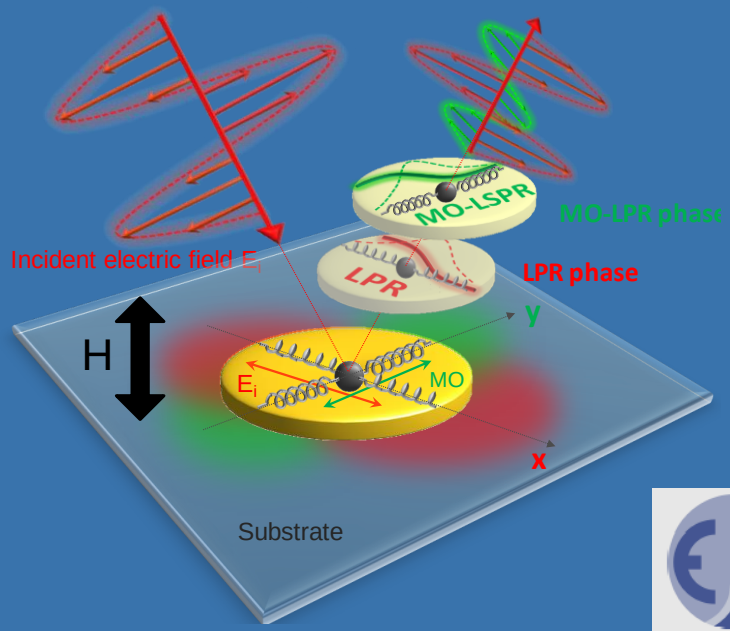
FT-3: Magneto-optics and Magneto-plasmonics Part 2

P. Vavassori

-IKERBASQUE, Basque Fundation for Science and
CIC nanoGUNE Consolider, San Sebastian, Spain.



THE EUROPEAN SCHOOL ON
MAGNETISM 2018
MAGNETISM BY LIGHT

Outline

NANOANTENNAs COMBINING MAGNETIC AND PLASMONIC FUNCTIONALITITES

- *Localized surface plasmons & Magneto-optical Kerr effects (MOKE): Introduction*
- *Physical picture and modeling*
- *LSPR-based sensing: Towards molecular sensing*
- *Photonics technology: control of the non-reciprocal light propagation*

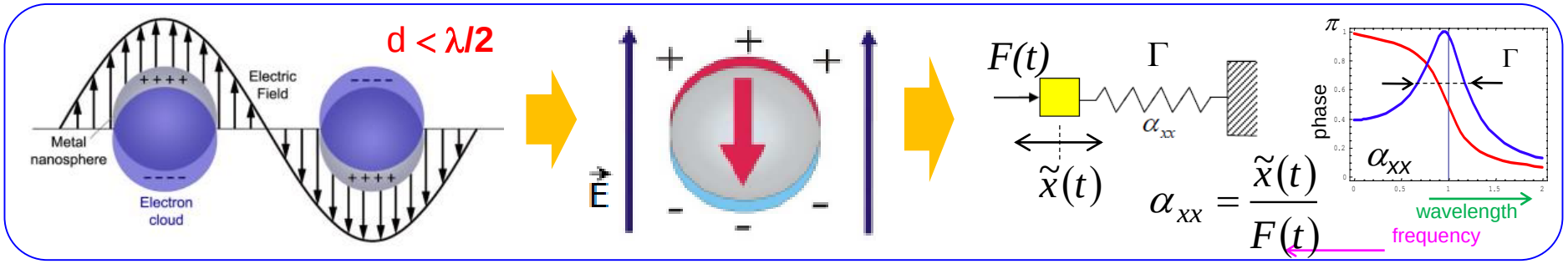
MAGNETOPLASMONIC METAMATERIALS

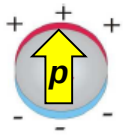
- *Surface lattice resonances in arrays of nanoantennae*
- *Arrays of elliptical nanoantennae*
- *Magnetoplasmonic gratings: arrays of antidots*

CONCLUSIONS

Localized surface plasmon resonances (LSPRs)

Localized surface plasmon resonances (LSPRs or LSPs) collective oscillations of conduction electrons in metallic nano structures.





For very small particles, $a << \lambda$ ⟹ Electrostatics approximation

Particle → dipole: $\vec{p} = \alpha(\omega)\vec{E}$

$$\alpha(\omega) = 4\pi\varepsilon_d a^3 \frac{\varepsilon_m(\omega) - \varepsilon_d}{\varepsilon_m(\omega) + 2\varepsilon_d}$$

Resonance for $\varepsilon_m = -2\varepsilon_d$

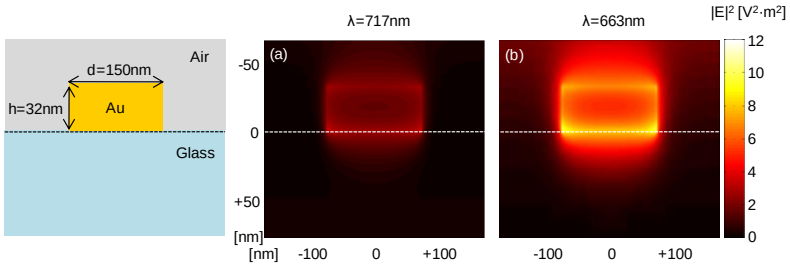
Small ε_d for excitation of a LSPR in the optical visible range (air, glass….)

Enhanced absorption and scattering

Intense local field

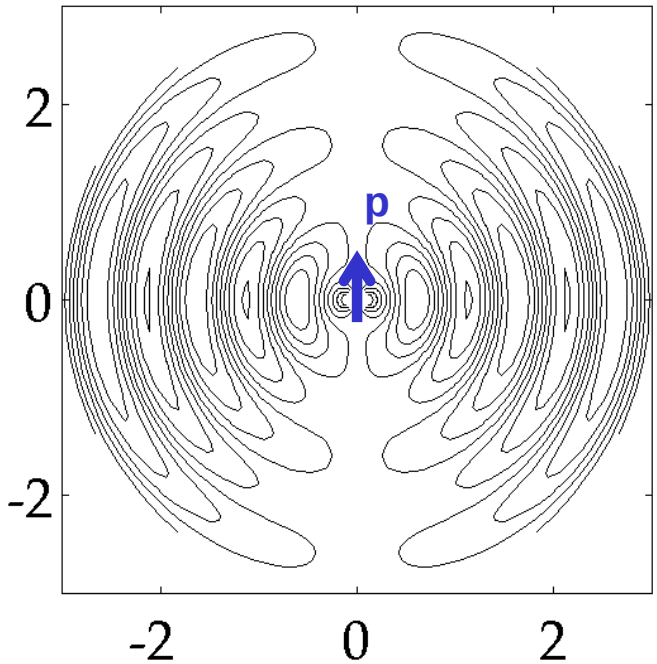
Ellipsoid

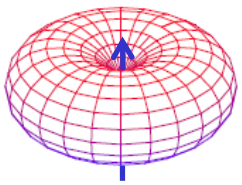
$$\tilde{\alpha} = \begin{bmatrix} \alpha_{xx} & \alpha_{xy} & \alpha_{xz} \\ \alpha_{yx} & \alpha_{yy} & \alpha_{yz} \\ \alpha_{zx} & \alpha_{zy} & \alpha_{zz} \end{bmatrix}$$



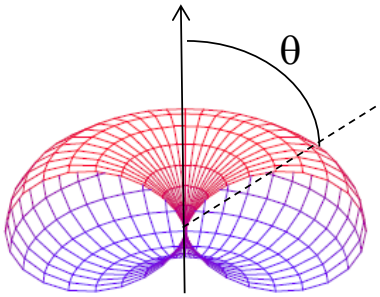
Subwavelength localization of electromagnetic energy

EM field irradiated by an oscillating dipole



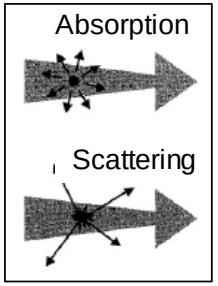


Dipole radiation pattern $\sin^2\theta$



Cut-out view of the same

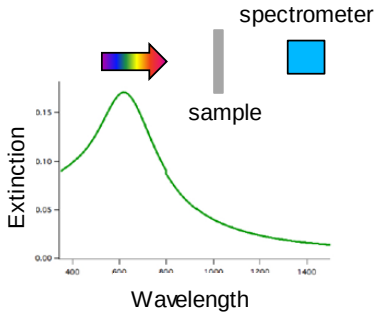
Scattering and absorption remove energy from the incoming EM



$$\sigma_{ext} = \sigma_{sca} + \sigma_{abs}$$

$$\sigma_{sca} \propto |\alpha|^2$$

$$\sigma_{ext} \propto Im\{\alpha\}$$

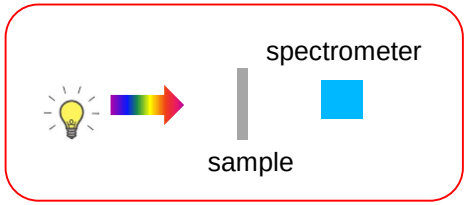


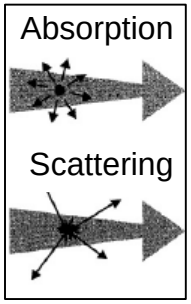
Electric field lines due to an electric dipole oscillating vertically at the origin. Near the dipole, the field lines are essentially those of a static dipole.

At a distance of the order of half wavelength or greater, the field lines are completely detached from the dipole

Localized surface plasmon resonances (LSPRs)

Scattering and absorption remove energy from the incoming EM





$$\sigma_{ext} = \sigma_{sca} + \sigma_{abs}$$

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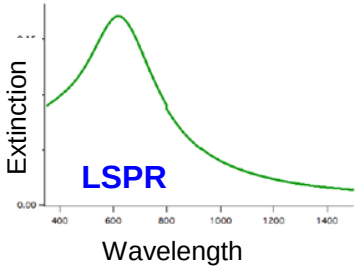
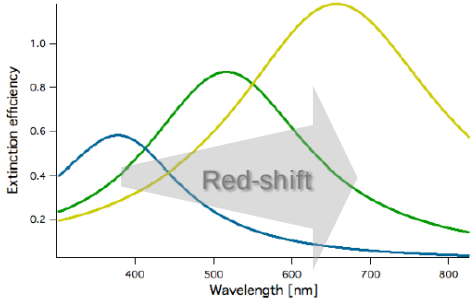
$$\sigma_{abs} \propto Im\{\alpha\}$$

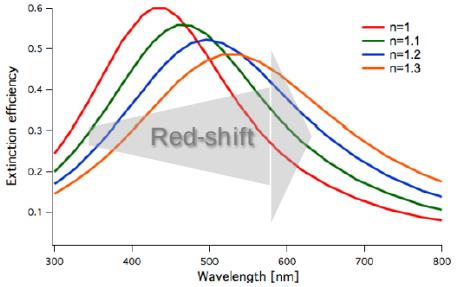
$$\sigma_{ext} \propto Im\{\alpha\}$$



Size

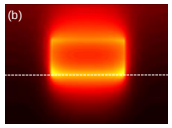


Embedding medium

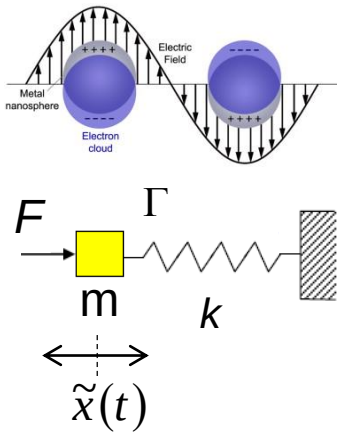


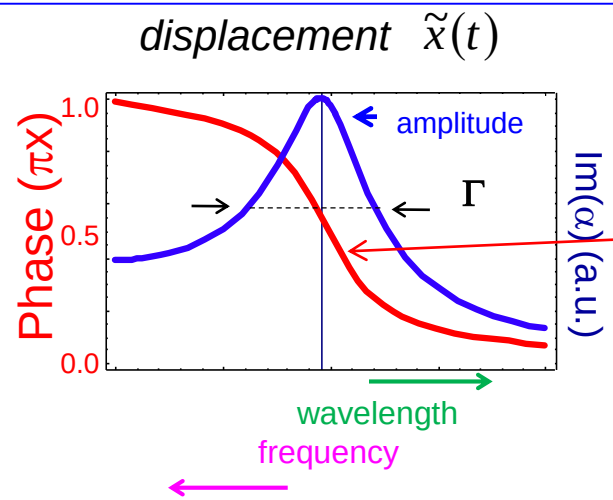
Applications:

- nanoantennas
- apertureless imaging
- spectroscopic techniques (SERS , SEF, ...)
- information storage
- waveguides
- solar cells
- new optical materials
- sensing, bio-sensing



LSPR as a damped harmonic oscillator



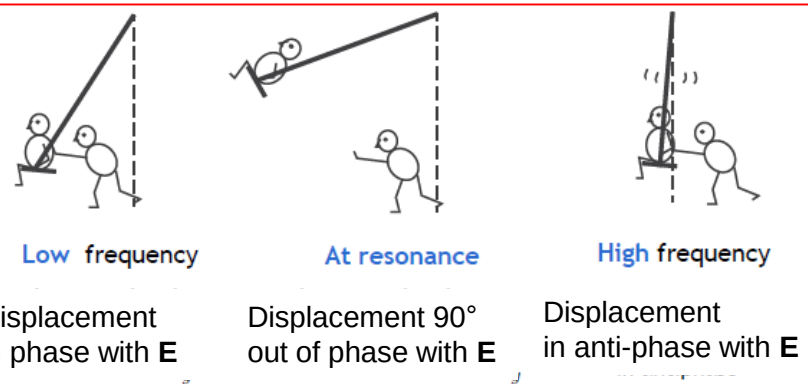


$\phi[\alpha]$

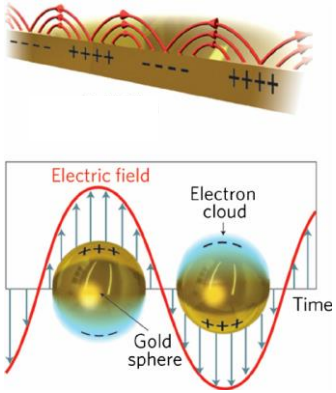
Polarizability phase

Phase

$\phi[\alpha]$

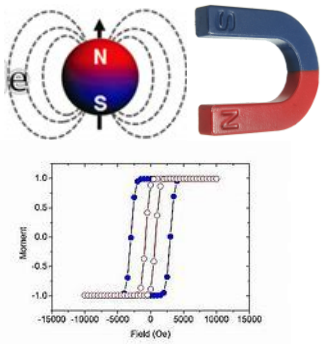


Magnetoplasmonics



Control of MO activity

Control of plasmon properties



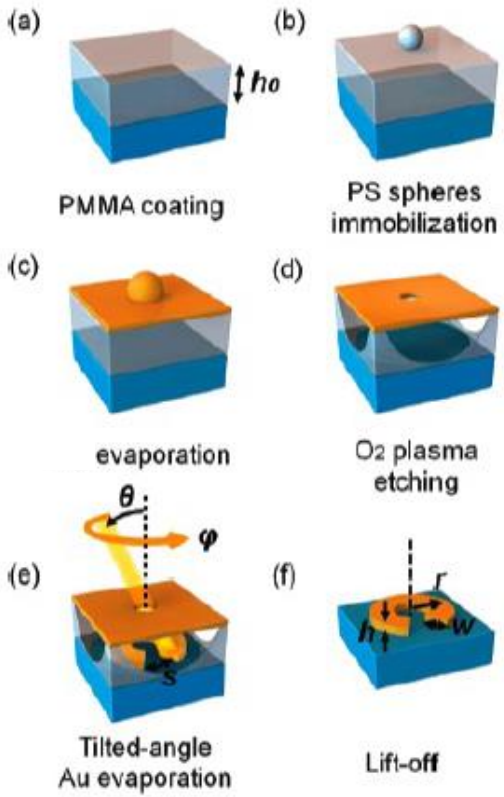
- Combination of magnetic materials with nanometer-scale systems supporting surface or localized surface plasmon resonances
  - Plasmons can be controlled by an external magnetic field (active plasmonics)

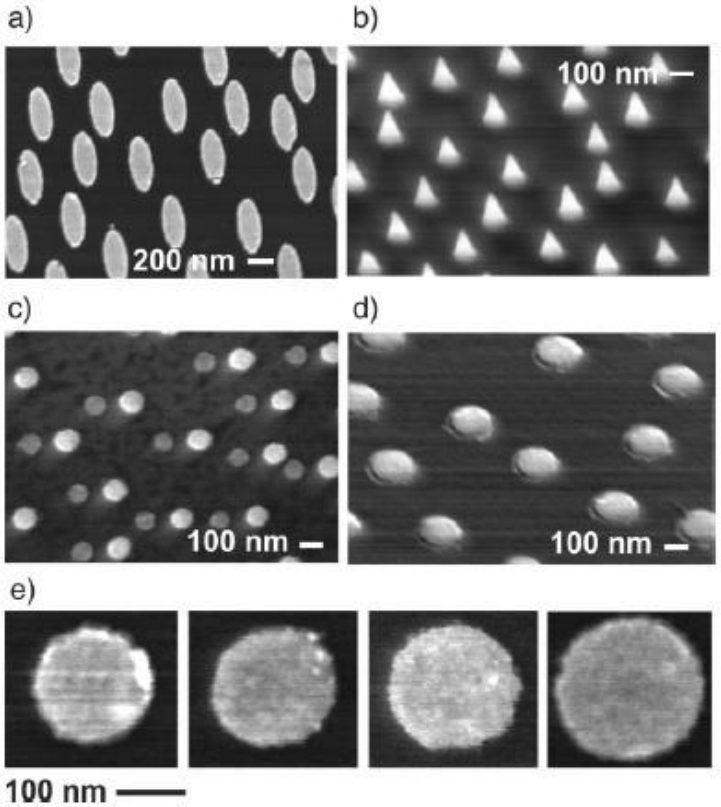
$$(\text{SPPs } M \perp K_{SPP} \rightarrow K'_{SPP} = K_{SPP} \pm \Delta K_{SPP})$$

- Magneto-optical response can be modified by plasmons: e.g., Faraday or Kerr enhancement

G.Armelles , A. Cebollada , A. García-Martín , and M. Ujué González, Adv. Optical Mater. **2013**, *1*, 10–35

Hole-Mask Colloidal Lithography



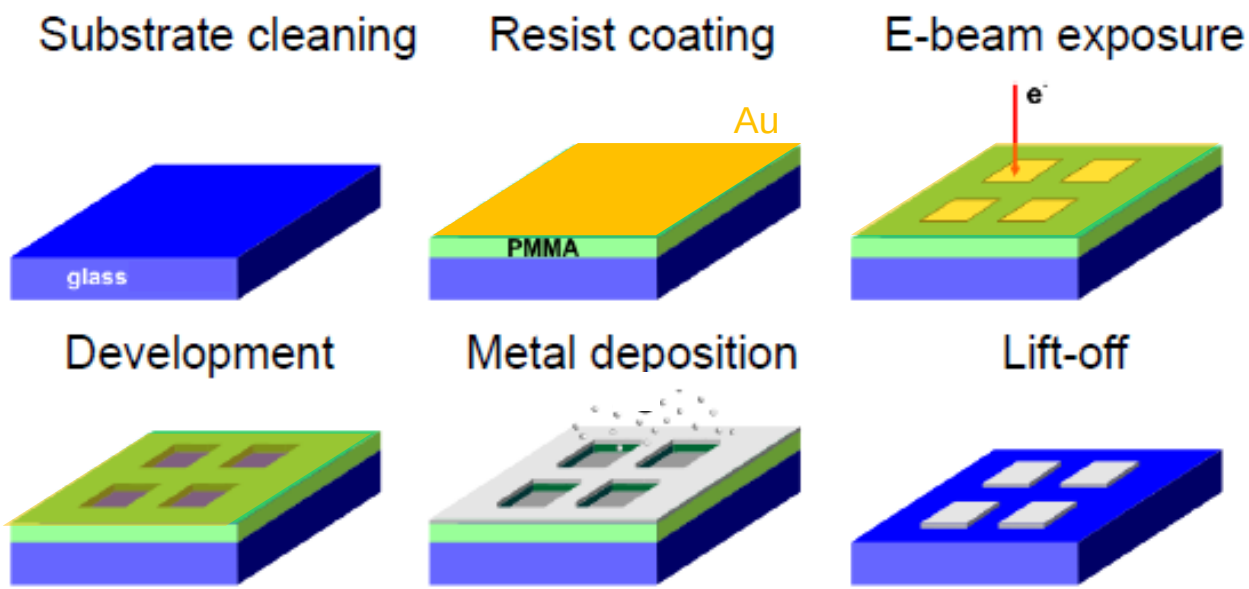


Adv. Mater. 19, 4297 (2007)

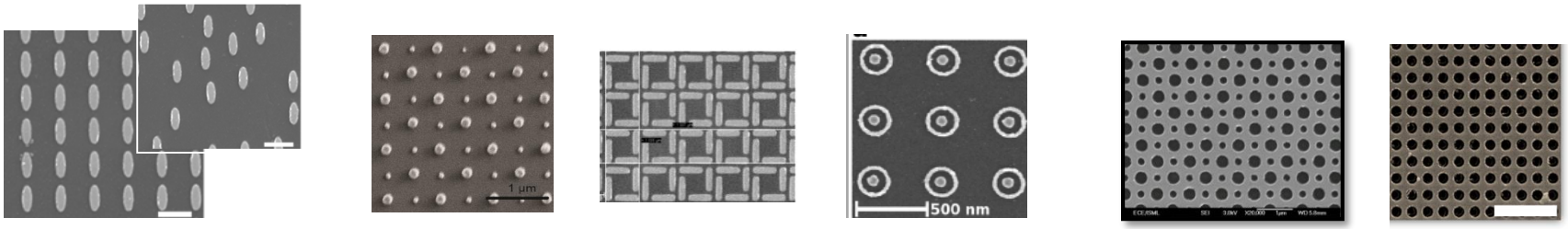
- Large areas
- Disordered distribution
- Insulating substrates
- Low concentration to avoid interactions

Chalmers

E-beam lithography on glass



Arrays written with a write field of 50 micron x 50 micron.



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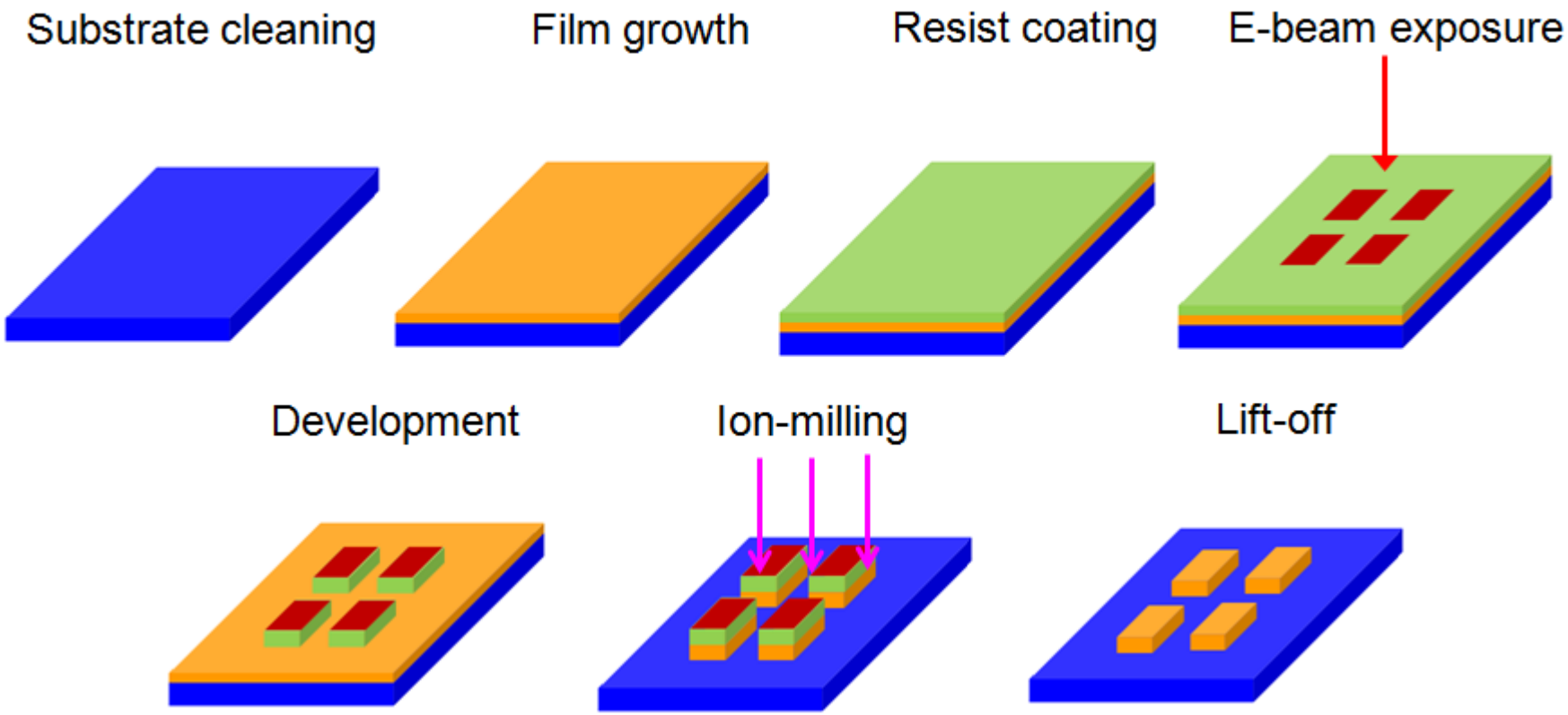
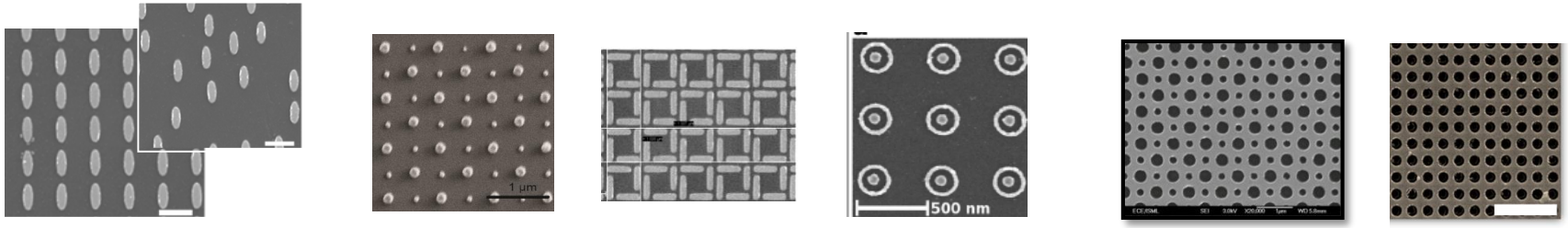
Negative e-beam lithography on glass





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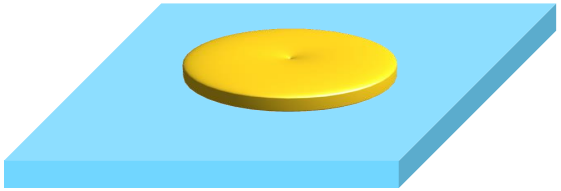
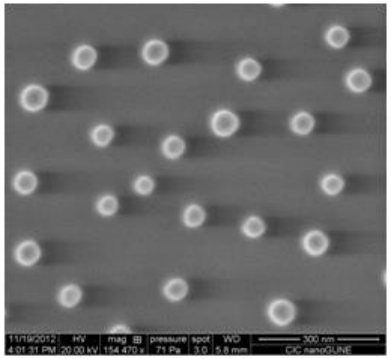
Ni nanoantennas

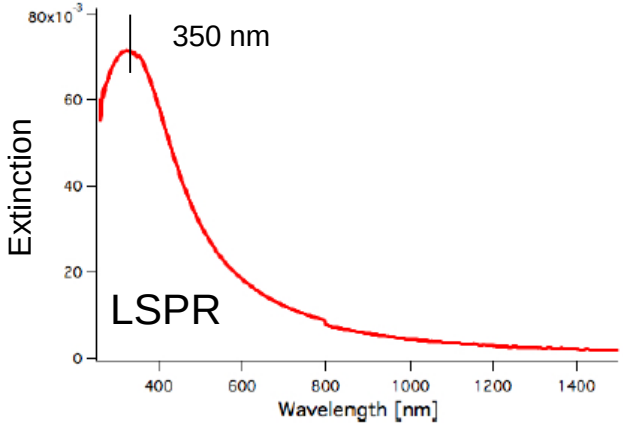
Hole-Mask Colloidal Lithography (Ni disks on glass)

Adv. Mater. 19, 4297 (2007)

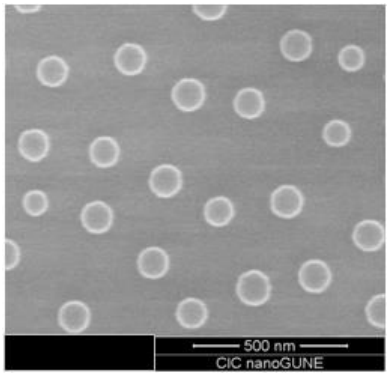


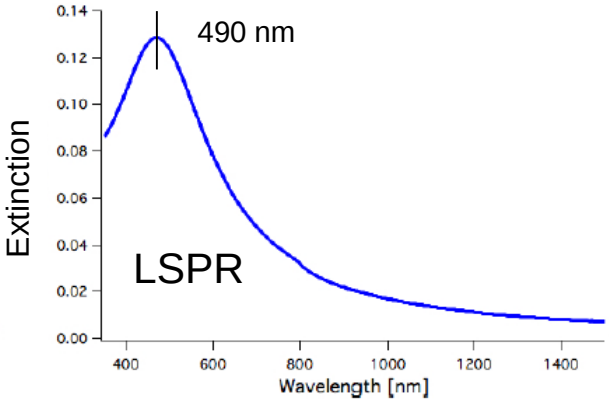
Disks 60x30 nm



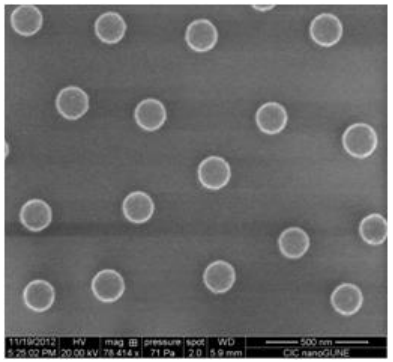


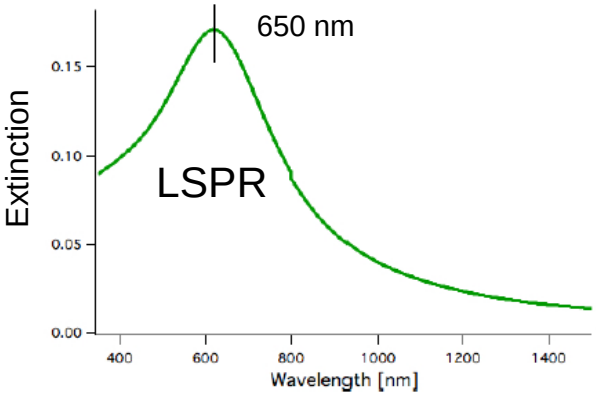
Disks 100x30 nm



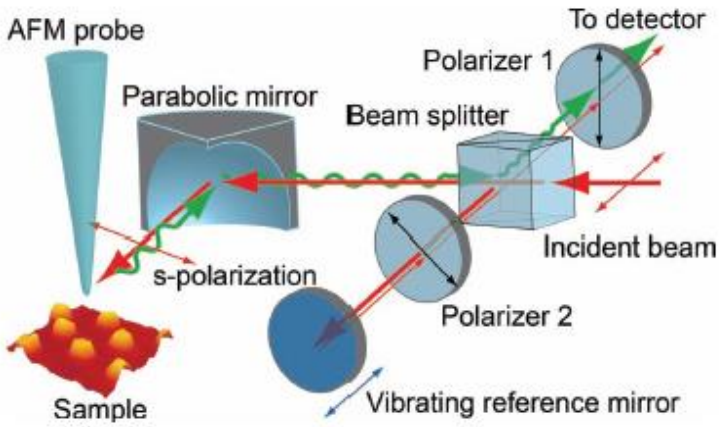


Disks 160x30 nm

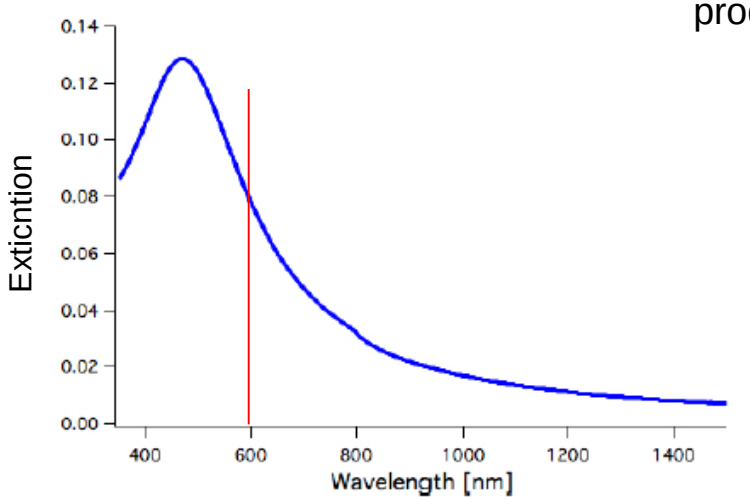




Is the effect due to a LSPR?

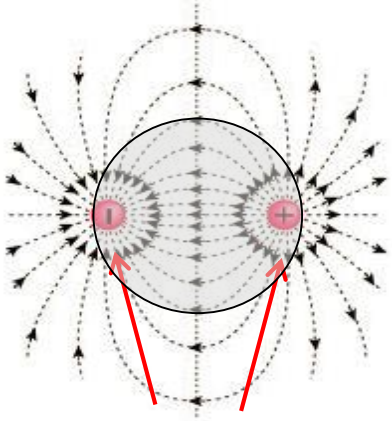


Scanning Near-Field Optical (SNOM) microscopy: amplitude and phase!

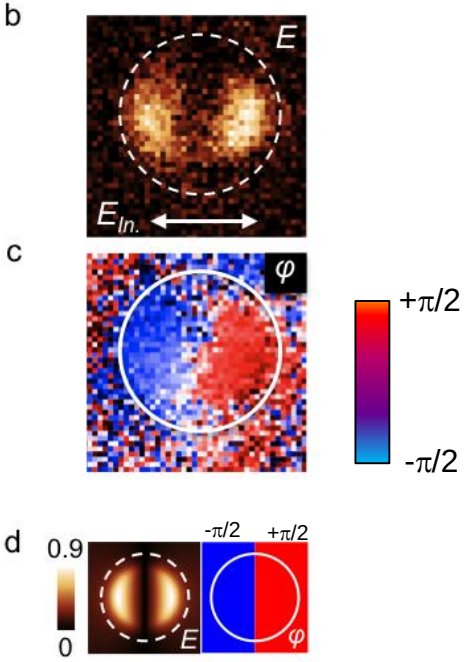


Small **7**, 2341 (2011)

In the NF, electric field is like the one produced by a static electric dipole

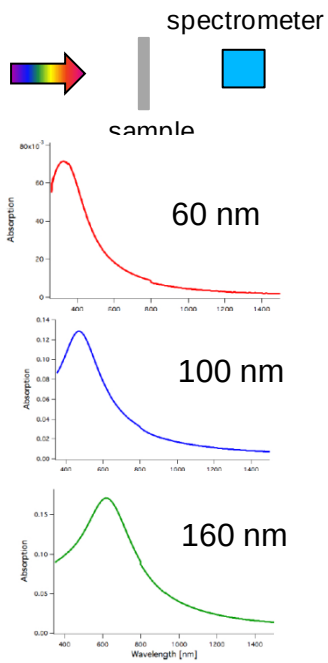


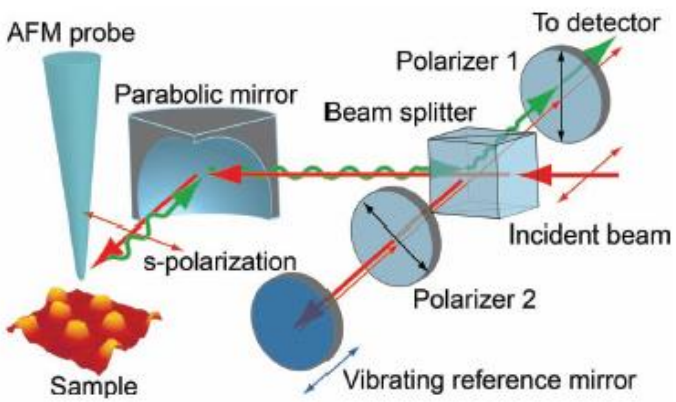
Intense E fields of opposite sign (π out of phase)

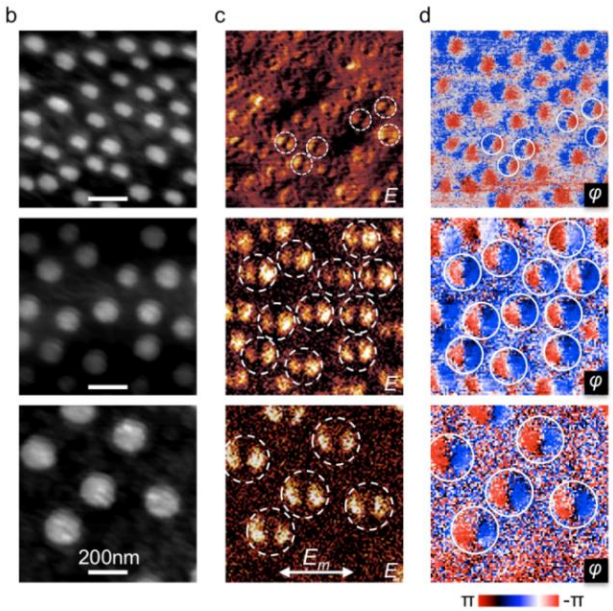


A real LSPR?

Scanning Near-Field Optical (SNOM) microscopy: amplitude and phase!

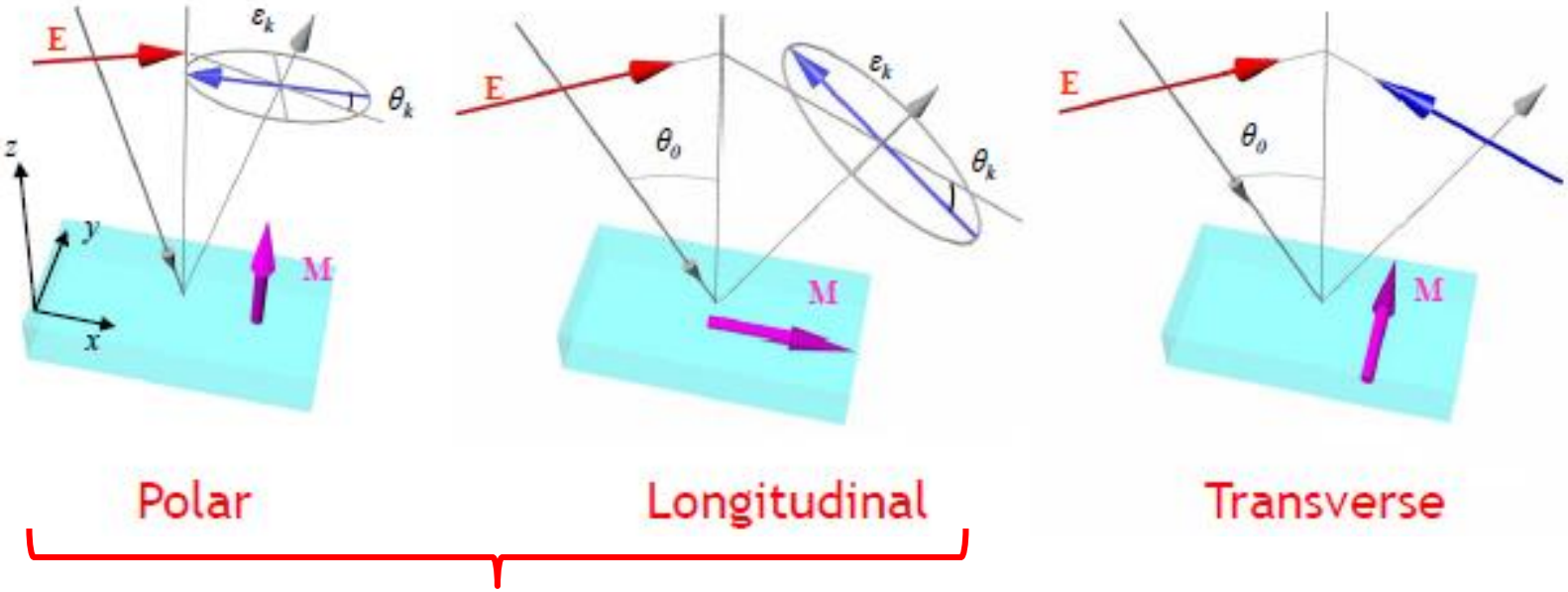






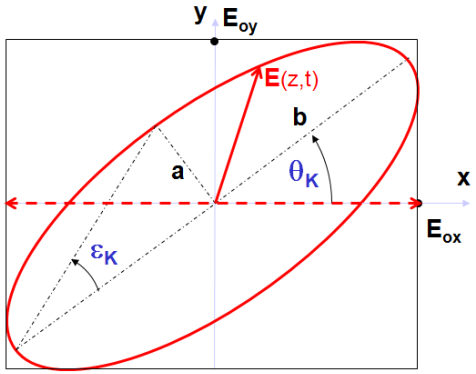
Small **7**, 2341 (2011)

Magneto-Optical Kerr effect configurations

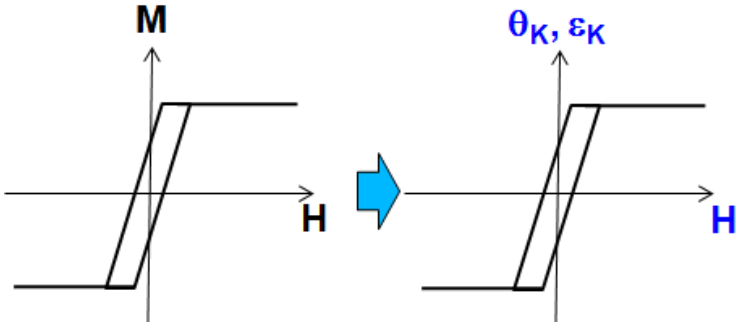


$\theta_{K,F}$

$\varepsilon_{K,F}$

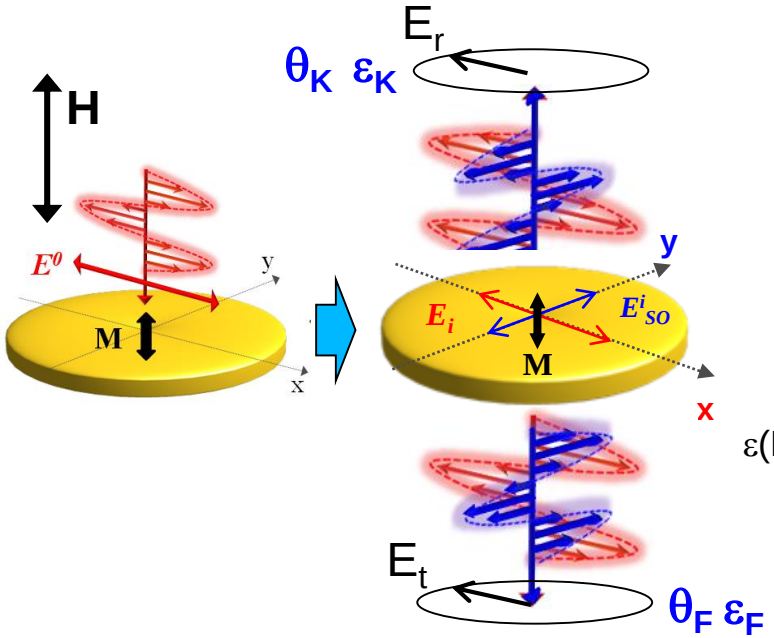


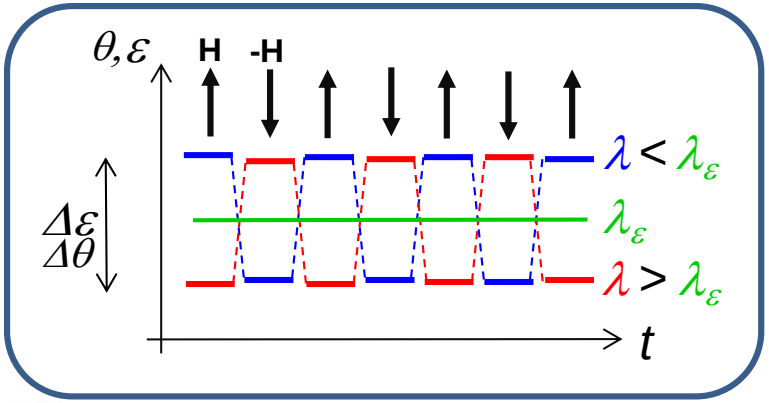
Magnetic characterization

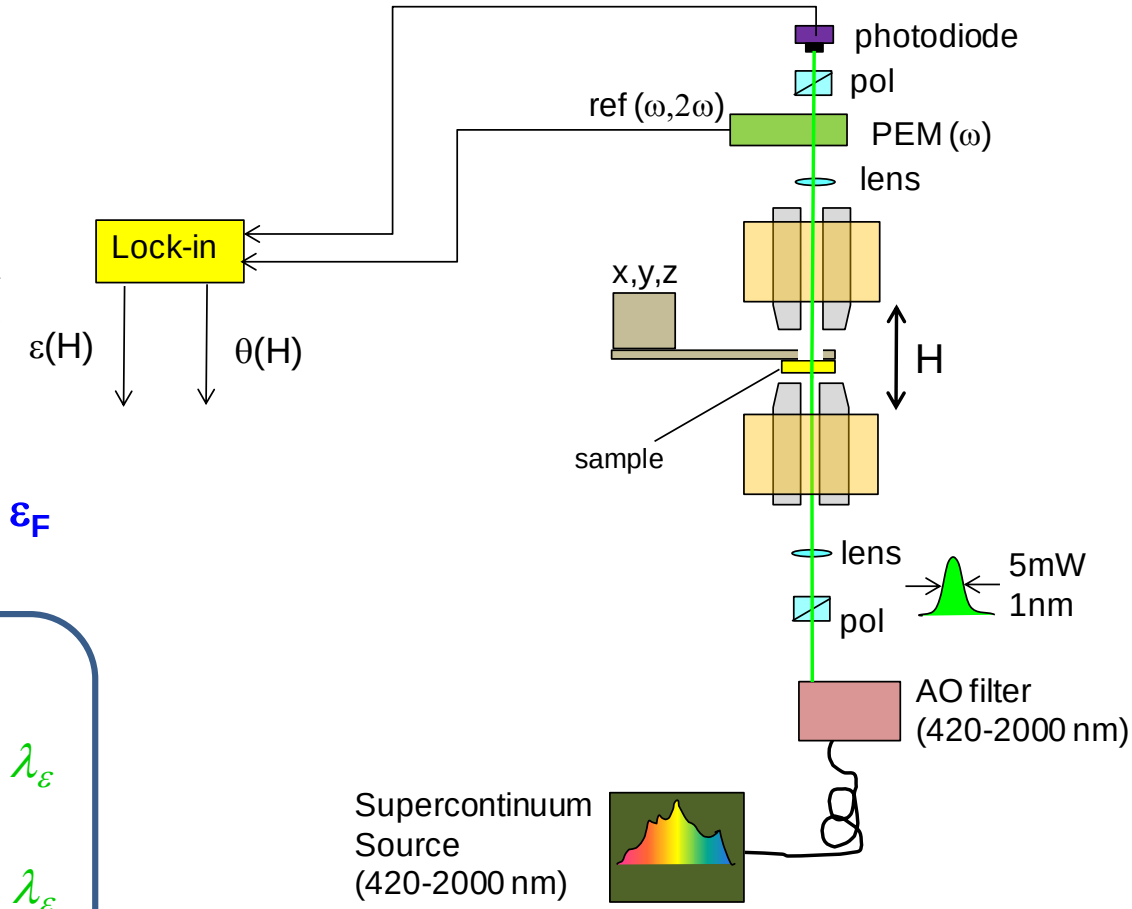


P. Vavassori, APL **77**, 1605 (2000)

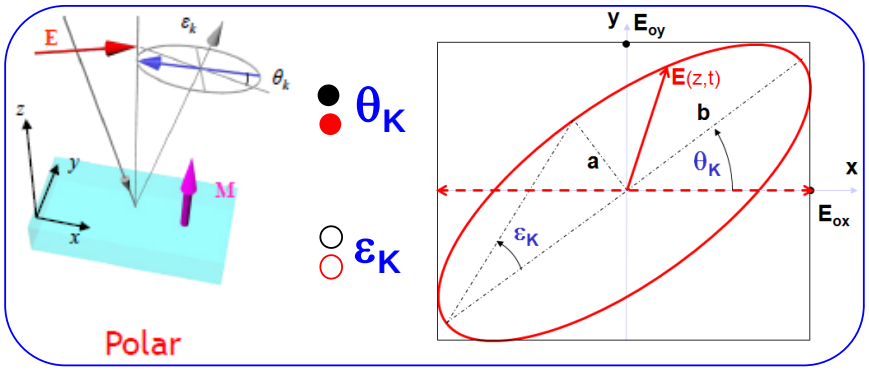
Spectroscopic Polar MOKE





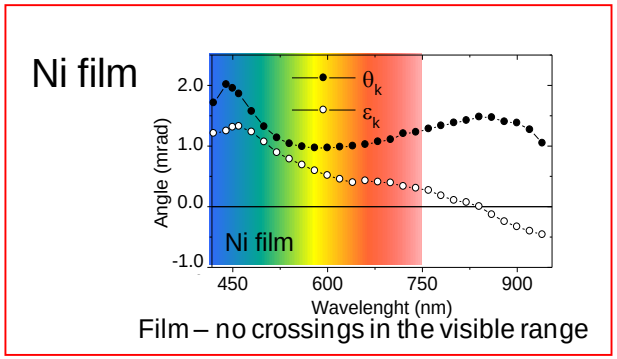


Polar MOKE spectra: polarization of reflected light linked to the LSPR position

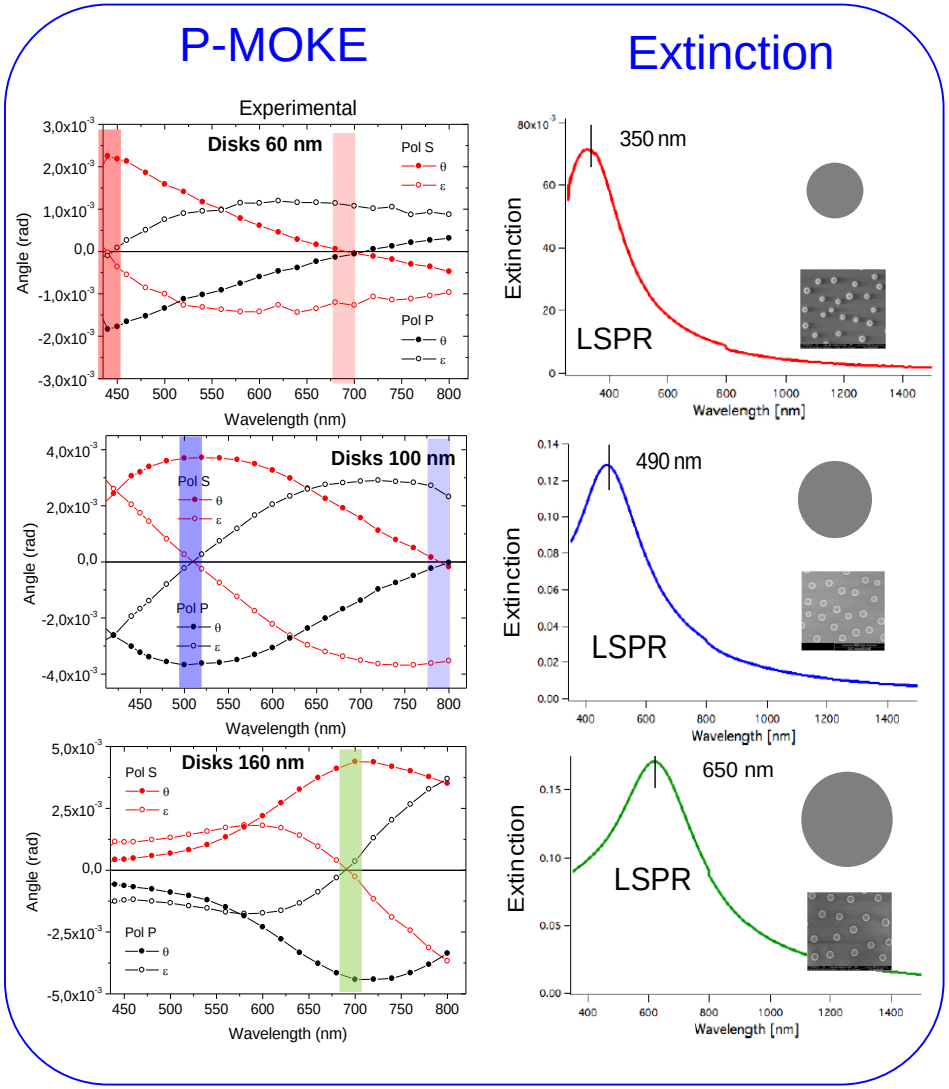


P. Vavassori, Appl. Phys. Lett. **77**, 1605 (2000)

Refence Ni film

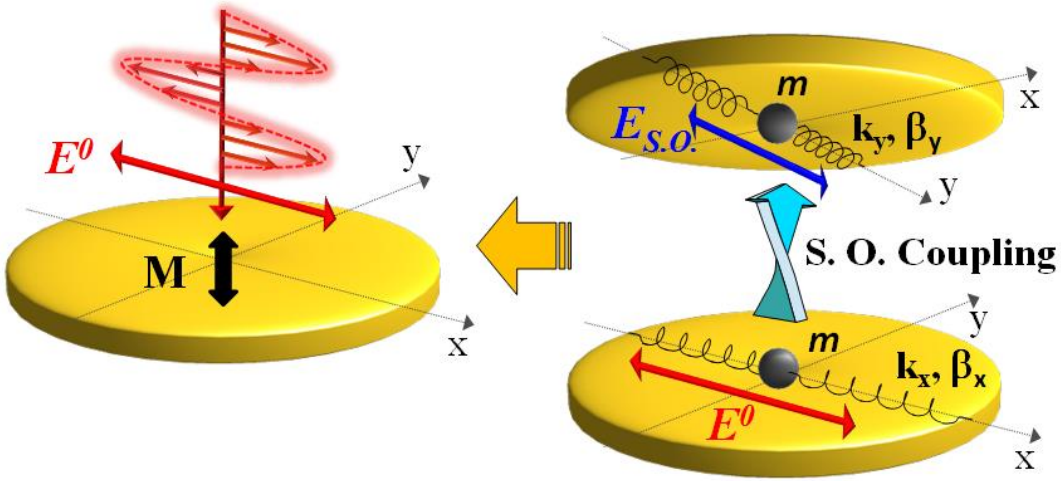


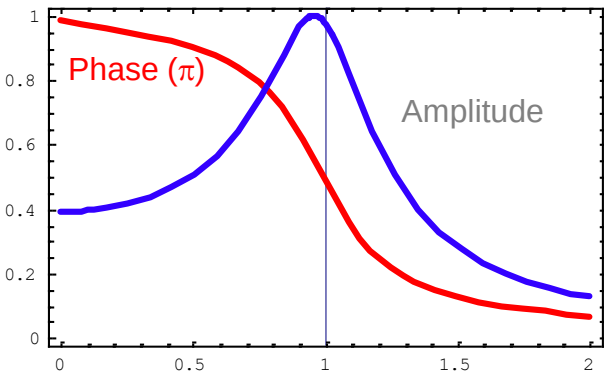
➢ Maximum of θ_K and crossing of ε_K follow the LSPR position



Phys. Rev. Lett. **111**, 167401 (2013)

Simple physical picture: two coupled damped harmonic oscillators!!!



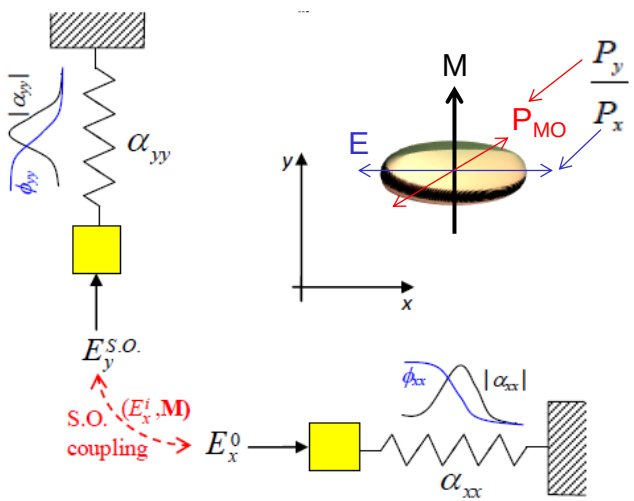


Damped harmonic oscillator
Phase contribution

- Damped H.O.: confinement
- S.O. coupling: material property

Fundamental hypothesis here: linear and perturbative regime

Induced electric dipoles



1. Oscillator along x

$$p_x = \chi_{xx} E_x^i = (\varepsilon - \varepsilon_m) E_x^i \qquad p_x = \alpha_{xx} E^0$$

$$E_x^i = E^0 - E_x^d$$

2. S.O. Coupling

S.O. coupling induces an electric dipole $P_y^{S.O.}$

Neglecting the *y*-confinement for now ($E_y^d = 0$)

and since $E_y^{ext} = E_y^0 = 0$

$$p_y^{S.O.} = \chi_{yx} E_x^i = \varepsilon_{yx} E_x^i$$

$$E^y_{S.O.} = p_y^{S.O.}/\chi_{yy} = p_y^{S.O.}/(\varepsilon - \varepsilon_m)$$

3. Oscillator along y

Now introducing the lateral confinement along *y*

$$p_y = \alpha_{yy} E^y_{S.O.} = E_x^i (\alpha_{yy}\, \varepsilon_{yx}) / (\varepsilon - \varepsilon_m)$$

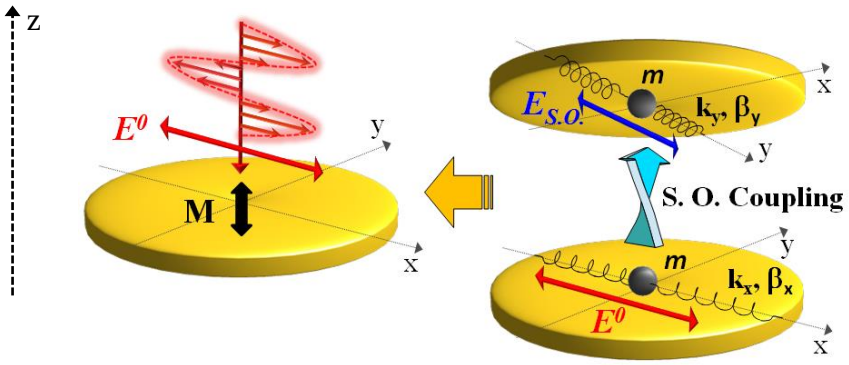
$$\frac{p_y}{p_x} = \frac{\varepsilon_{yx}\alpha_{yy}}{(\varepsilon - \varepsilon_m)^2}$$

Gives the polarization of the far-field radiated in the z-direction by these two mutually orthogonal oscillating electric dipoles

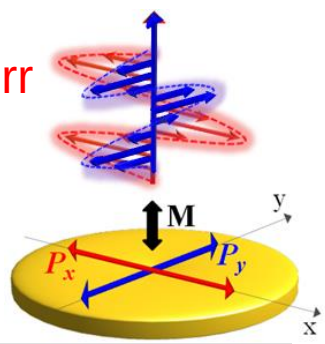
- **MO enhancement depends only on α_{yy} (shape can improve enhancement)**
- **Relative phase on both α_{yy} and ε_{yx}**

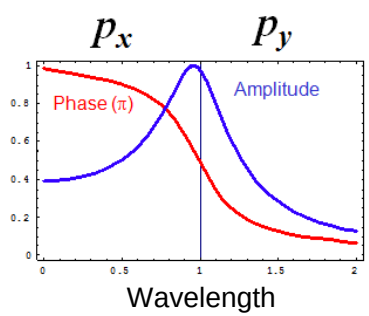
Simple physical picture: two S.O. coupled damped harmonic oscillators: relative phase

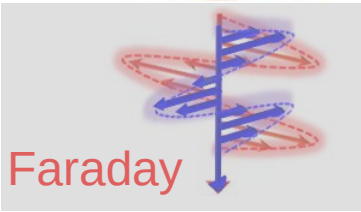
- Damped H.O.: confinement
- S.O. coupling: material property



Kerr







S.O.

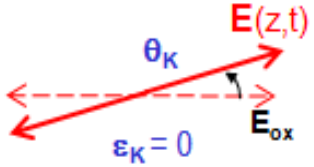
$$\frac{p_y}{p_x} = \frac{\varepsilon_{yx}}{(\varepsilon - \varepsilon_m)^2} \quad \alpha_{yy}$$

Polarization of the radiated field $E(z, t)$

$$\Delta\phi = \phi\left[\frac{\tilde{p}_y}{\tilde{p}_x}\right] = \phi[\tilde{p}_y] - \phi[\tilde{p}_x] =$$

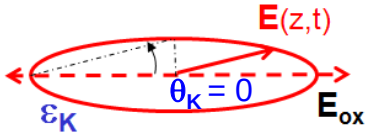
$$= \phi\left[\frac{\varepsilon_{yx}}{(\varepsilon - \varepsilon_m)^2}\right] + \phi[\alpha_{yy}]$$

$\Delta\phi = 0$

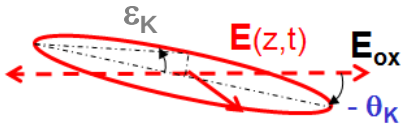


$0 < \Delta\phi < \pi/2$

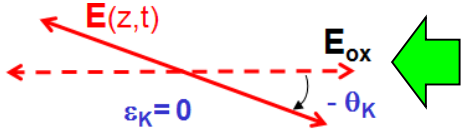
$\Delta\phi = \pi/2$



$\pi/2 < \Delta\phi < \pi$



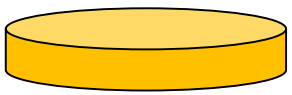
$\Delta\phi = \pi$



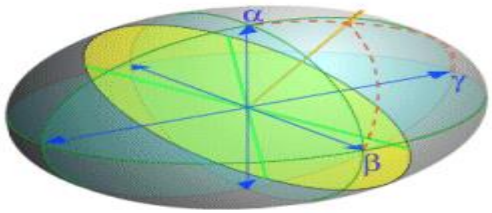
Phys. Rev. Lett. **111**, 167401 (2013)

Depolarizing field is the key

Cilindrical disk



Oblate ellipsoid



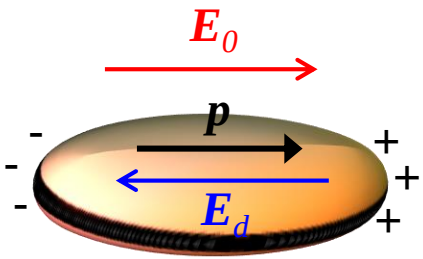
Internal field

Embedding medium

External field

$$\boldsymbol{p} = (\tilde{\varepsilon} - \varepsilon_m)\, \boldsymbol{E}_i \; ; \qquad \boldsymbol{E}_i = \boldsymbol{E}_0 + \boldsymbol{E}_d$$

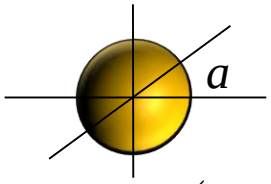
Depolarizing field



N. Maccaferri et al., Opt. Express 21, 9875-89 (20113)

Internal and depolarizing fields: quasi static approx

Static depolarization: the sphere case



$$\boldsymbol{E}_d = -\frac{1}{\varepsilon_m} L\boldsymbol{p} \qquad L = \frac{1}{3}$$

$$\boldsymbol{p} = \left(\tilde{\boldsymbol{\varepsilon}} - \varepsilon_m\right)\boldsymbol{E}_i \qquad \boldsymbol{E}_i = \boldsymbol{E}_0 + \boldsymbol{E}_d$$

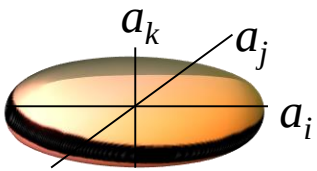
$$\boldsymbol{p} = \tilde{\alpha}\boldsymbol{E}_0$$

$$\boldsymbol{p} = \frac{3\varepsilon_m\left(\tilde{\boldsymbol{\varepsilon}} - \varepsilon_m\right)}{\left(\tilde{\boldsymbol{\varepsilon}} + 2\varepsilon_m\right)}\boldsymbol{E}_0$$

Clausius-Mossotti

$$\boldsymbol{P} = \frac{3V\varepsilon_m\left(\tilde{\boldsymbol{\varepsilon}} - \varepsilon_m\right)}{\left(\tilde{\boldsymbol{\varepsilon}} + 2\varepsilon_m\right)}\boldsymbol{E}_0 = \frac{4\pi a^3\varepsilon_m\left(\tilde{\boldsymbol{\varepsilon}} - \varepsilon_m\right)}{\left(\tilde{\boldsymbol{\varepsilon}} + 2\varepsilon_m\right)}\boldsymbol{E}_0 = \alpha\boldsymbol{E}_0$$

More in general, for an ellipsoid:



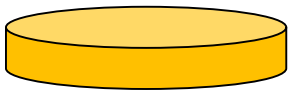
$$N_{ii} = L_i$$

$$\boldsymbol{E}_d = -\frac{1}{\varepsilon_m}\tilde{\boldsymbol{N}}\,\boldsymbol{p} \Rightarrow \tilde{\boldsymbol{\alpha}} = \frac{\left(\tilde{\boldsymbol{\varepsilon}} - \varepsilon_m\tilde{\boldsymbol{I}}\right)\varepsilon_m\tilde{\boldsymbol{I}}}{\varepsilon_m\tilde{\boldsymbol{I}} + \tilde{\boldsymbol{N}}\left(\tilde{\boldsymbol{\varepsilon}} - \varepsilon_m\tilde{\boldsymbol{I}}\right)}$$

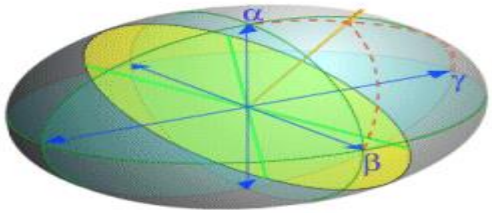
$$L_i = \frac{a_i a_j a_k}{2}\int_0^\infty \left(q + a_i^2\right)^{-\frac{3}{2}}\left(q + a_j^2\right)^{-\frac{1}{2}}\left(q + a_k^2\right)^{-\frac{1}{2}} dq$$

Wavelength dependent corrections to polarizability: modified long-wavelength approximation (MLWA)

Cilindrical disk



Oblate ellipsoid



$$\boldsymbol{E}_d = \int d\boldsymbol{E}_d = \int \left(\frac{3\hat{\boldsymbol{u}}\left(\boldsymbol{P}\cdot\hat{\boldsymbol{u}}\right) - P}{r^3} + i\frac{2\boldsymbol{P}}{3}k^3 + \frac{\hat{\boldsymbol{u}}(\boldsymbol{P}\cdot\hat{\boldsymbol{u}})}{2r}k^2 \right) dV$$

k is the light wave vector modulus, r the distance from the center of the ellipsoid, and $\hat{\boldsymbol{u}}$ a unit vector in the direction of r.

Static depolarization due to a uniform $\boldsymbol{E_0}$ (shape of the nanoparticle) $\rightarrow L_i$

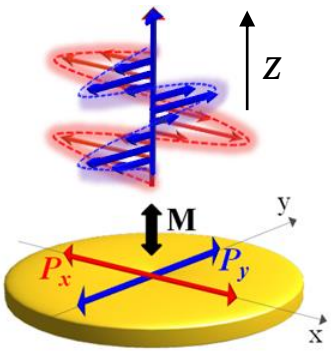
Radiative reaction due to the recoil force (Abraham–Lorentz force) acting on an oscillating dipole emitting electromagnetic radiation

Dynamic depolarization arising from de-phasing of the radiation emitted by different points in the ellipsoid

$$\boldsymbol{E}_d = -\frac{1}{\varepsilon_m}\tilde{\boldsymbol{N}}\ \boldsymbol{p} \qquad N_{ii} = L_i - \frac{Vk^2}{4\pi}D_i - i\frac{Vk^3}{6\pi} \qquad D_i = \int_V \frac{x_i^2 + r^2}{r^2}dV \quad ; x_i = x, y, z$$

N. Maccaferri et al., Opt. Express **21**, 9875-89 (20113)

It is a phase business

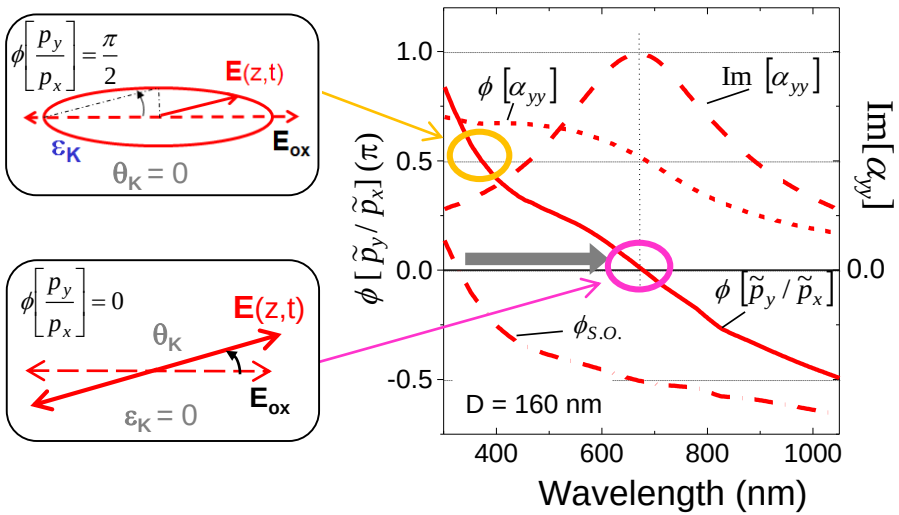


The polarization of the far-field radiated in the z-direction by these two mutually orthogonal oscillating electric dipoles is given by the ratio

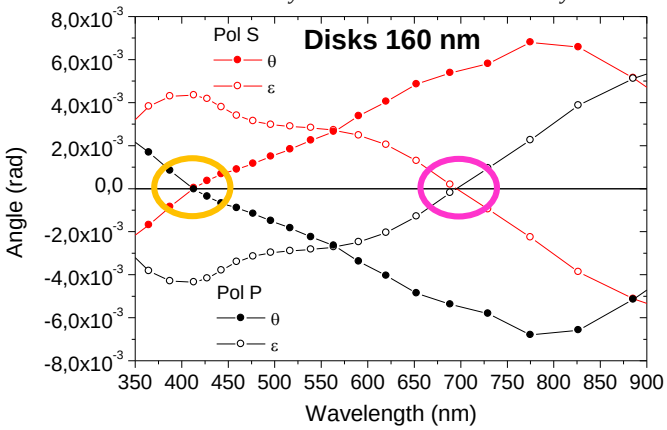
$$\frac{\tilde{p}_y}{\tilde{p}_x} = \frac{\varepsilon_{yx}\alpha_{yy}}{(\varepsilon-\varepsilon_m)^2}$$

Phase difference between the two radiating dipoles p_x and p_y

$$\Delta\phi = \phi\left[\frac{p_y}{p_x}\right] = \phi\left[\frac{\varepsilon_{yx}}{(\varepsilon-\varepsilon_m)^2}\right] + \phi[\alpha_{yy}] = \phi_{S.O.} + \phi_{\alpha_{yy}}$$



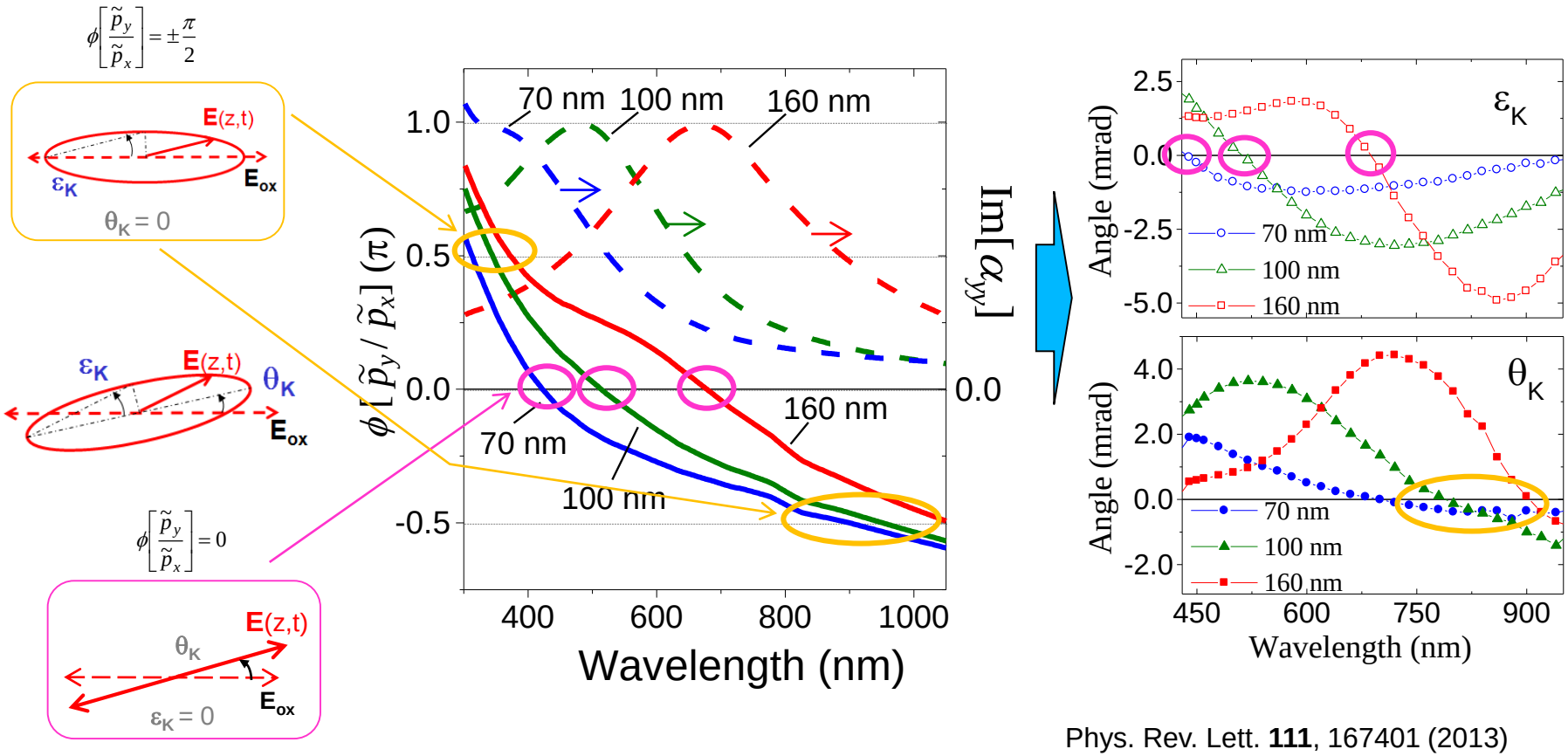
Kerr rotation and ellipticity spectra for an isolated nanostructure $\theta_K = Re[p_y/p_x]$ and $\varepsilon_K = Im[p_y/p_x]$.



Phys. Rev. Lett. **111**, 167401 (2013)

It is a phase business

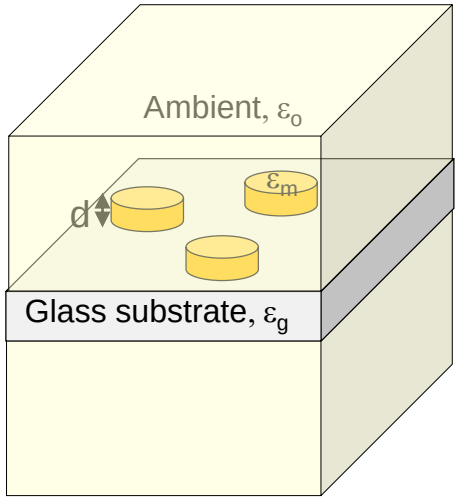
$$\frac{\tilde{p}_y}{\tilde{p}_x} = \frac{\varepsilon_{yx}\alpha_{yy}}{(\varepsilon-\varepsilon_m)^2} \quad \Rightarrow \quad \Delta\phi = \phi\left[\frac{\tilde{p}_y}{\tilde{p}_x}\right] = \phi\left[\frac{\varepsilon_{yx}}{(\varepsilon-\varepsilon_m)^2}\right] + \phi[\alpha_{yy}] = \phi_{S.O.} + \phi_{\alpha_{yy}}$$



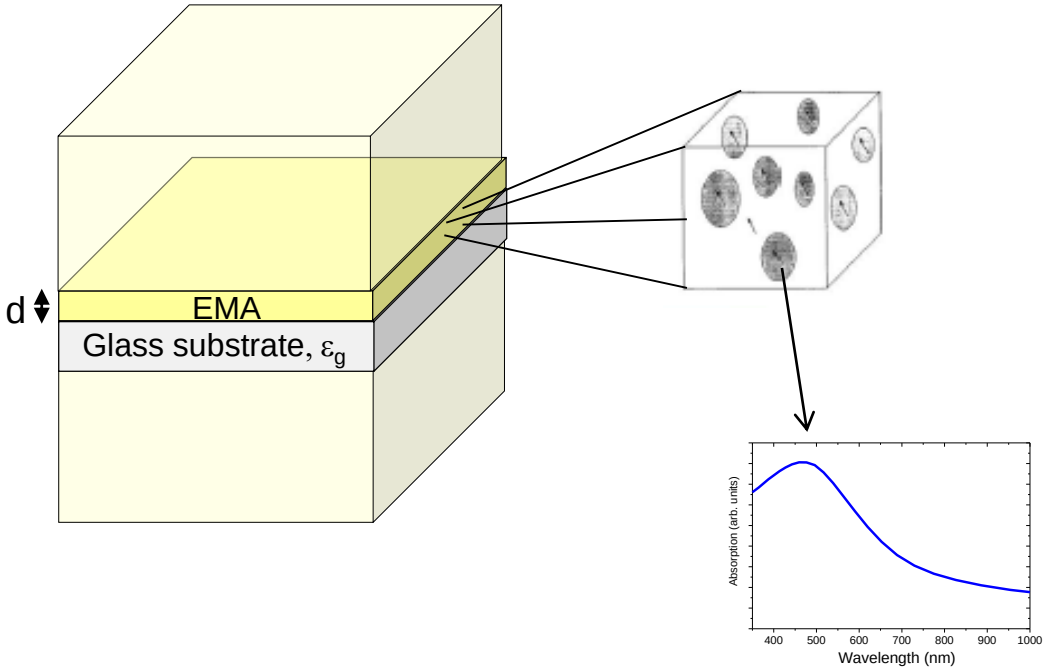
Phys. Rev. Lett. **111**, 167401 (2013)

Modeling the spectra

Our system



Model system

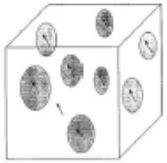


Modeling the spectra: steps 2&3

Step 2 (far-field)

Effective medium approximation (EMA)

Fictitious MO film



$$\tilde{\varepsilon}_{ef} = \tilde{\varepsilon}_1 + f(\tilde{\varepsilon}_2 - \tilde{\varepsilon}_1)\left[\tilde{\mathbf{1}} + (1-f)\left(\tilde{\mathbf{L}} - \frac{k^2V}{4\pi}\tilde{\mathbf{D}} - \frac{ik^3V}{6\pi}\tilde{\mathbf{1}}\right)(\tilde{\varepsilon}_2 - \tilde{\varepsilon}_1)\varepsilon_1^{-1}\right]^{-1}$$

$$R = \begin{pmatrix} r_{s\to s} & r_{p\to s} \\ r_{s\to p} & r_{p\to p} \end{pmatrix}$$

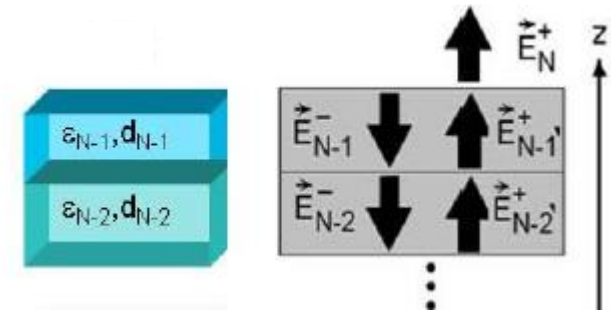
$$\theta_K \quad \mathrm{Re}\left[\frac{r_{sp}}{r_{pp}}\right] \quad \mathrm{Re}\left[\frac{r_{ps}}{r_{ss}}\right]$$

$$\varepsilon_K \quad \mathrm{Im}\left[\frac{r_{sp}}{r_{pp}}\right] \quad \mathrm{Im}\left[\frac{r_{ps}}{r_{ss}}\right]$$

D. Stroud, Phys. Rev. **B 12** (8), 3368 (1975)
M. Abe, Phys. Rev. **B 53** (11), 7065 (1996)
M. Abe and T. Suwa, Phys. Rev. **B 70**, 235103 (2004)

Step 3 (far-field including substrate)

Transfer matrix method (multilayers)



Complete system

$$R = \begin{pmatrix} r_{s\to s} & r_{p\to s} \\ r_{s\to p} & r_{p\to p} \end{pmatrix}$$

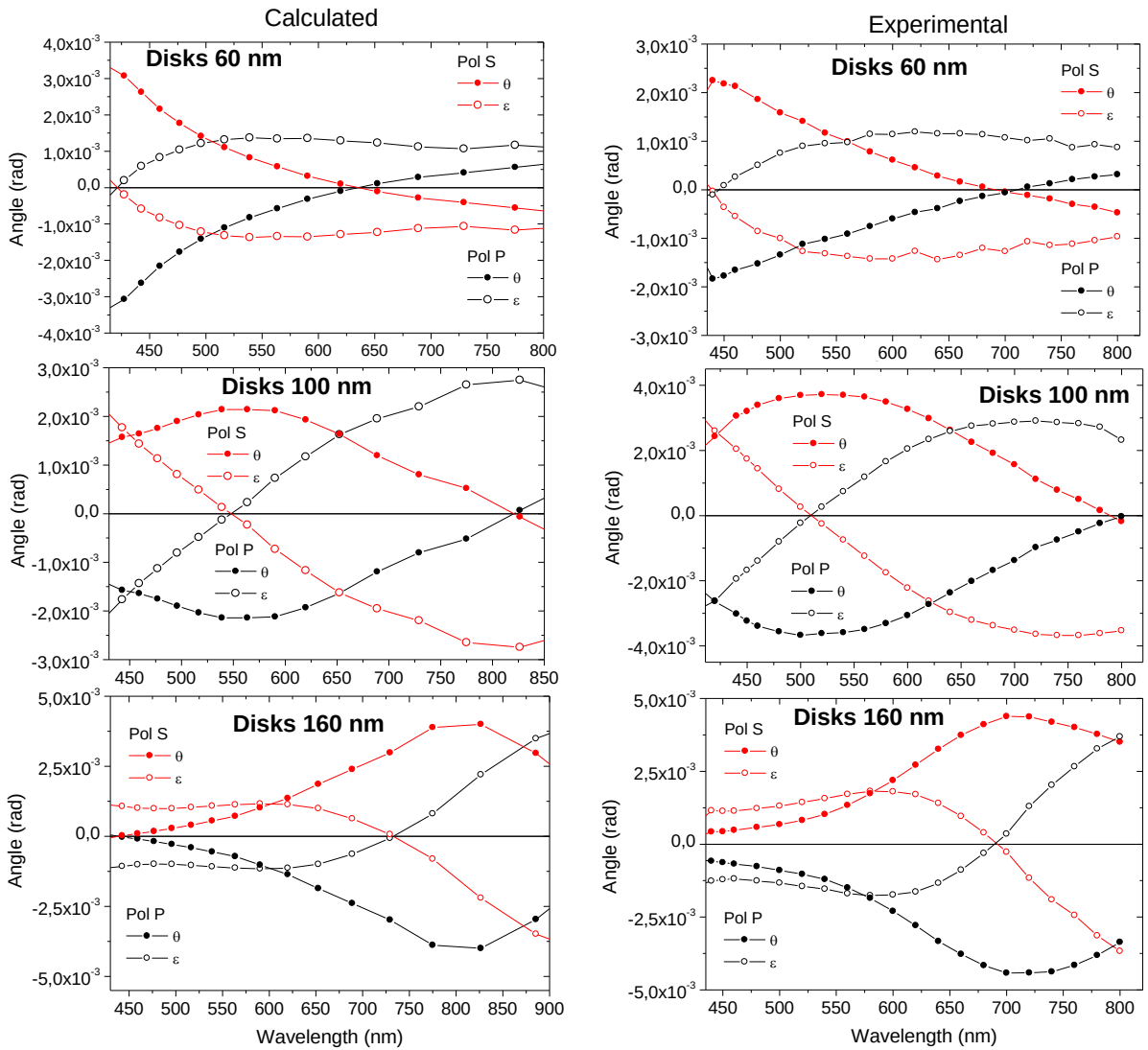
$$\theta_K \quad \mathrm{Re}\left[\frac{r_{sp}}{r_{pp}}\right] \quad \mathrm{Re}\left[\frac{r_{ps}}{r_{ss}}\right]$$

$$\varepsilon_K \quad \mathrm{Im}\left[\frac{r_{sp}}{r_{pp}}\right] \quad \mathrm{Im}\left[\frac{r_{ps}}{r_{ss}}\right]$$

M. Schubert, T. E. Tiwald and J. A. Woollam, Applied Optics **38** (1), 177 (1999)
J. Zak, E. R. Mook, C. Liu and S. D. Bader, JMMM **89**, 107 (1990)
S. Visnovsky et al., Optics Express **9** (3), 121 (2001)

N. Maccaferri et al., Opt. Express 21, 9875-89 (2013)
N. Maccaferri et al., Phys. Stat. Solidi (a) (2014)

Response of an ensemble of such oscillators randomly distributed on a glass substrate (EMA)



Agreement between calculated and experimental spectra is almost perfect!

No adjustable parameters:

tabuled optical and MO constants;

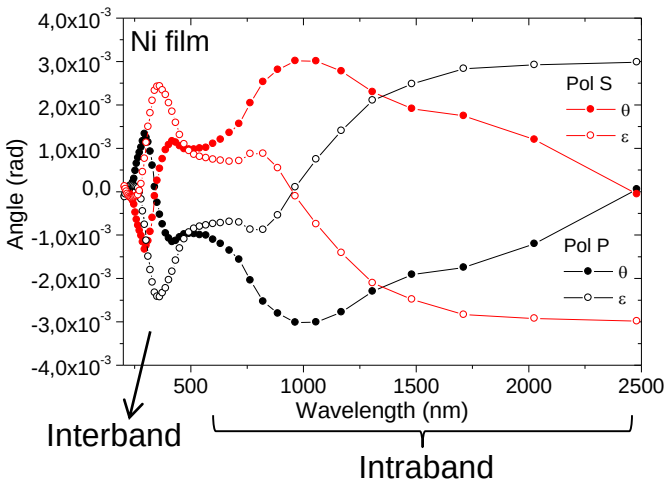
sizes and nanoantennae density from SEM images

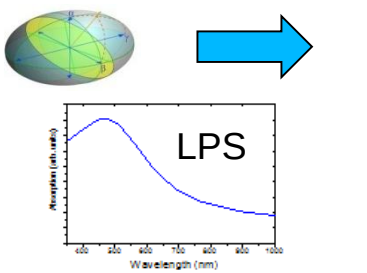
N. Maccaferri et al.,
Opt. Express **21**, 9875-89 (2013)

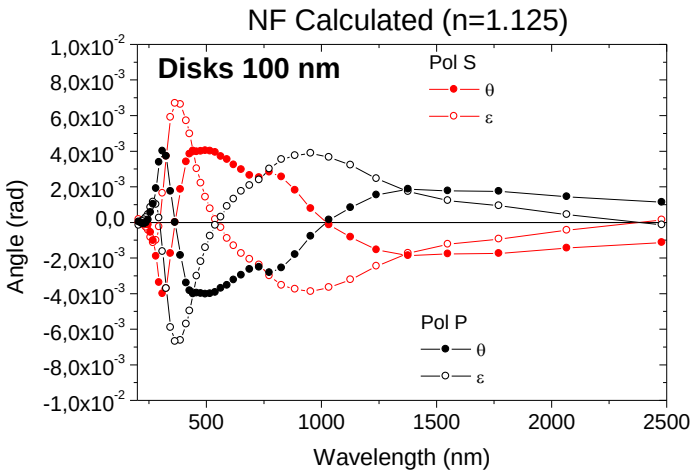
Substrate plays a role

N. Maccaferri et al.,
Phys. Status Solidi A **211,** 1067-75 (2014)

Phase adjustment: spectral features redistribution

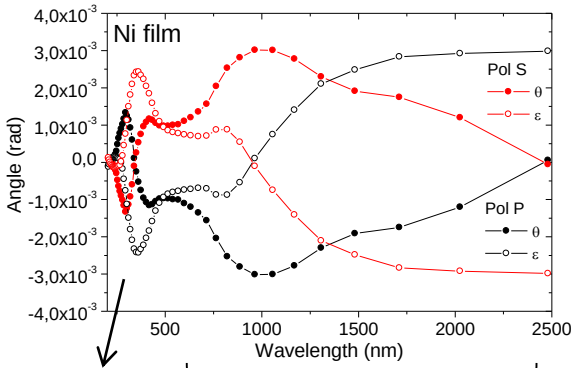


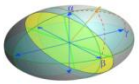




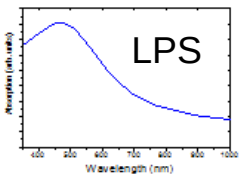
❑ Confinement (LSPR) – redistribution (blue shift) of the main spectral features due to intraband transitions (material properties, θ and ε linked via Kramers-Kronig relations)

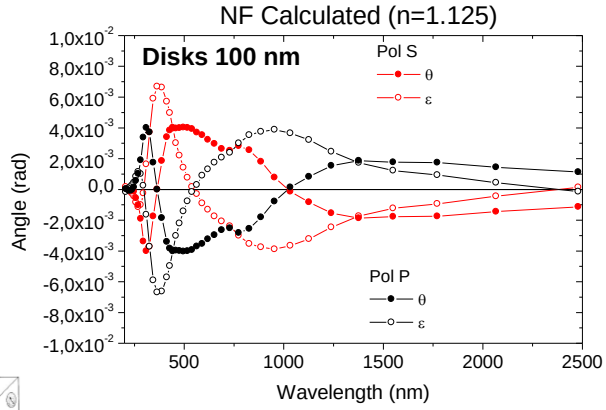
Let's have a look at the individual steps





Confinement

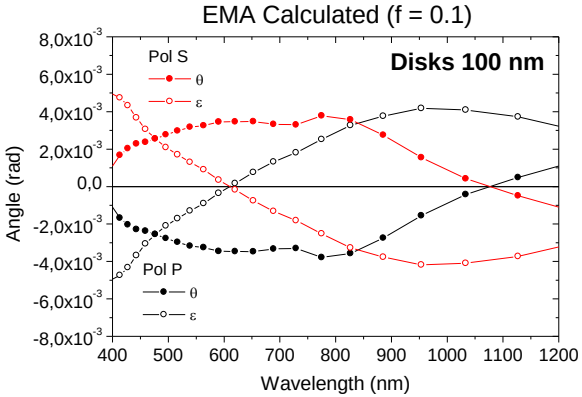




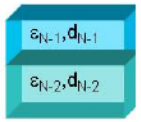
Step 1

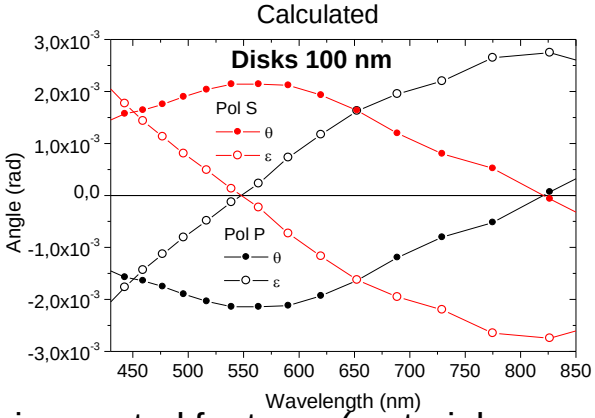
Far field

Step 2



Substrate



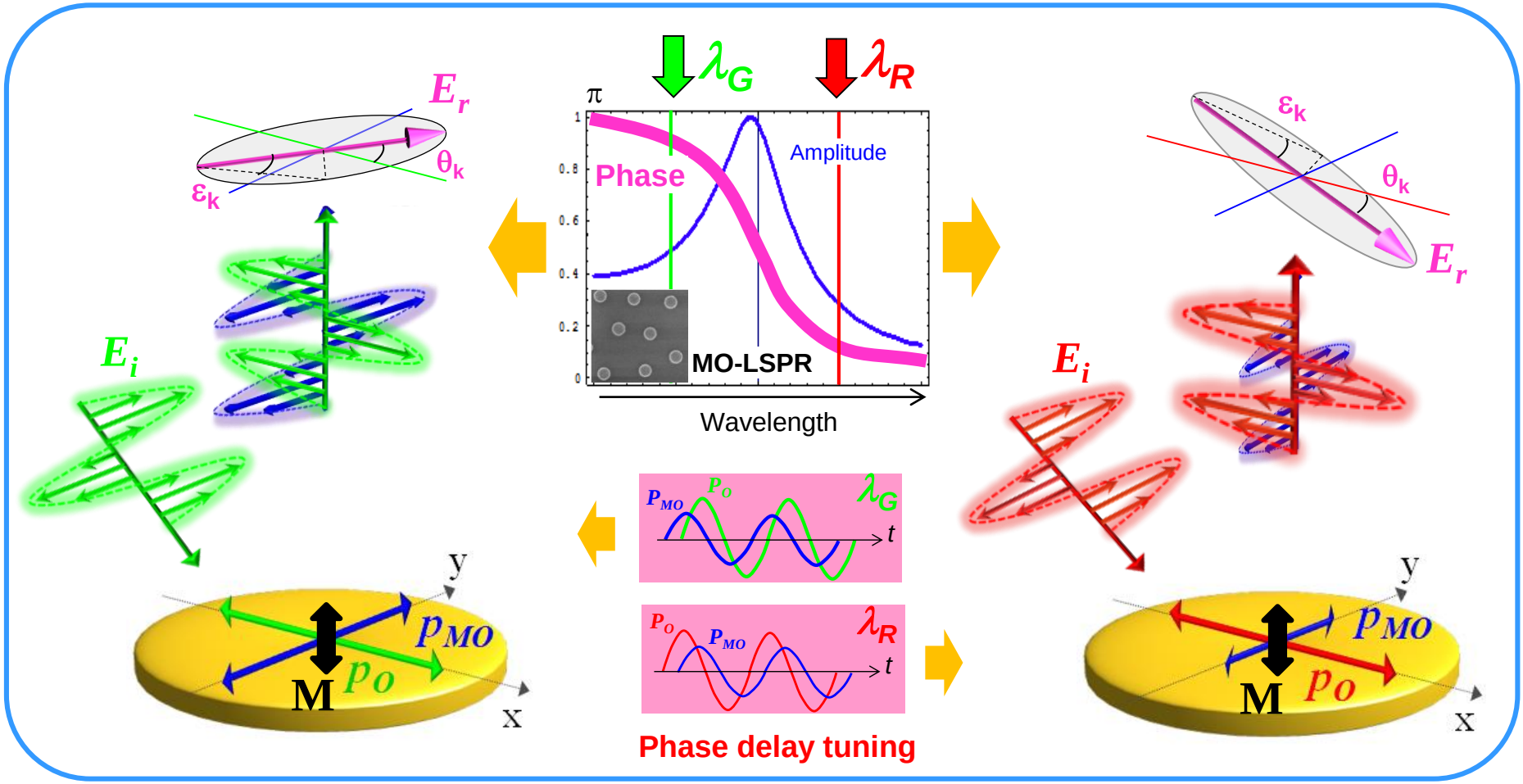


Step 3

- ❑ Confinement (LSPR) – redistribution (blue shift) of the main spectral features (material properties, θ and ε linked via Kramers-Kronig relations)
- ❑ Substrate – reduction of MOKE contrast and slight additional blue shift of the spectral features

Phys. Rev. Lett. **111**, 167401 (2013); Phys. Status Solidi A **211,** 1067-75 (2014)

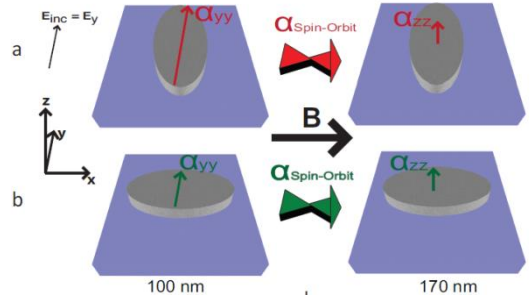
Summary for an individual magnetic nano-antenna



The concerted action of LSPRs and MO activity allows for the controlled manipulation of Kerr rotation/ellipticity of ferromagnetic nanostructures (beyond intrinsic material properties). Phys. Rev. Lett. **111**, 167401 (2013)

Control of magneto-optics via magnetoplasmonic anisotropy

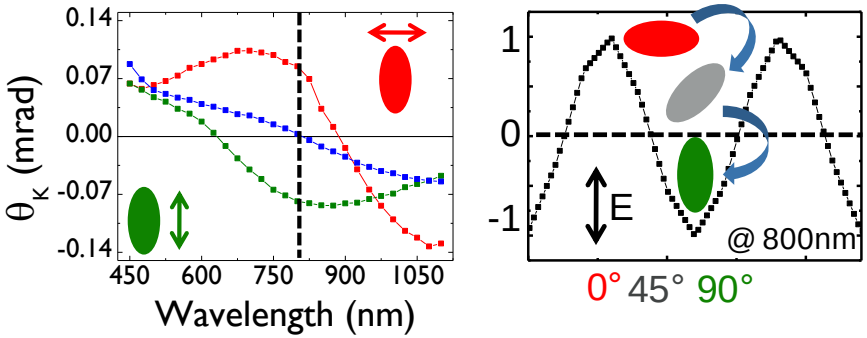
Active tuning



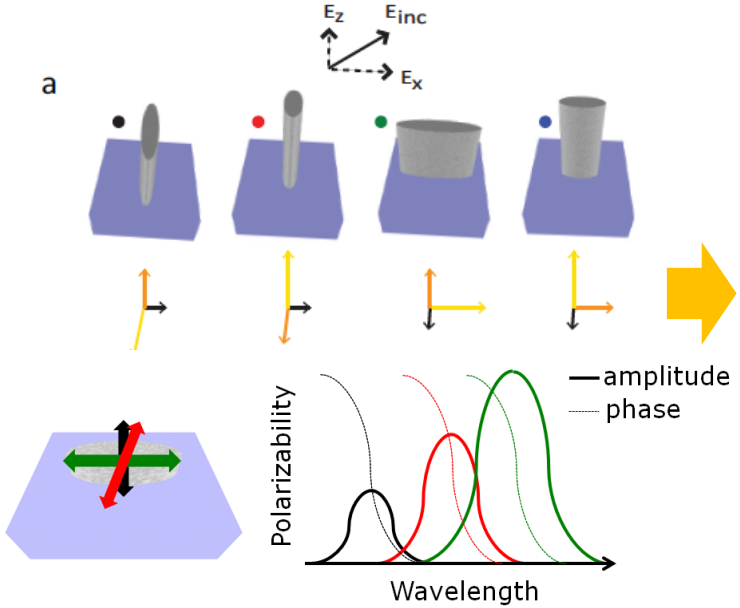
Shape engineering

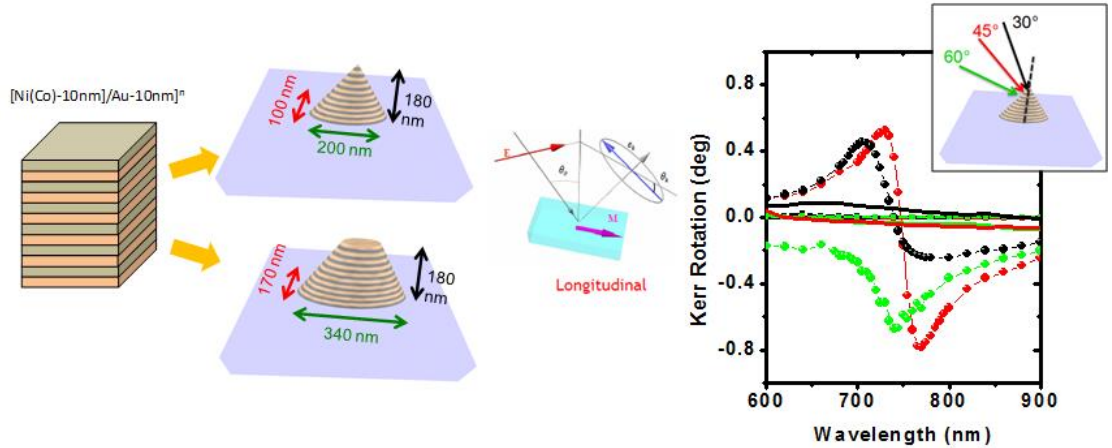
L-MOKE

170/240 nm; t = 30 nm



MO enhancement (3D structures)



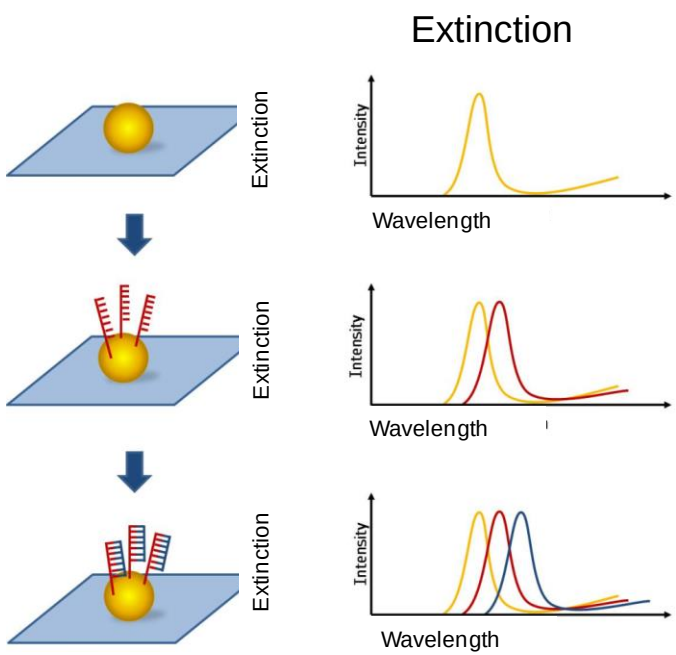


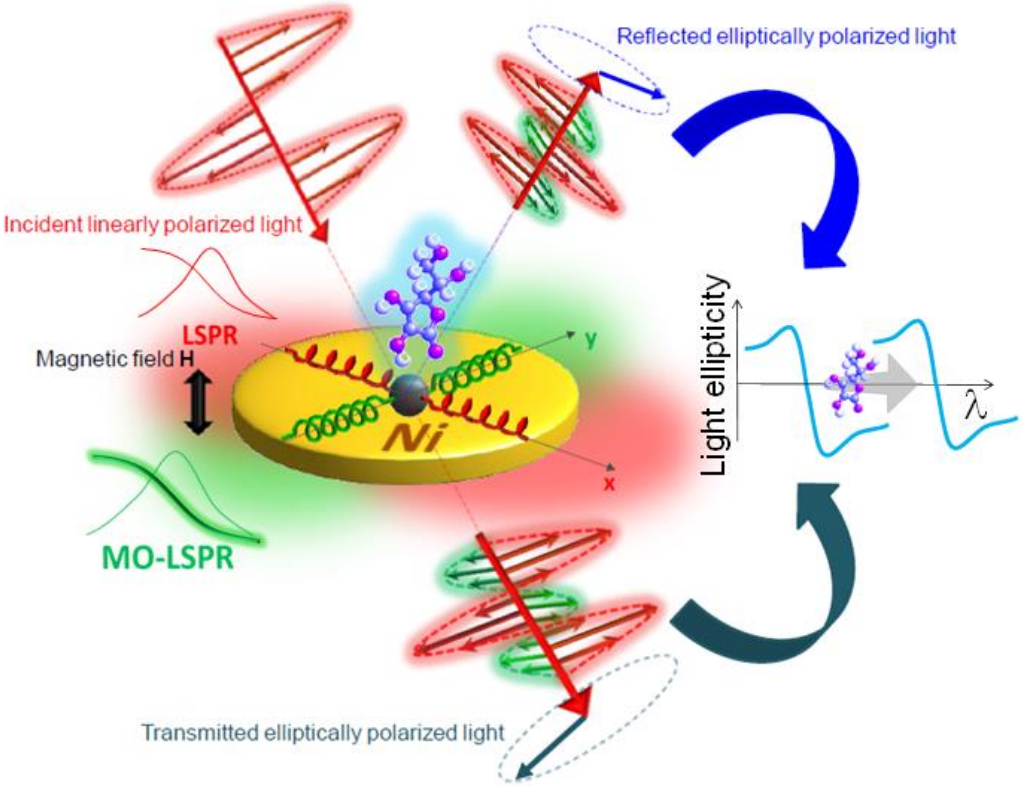
"Magnetoplasmonic design rules for active magneto-optics"

Enhancement by a factor of 20

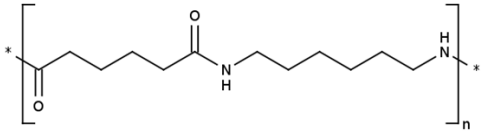
Nano Letters **14**, 7207 (2014)

LPRS phase-sensitivity in the reflected/transmitted light polarization





ALD deposition



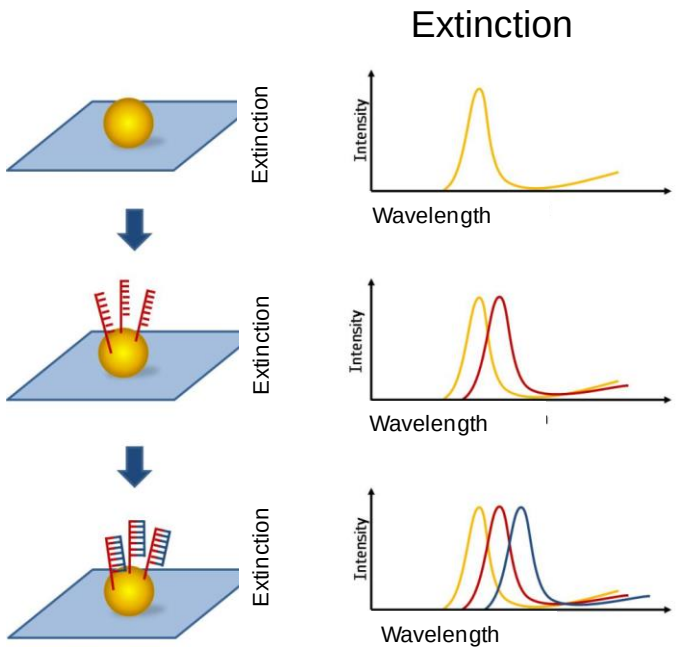
Nylon 66 (n =1.51)

Min $\Delta\lambda$ detectable ~ 0.5 nm

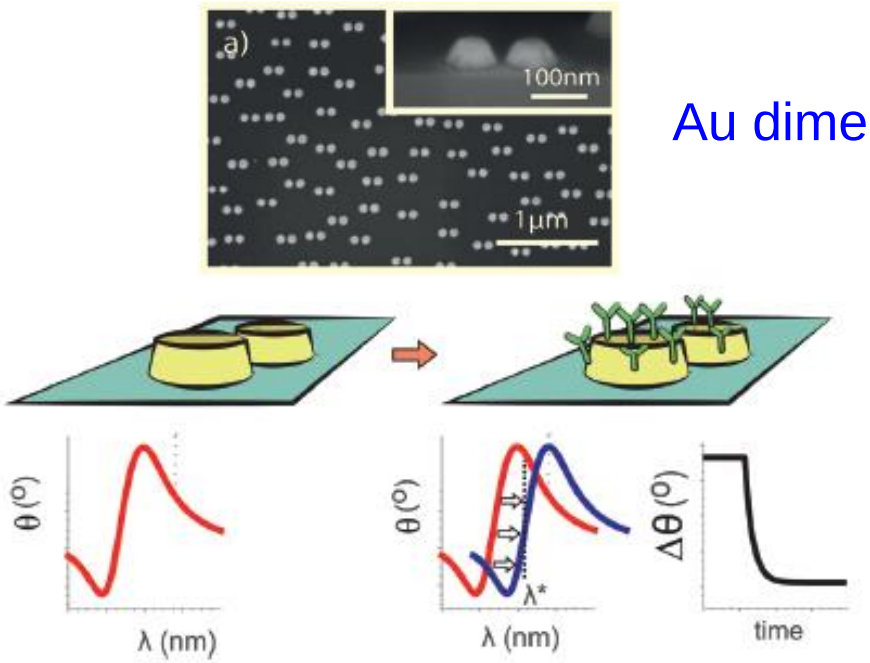
$$\Delta t_{Min} = \frac{1}{10} ML \text{ of PA-6.6}$$

N. Maccaferri et al., Nature Commun. **6**, 6150 (2015)

LPRS phase-sensitivity in the reflected/transmitted light polarization

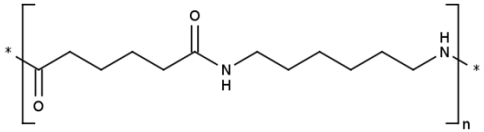


R. Verre et al. Nanoscale 8, 10576 (2016)



Au dimers

ALD deposition



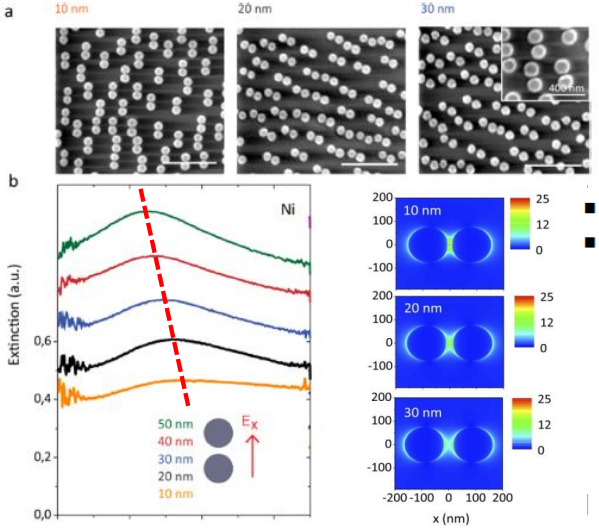
Nylon 66 (n =1.51)

Min $\Delta\lambda$ detectable ~ 0.5 nm

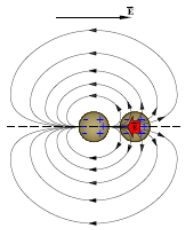
$$\Delta t_{Min} = \frac{1}{10} ML \text{ of PA-6.6}$$

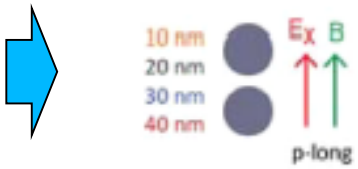
Near field interactions: Magnetoplasmonic ruler

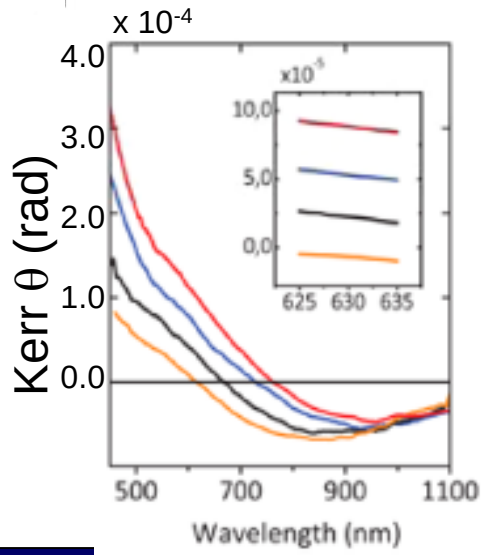
Plasmon ruler is an emerging concept where strong near-field coupling of plasmon nanoantenna elements is employed to obtain the structural information at the nanoscale (nanoscale distances).



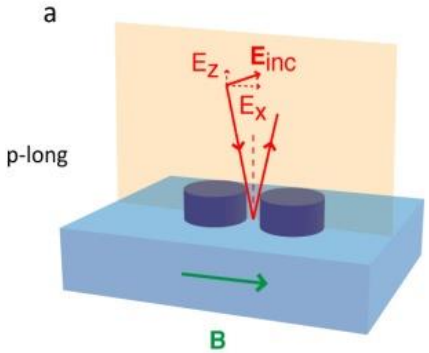
- *Reduced* restoring force
- LSPR red-shifted

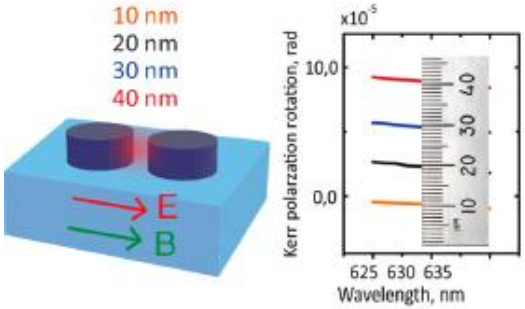






Magnetoplasmonic ruler concept





MP ruler: two orders of magnitude higher precision compared to the state-of-the-art plasmon rulers.

Nano Letters ***15***, *3204 (2015)*

Outline

NANOANTENNAs COMBINING MAGNETIC AND PLASMONIC FUNCTIONALITITES

- *Localized surface plasmons & Magneto-optical Kerr effects (MOKE): Introduction*
- *Physical picture and modeling*
- *LSPR-based sensing: Towards molecular sensing*
- *Photonics technology: control of the non-reciprocal light propagation*

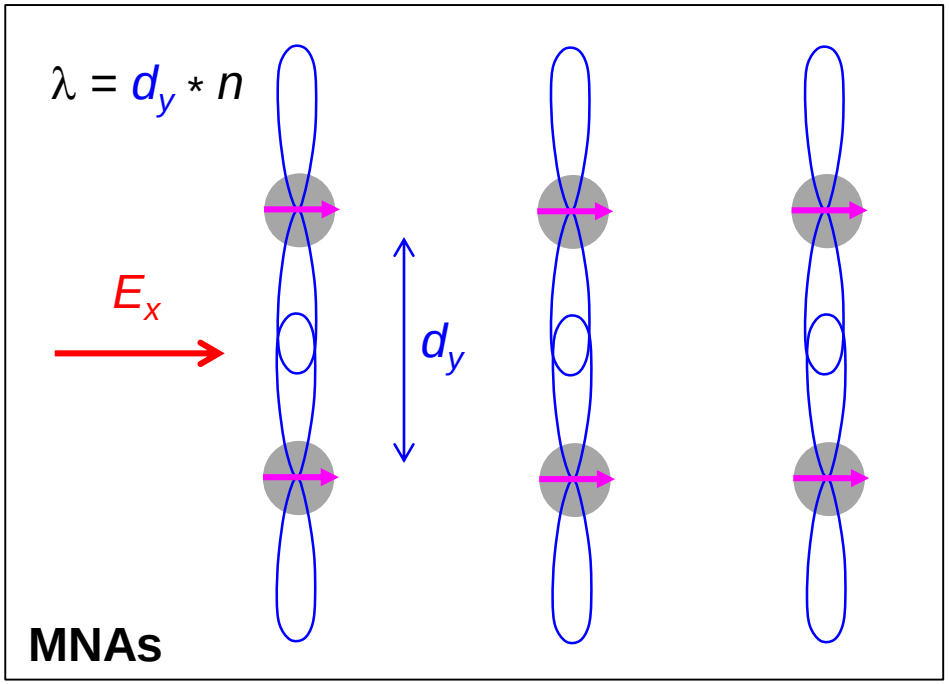
MAGNETOPLASMONIC METAMATERIALS

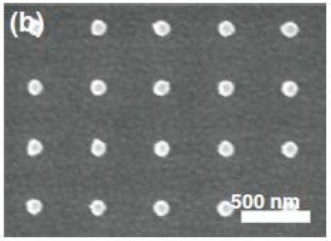
- *Surface lattice resonances in arrays of nanoantennae*
- *Arrays of elliptical nanoantennae*
- *Magnetoplasmonic gratings: arrays of antidots*

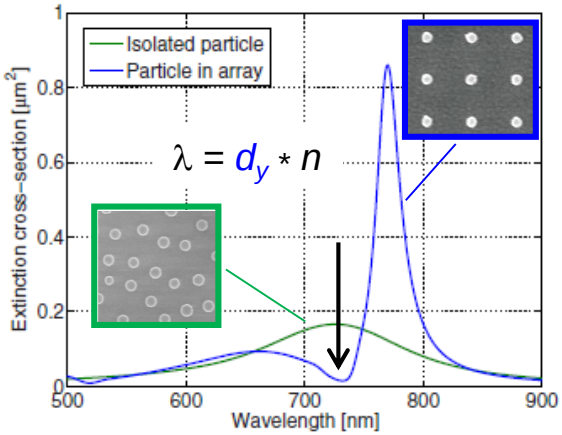
CONCLUSIONS

Reduced plasmon radiative damping – Fano-like resonance

Ordered arrays of metallic nano-antennas (MNAs) placed in symmetric or quasi-symmetric refractive index environment exhibit **surface lattice resonances** (**SLRs**) *which arise from diffraction-induced coupling between LSPRs of the MNAs*.



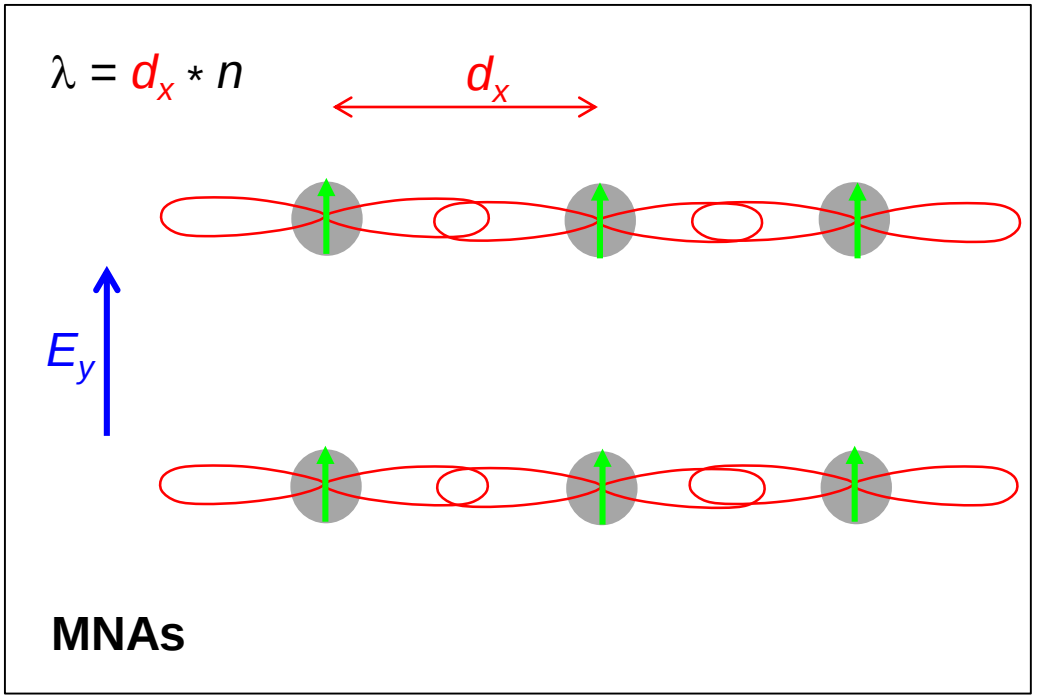


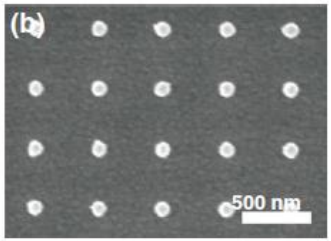


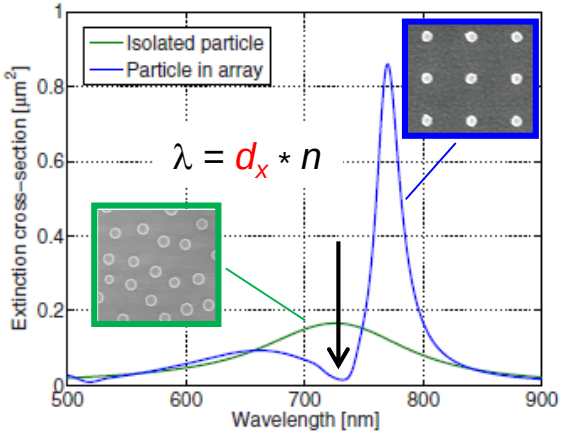
This coupling may result in significant reduction of plasmon radiative damping, and therefore, narrowing of plasmon resonance, which is of interest for plasmon based sensors.

Reduced plasmon radiative damping – Fano-like resonance

Ordered arrays of metallic nano-antennas (MNAs) placed in symmetric or quasi-symmetric refractive index environment exhibit **surface lattice resonances** (**SLRs**) *which arise from diffraction-induced coupling between LSPRs of the MNAs*.







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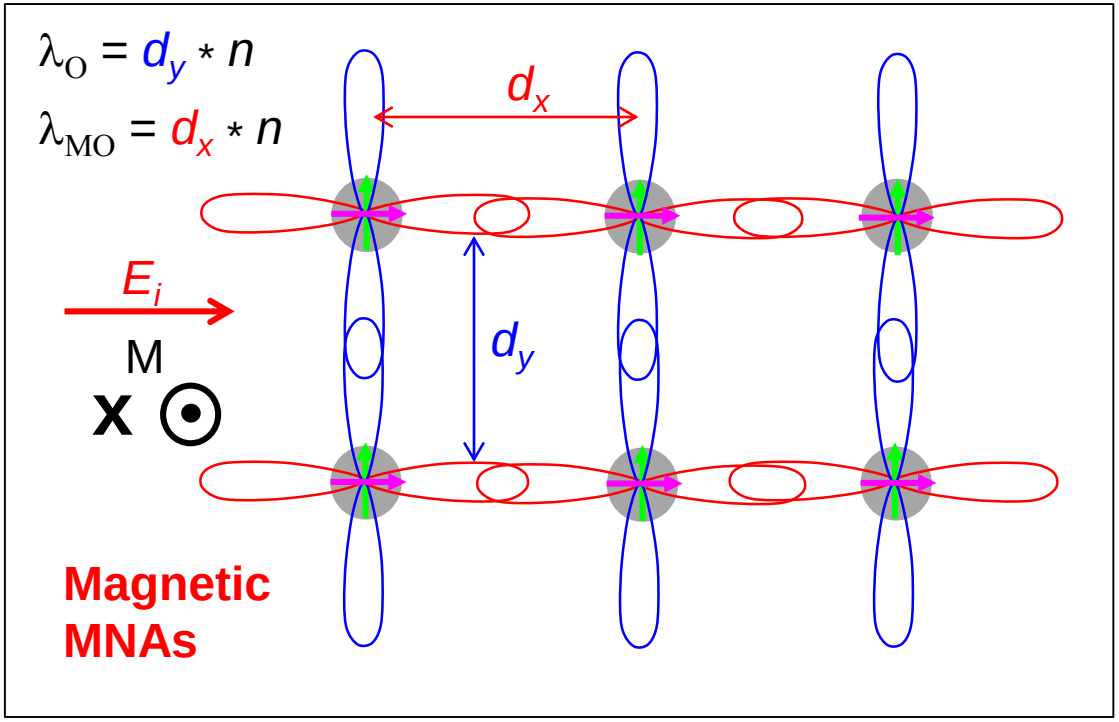
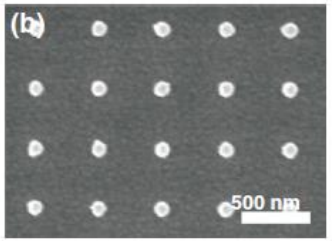
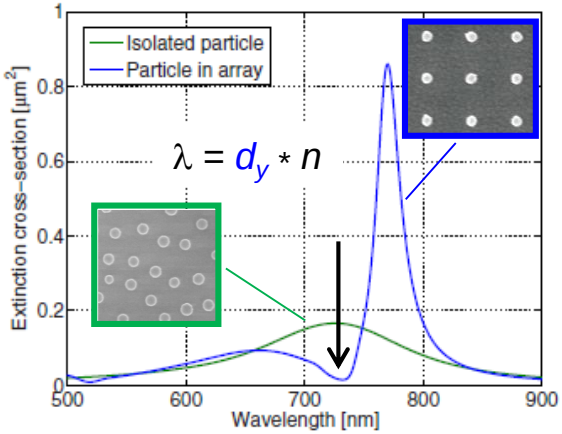
Arrays of magnetoplasmonic nanoantennas

Ordered arrays of metallic nano-antennas (MNAs) placed in symmetric or quasi-symmetric refractive index environment exhibit **surface lattice resonances** (**SLRs**) *which arise from diffraction-induced coupling between LSPRs of the MNAs*.





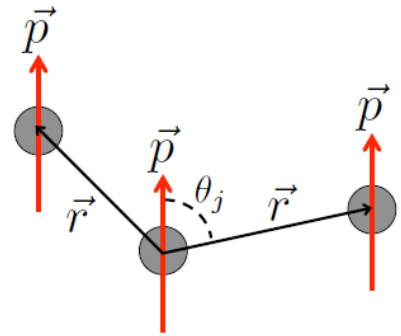


This coupling may result in significant reduction of plasmon radiative damping, and therefore, narrowing of plasmon resonance which is of interest for plasmon based sensors.

From random to ordered arrays: Polarizability

$$\vec{p}_{\text{single}} = \alpha \vec{E}_{\text{inc}}$$

$$\alpha^* = \frac{1}{1/\alpha - S}$$



$$\vec{p}_{\text{arr}} = \frac{1}{(1/\alpha - S)} \vec{E}_{\text{inc}}$$

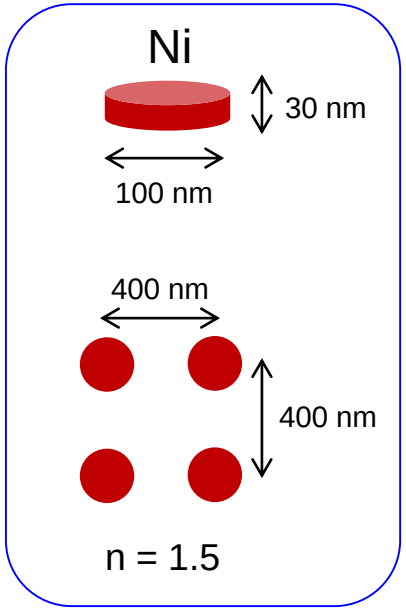
SLRs occur when

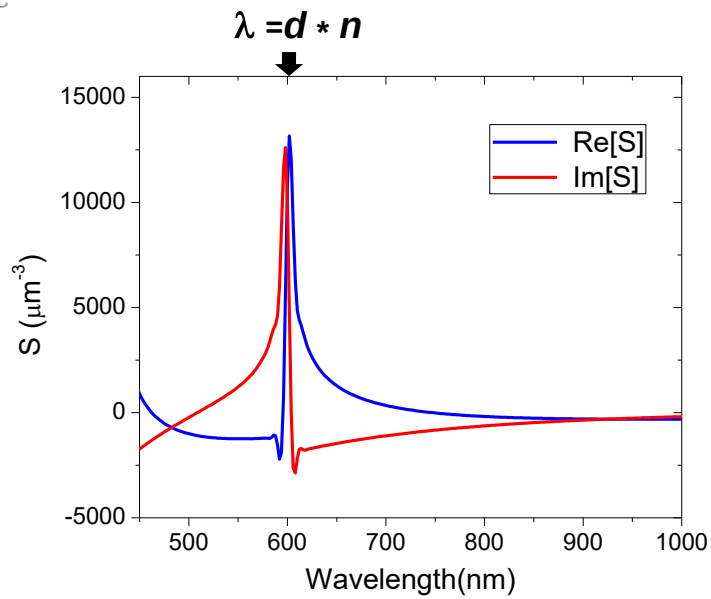
$$\frac{1}{\alpha} = S$$ ➡ **λ = *d* ∗ *n***

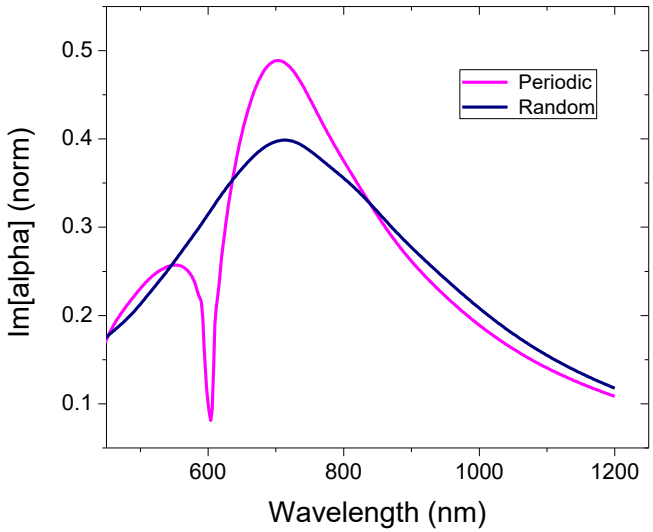
How does *S* depend on lattice?

$$S = \sum_j \exp(ikr_j) \left[\frac{(1 - ikr_j)(3\cos^2\theta_j - 1)}{r_j^3} + \frac{k^2 \sin^2\theta_j}{r_j} \right]$$

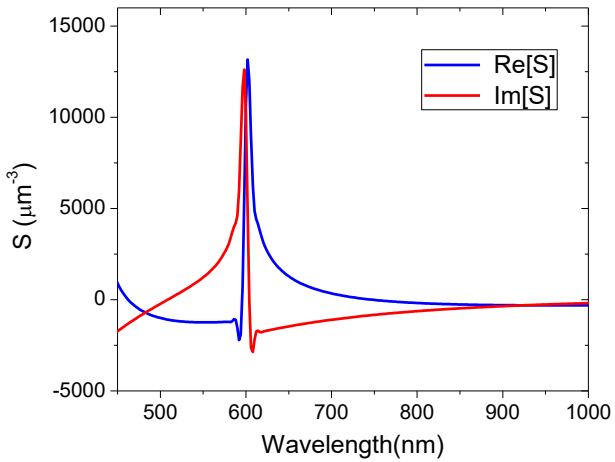
$$\vec{p}_{\text{arr}} = \alpha^* \vec{E}_{\text{inc}}$$

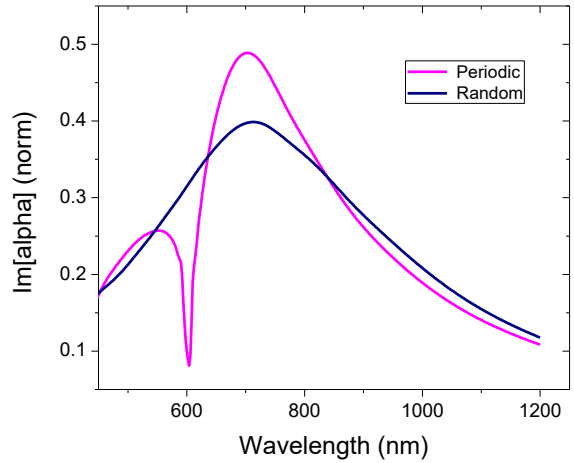






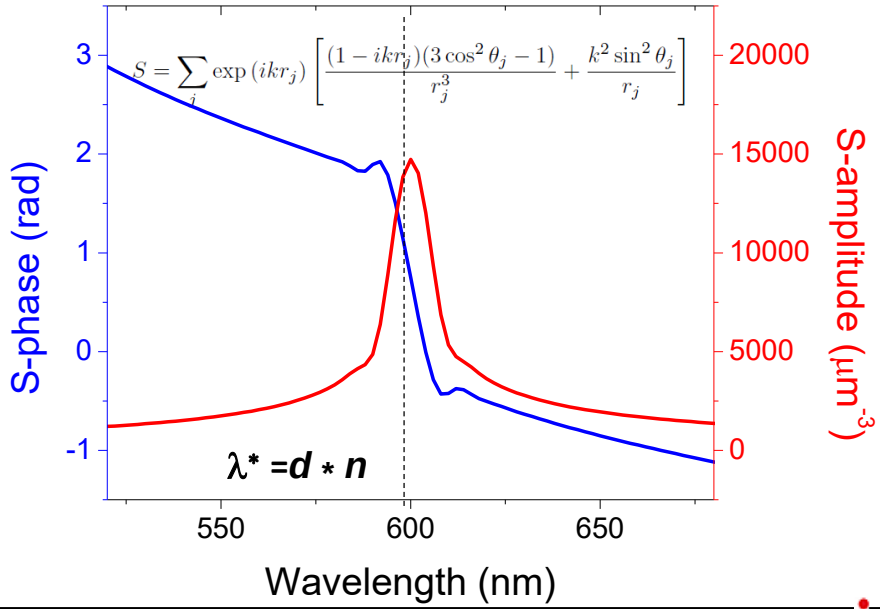
On the origin of SLMs





The S coupling factor shows a suddend and large phase change around λ*.

Constructive/destructive interference.



On the origin of SLMs

$$\alpha^* = \frac{1}{1/\alpha - S}$$

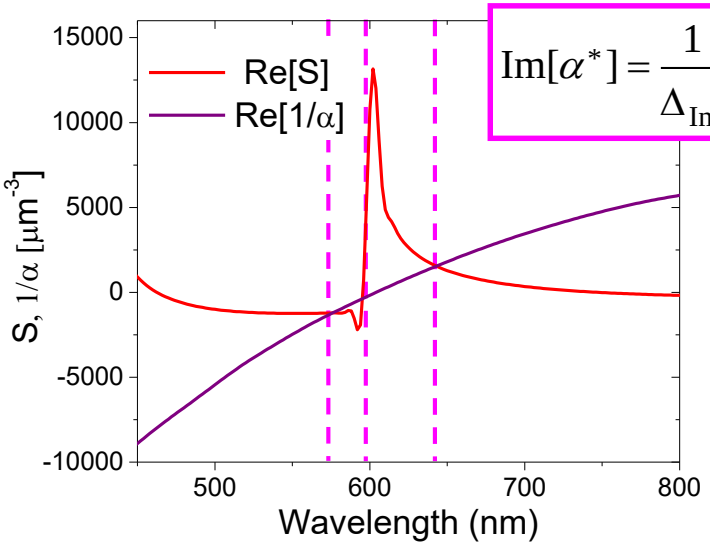
$$\mathrm{Im}[\alpha^*] = \frac{\Delta_{\mathrm{Im}}}{\Delta_{\mathrm{Re}}^2 + \Delta_{\mathrm{Im}}^2}$$

$$\Delta_{\mathrm{Re}} = \mathrm{Re}[1/\alpha] - \mathrm{Re}[S]$$

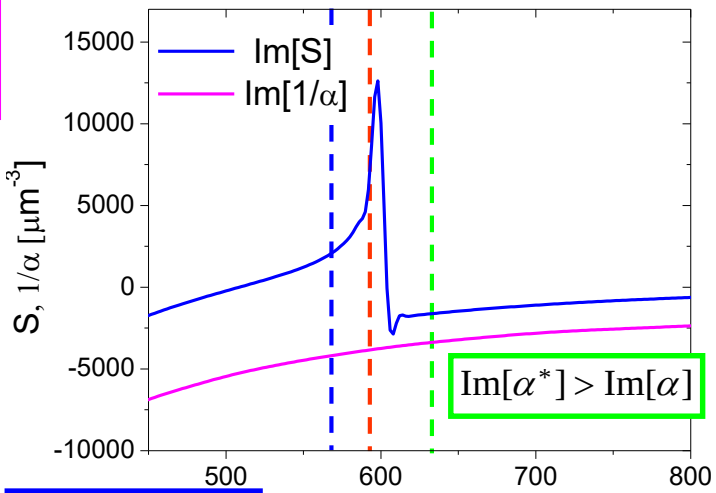
$$\Delta_{\mathrm{Im}} = \mathrm{Im}[S] - \mathrm{Im}[1/\alpha]$$

Resonance position mainly determined by crossing points of real parts.

$$\mathrm{Im}[\alpha^*] = \frac{1}{\Delta_{\mathrm{Im}}}$$



Strength of resonance determined by difference between imaginary parts

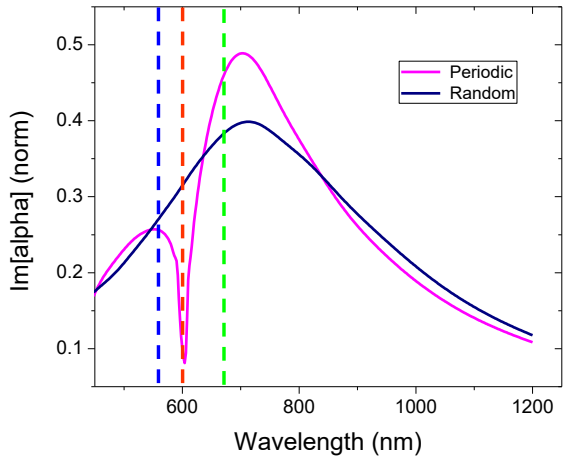


$$\mathrm{Im}[\alpha^*] > \mathrm{Im}[\alpha]$$

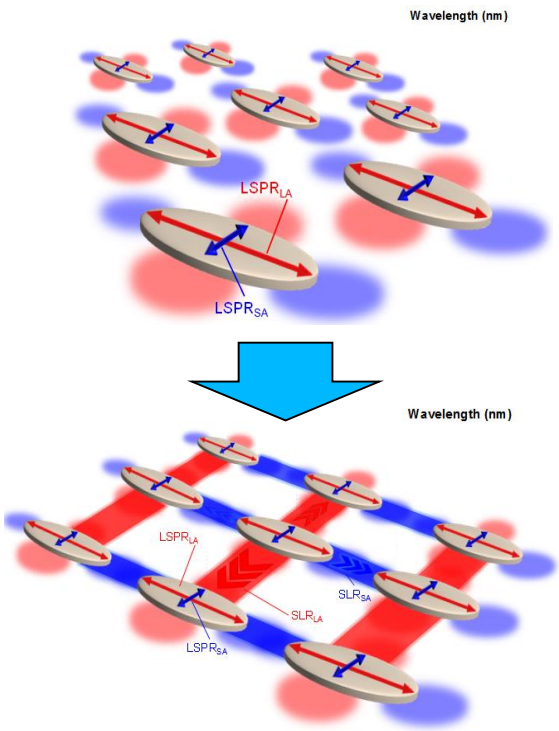
$$\mathrm{Im}[\alpha^*] \geq \mathrm{Im}[\alpha]$$

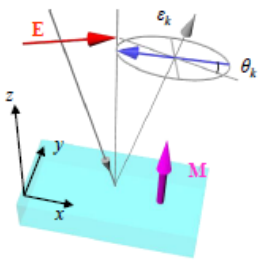
$$\mathrm{Im}[\alpha^*] << \mathrm{Im}[\alpha]$$

$\lambda \approx d * n$



From random to ordered arrays: MP crystals

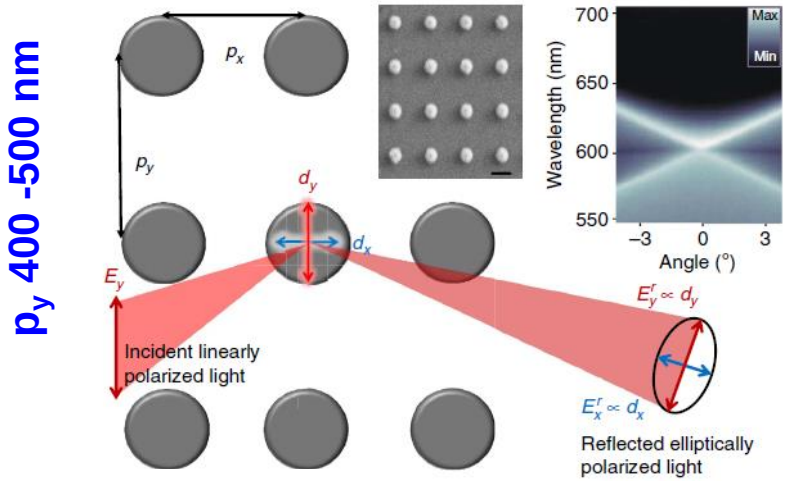




Polar

Material: Py; Lattice parameters: p_x 400 nm p_y 400 -500 nm

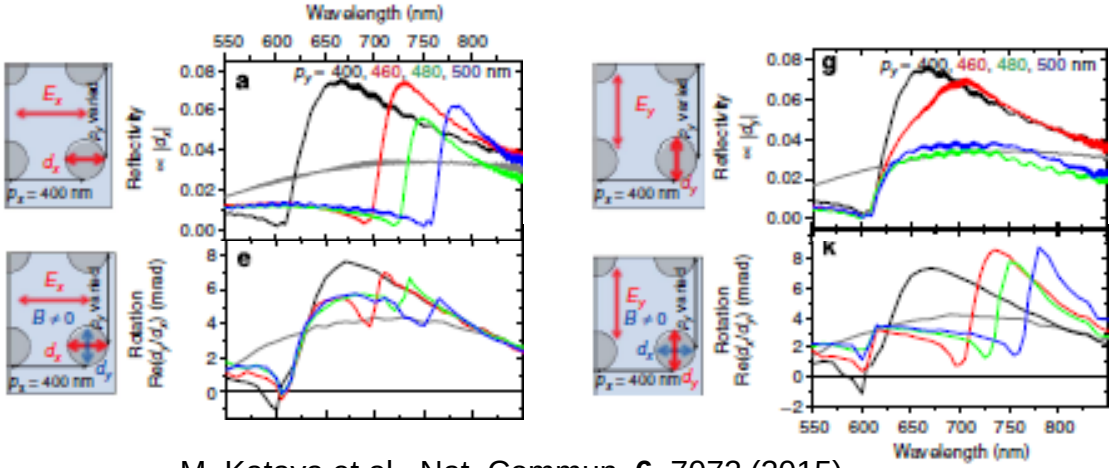
Refractive index matching oil (n = 1.5)



p_x 400 nm

Exct.

θ_K

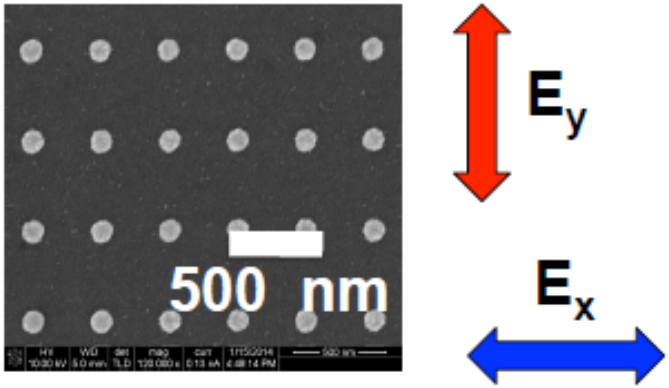


M. Kataya et al., Nat. Commun. **6**, 7072 (2015)

Rectangular arrays

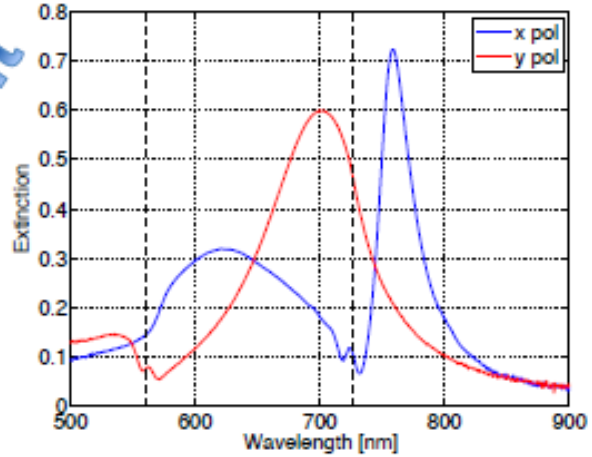
- Index matched to give homogeneous environment.

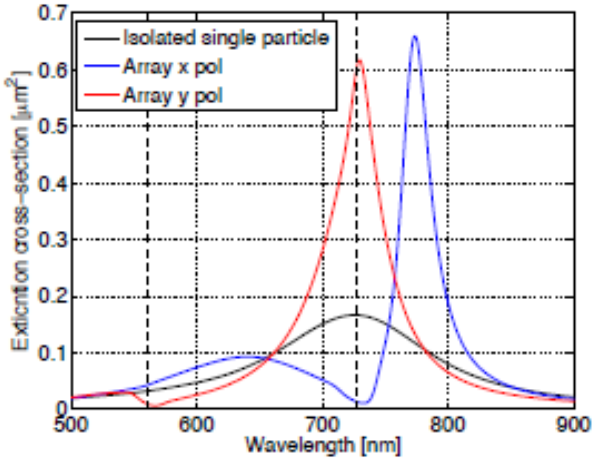
a_y=480 nm



a_x=370 nm

Experiment

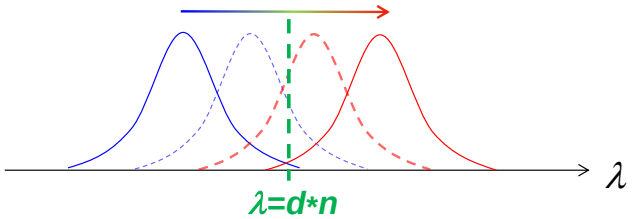


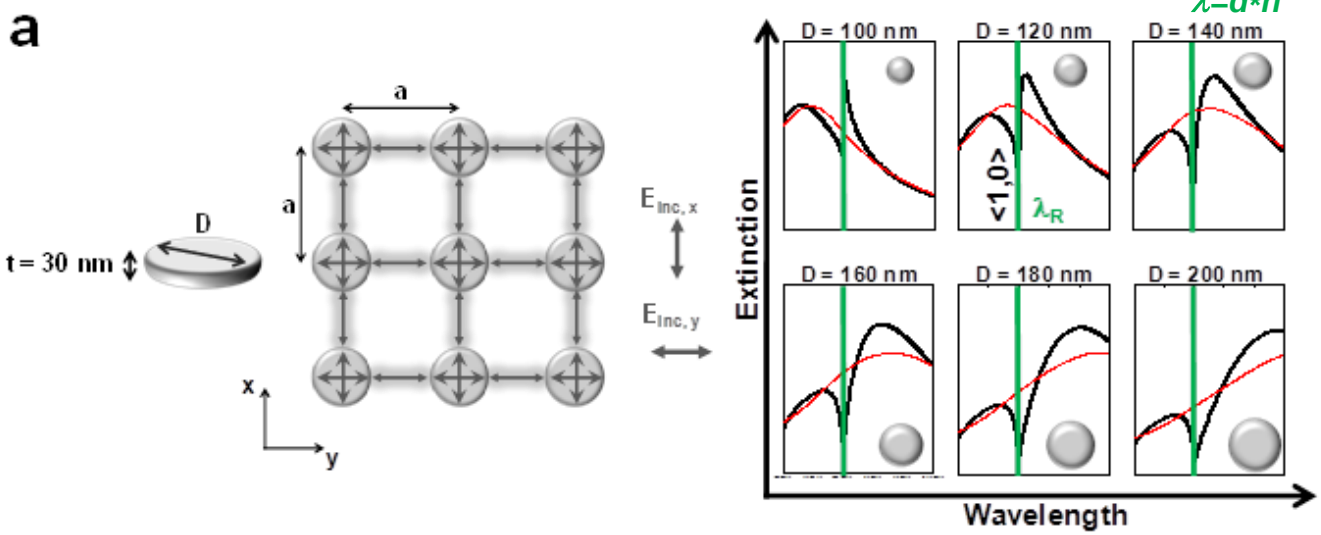


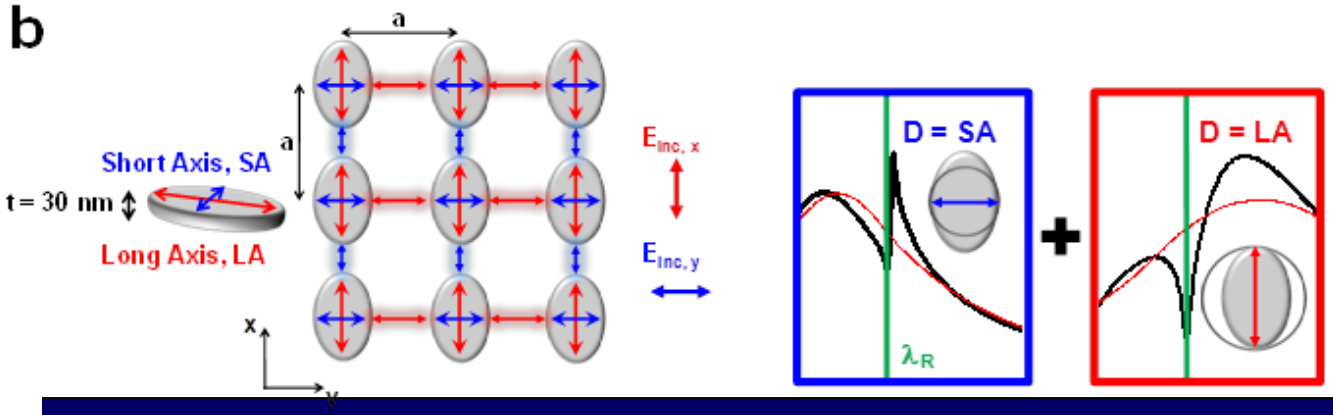
Model

Relative position of the LSPR and the diffractive interference

Resonance lineshape evolution varying the relative position of the LSPR with respect to the Rayleigh's anomaly



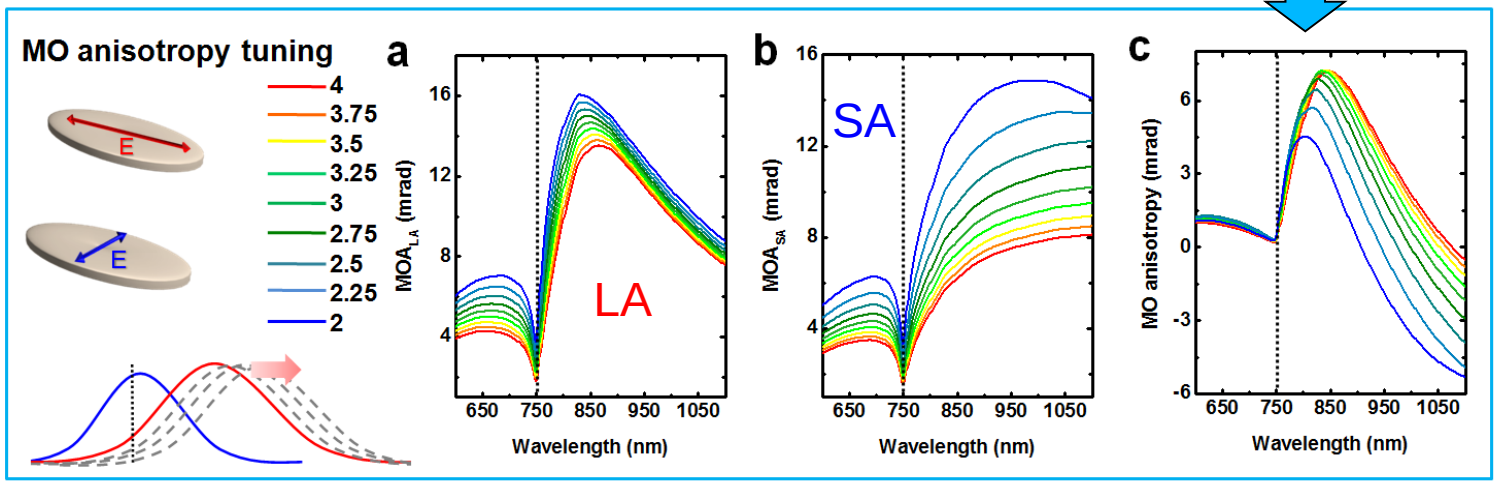


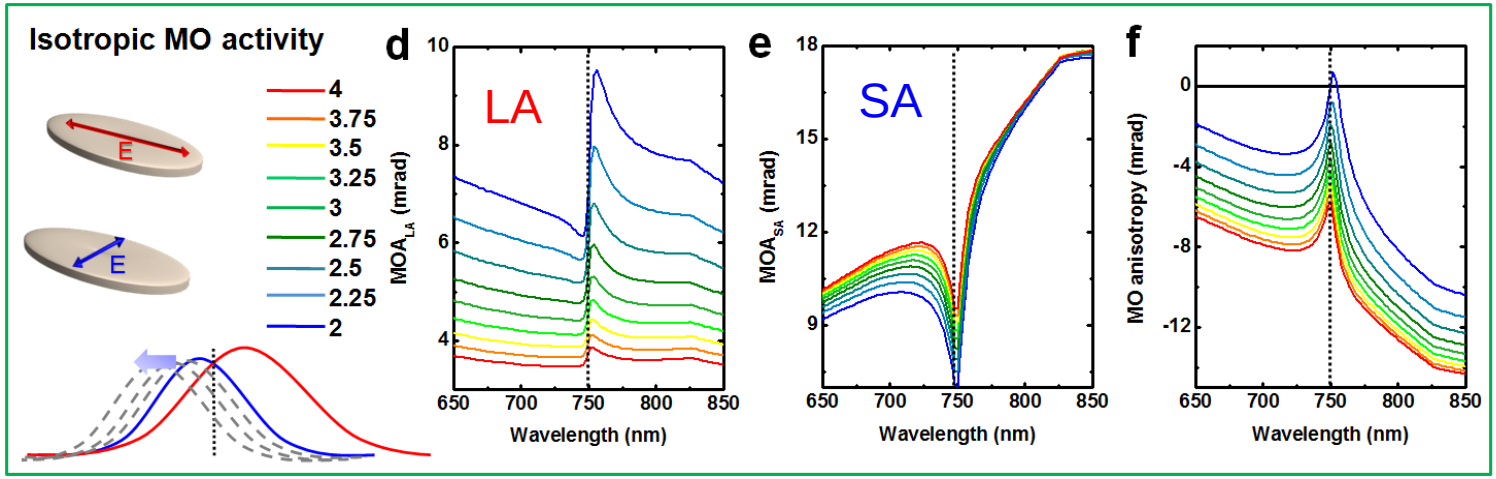


Enhanced and tunable O and MO-Anisotropy

$$\text{MOA} = \sqrt{\theta_K^2 + \varepsilon_K^2}$$

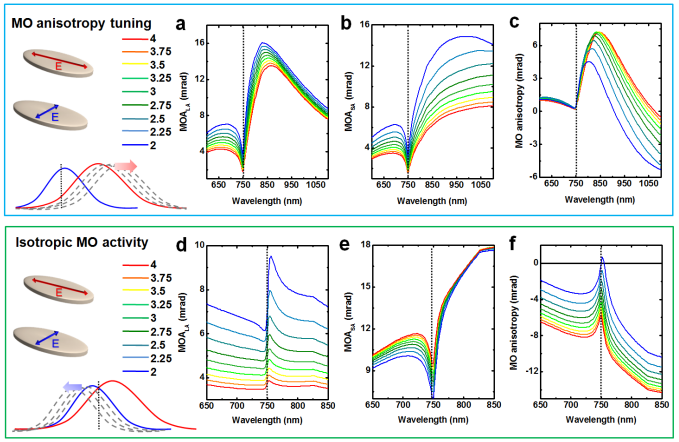
$\text{MOA}_{LA}\text{-MOA}_{SA}$



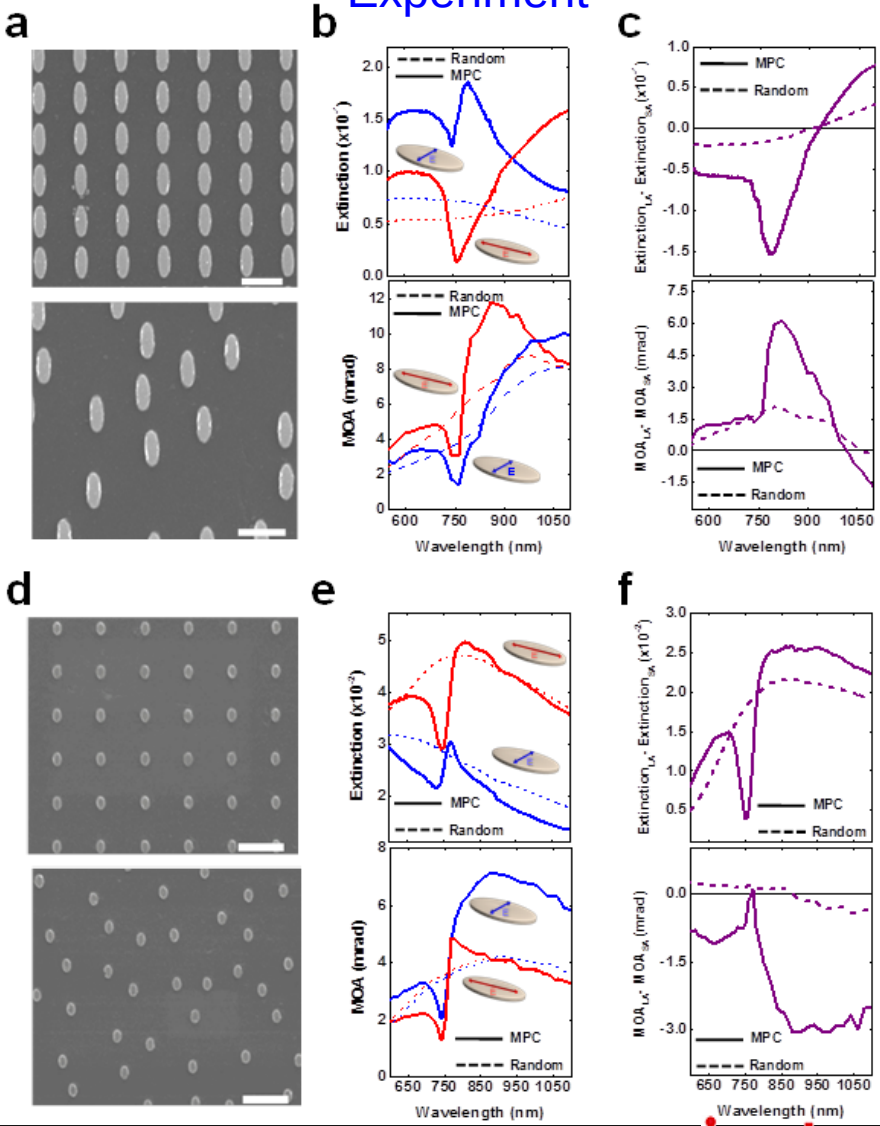


N. Maccaferri et al., Nano Lett. **16**, 2533 (2016)

Enhanced and tunable O and MO-Anisotropy

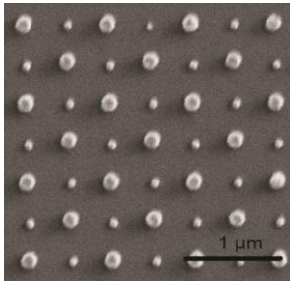


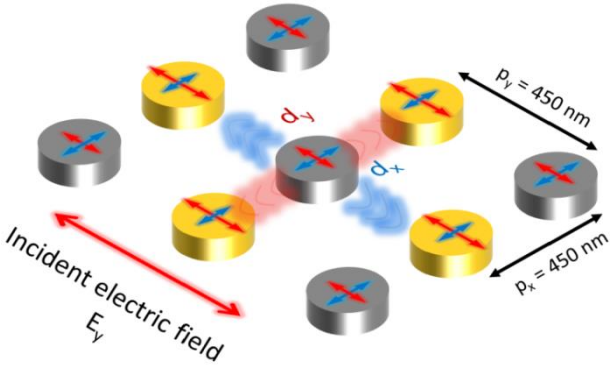
Experiment

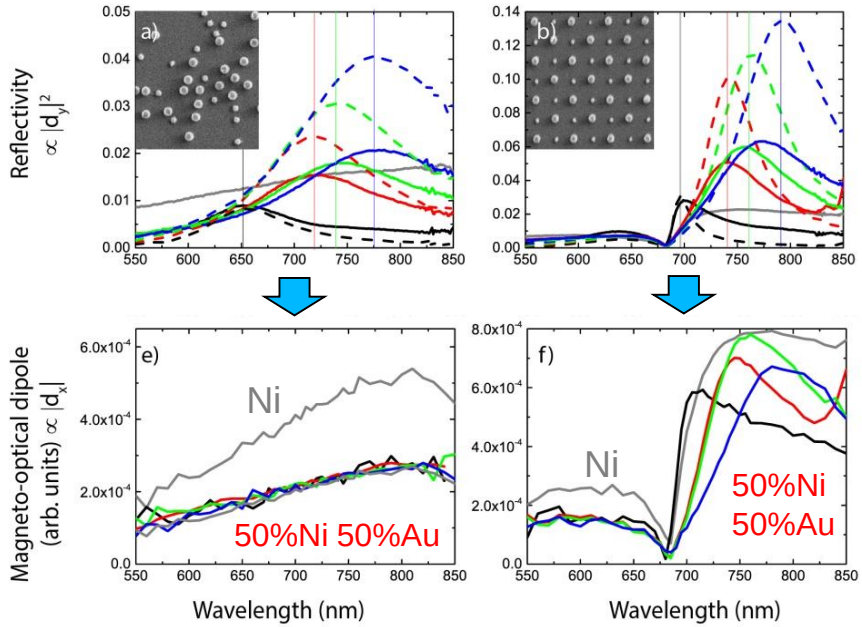


N. Maccaferri et al., Nano Lett. **16**, 2533 (2016)

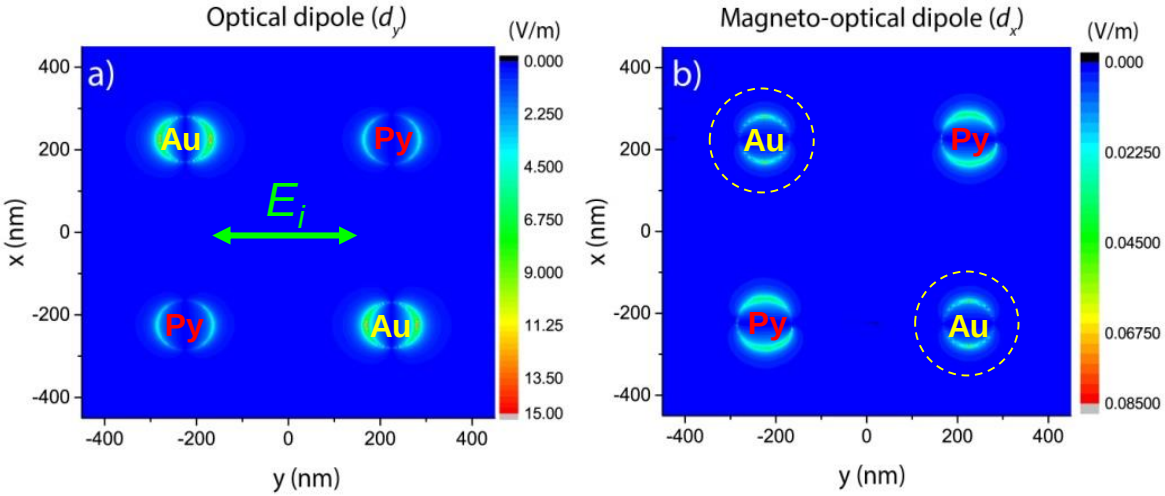
Checkerboard hybrid arrays of Py and Au nanoantennae







Efficient radiative far-field coupling between the magnetic and noble-metal components

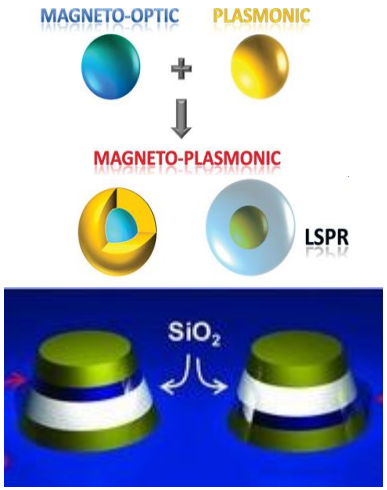


Integrating MO active and pure plasmonic nanostructures:

combination of intense optical resonances with strong MO activity.

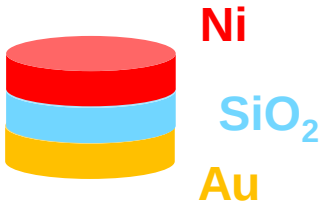
M. Kataia et al., Opt. Express **24**, 3652 (2016)

LSMs with hybrid nanostructures



Another common strategy to overcome the excess of damping is to develop hybrid structures consisting of noble metals and ferromagnets.

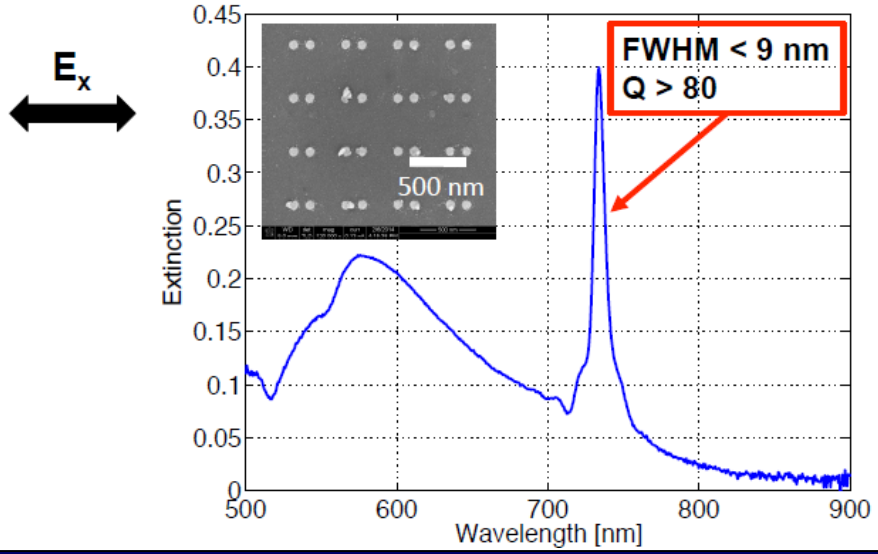
Banthí et. al Adv. Opt. Mat. **24**, OP36 (2012).



Mikko Kataja, Pourjamal Sara &Sebastiaan van Dijken

Aalto, Finland

Dimers



Concluding remarks

- **Concerted action of LSPRs (or SPPs) and MO-coupling can be exploited to achieve a controlled manipulation of the MO response (control Kerr rotation/ellipticity) beyond what is offered by intrinsic material properties.**

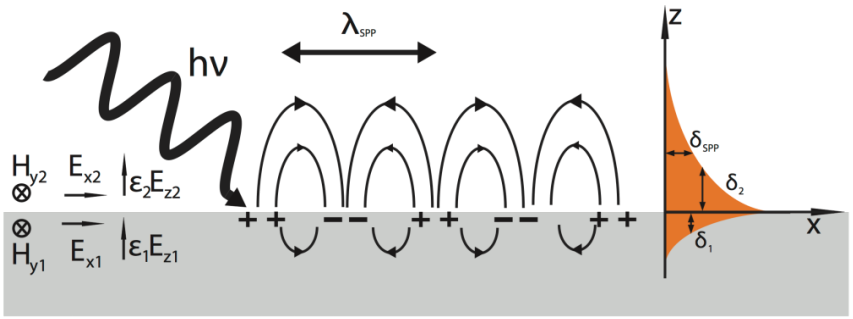
Patterning magnetic nanostructures for resonant interaction with light: Magnetoplasmonic Crystals

- **Magnetically tunable plasmonic crystal based on the excitation of Fano-like lattice surface modes in periodic arrays.**
  - ✓ **Highly tunable and amplified magneto-optical effects as compared to disordered systems.**

- **Two-dimensional magnetoplasmonic crystals supporting surface plasmon polariton modes and displaying a two-dimensional photonic band structure.**
  - ✓ **Design of metamaterials with tailored and enhanced magneto-optical response by engineering the plasmonic band structure via lattice engineering.**

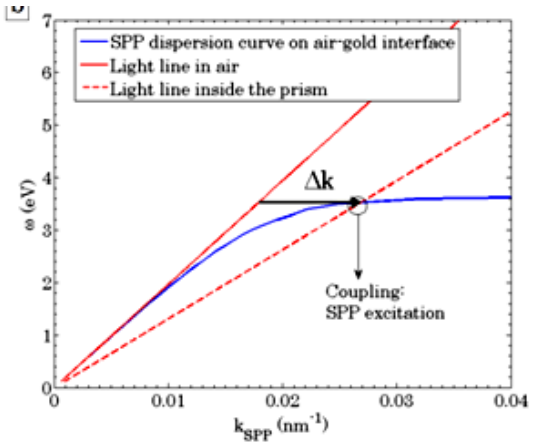
Other directions explored: magneto-plasmonics with SPP s

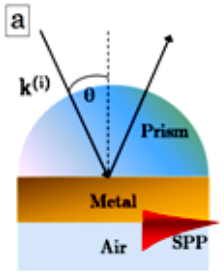
SPPs are localized electromagnetic modes/charge density oscillations at the interface of two media with dielectric constants of opposite signs, e.g. a metal and a dielectric,.

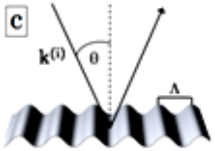


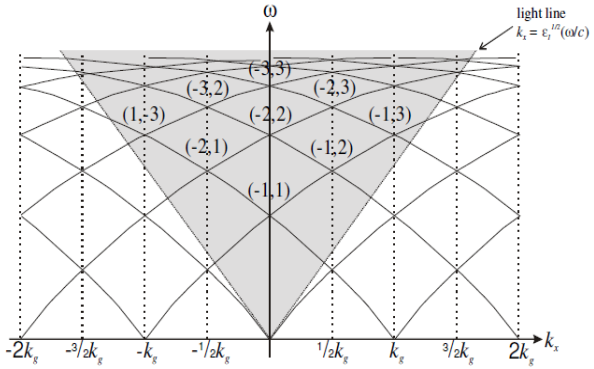
p-polarization only

$$k_x = \frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2}.$$





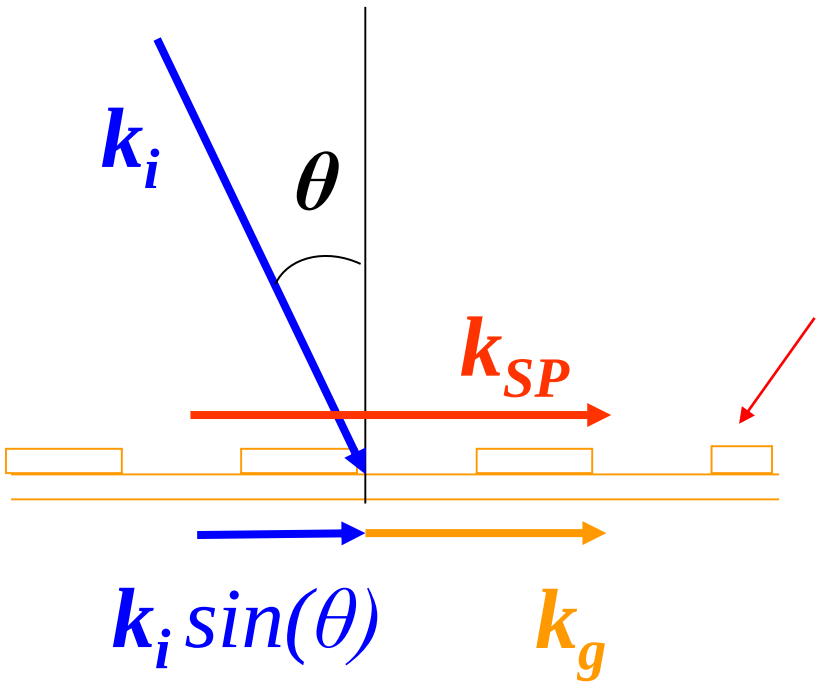


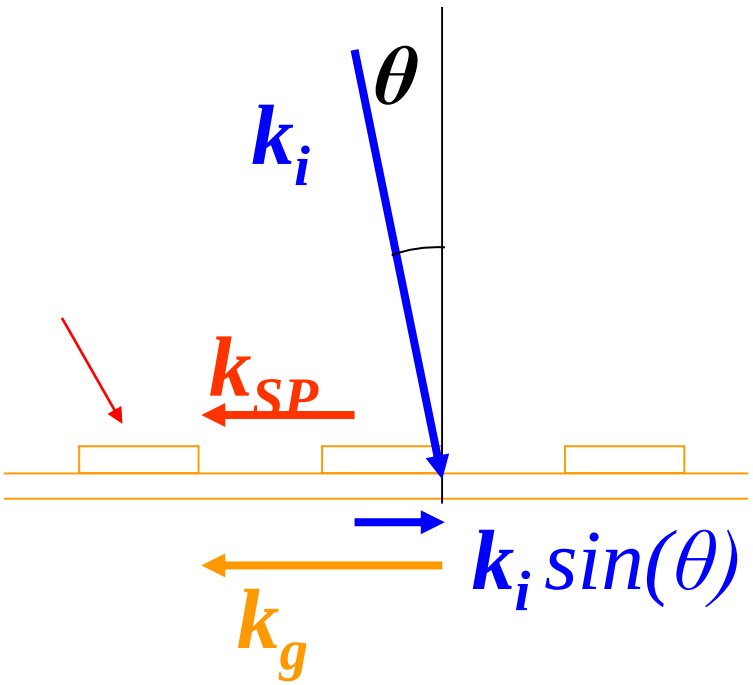


s ↔ p-polarization coversion!!

$$k_{SPP} = k_{x,\text{photon}} \pm n\ k_{\text{grating}} = \frac{\omega}{c}\sin\theta_0 \pm n\frac{2\pi}{a}$$

SP resonance: coupling with a grating (conservation of momentum)





$$k_{SP} = k_i \sin(\theta) + k_g$$

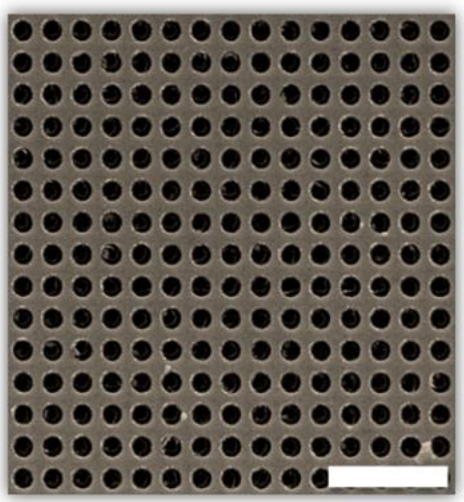
+1 order coupling

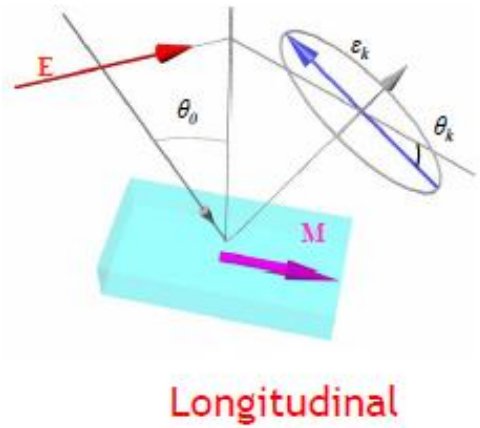
$$k_{SP} = k_i \sin(\theta) - k_g$$

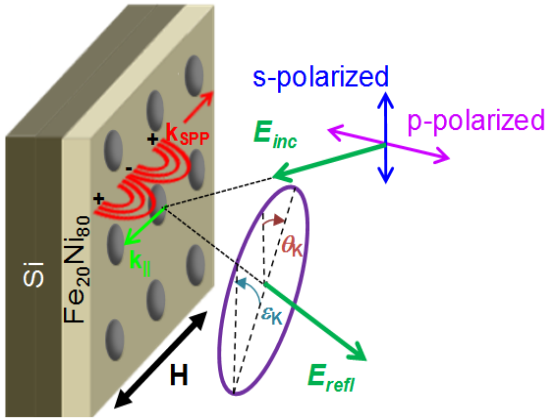
-1 order coupling

Magntoplasmonic gratings: MOKE enhancement due to resonant coupling with SPPs

Magnetic diffraction grating
Antidot array (square lattice):
material **Py** ($Fe_{20}Ni_{80}$), thickness = **80 nm**,
lattice parameter = **405 nm**,
hole diameter = **265 nm**
by deep-UV photolithography
(Prof. A. Adeyeye, Singapore)







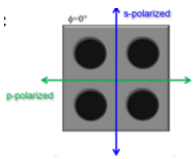
N. Maccaferri et al., ACS Photonics **2**, 1769 (2015)

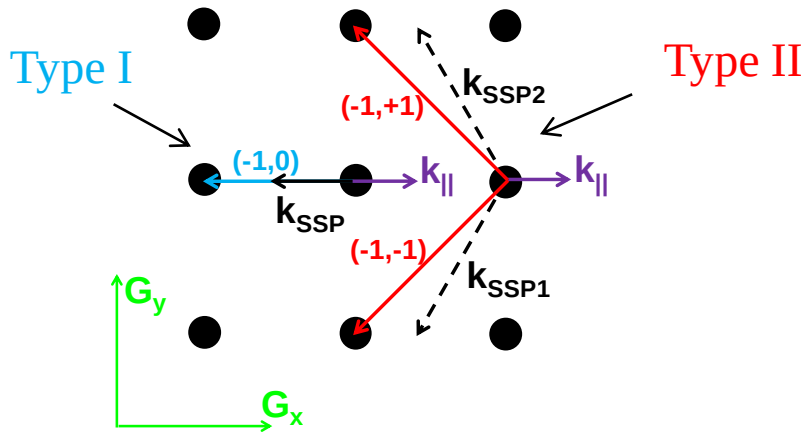
SPP band structure: perturbative approach

$$k_{spp}(\lambda) = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_d \cdot \varepsilon_m}{\varepsilon_d + \varepsilon_m}} \qquad \left|\mathrm{Re}(k_{spp}(\lambda))\right| = \left|k_{\parallel}(\lambda) + m \cdot \frac{2\pi}{a}\boldsymbol{i} + n \cdot \frac{2\pi}{a}\boldsymbol{j}\right|$$

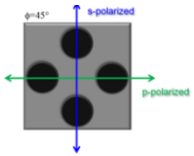
$k_{\parallel} = k_0 \mathrm{Sin}\theta$

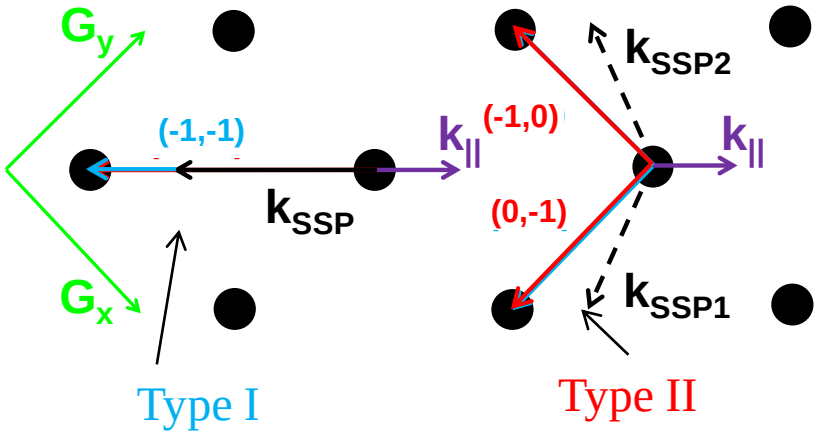
$\phi = 0°$





$\phi = 45°$



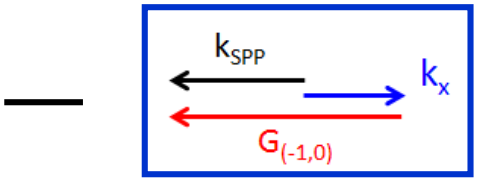


Key property

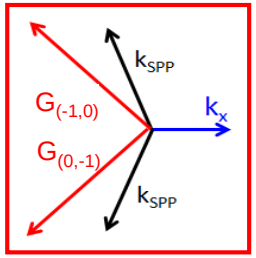
Type I:
only p-pol

Type II:
both p- and s-pol

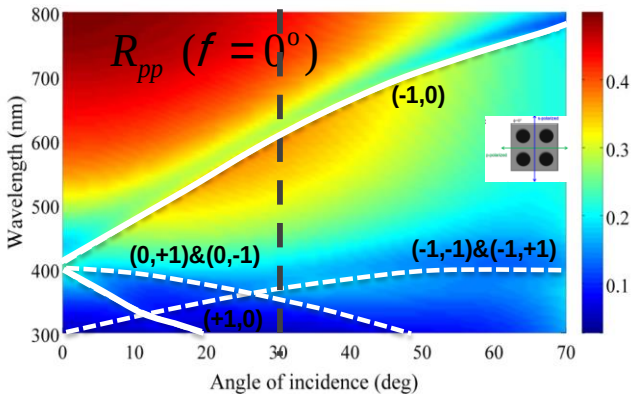
Reflectivity maps: full calculations (antidots size and cross section)

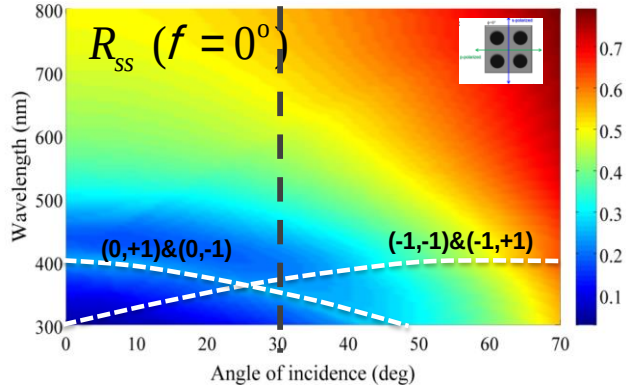


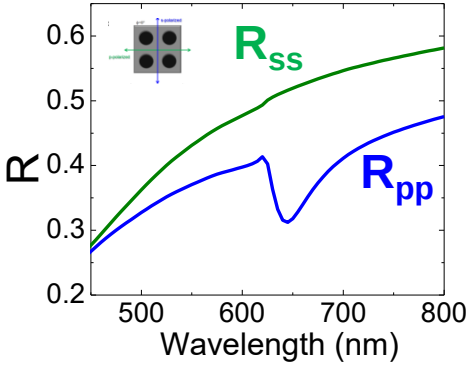
Type I



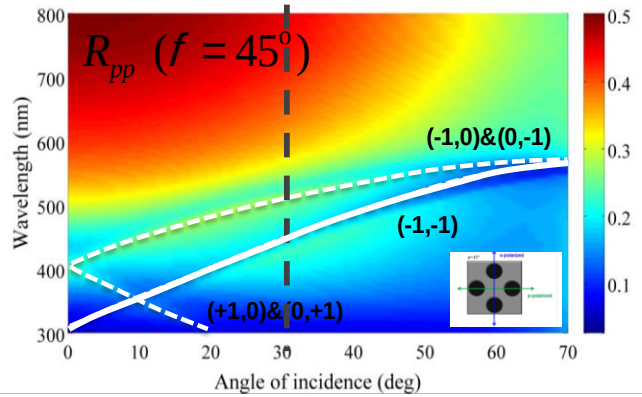
Type II

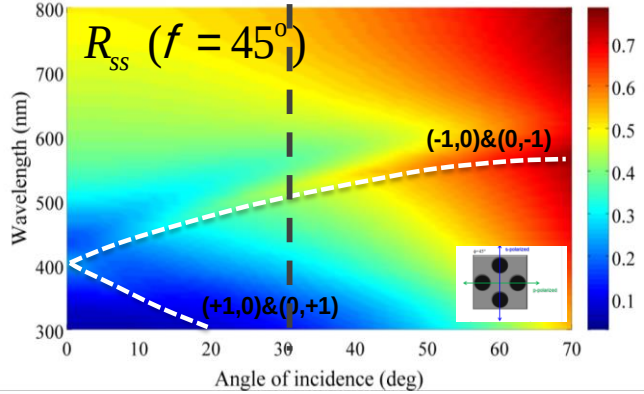


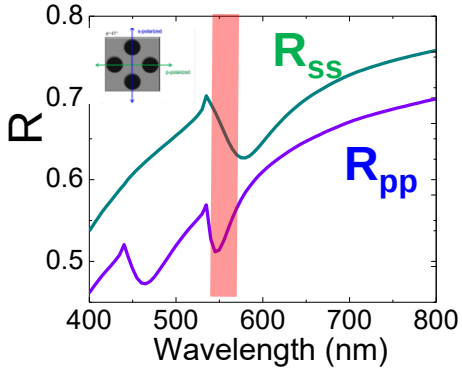




No channels for s↔p conversion in the VIS



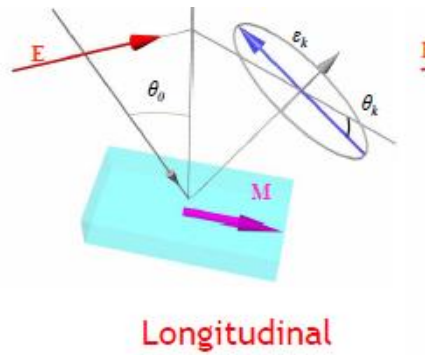




1 channel for s↔p conversion in the VIS

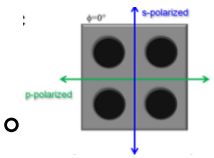
"Generalized scattering-matrix approach for magneto-optics in periodically patterned multilayer systems"
B. Caballero, A. García-Martín, and J. C. Cuevas, Phys. Rev. **B 85**, 245103 (2012)

MO activity enhancement mechanism (L-MOKE)

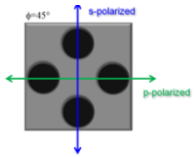


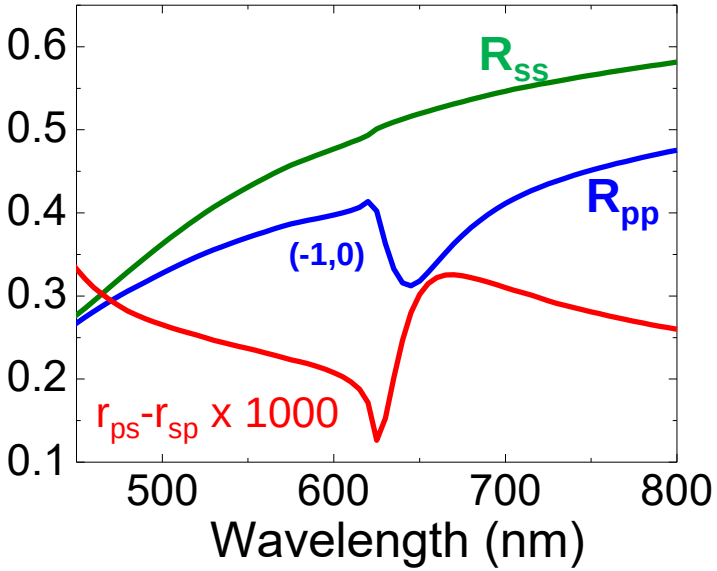
(L-MOKE and P-MOKE involve s ↔ p polarization conversion
T-MOKE p ↔ p: no polarization conversion,)

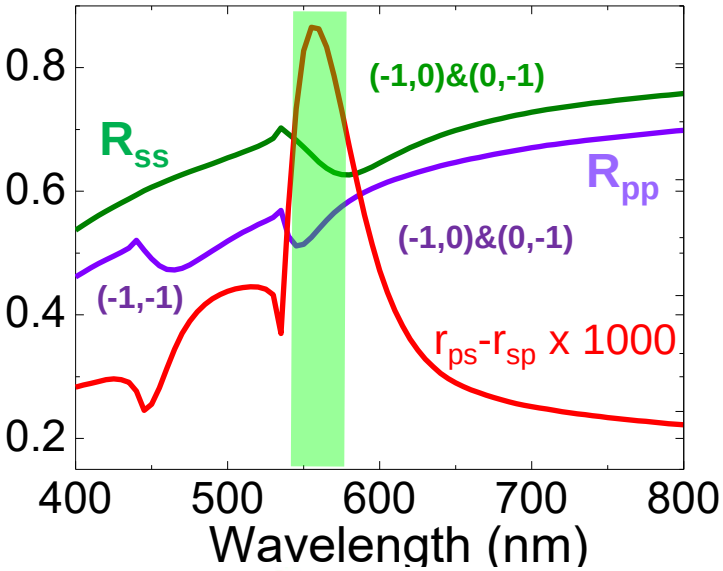
$\phi = 0°$
$\theta = 30°$



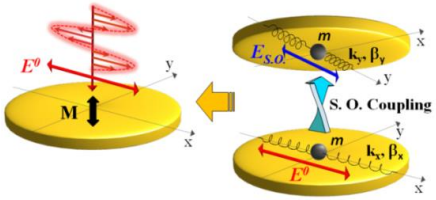
$\phi = 45°$
$\theta = 30°$







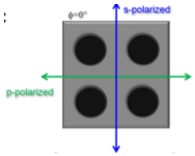
Plasmonic channel "open" for resonant MO induced polarization conversion.



N. Maccaferri et al., ACS Photonics **2**, 1769 (2015)

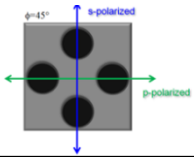
Experimental MO-activity

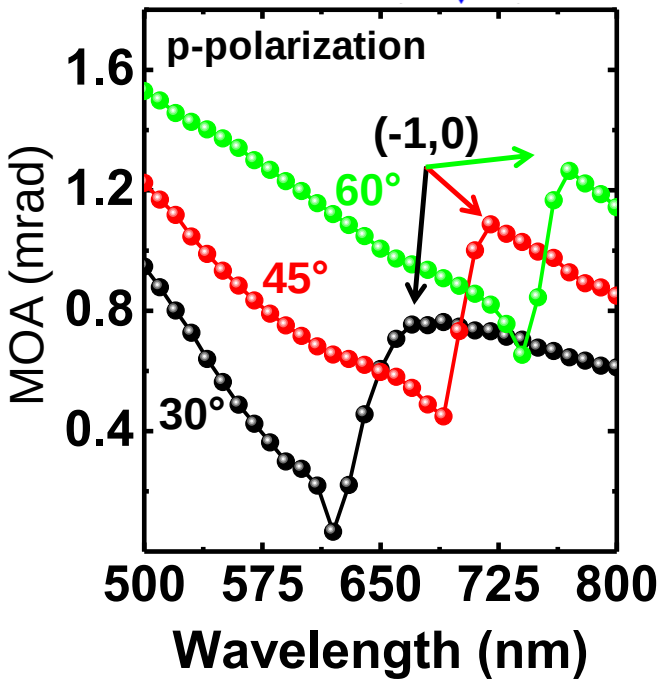
$\phi = 0°$

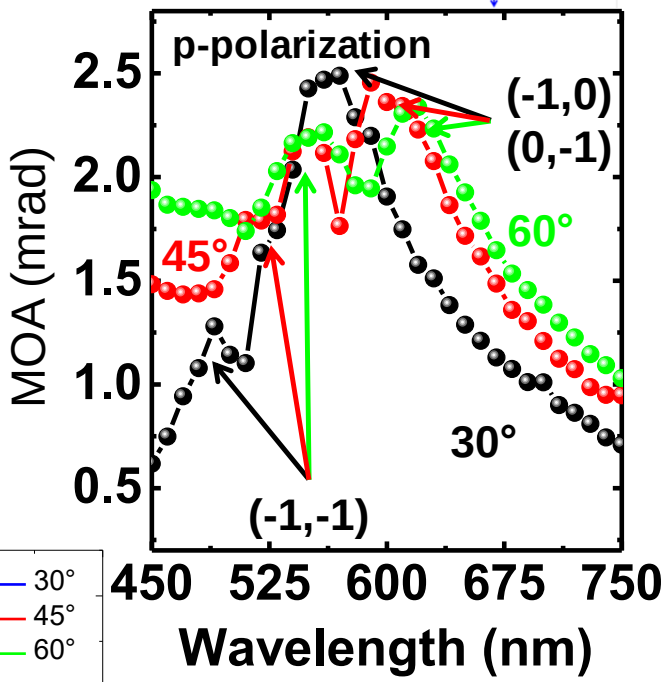


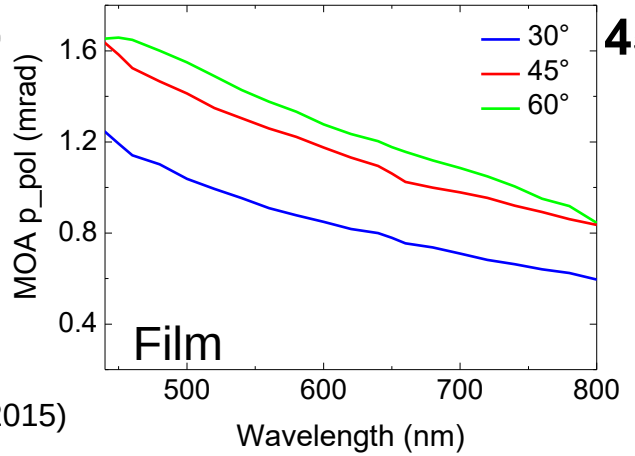
$$\text{MOA} = \sqrt{\theta_K^2 + \varepsilon_K^2}$$

$\phi = 45°$





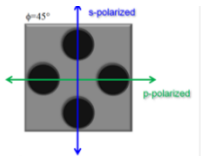


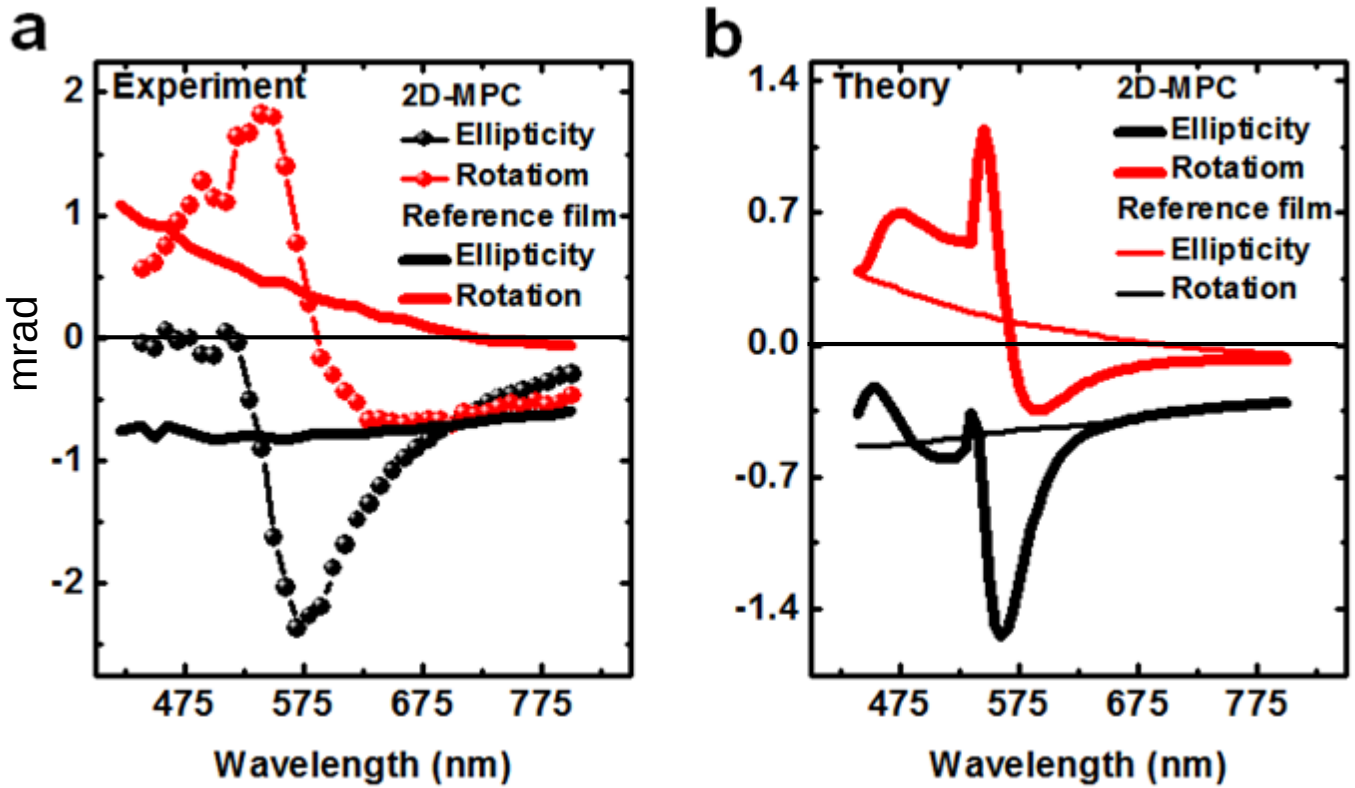


N. Maccaferri et al., ACS Photonics **2**, 1769 (2015)

Rotation and ellipticity

$\phi = 45°$
$\theta = 30°$



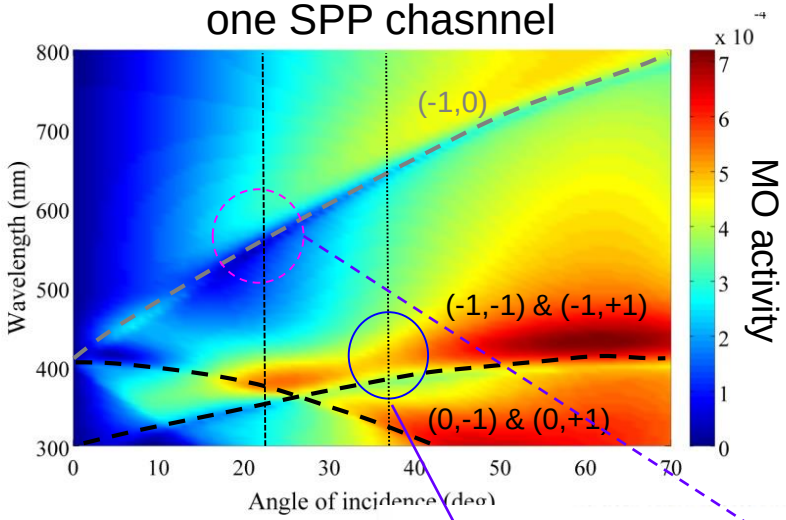


N. Maccaferri et al., ACS Photonics **2**, 1769 (2015)

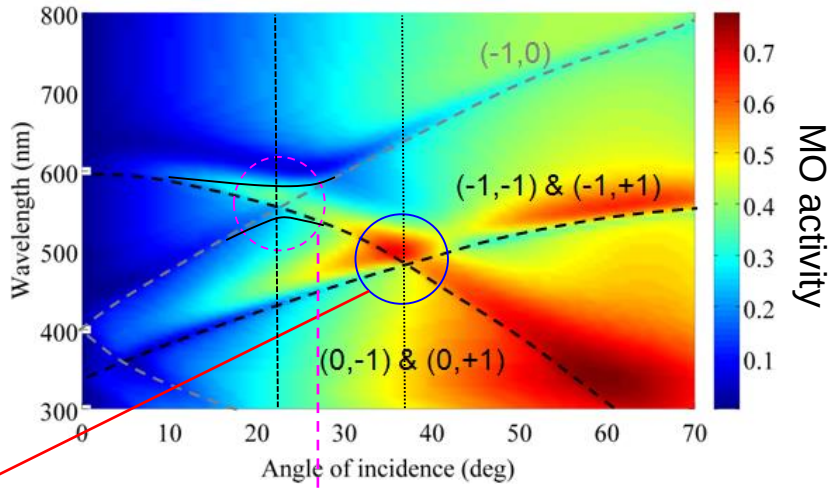
SPP band structure engineering

Black dashed lines: MO-active SPPs

Square array: one SPP chasnnel

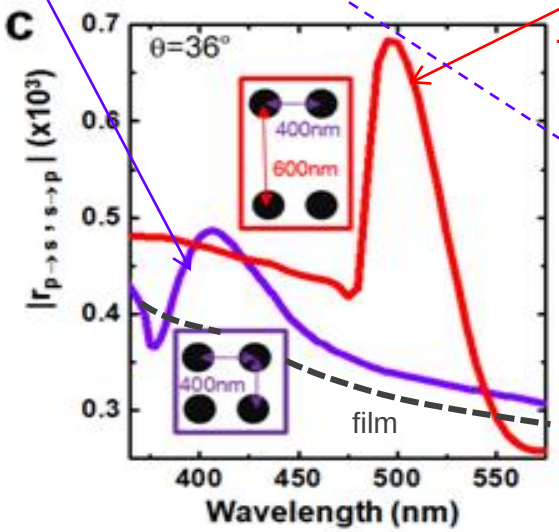


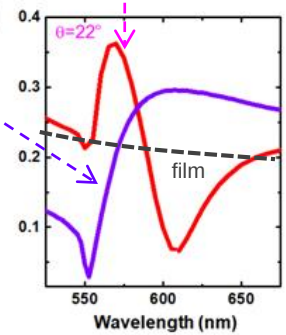
Rectangular array: two SPPs channels



Two SPPs assisted MO enhancement

One SPP assisted MO enhancement

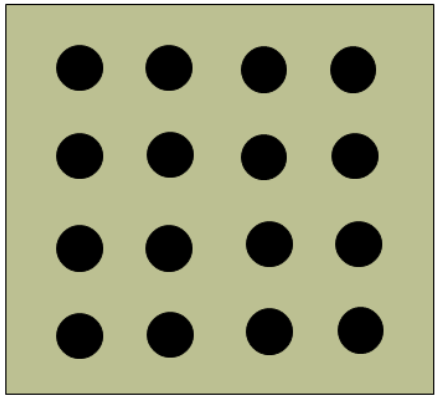




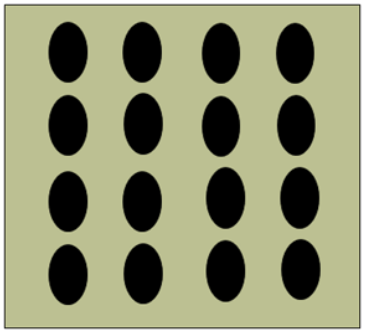
Modes of different nature
bandgap opening
Resonant-antiresonant lineshape

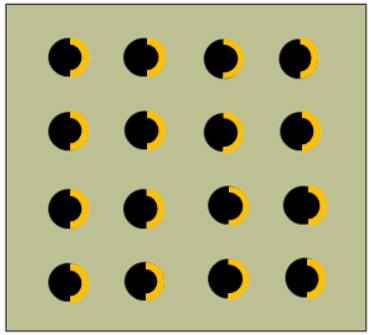
N. Maccaferri et al., ACS Photonics **2**, 1769 (2015)

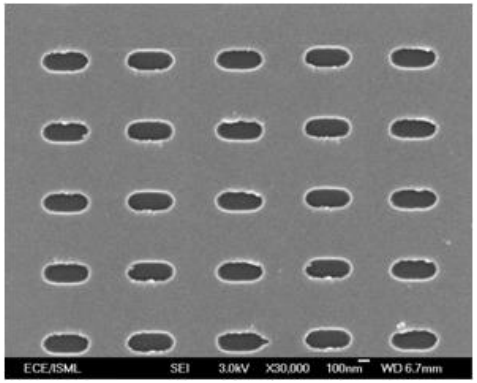
SPPs

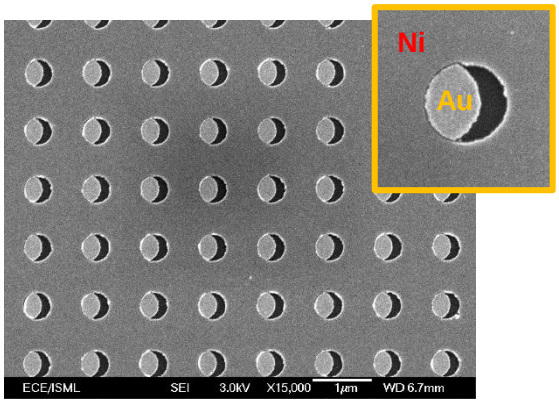


Where to go?









Zhou Xue & Adekulne O. Adeyeye

National University of Singapore

Concluding remarks

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  - ✓ **Highly tunable and amplified magneto-optical effects as compared to disordered systems.**

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