The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2328-17

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

Plasmonics basic, waveguides & crystals

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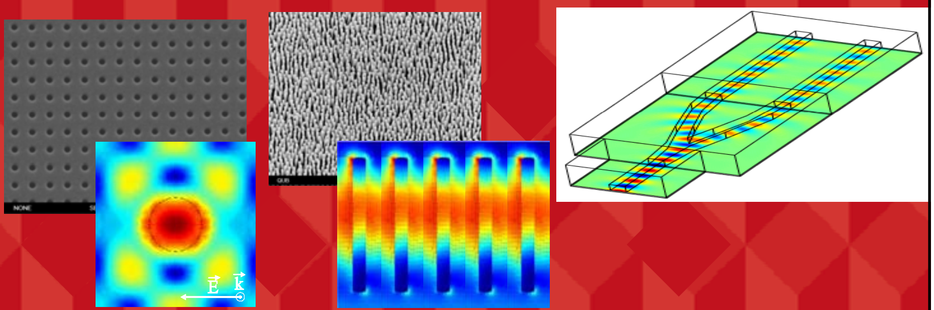
Plasmonics, plasmonic waveguides plasmonics crystals

Anatoly V Zayats

Nano-optics and Near-field Spectroscopy Group

www.nano-optics.org.uk



Nanophotonics:

generating, guiding, manipulating and detecting light on subwavelength scales

- information processing
- opto-electronics
- healthcare
- energy

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OUTLINE:

- Surface plasmon polaritons
- SPP waveguides and circuits
- Surface polaritonic crystals:
  - principles
  - dispersion engineering
- Controlling light using plasmonic crystals:
  - all-optical control
  - electric field control
  - magnetic field control
  - mechanical control

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Surface plasmons

- **Plasmons:**
  collective excitation of electrons (in metal)

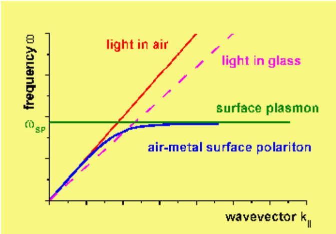
$$\omega_p^2 = \frac{4\pi N e^2}{m} \qquad \mathrm{Re}\,\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2} < 0 \quad \text{for } \omega<\omega_p$$

- **Surface plasmons:**
  collective excitation of electrons close to a surface

$$\omega_{SP} = \omega_p / \sqrt{2}$$

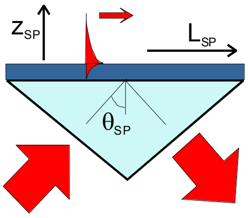
- **Surface plasmon polaritons:**
  propagating surface wave (surface plasmon + photon)

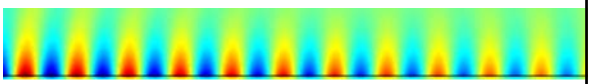
Surface plasmon polaritons



SPP dispersion:

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

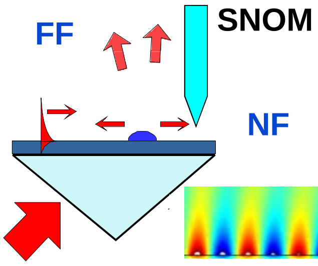


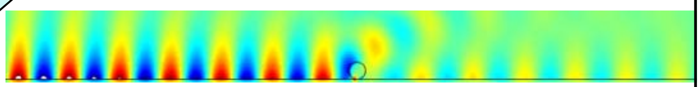


SPP excitation:

$$k_{\|} = \frac{\omega}{c} n_{prism} \sin\theta_{SP}$$

Surface polariton optics



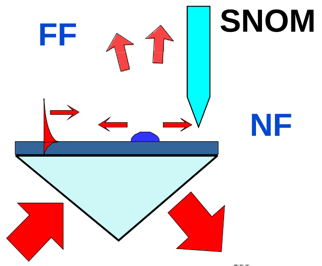


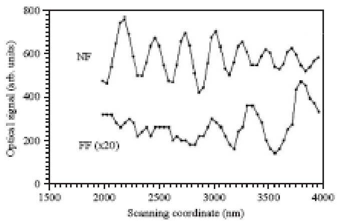
- Defect size
- Defect shape
- Defect dielectric constant

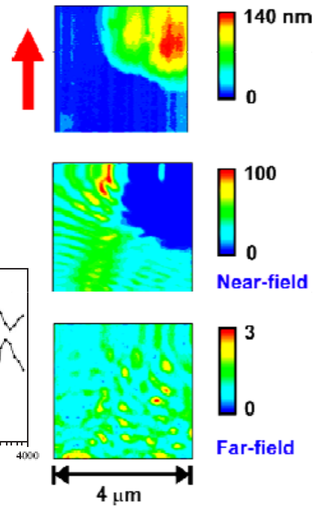
2D optics of surface polaritons

- SPP mirrors
- SPP lenses
- SPP resonators
- SPP crystals

Surface polariton optics







- SPP mirrors
- SPP lenses
- SPP resonators
- SPP crystals

Plasmonic waveguides

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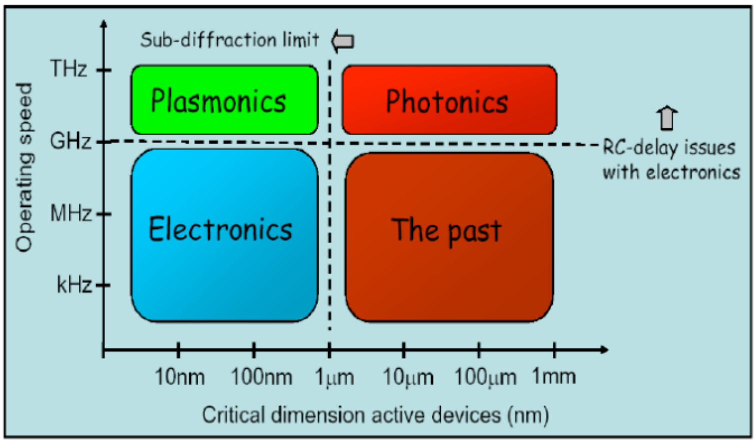
Why plasmonics ?



- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

M Bongersma, Stanford

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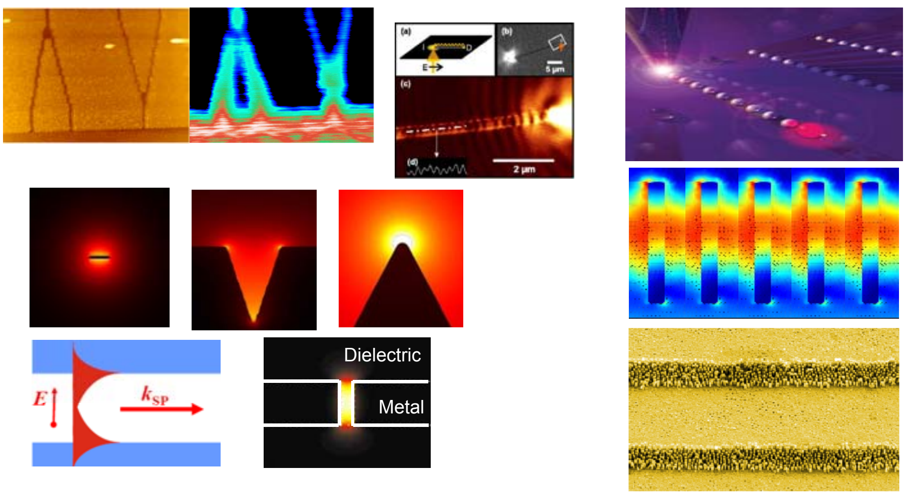
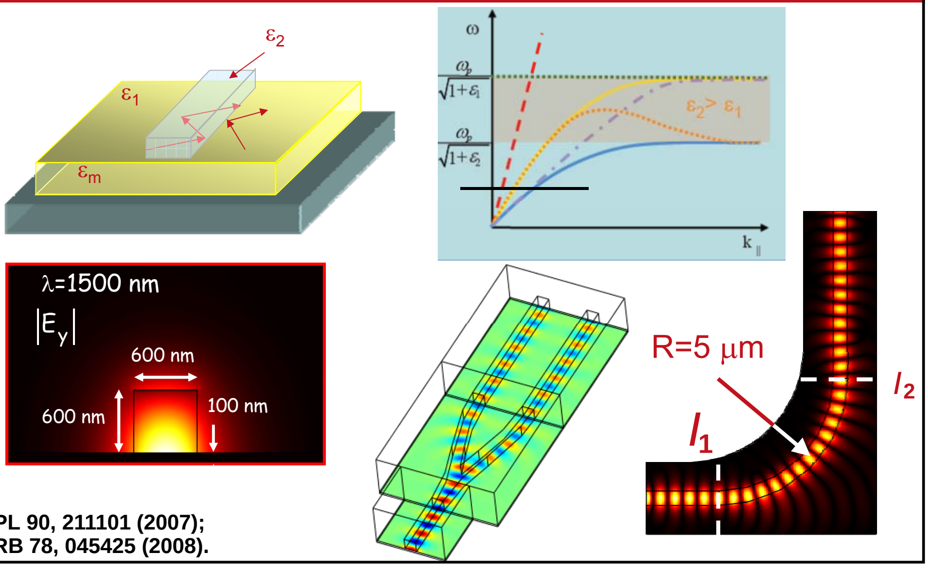
Plasmonic waveguides



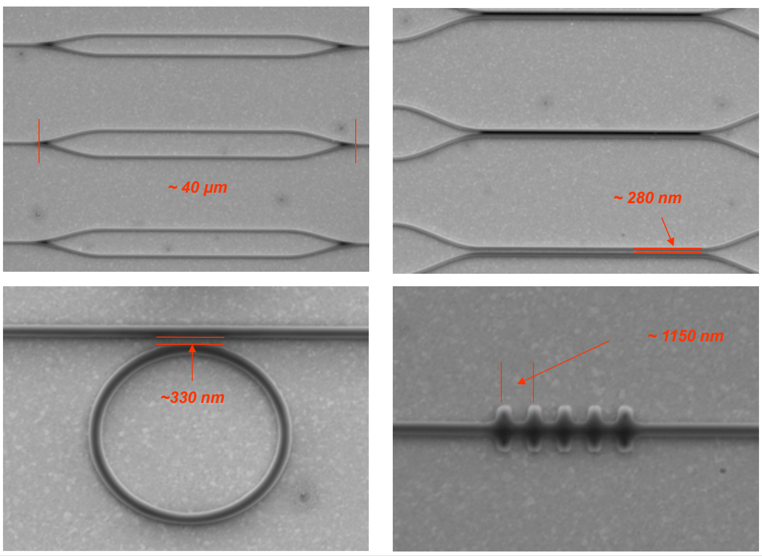
Bozhevolnyi, Krenn, Dereux, Ebbesen, Brongersma, Berini, Atwater, Maier, Orenstein, Zayats et al

DLSPPW waveguides

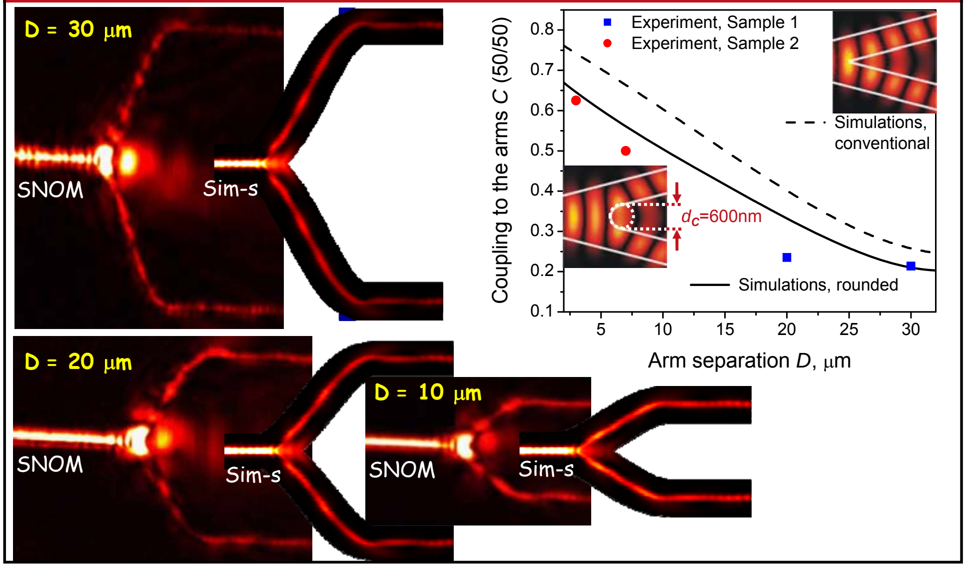


APL 90, 211101 (2007);
PRB 78, 045425 (2008).

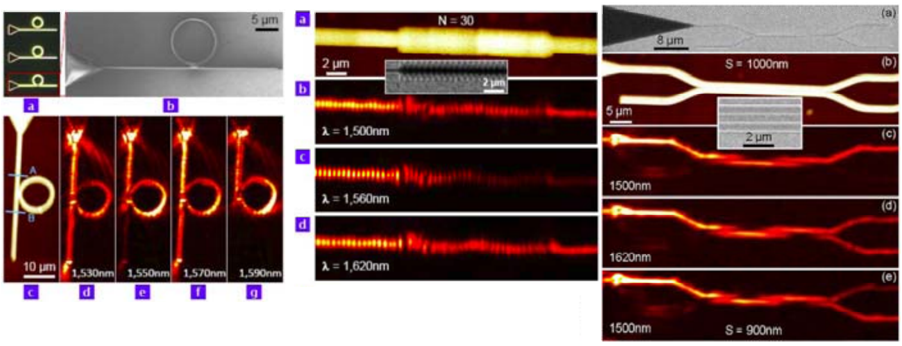
DLSPPW waveguides



DLSPPW splitters



Dielectric-loaded SPP waveguides



Wavelength selection with DLSPPW

APL 94, 051111 (2009); OL 34, 310 (2009).

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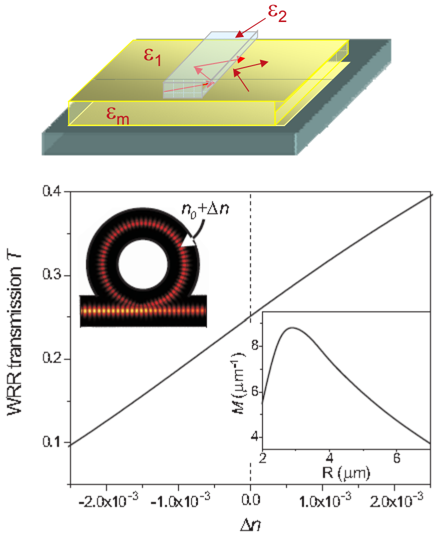
Active DLSPPW components



Polymer can be "active":
- thermo-optical properties
- electro-optical properties
- nonlinear optical properties
- gain to compensate loss

Resonant structures:
- MZI
- waveguide ring resonator
- Bragg gratings

$$FOM \sim \frac{\partial T}{\partial \theta}\frac{\partial n_{eff}}{\partial n}$$

APL 97, 041107 (2010).

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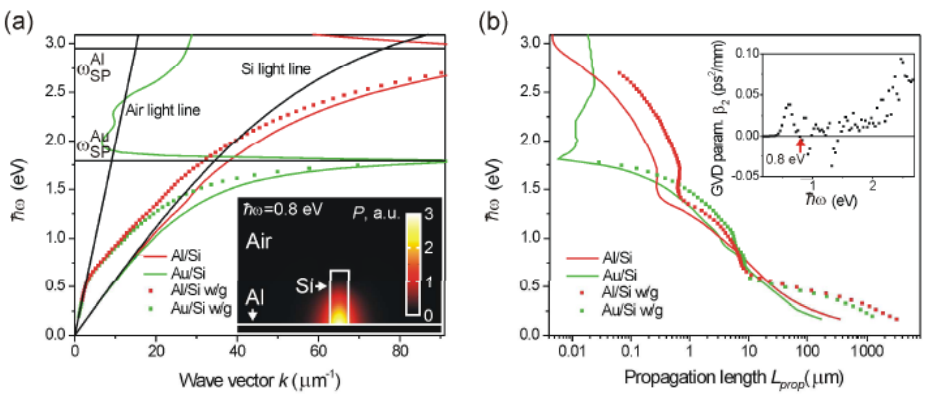
Si-SPP waveguides



Si-loaded plasmonic waveguides

Opt. Express 18, 11791 (2010).

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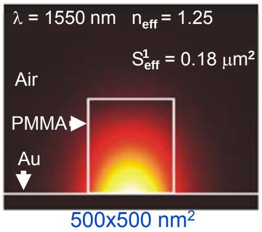
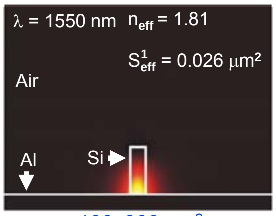
CMOS-compatible DLSPPW

Si-loaded SPPW

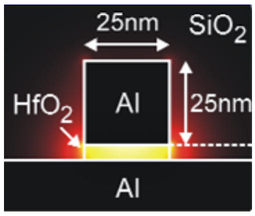


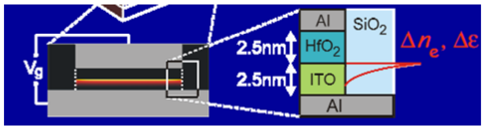
500x500 nm²



100x300 nm²

loaded-MIM SPPW





SPP MOSFET:
- **$20\times20\times200$ nm³**
- **>60% @ ~1V**

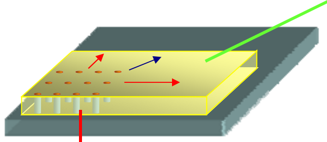
OE 18, 11791 (2010); A. Krasavin SPP5 (2011)

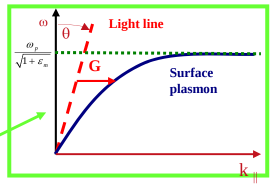
Surface plasmon polaritonic crystals

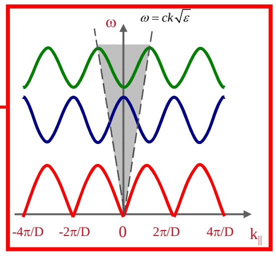
Surface polaritonic crystals

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

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



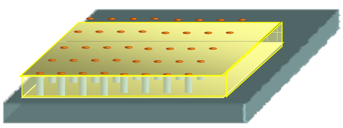


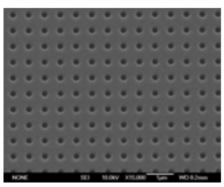


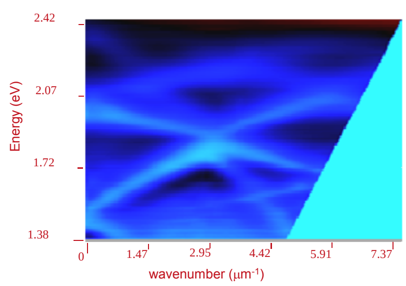
Periodic structure: SPP excitation

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

Surface polaritonic crystals

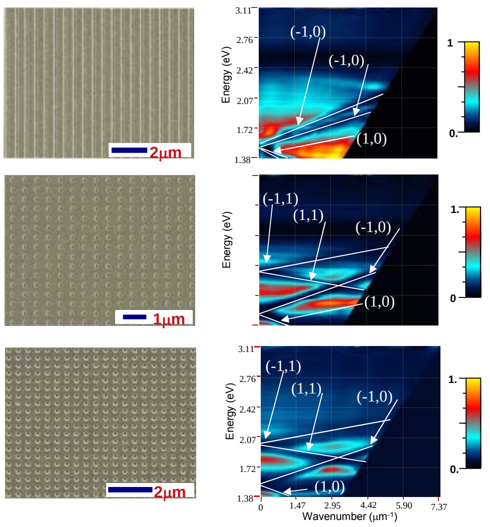


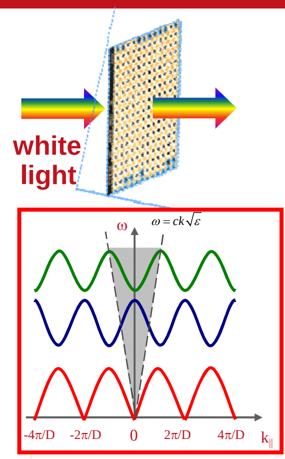




Flat SPP bands:
- **field enhancement**
- **strong sensitivity to the refractive index changes**

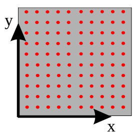
Surface polaritonic crystals

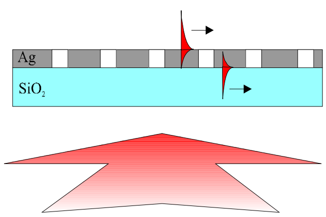


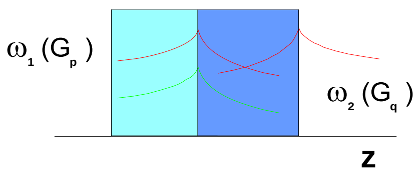


Enhanced transmission near the band edges

Surface polaritonic crystals







$$T \sim \int e^{-\kappa_L z} e^{-\kappa_R z} dz$$

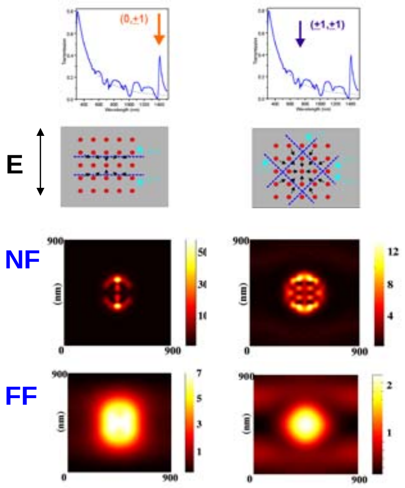
$T \sim 1$ in the resonance

- **Light tunnelling via SPP states**
- **Interaction time: SPP lifetime**
- **Lateral overlapping of the SPP modes**

Enhanced transmission through a periodically nanostructured metal film

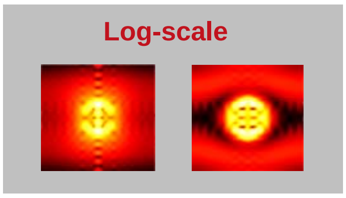
Phys. Rev. B, vol.67, 2003, 035424.

SPPC and the enhanced optical transmission



2^{nd} Brillouin zone Γ-X direction
glass-Ag interface

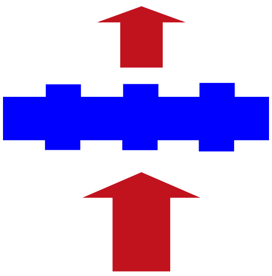
2^{nd} Brillouin zone Γ-M direction
air-Ag interface

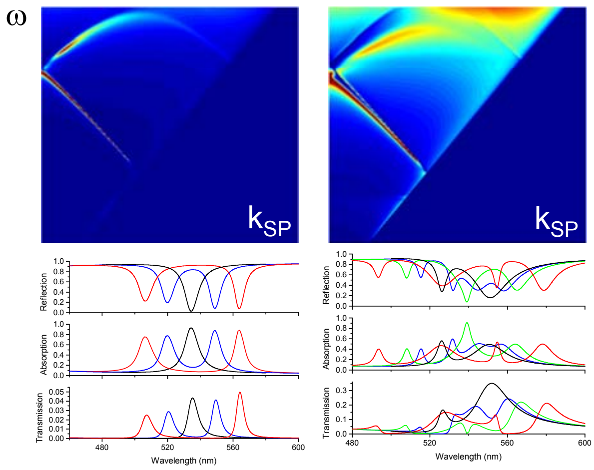


D = 900 nm
d = 300 nm
h = 20 nm

Phys. Rev. Lett., vol.86, 2001, pp.1110-1113

SPPC and the enhanced optical transmission





SPP Bloch modes | 100 nm | 40 nm

Phys. Rev. B, vol.69, 2004, 113405.

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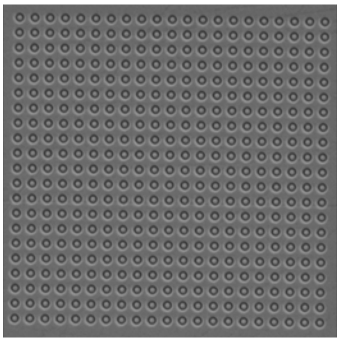
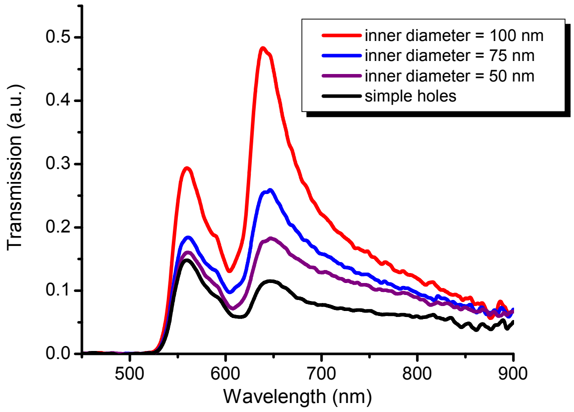
Surface polaritonic crystals



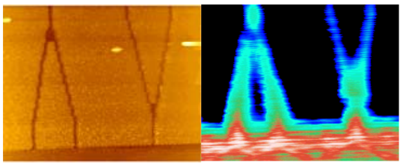


Annular holes:
more metal – higher transmission

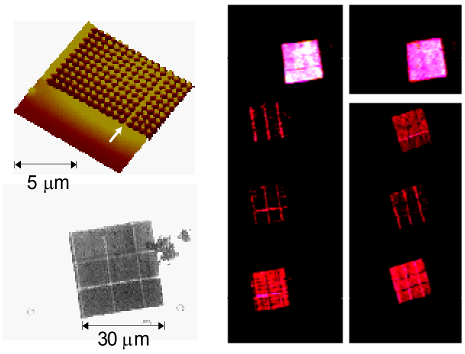
Appl. Phys. Lett.96, 201101 (2010).

Waveguiding in plasmonic crystals

Surface polariton waveguiding



Line-defects in the SPP crystal (S. Bozhevolnyi)



Polarisation-controlled coupling to the SPP modes in the waveguides formed by line defects

Appl. Phys. Lett., vol.82, 2003, 4438-4440.

Plasmonic crystals and dispersion control

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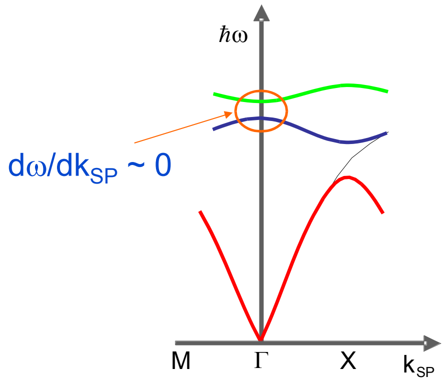
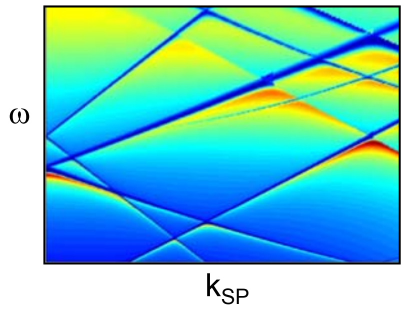
Spectral dispersion of SPP crystal





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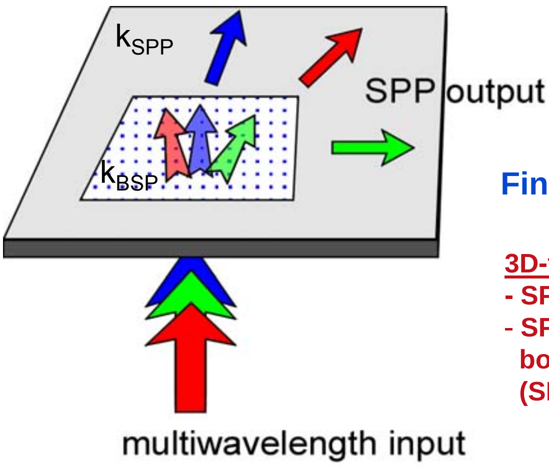
Spectral dispersion of SPP crystal



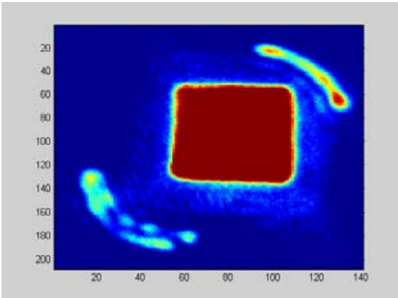
Finite-size SPP crystal

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

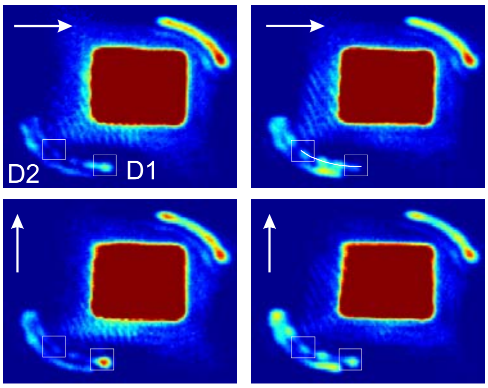
λ =1522.0 nm



Start movie

Spectral dispersion of SPP crystal

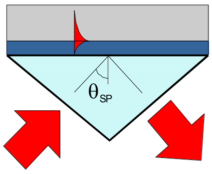
λ=1522.4 nm **λ=1522.8 nm**



Angular spectral dispersion:
~ 20—30 deg/nm

PRL 99, 083901 (2007).

Plasmonic resonances



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

SPP and LSP resonances are extremely sensitive to dielectric environment:

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

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

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

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

$\varepsilon_d = F(T)$ – temperature control

Electronically controlled SPPC

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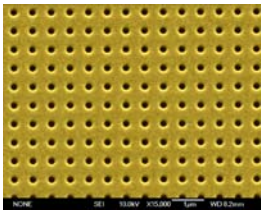
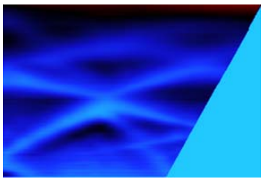
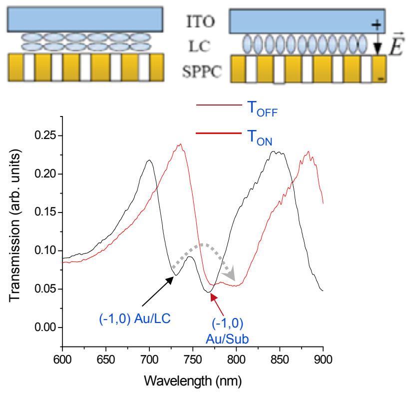
Electrically tuneable SPP crystals





Periodically structured surfaces: SPP Bloch mode engineering



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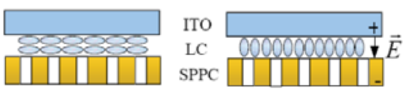
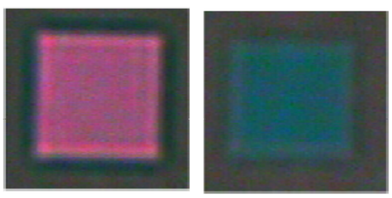
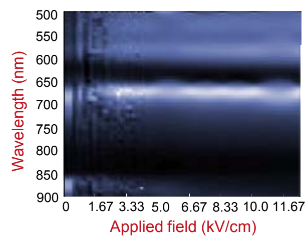
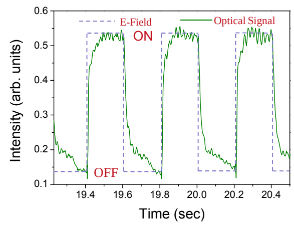
Electrically tuneable SPP crystals









Nano Letters 8, 281 (2008).

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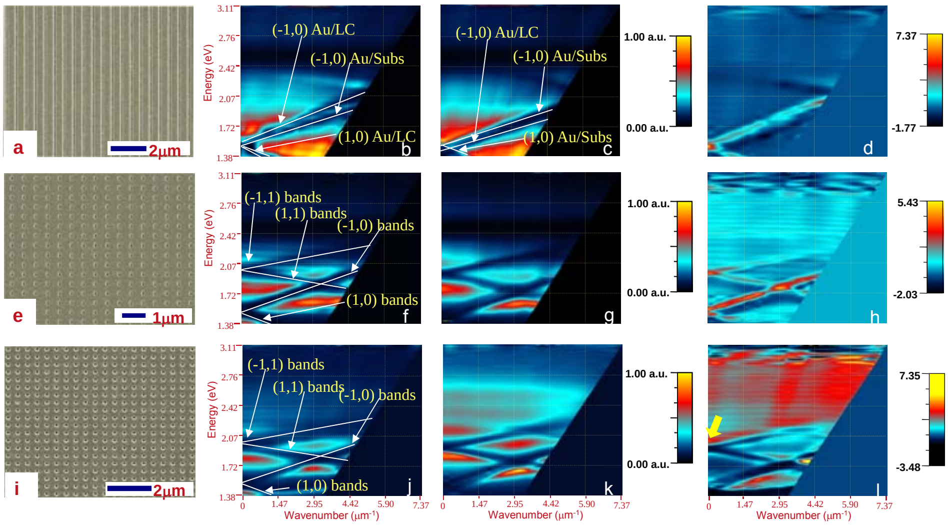
Electrically tuneable SPP crystals



Nano Letters 8, 281 (2008).

Magnetic-field controlled SPPC

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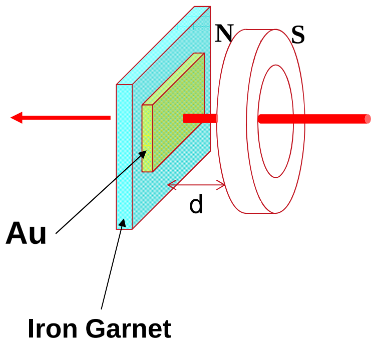
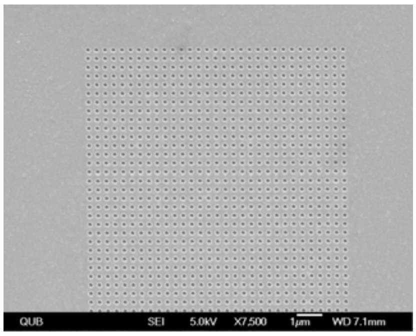
Magneto-plasmonic crystals





Magneto-plasmonic crystal

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

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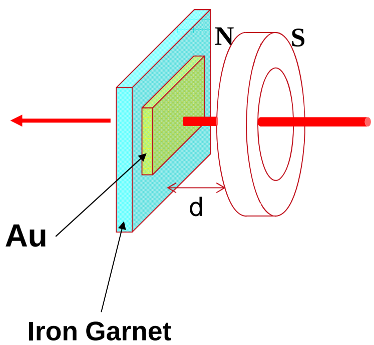
Magneto-plasmonic crystals



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

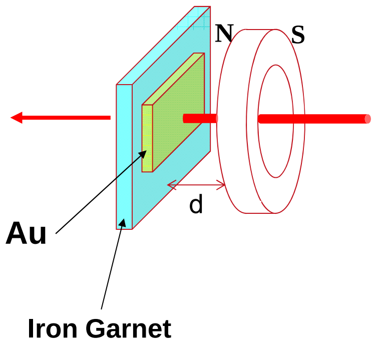
SPP field (E_x;E_z)

$\varepsilon_i = f(M)$ - ?

Magneto-plasmonic crystal

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

Magneto-plasmonic crystals



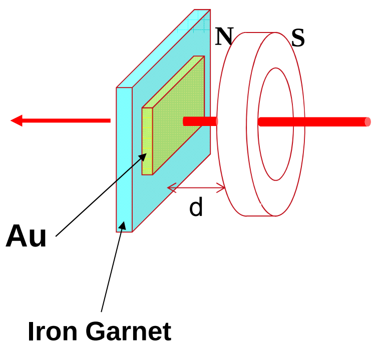
$$\varepsilon = \begin{pmatrix} \varepsilon_0 & \cancel{i\varepsilon_p} & i\varepsilon_t \\ \cancel{-i\varepsilon_p} & \varepsilon_0 & i\varepsilon_l \\ -i\varepsilon_t & -i\varepsilon_l & \varepsilon_0 \end{pmatrix}$$

No external magnetic field (in-plane magnetisation)

Magneto-plasmonic crystal

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

Magneto-plasmonic crystals



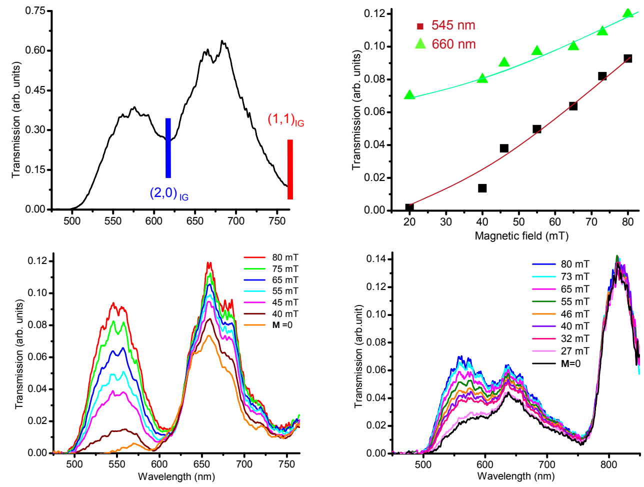
$$\varepsilon = \begin{pmatrix} \varepsilon_0 & i\varepsilon_p & \cancel{i\varepsilon_t} \\ -i\varepsilon_p & \varepsilon_0 & \cancel{i\varepsilon_l} \\ \cancel{-i\varepsilon_t} & \cancel{-i\varepsilon_l} & \varepsilon_0 \end{pmatrix}$$

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

Magneto-plasmonic crystal

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

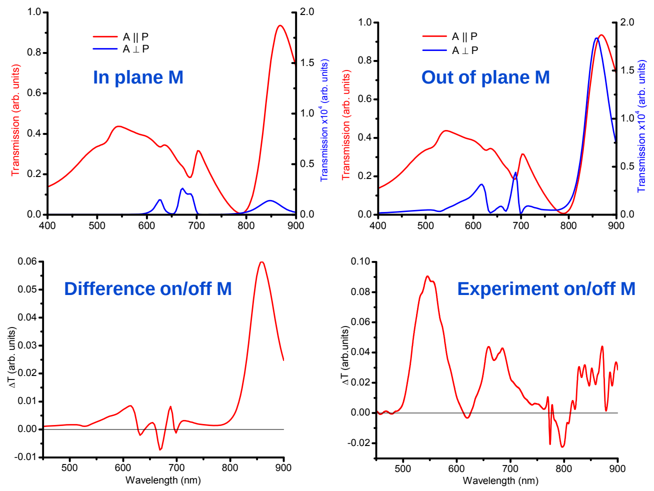
Magneto-plasmonic crystals



Cross-polarised transmission

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

Magneto-plasmonic crystals

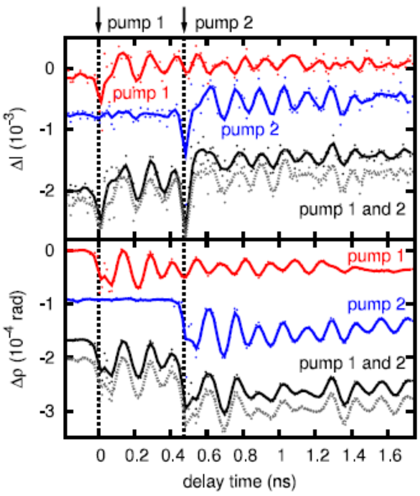


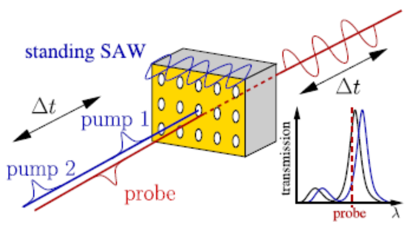
Dispersion of ε_{garnet} is not taken into account

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

Acoustically tuneable SPP crystals

Coherent control of SPPs





J Phys D 41, 195102 (2008).

Nonlinear SPPC
(all-optical effects)

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**

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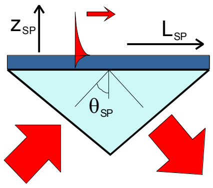
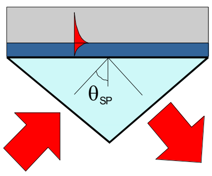
Nonlinearity and surface plasmons



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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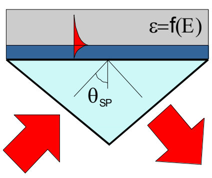
Nonlinearity and surface plasmons



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

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

Kerr-nonlinearity for controlling SPPs with SPPs_

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

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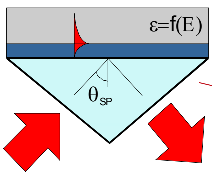
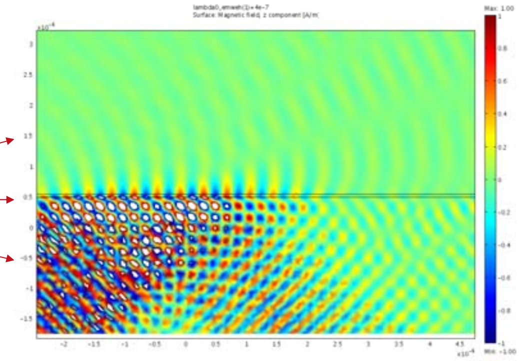
Nonlinearity and SPPs





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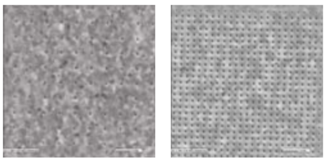
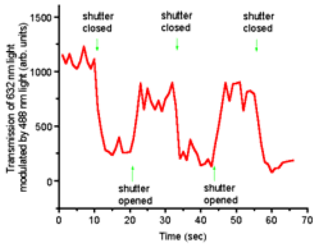
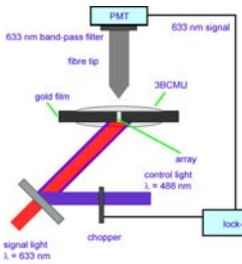
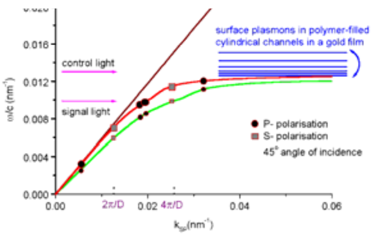
Controlling SPP with external light: cylindrical surface plasmon effects



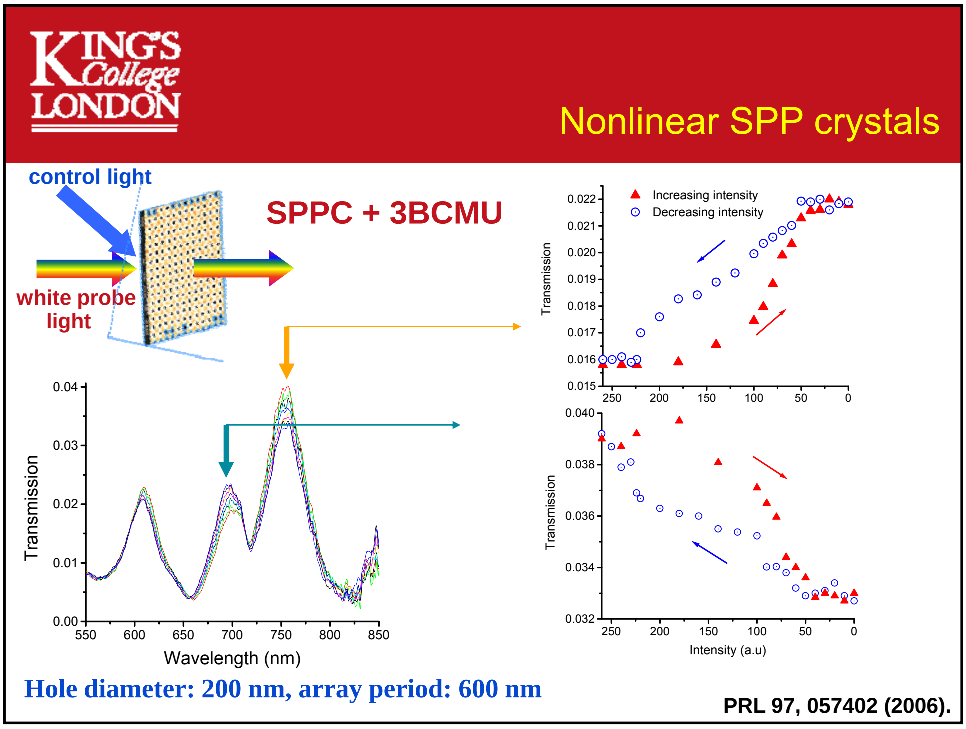
Arrays of the 20 nm cylindrical channels in 400 nm Au film.







PRB 66, 205414 (2002).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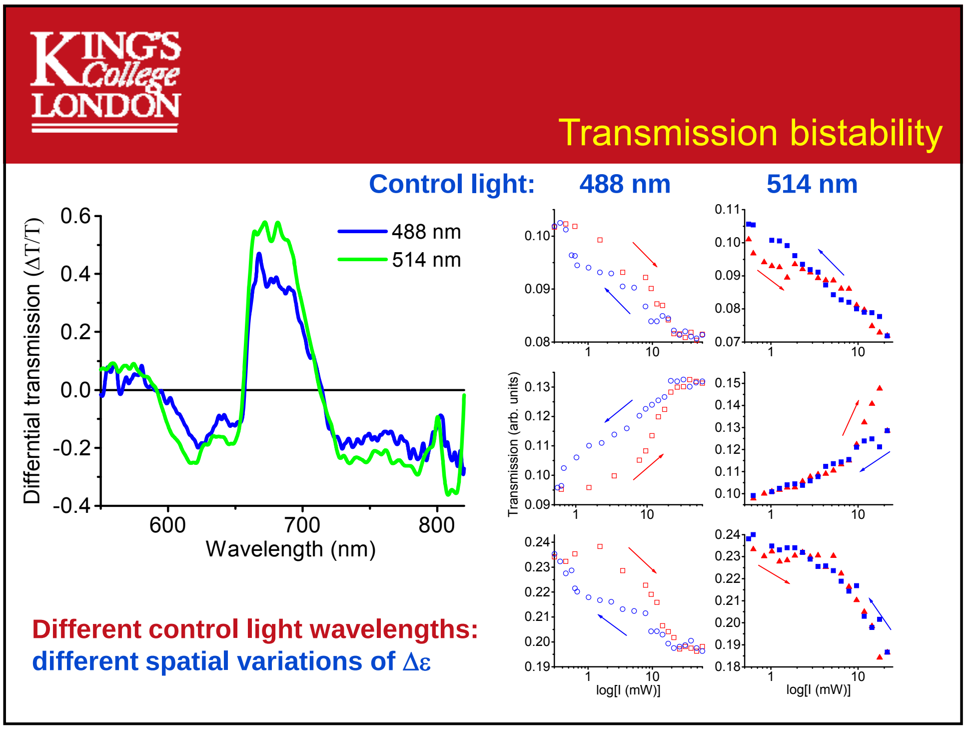
Nonlinear SPP crystals
control light
white probe light
SPPC + 3BCMU
Transmission
Wavelength (nm)
Increasing intensity
Decreasing intensity
Intensity (a.u)
Hole diameter: 200 nm, array period: 600 nm
PRL 97, 057402 (2006).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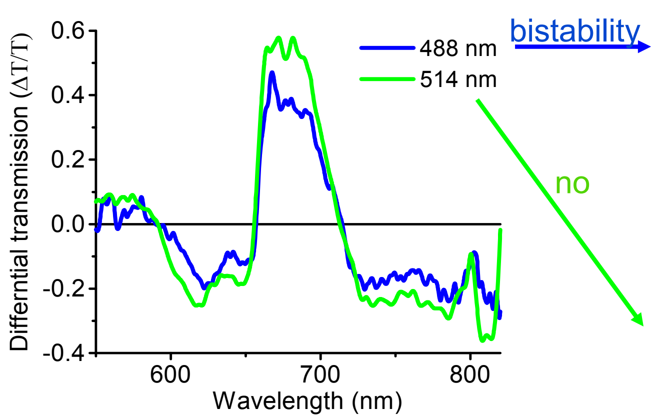
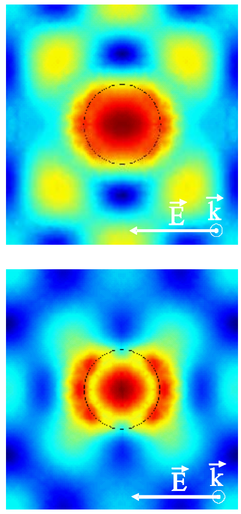
Transmission bistability
Control light: 488 nm 514 nm
488 nm
514 nm
Differential transmission (ΔT/T)
Wavelength (nm)
Transmission (arb. units)
log[I (mW)]
Different control light wavelengths:
different spatial variations of Δε

All-optical switching in nonlinear SPPC

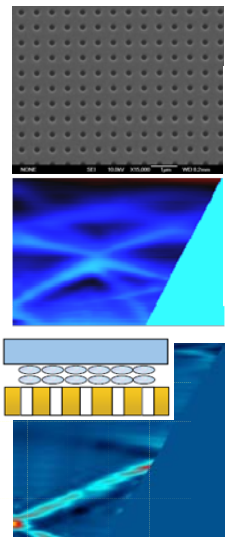




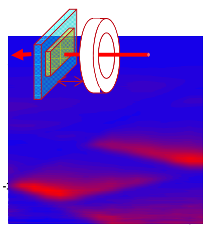
$$\varepsilon(\vec{r}) = \varepsilon^{(0)} + 4\pi\chi^{(3)} \left| \vec{E}\left(\varepsilon(\vec{r}), \omega_{pump}, \vec{r}\right) \right|^2$$

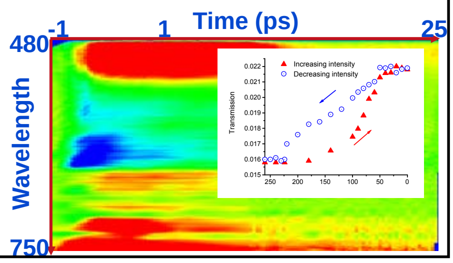
PRL 97, 057402 (2006).

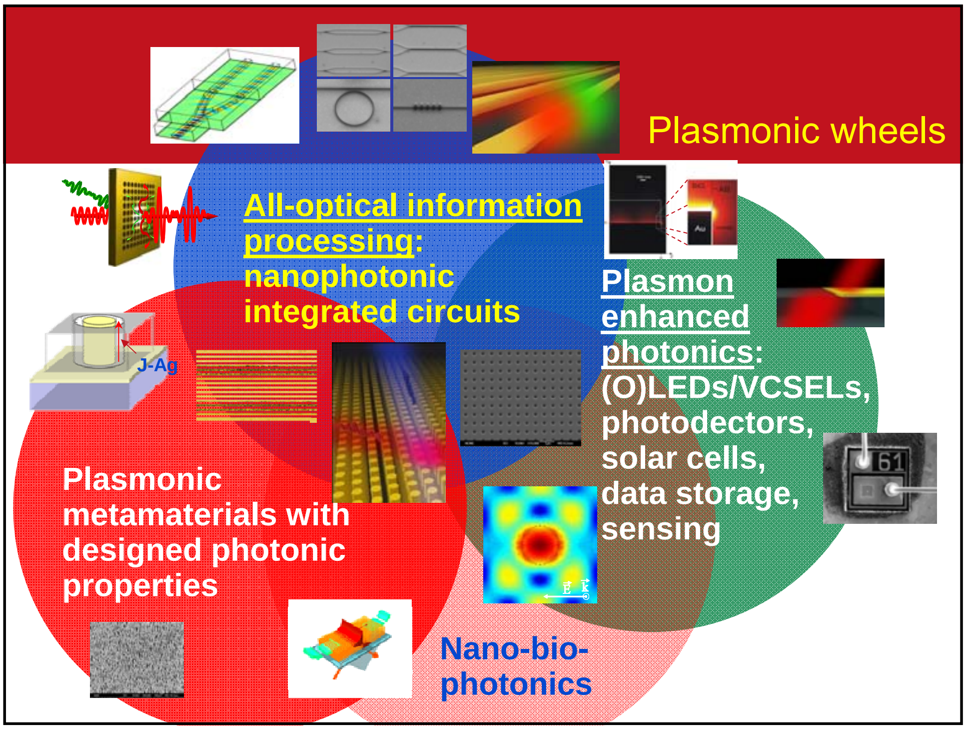
Active plasmonic crystals



- SPP dispersion engineering
- flat SPP bands @ field enhancement
- tuneability and switching with hybrid SPPC:
  - electric-field controlled
  - magnetic-field controlled
  - mechanical (acoustic)
  - all-optical: bistability with ps response







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Take home messages (1):

- Functional plasmonics with nanostructured metal films
- Plasmonics waveguides (careful analysis before chosing)
- 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

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Fast growing area (follow new publications)

- Nano-optics of surface plasmon polaritons, Phys. Rep., vol.408, 2005, pp.131-314.
- Near-field photonics: surface plasmon polaritons and localised surface plasmons, J. Opt. A: Pure Appl. Opt., vol. 5, 2003, pp.S16-S50.
- Nonlinear surface plasmon polaritonic crystals, Laser and Photon. Rev., vol. 2, 2008, pp. 125-135.
- Optics of metallic nanostructures, in *Handbook of Nanoscale Optics and Electronics*, G. Wiederrecht, Ed., pp. 1-52 (Elsevier, 2009).
- D. Richards, A.V. Zayats, Eds., *Nano-optics and near-field optical microscopy* (Artech, Boston, 2008), ISBN: 978-1-59693-238-8.

WWW.NANO-OPTICS.ORG.UK