Controlling light with plasmonic nanostructures

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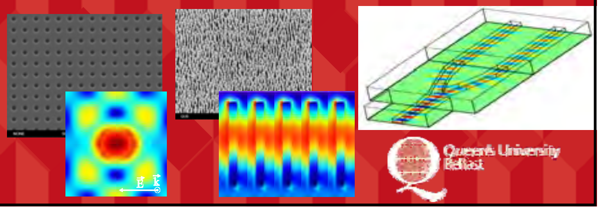
Controlling light with plasmonic nanostructures

- Controlling plasmonic resonances in nanostructures
- Surface plasmon polaritonic crystals
- Plasmonic nanorod arrays



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Controlling plasmonic resonances in metal-dielectric nanostructures

- structural parameters: size, shape, arrangement

- dynamic control via
  dielectric environment modification
  - all-optical using nonlinear dielectrics
  - electric-field
  - magnetic-field
  - mechanical

Manipulating electromagnetic fields on the nanoscale

Passive functionalities:
- guiding, sensing, enhancing

Active functionalities:
- tuneability, modulating/switching, (sp)lasing

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Optical signal processing

principles and optical devices to provide the same functionality as electronic devices:

Controlling light with light:
optical transistors, diodes, interconnects, to build optical chip and ultimately all-optical integrated circuit

Electronic-photonic convergence

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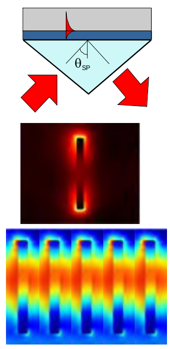
Plasmonic resonances



SPP and LSP resonances are extremely sensitive

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

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

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

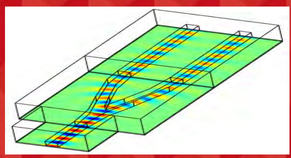
$\varepsilon_d = F(I_c)$ – optical control

$\varepsilon_d = F(E_{ext})$ – electric control

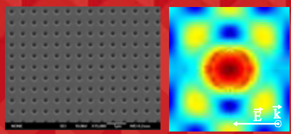
$\varepsilon_d = F(M_{ext})$ – magnetic control

$\varepsilon_d = F(f_{ext})$ – mechanical control

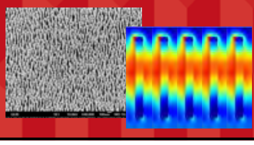
Waveguides



SPP crystals



Nanorod assemblies



Surface plasmon polaritonic crystals

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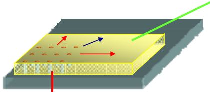
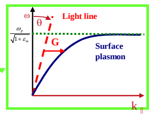
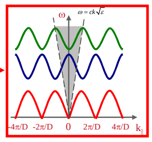
Surface polaritonic crystals

$$k_{SP} = \frac{\omega}{c}\vec{u}_{xy}\delta_p \sin\theta \pm p\frac{2\pi}{D}\vec{u}_x \pm q\frac{2\pi}{D}\vec{u}_y$$

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







Periodic structure: SPP excitation

(p,q)-parameters:
- **SPP spectrum**
- **SPP propagation direction**

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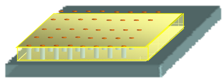
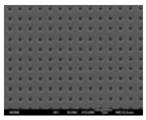
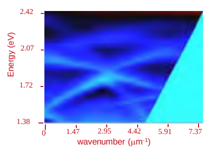
Surface polaritonic crystals



SPP Bloch mode engineering





Flat SPP bands:
- **field enhancement**
- **strong sensitivity to the refractive index changes**

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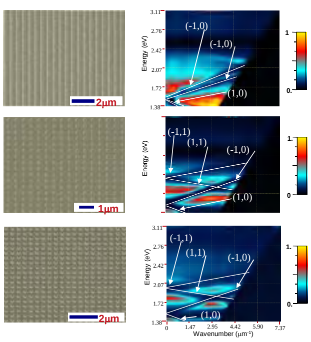
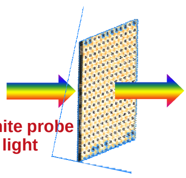
Surface polaritonic crystals





white probe light

Enhanced transmission near the band edges

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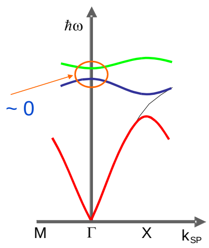
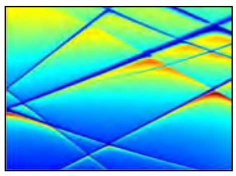
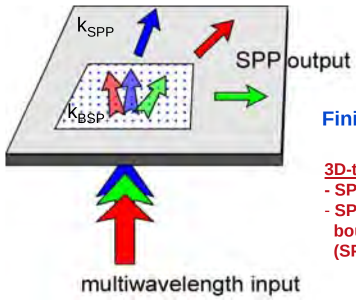
Spectral dispersion of SPP crystal

$d\omega/dk_{SP} \sim 0$





Spectral dispersion of SPP crystal



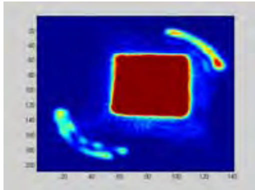
Finite-size SPP crystal

3D-to-2D diffraction
- **SPP Bloch mode excitation**
- **SPP modes crossing the boundary of SPP crystal (SPP refraction)**

PRL 99, 083901 (2007).

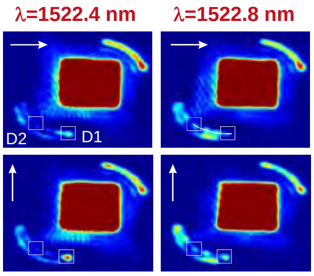
Spectral dispersion of SPP crystal

λ =1522.0 nm



Start movie

Spectral dispersion of SPP crystal

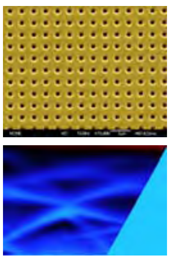


Angular spectral dispersion:
~ 20—30 deg/nm

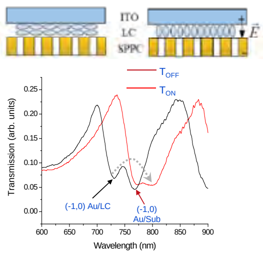
PRL 99, 083901 (2007).

Electronically controlled SPPC

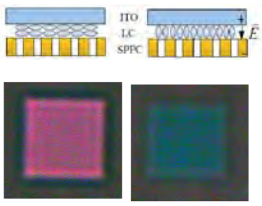
Electrically tuneable SPP crystals

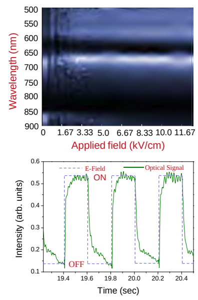


Periodically structured surfaces:
SPP Bloch mode engineering



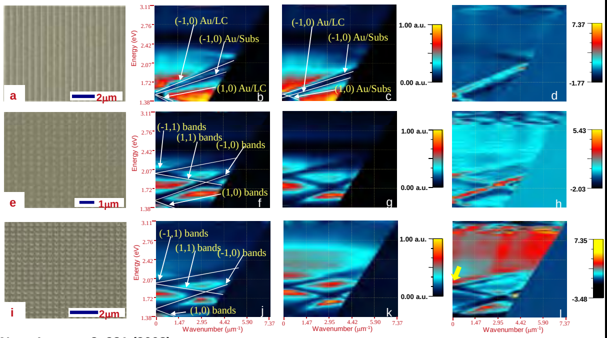
Electrically tuneable SPP crystals





Nano Letters 8, 281 (2008).

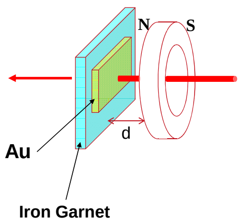
Electrically tuneable SPP crystals

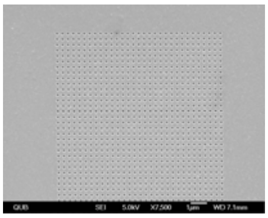


Nano Letters 8, 281 (2008).

Magnetic-field controlled SPPC

Magneto-plasmonic crystals

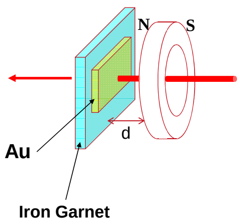




Magneto-plasmonic crystal

New J. Phys. 10, 105012 (2008).

Magneto-plasmonic crystals



$$\varepsilon = \begin{pmatrix} \varepsilon_0 & i\varepsilon_p & i\varepsilon_t \\ -i\varepsilon_p & \varepsilon_0 & i\varepsilon_l \\ -i\varepsilon_t & -i\varepsilon_l & \varepsilon_0 \end{pmatrix}$$

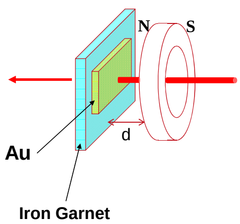
SPP field (E_x;E_z)

ε_i = f(M) - ?

Magneto-plasmonic crystal

New J. Phys. 10, 105012 (2008).

Magneto-plasmonic crystals



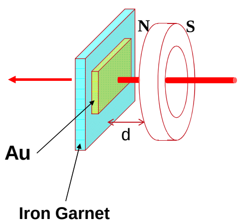
$$\varepsilon = \begin{pmatrix} \varepsilon_0 & i\varepsilon_p & i\varepsilon_t \\ -i\varepsilon_p & \varepsilon_0 & i\varepsilon_l \\ -i\varepsilon_t & -i\varepsilon_l & \varepsilon_0 \end{pmatrix}$$

No external magnetic field (in-plane magnetisation)

Magneto-plasmonic crystal

New J. Phys. 10, 105012 (2008).

Magneto-plasmonic crystals



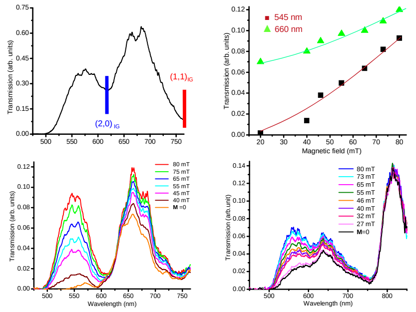
$$\varepsilon = \begin{pmatrix} \varepsilon_0 & i\varepsilon_p & i\varepsilon_t \\ -i\varepsilon_p & \varepsilon_0 & i\varepsilon_l \\ -i\varepsilon_t & -i\varepsilon_l & \varepsilon_0 \end{pmatrix}$$

External magnetic field normal to the film (out-of-plane magnetisation)

Magneto-plasmonic crystal

New J. Phys. 10, 105012 (2008).

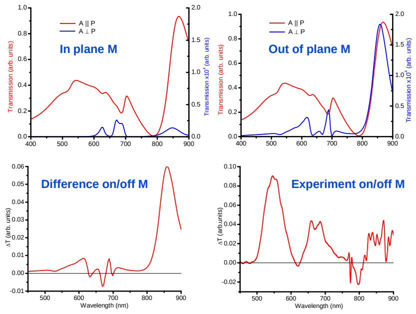
Magneto-plasmonic crystals



Cross-polarised transmission

New J. Phys. 10, 105012 (2008).

Magneto-plasmonic crystals

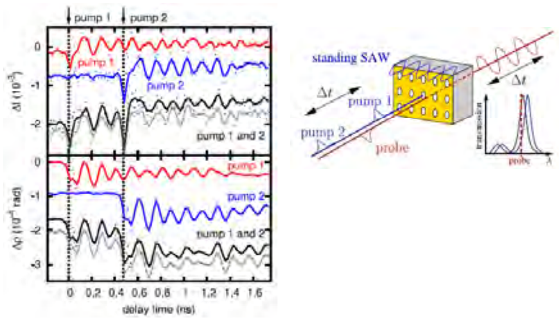


Dispersion of ε_{garnet} is not taken into account

New J. Phys. 10, 105012 (2008).

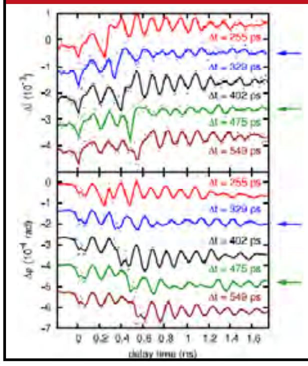
Acoustically tuneable SPP crystals

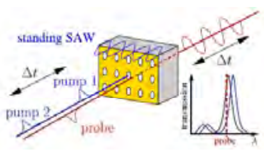
Coherent control of SPPs



J Phys D 41, 195102 (2008).

Coherent control of SPPs





J Phys D 41, 195102 (2008).

Nonlinear SPPC (all-optical efefcts)

Nonlinear optical effects at metal surfaces, films and metallic particles:

- **intrinsic:** second- and higher order optical nonlinear effects related to the nonlinear response of electron plasma
- **extrinsic:** enhancement of second- and third-order nonlinearities, Raman scattering *etc* in adjacent dielectric due to the field enhancement associated with plasmonic excitations

How to design nonlinear plasmonic metamaterials using the enhanced effective nonlinear susceptibility provided by surface plasmons

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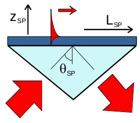
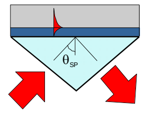
Surface plasmon polaritons



Electromagnetic field enhancement:

$$T = \left|\frac{E_{SP}(0^+)}{E_0}\right| >> 1$$



SPP resonance is sensitive to the dielectric constant of surroundings:

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

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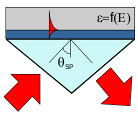
Nonlinearity and SPPs



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

$$k_{SP}(E_L) = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_i(E_L)}{\varepsilon_m + \varepsilon_i(E_L)}\right)^{1/2}$$

Kerr-nonlinearity and controlling light with light

Laser & Photon. Rev. 2, 125 (2008).

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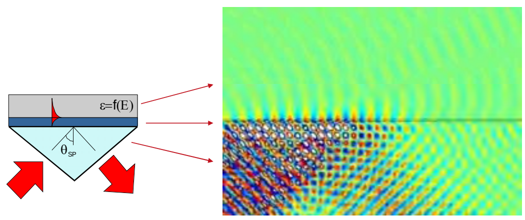
Nonlinearity and SPPs



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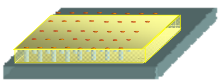
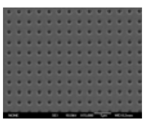
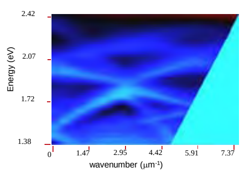
Surface polaritonic crystals







Flat SPP bands:

- **field enhancement**
- **strong sensitivity to the refractive index changes**

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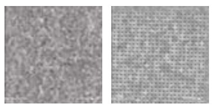
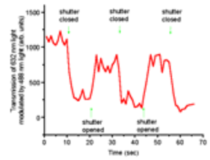
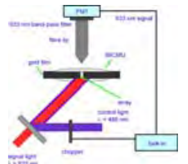
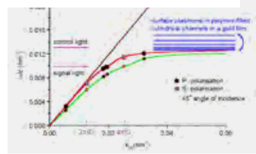
Controlling SPP with external light: cylindrical surface plasmon effects



Arrays of the 20 nm cylindrical channels in 400 nm Au film.

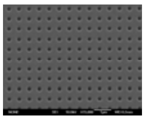




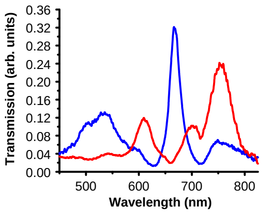


PRB 66, 205414 (2002).

Hybridised surface polaritonic crystals



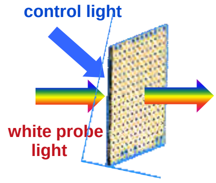
D = 600 nm
d = 200 nm
h = 220 nm

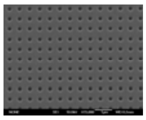


bare SPP crystal
coated with 3BCMU polymer: 100 nm

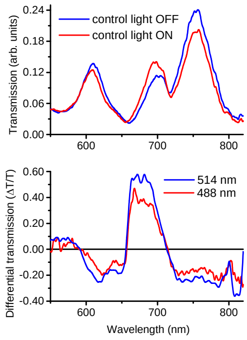
PRL 97, 057402 (2006).

Nonlinear transmission measurements



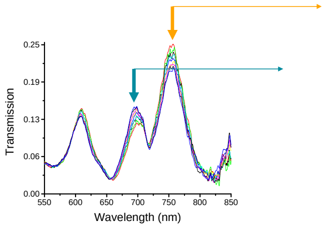


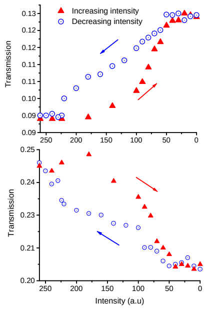
D = 600 nm
d = 200 nm
h = 220 nm
200 nm 3BCMU



Transmission bistability

Different signal light wavelengths:
different origin of the resonances

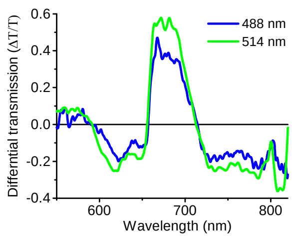


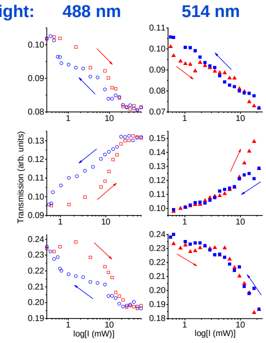


Control light: 488 nm

Transmission bistability

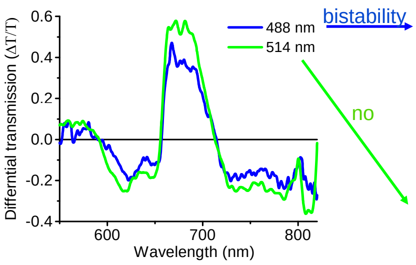
Control light: 488 nm 514 nm

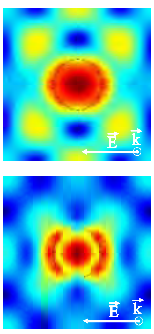




Different control light wavelengths:
different spatial variations of $\Delta\varepsilon$

All-optical switching in nonlinear SPPC



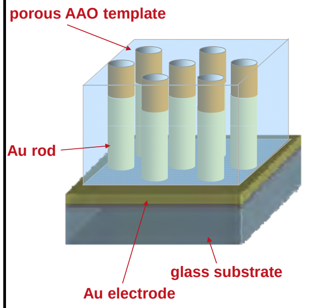


$$\varepsilon(\vec{r}) = \varepsilon^{(0)} + 4\pi\chi^{(3)}\left|\vec{E}\left(\varepsilon(\vec{r}),\omega_{pump},\vec{r}\right)\right|^2$$

PRL 97, 057402 (2006).

Plasmonic nanorod arrays

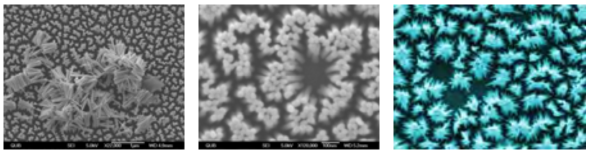
Plasmonic nanorod arrays



free standing nanorods
diameter 20—50 nm
length 20—500 nm
separation 20—50 nm
periodicity: almost
area up to 1 cm²

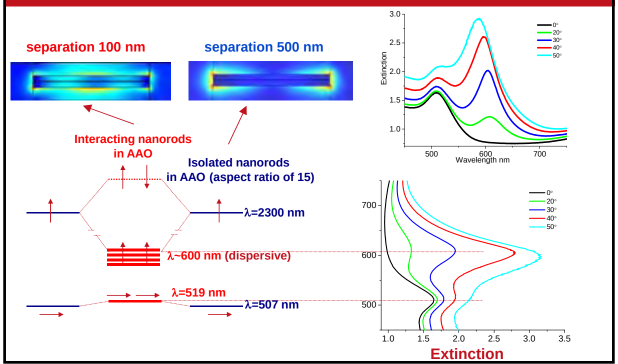
APL 89, 231117 (2006).

Plasmonic nanorod arrays

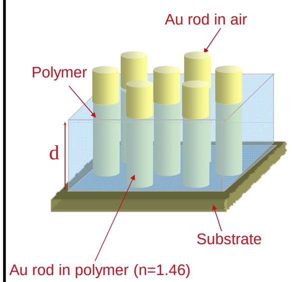


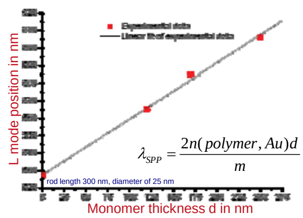
If something goes wrong ….

Plasmonic nanorod arrays



Plasmonic nanorod arrays



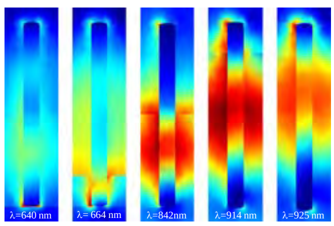


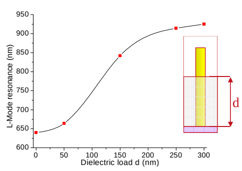
$$\lambda_{SPP} = \frac{2n(polymer, Au)d}{m}$$

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

PRB 76, 115411 (2007).

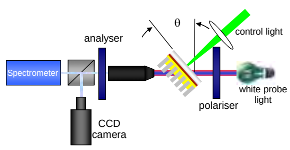
Plasmonic nanorod arrays

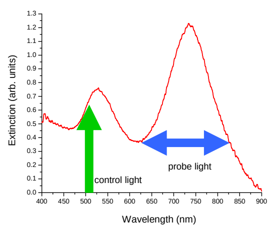




PRB 76, 115411 (2007).

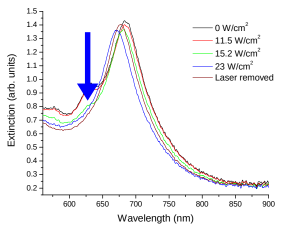
Plasmonic nanorod arrays

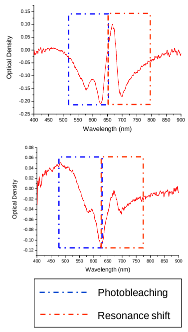




J Microscopy 229, 415 (2008).

Plasmonic nanorod arrays

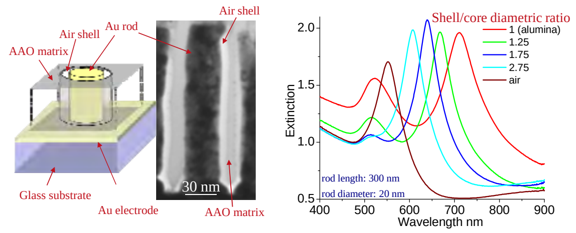




Optical control:
20 nm tuneability range
10 nm reversible range

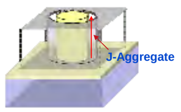
PRB 76, 115411 (2007).

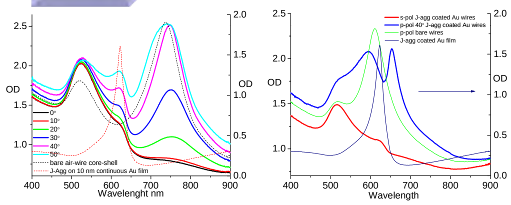
Plasmonic nanorod arrays



J Phys Chem C 111, 12522 (2007).

Molecular plasmonics

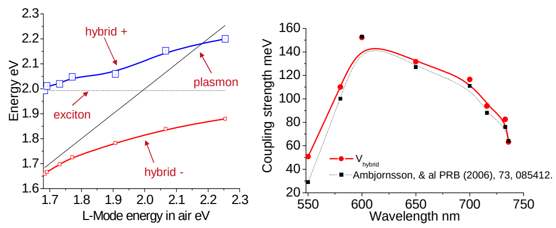




Tuning exciton-plasmon coupling strength

Nano Letters 7, 1297 (2007).

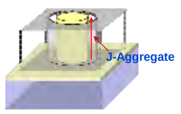
Molecular plasmonics



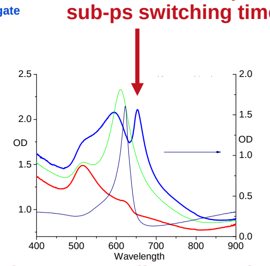
Tuning exciton-plasmon coupling strength:
towards active plasmonic metamaterials

Nano Letters 7, 1297 (2007).

Molecular plasmonics



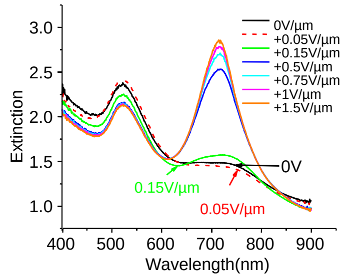
ΔT/T ~ 30% at 10 pJ/cm²
sub-ps switching time

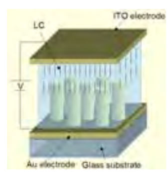


Modulating exciton-plasmon coupling strength

Wurtz et al, in preparation

Electrically controlled extinction





Electrical switching but NO tuneability

APL 91, 043101 (2007).

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Conclusions

Take home messages (1):

- Functional plasmonics with nanostructured metal films
- Surface-plasmon polaritonic crystals:
  optical properties are determined by SPP Bloch modes
  SPPC+functional dielectric = optical metamaterial with
  controlled optical properties
  optical control of SPP modes
  electric control of SPP modes
  acoustic (coherent) control of SPP modes
  magnetic control of SPP modes

Queen's University Belfast

Conclusions

Take home messages (2):

- Plasmonic nanorod arrays (interacting localised plasmons):
  - optical metamaterial with fully adjustable spectral properties
  - nanofluidic tuneability
  - control of exciton-plasmon coupling
  - practical (scaleable) route to plasmonic metamaterials