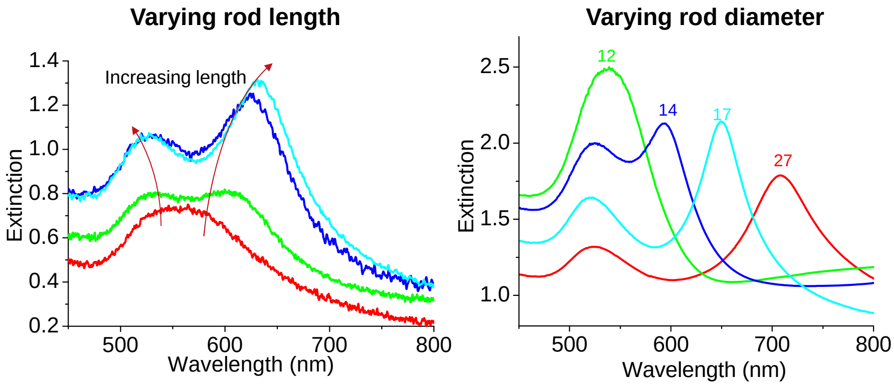
Optical properties



PRB 76, 115411 (2007).

Effective medium description and nonlocalities

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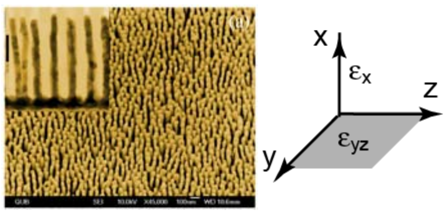
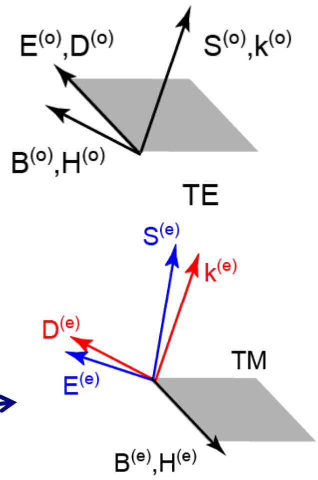
Effective medium approximation





TE waves $\frac{k_x^2 + k_y^2 + k_z^2}{\varepsilon_{yz}} = \frac{\omega^2}{c^2}$

TM waves $\frac{k_x^2}{\varepsilon_{yz}} + \frac{k_y^2 + k_z^2}{\varepsilon_x} = \frac{\omega^2}{c^2}$

Uniaxial anisotropic metamaterial

PRB 73, 235402 (2006); APL 89, 261102 (2006)

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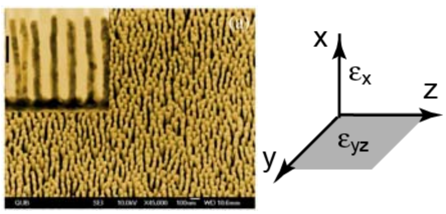
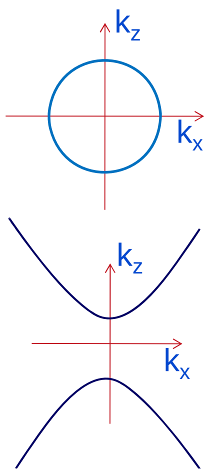
Effective medium approximation





TE waves $\frac{k_x^2 + k_y^2 + k_z^2}{\varepsilon_{yz}} = \frac{\omega^2}{c^2}$

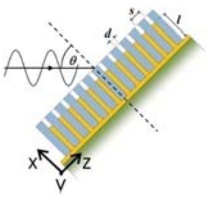
TM waves $\frac{k_x^2}{\varepsilon_{yz}} + \frac{k_y^2 + k_z^2}{\varepsilon_x} = \frac{\omega^2}{c^2}$

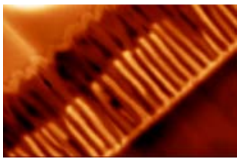
$\varepsilon_{yz} > 0$; $\varepsilon_x < 0$

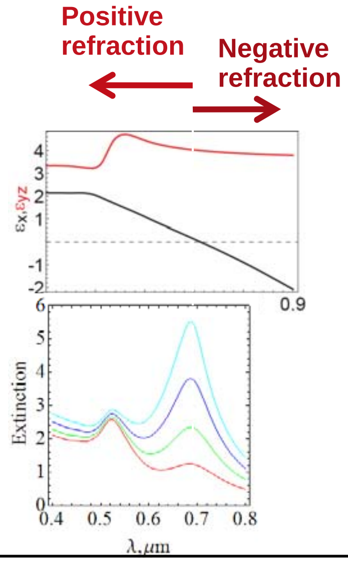
PRB 73, 235402 (2006); APL 89, 261102 (2006).

Hyperbolic dispersion

Effective medium approximation

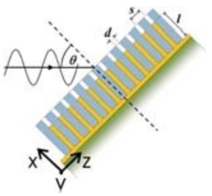


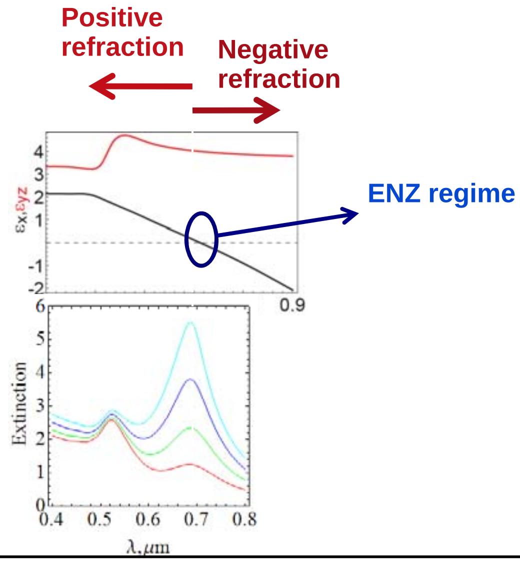




PRL 102, 127405 (2009);
Opt. Exp. 16, 7460 (2008).

Effective medium approximation





PRL 102, 127405 (2009);
Opt. Exp. 16, 7460 (2008).

Spatial dispersion effects

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Spatial dispersion

Spatial dispersion:

$$\varepsilon = \varepsilon(\omega,k) \approx \cancel{\varepsilon(\omega_0)} + i\varepsilon''(\omega_0) - \delta_x \frac{k_x^2 c^2}{\omega^2}$$

ENZ regime:

$$\varepsilon = i\varepsilon''(\omega_0) - \delta_x \frac{k_x^2 c^2}{\omega^2}$$

$\varepsilon'' >> \gamma$ (strong loss) → Limited performance

$\delta_x << 1$

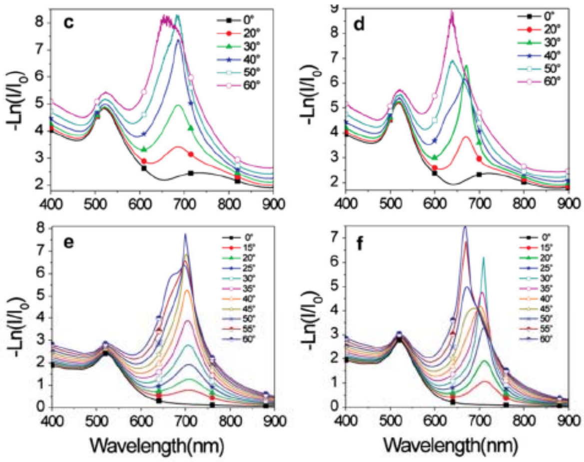
$\varepsilon'' << \gamma$ (low loss) ↓

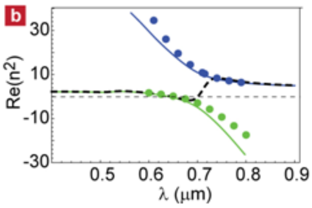
"New" physics

- *k*-dependent corrections to dispersion
- new (additional) waves (seen in ultra-pure crystals at ultra-low temperatures)

Pekar (1058); Ginzburg (1958) Efros(2002) , Stockman (2004) , Belov (2004), Shvets (2004), Silverinha (2006)

Reducing loss

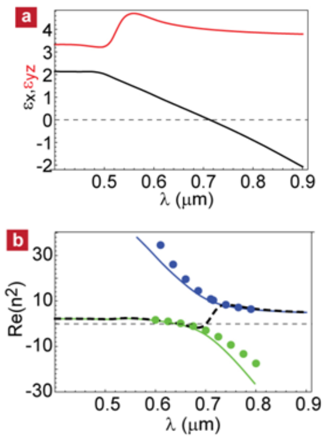


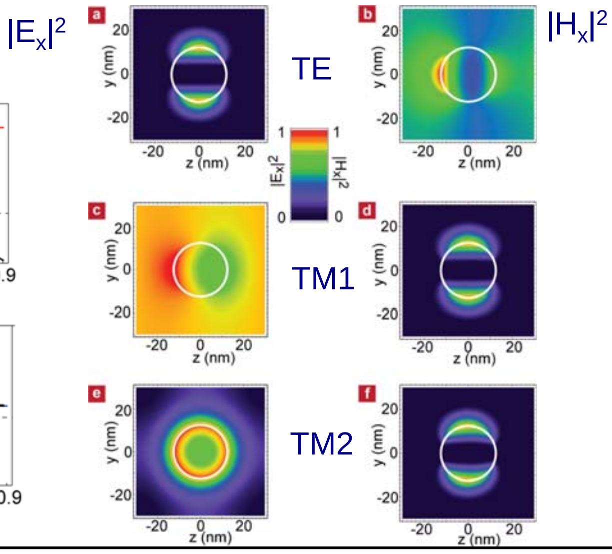


Improving quality of gold

PRL 102, 127405 (2009).

Additional waves in nanorod metamaterials



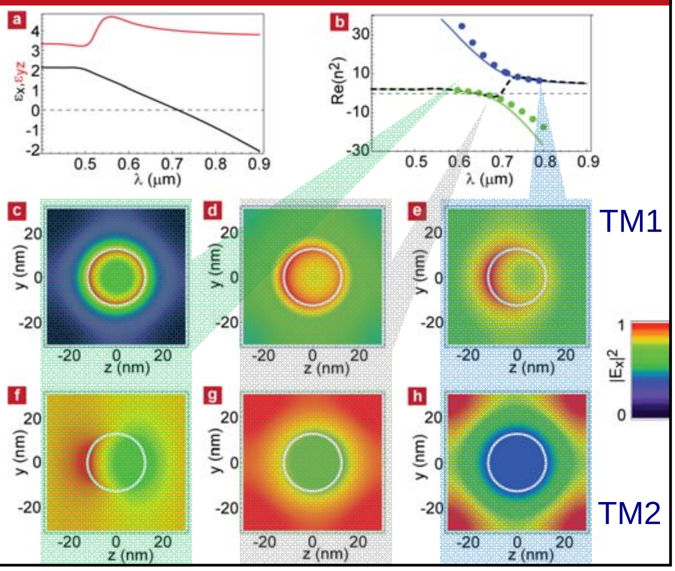


Additional waves in nanorod metamaterials

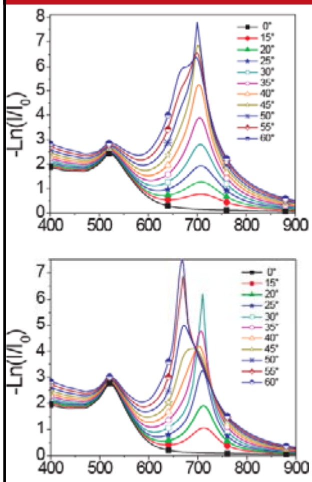
$$\varepsilon_x = \varepsilon_x^0(\omega) - \delta_x \frac{k_x^2 c^2}{\omega^2}$$

$$\delta_x << 1$$

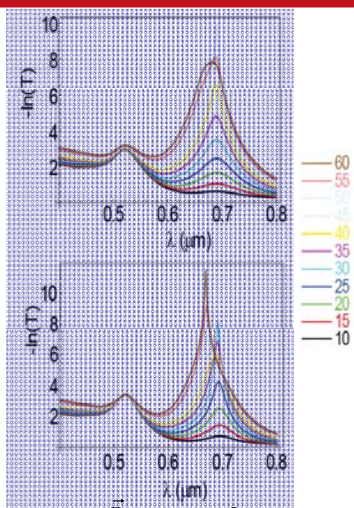
$$\varepsilon_{yz} = \varepsilon_{yz}^0(\omega)$$



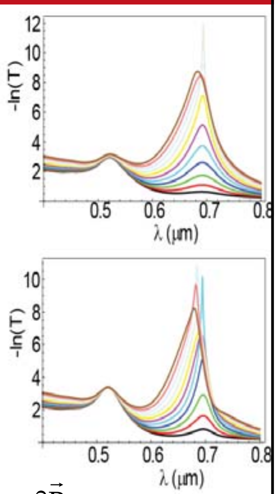
Additional boundary conditions



3D simulations



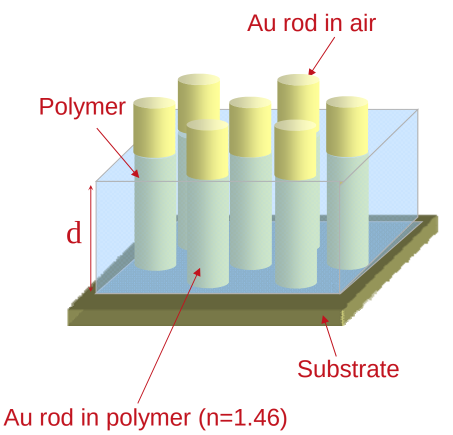
$$\vec{P}_{nonlocal} = 0$$

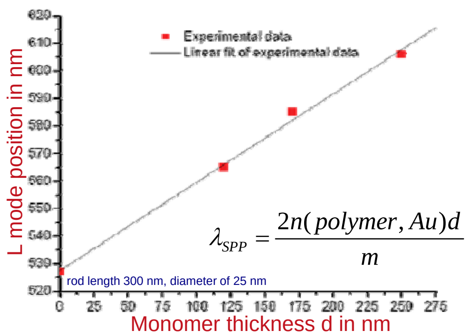


$$\frac{\partial \vec{P}_{nonlocal}}{\partial n} = 0$$

Controlling optical properties:
controlling interaction between nanorods

Plasmonic nanorod arrays





Spectral sensitivity:
~5 nm per 10 nm of dielectric within 600-800 nm range

PRB 76, 115411 (2007).

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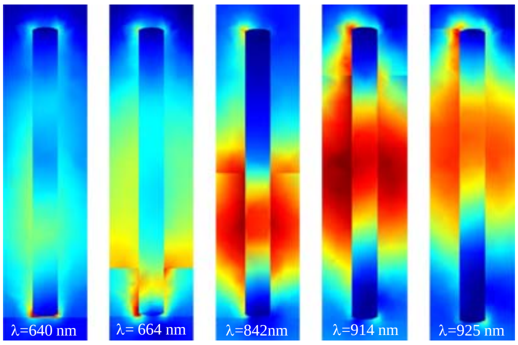
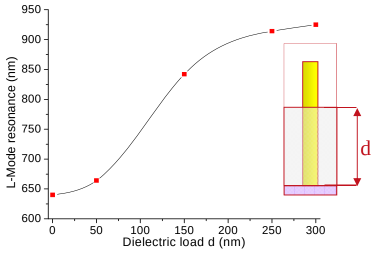
Plasmonic nanorod arrays





PRB 76, 115411 (2007).

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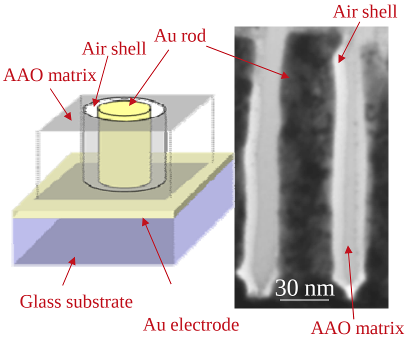
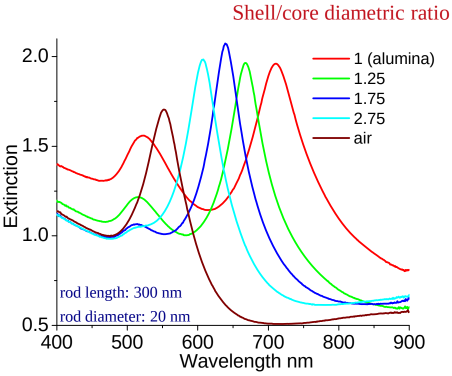
Plasmonic nanorod arrays





J Phys Chem C 111, 12522 (2007).

Nonlinear optical properties

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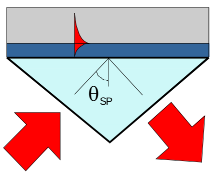
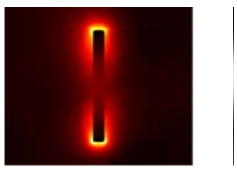
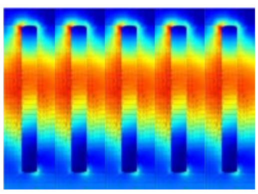
Plasmonic resonances



$$k_{SPP} = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$$



$\omega_{LSP} = f(a, \varepsilon_m, \varepsilon_d)$



$\omega_{meta} = f(a, d, \varepsilon_m, \varepsilon_d)$

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Nonlinearities in nanorod metamaterials

- nonlocality enhanced nonlinearity
- hybrid nonlinear metamaterials
- strong exciton-plasmon coupling

$$\omega_{meta} = f(a,d,\varepsilon_m,\varepsilon_d)$$

$$\varepsilon_m = \mathrm{Re}\varepsilon_m + \mathrm{Im}\varepsilon_m$$

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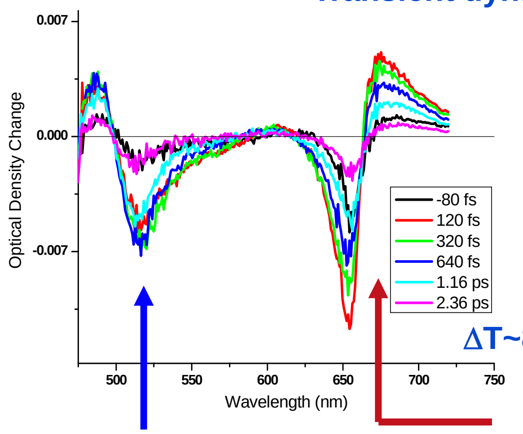
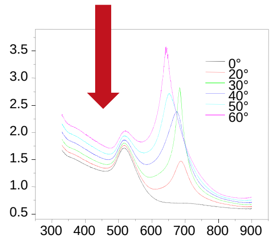
Nonlinear optical response

Transient dynamics: bare nanorods





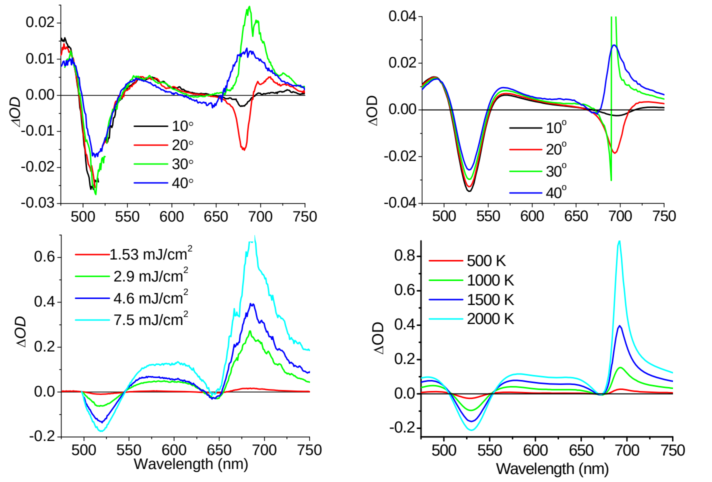
ΔT~80%, 10fj, 100x100 nm²

L-mode: dispersive, ~ 800 fs

T-mode: absorptive, ~ 1 ps

Nature Nanotech. 6, 107 (2011).

Nonlinear optical response



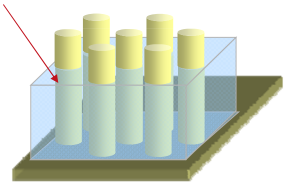
Experiment **Nonlocal modelling**

Nature Nanotech. 6, 107 (2011).

Nonlinearities in nanorod metamaterials

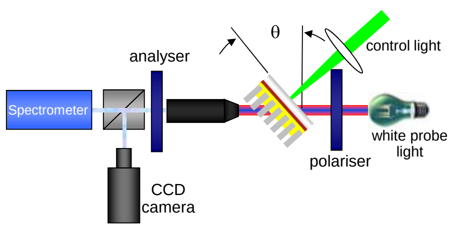
- nonlocality enhanced nonlinearity
- hybrid nonlinear metamaterials
- strong exciton-plasmon coupling

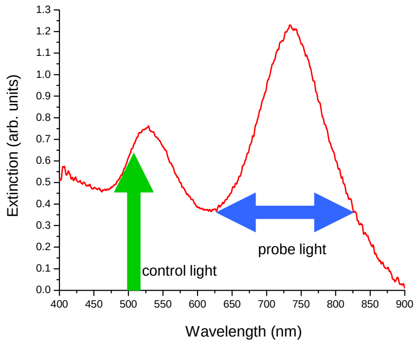
Plasmonic nanorod arrays



$$\varepsilon_d = \varepsilon_0 + 4\pi\chi^{(3)}|E_L|^2$$

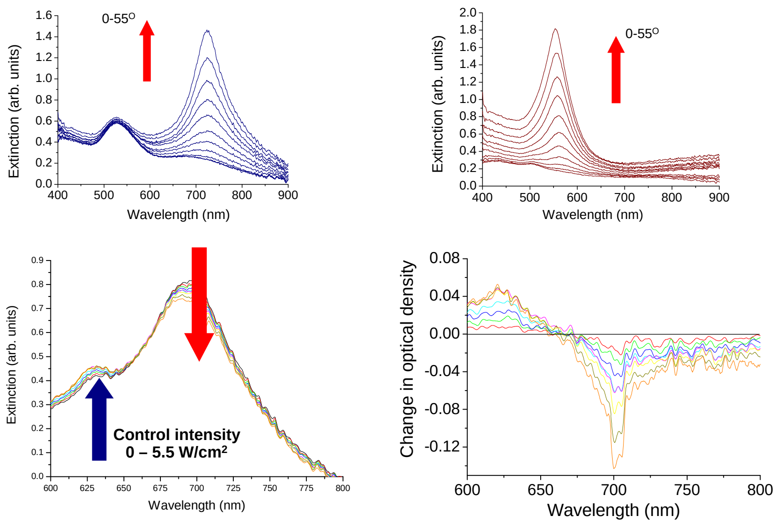
$$\omega_{meta} = f(a,d,\varepsilon_m,\varepsilon_d)$$





J Microscopy 229, 415 (2008).

Nonlinear nanorod arrays



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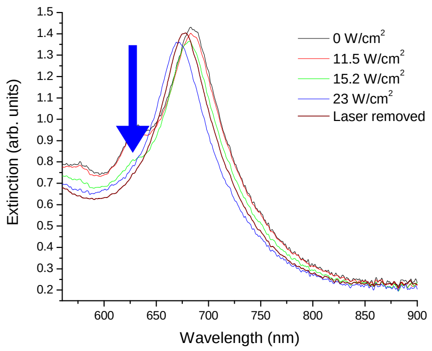
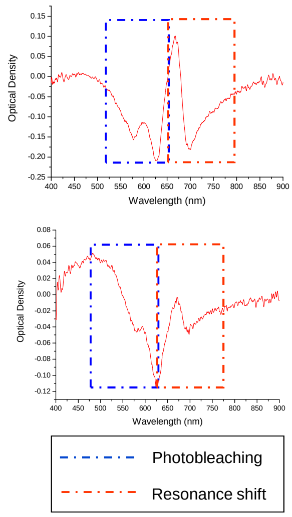
Plasmonic nanorod arrays





Optical control:
20 nm tuneability range
10 nm reversible range

PRB 76, 115411 (2007).

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Nonlinearities in nanorod metamaterials

- nonlocality enhanced nonlinearity
- hybrid nonlinear metamaterials
- strong exciton-plasmon coupling

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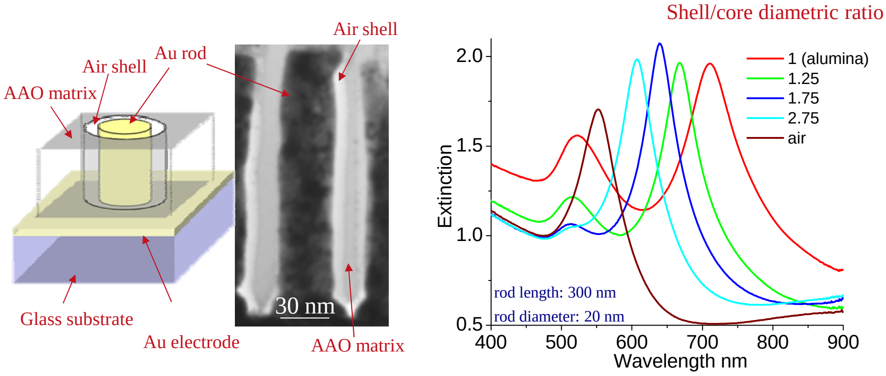
Plasmonic nanorod arrays



J Phys Chem C 111, 12522 (2007).

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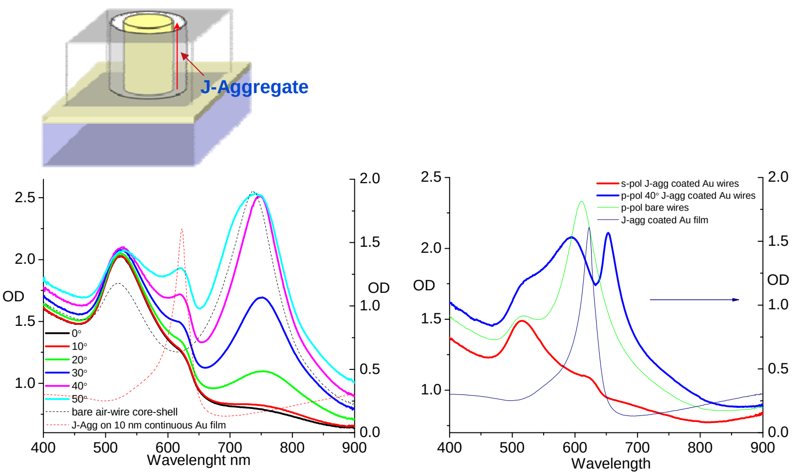
Molecular plasmonics



Tuning exciton-plasmon coupling strength

Nano Letters 7, 1297 (2007).

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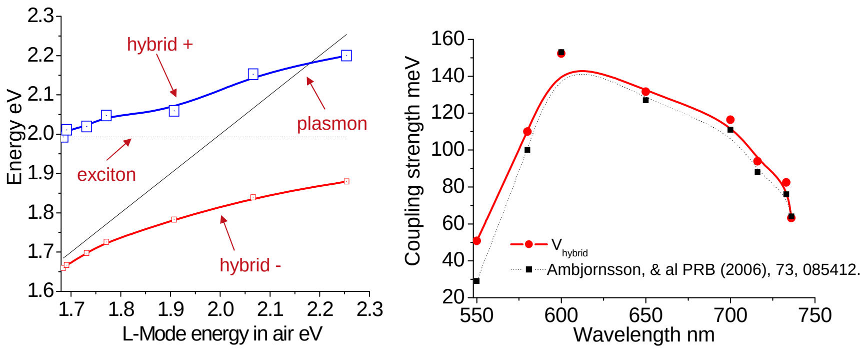
Molecular plasmonics



Tuning exciton-plasmon coupling strength: towards active plasmonic metamaterials

Nano Letters 7, 1297 (2007).

Electro-optical control ?

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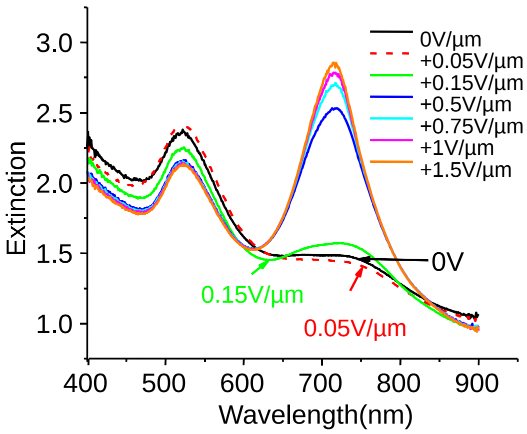
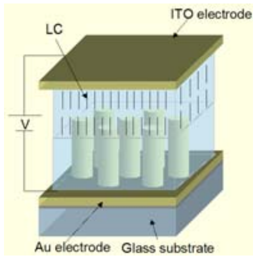
Electrically controlled extinction





Electrical switching but NO tuneability

APL 91, 043101 (2007).

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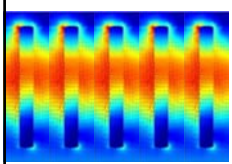
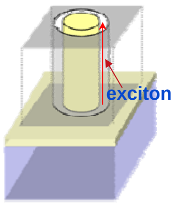
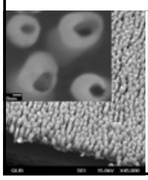
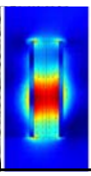
Plasmonic nanorod metamaterials

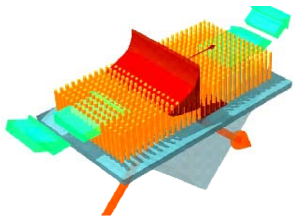




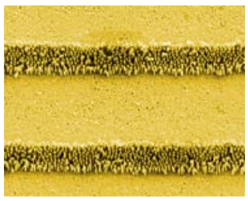
- tuneable resonances in visible: 510-900 nm
- hyberbolic dispersion @ negative refraction
- nonlocal (spatial dispersion) effects
- enhanced nonlinearity in sub-ps regime
- molecular plasmonics
- nanorod chain waveguides
- unprecedented biosensing capabilities







$\Delta\lambda$ = 30,000 nm/RIU
FOM = 300



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Conclusions

Take home messages (2):

- metamaterial with fully adjustable spectral properties
- metamaterial with hyberbolic dispersion
- ENZ response is strongly nonlocal (at room temperature)
- experimental demonstration of additional wave excitation
- nonlinearities with ultrafast temporal response
- ultrafast optical control of exciton-plasmon coupling
- nanofluidic tuneability
- practical (scaleable) route to plasmonic devices and active tuneable metamaterials