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(CENTRO NACIONAL DE MICROELECTRÓNICA)

Magnetic Nanostructures MN-MP Magneto Plasmonics

Optimizing light harvesting for high magneto-optical performance in metal-dielectric magnetoplasmonic nanodiscs

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E-28760 Tres Cantos, Madrid, Spain

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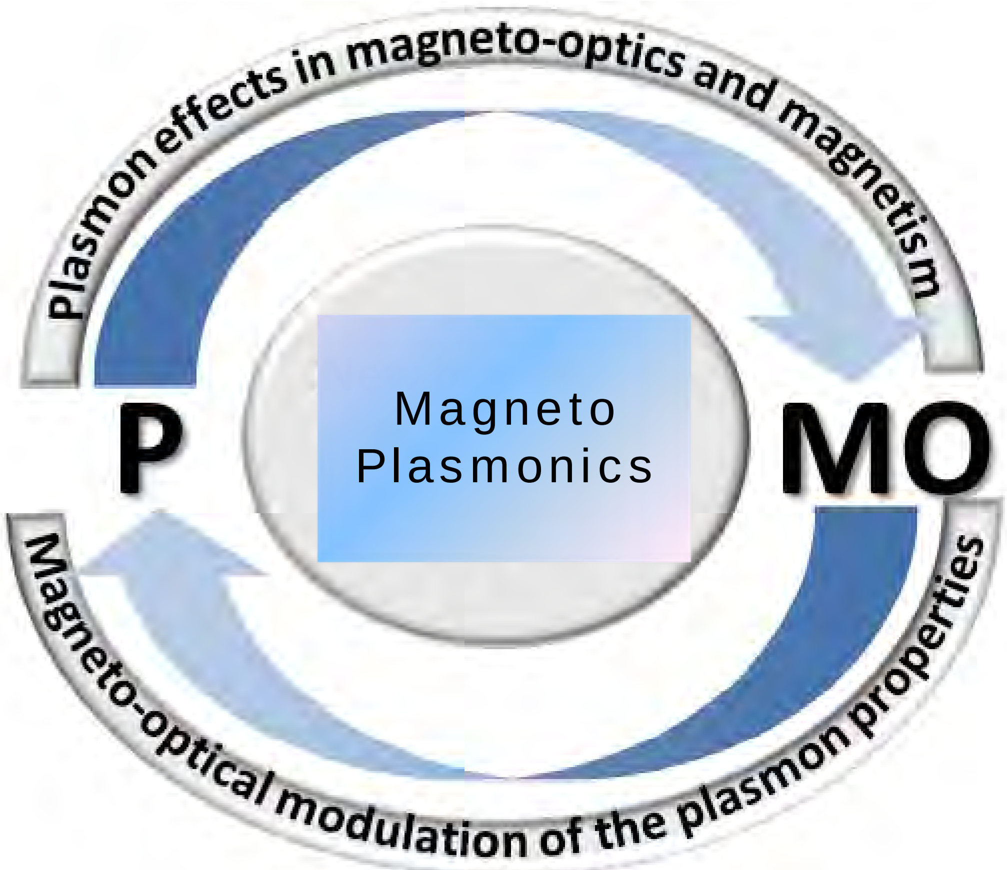
Magneto-Plasmonic structures

Systems where constituents with Plasmonic and Ferromagnetic (Magneto-Optical) properties coexist



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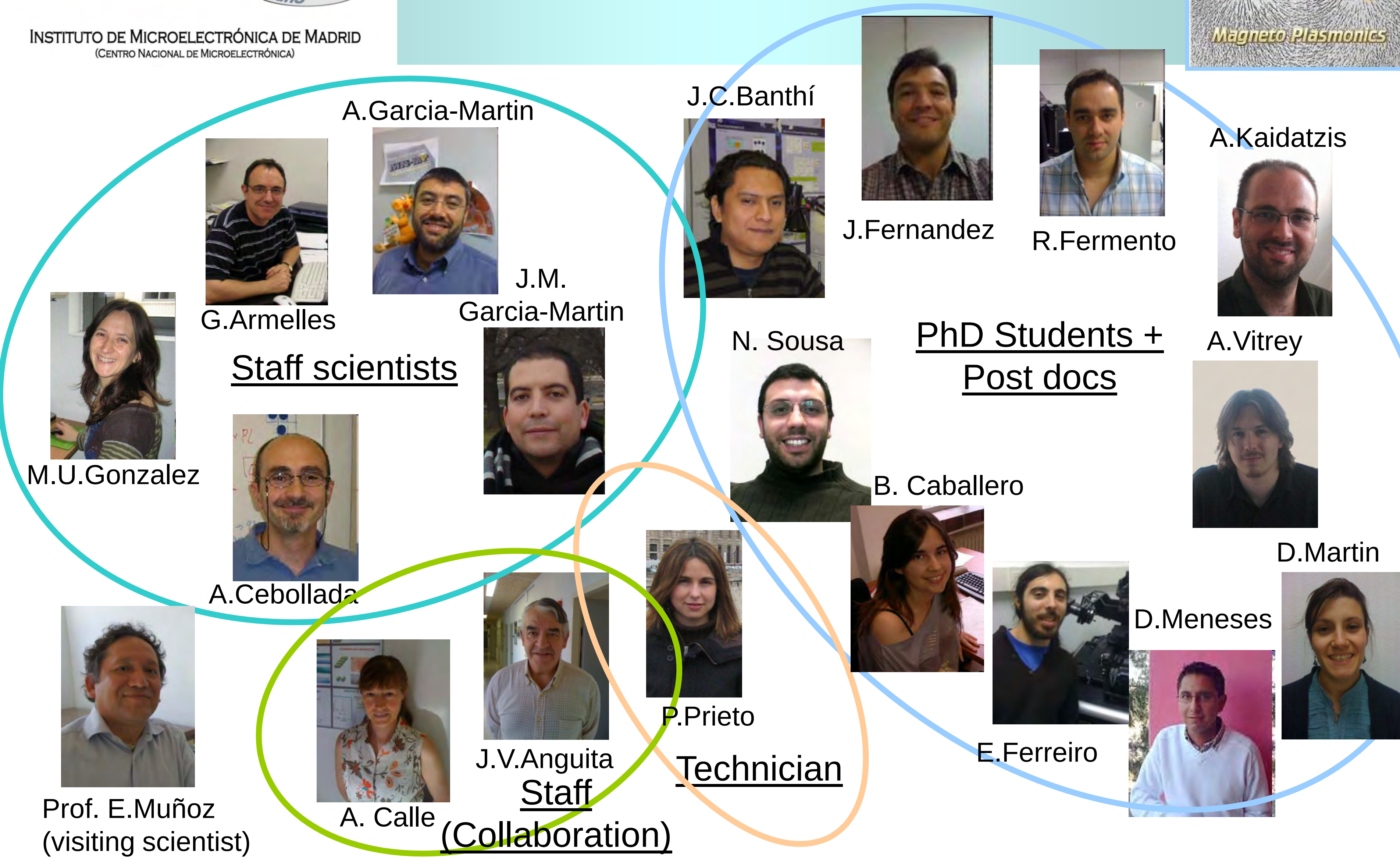
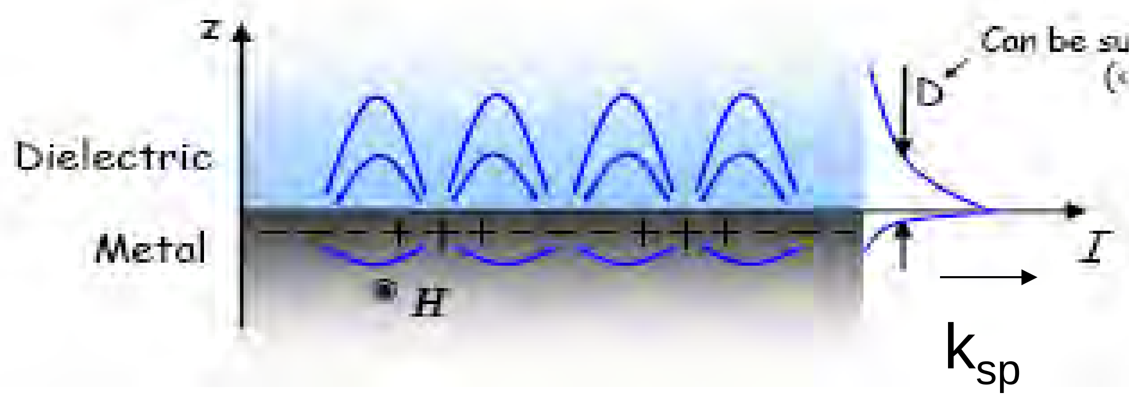
Group Members

Magnetic Nanostructures
MN-MP
Magneto Plasmonics



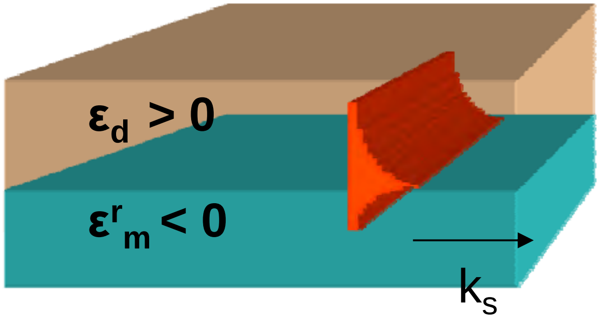
Surface Plasmons

Electromagnetic waves associated to a collective oscillation of conduction electrons localized at the interface between a media $\varepsilon_r<0$ (metal) and a media $\varepsilon_r>0$ (dielectric material)



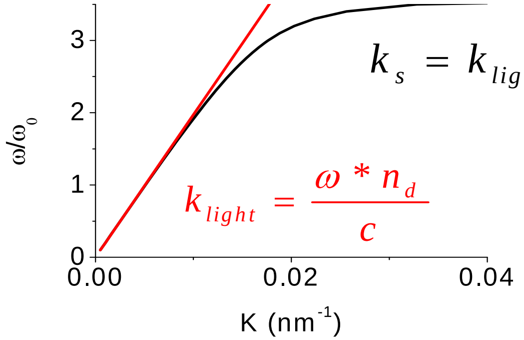
- Propagating or Surface Plasmon Polaritons (SPP): continuous layers
- Localized Surface Plasmons (LSP): Nanoparticles/Nanoentities

Propagating surface plasmons (SPP)



-In plane propagating excitation but localized at the interface: surface localized waves.

-Can be excited only if both frequency **and wavevector** of the exciting light match those of the SPP.

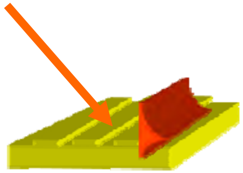


$$k_s = k_{light}\sqrt{\frac{\varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

$$k_{light} = \frac{\omega * n_d}{c}$$

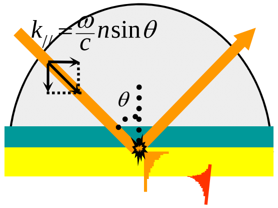
$k_s > k_{light}$ $\quad$ $k_s = k_{light} + k'$

Grating



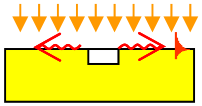
Prism

$k_{//}^{Light} = k_{sp}$

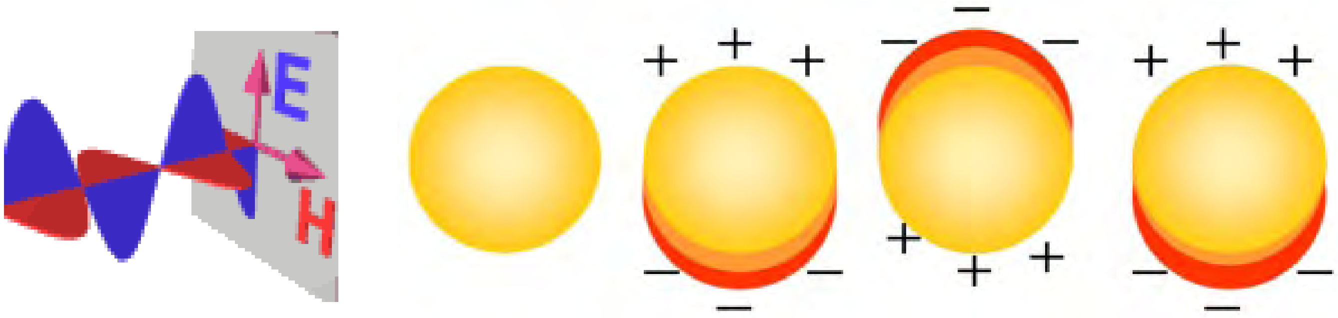


(Kretchsmann)

Defect



Localized Surface Plasmons (LSP)



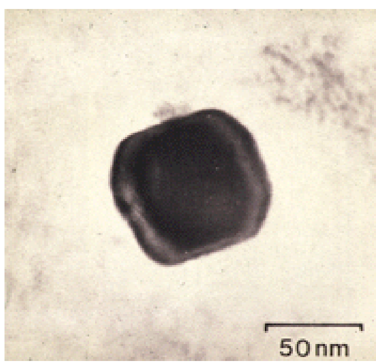
-Occur when the incident photon frequency is resonant with the collective excitation of the conduction electrons of the particle.

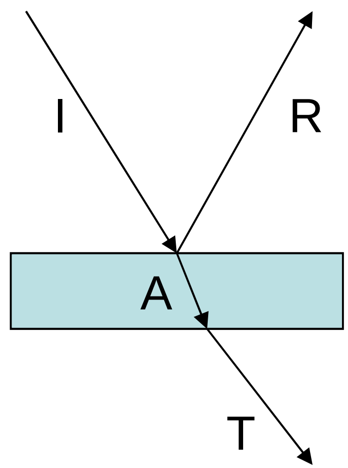
-Can be excited with light of appropriate frequency irrespective of the wavevector of the exciting light.

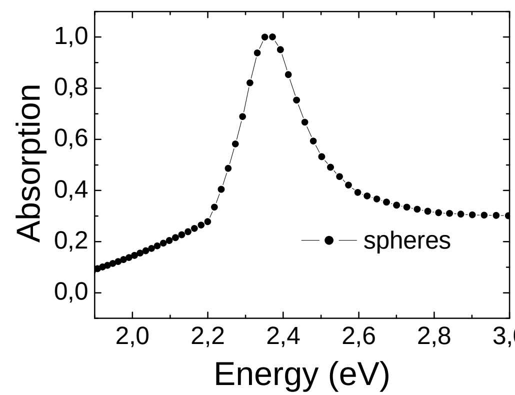
-Localized excitation.

<u>The Lycurgus cup</u>
(British Museum. 4th Century)
When illuminated from outside cup appears green, but turns into red when illuminated from inside.

<u>"Labors of the Months"</u>
(Norwich, England, ca. 1480)
The ruby color is probably due to embedded gold nanoparticles.







Messages:

Both LSP and SPP are characterized by:

-Strong localization of the electromagnetic field in subwavelength volumes $\Rightarrow$ Enhanced electromagnetic field due to its localization.

-Very sensitive to the metal dielectric interface.

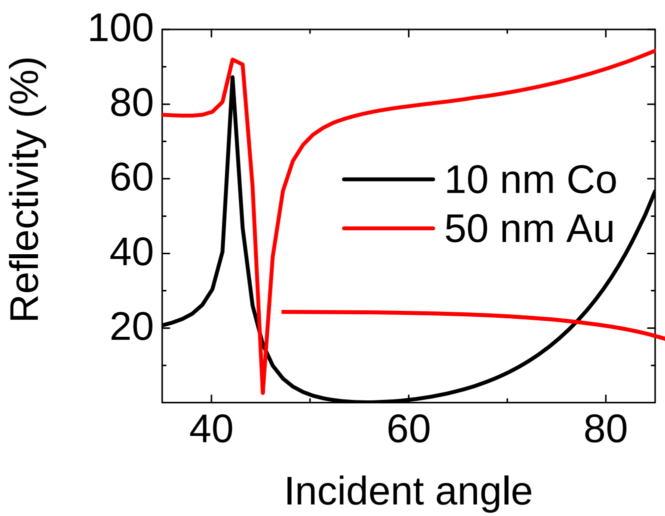
$$k_s = k_{light}\sqrt{\frac{\varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

$\Rightarrow$*Application in Optical nanodevices + Sensors*

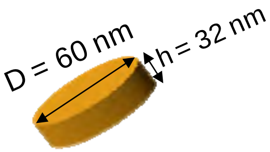
$\Rightarrow$*Absorb (emit) light: (nano)antennas.*

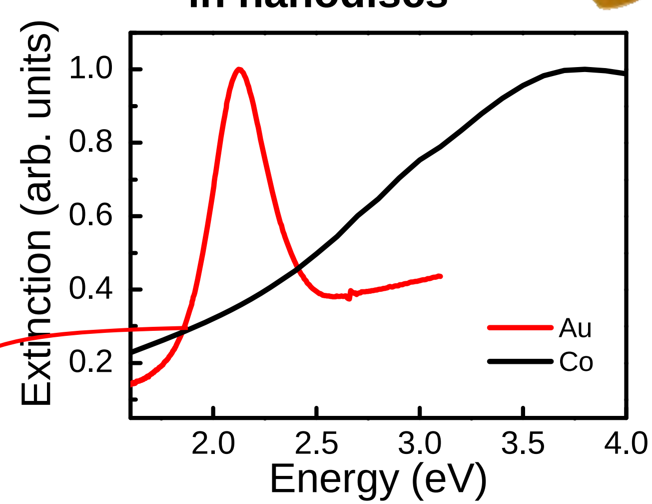
Signature of plasmon excitation

Propagating plasmons in continuous films
(Kretchsmann)



Localized plasmons in nanodiscs



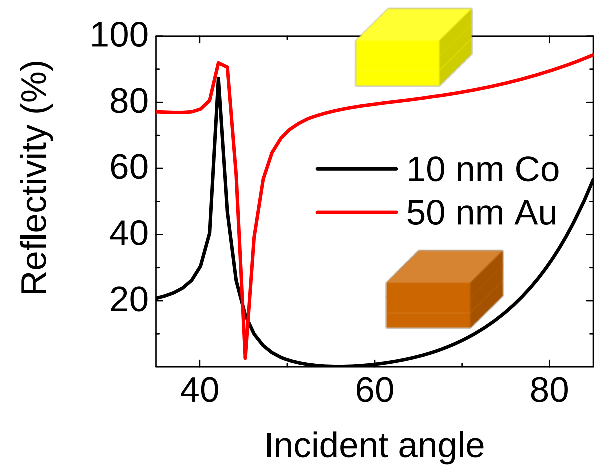


Typical plasmonic material: noble metal

Magneto-Plasmonic systems

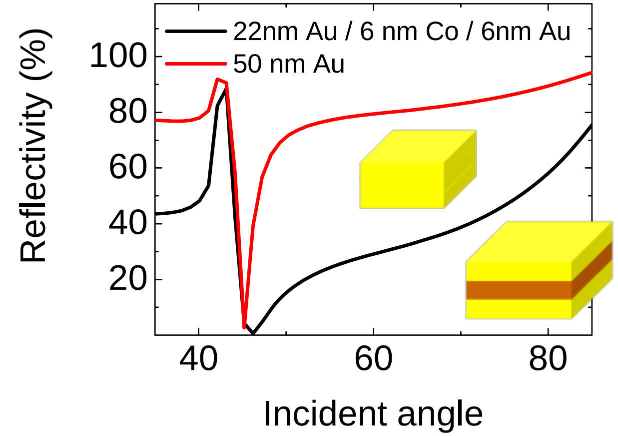
<u>Noble metals</u>:

Exhibit intense plasmon resonances
Low optical absorption:
Long propagation length
Narrow Resonances (Optical constants)
No MO activity (MO constants)



<u>Ferromagnetic metals</u>:

Weak plasmon resonances
High optical absorption:
Shorter propagation length
Boarder resonances
MO at low magnetic fields



Magnetoplasmonics: Materials explored

Noble metals: Au, Ag. Low optical absorption. No MO activity

Ferromagnets:

Metals: Fe, Co. High MO activity. High optical absorption.

Take the best of each counterpart:

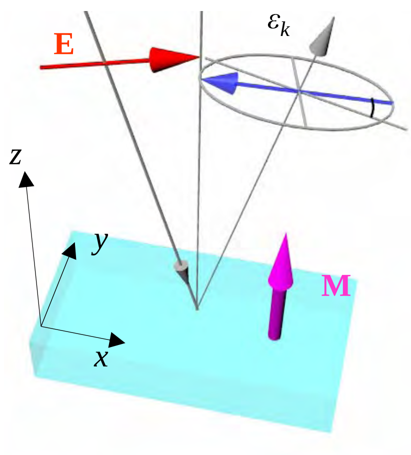
$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ -\varepsilon_{xy} & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

Ferromagnet

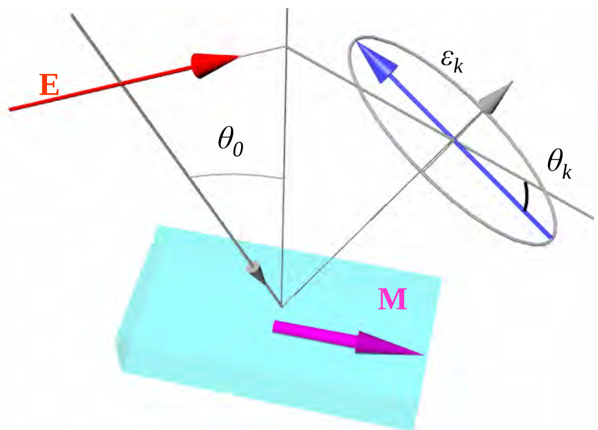
Noble metal

MO effects

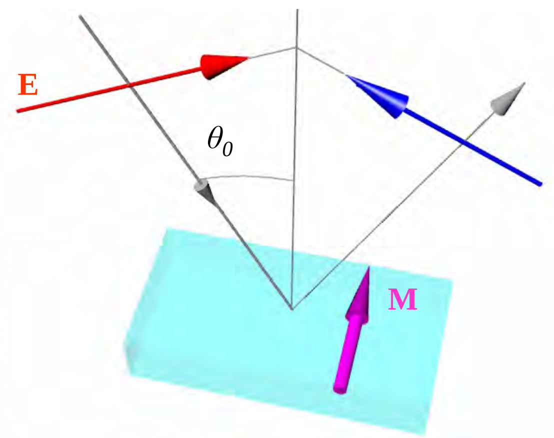
Polar

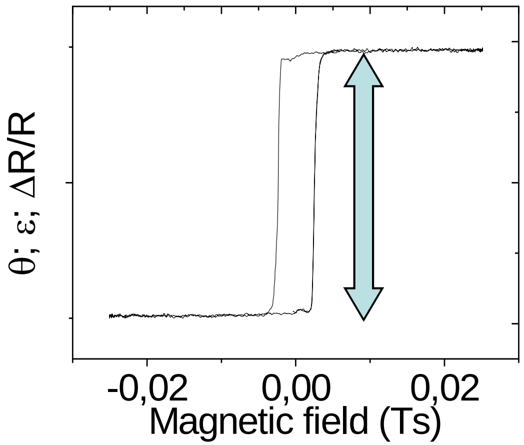


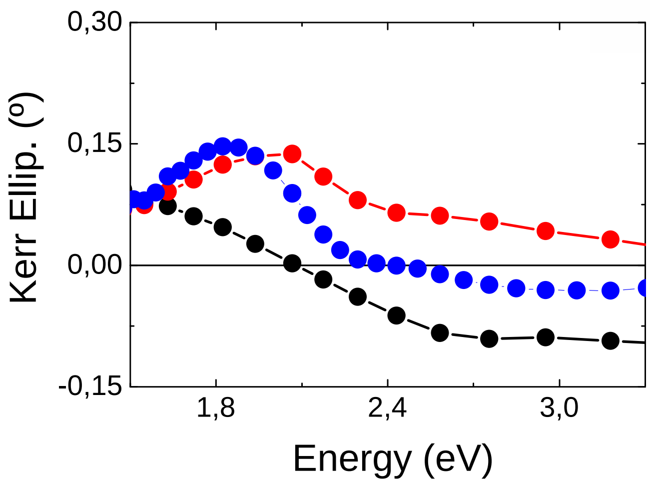
Longitudinal



Transverse (ΔR/R)



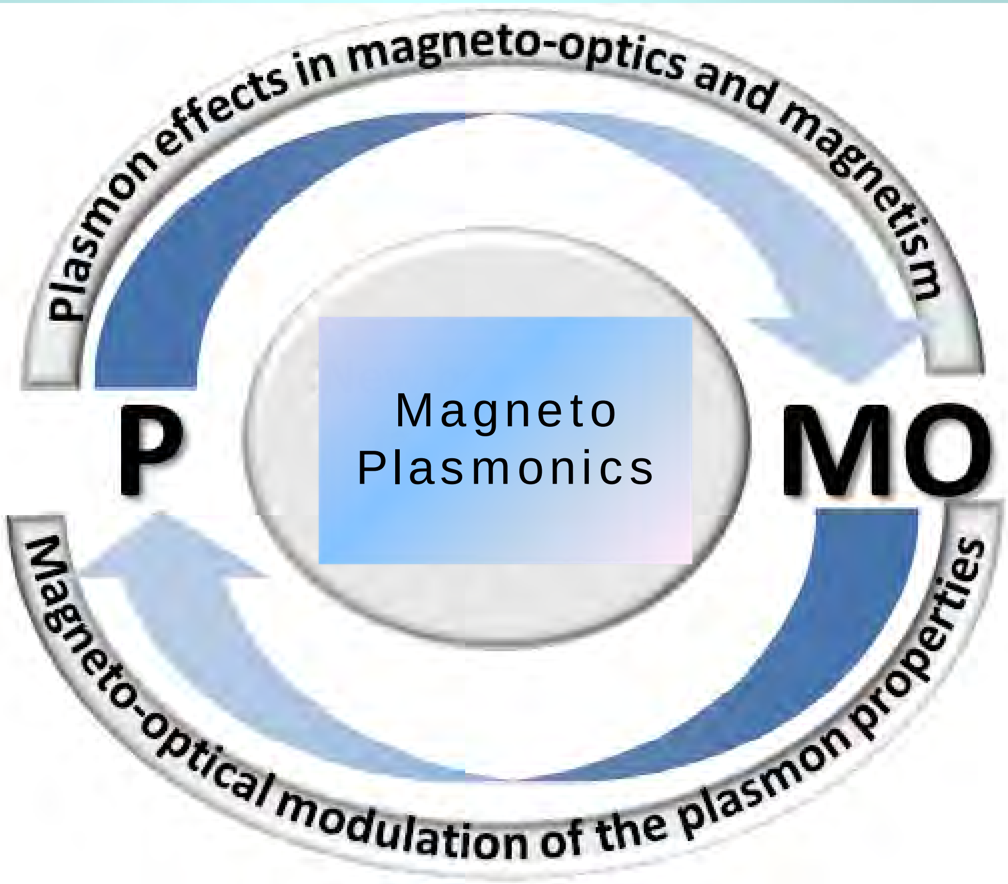




$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ -\varepsilon_{xy} & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

Magnetic Modulation of Plasmon properties:

ACTIVE PLASMONICS



Plasmonic properties depend on the constituents' dielectric tensor (which in the case of the MO component can be "activated" by an external magnetic field).

$$k_s = k_{light}\sqrt{\frac{\varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ -\varepsilon_{xy} & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

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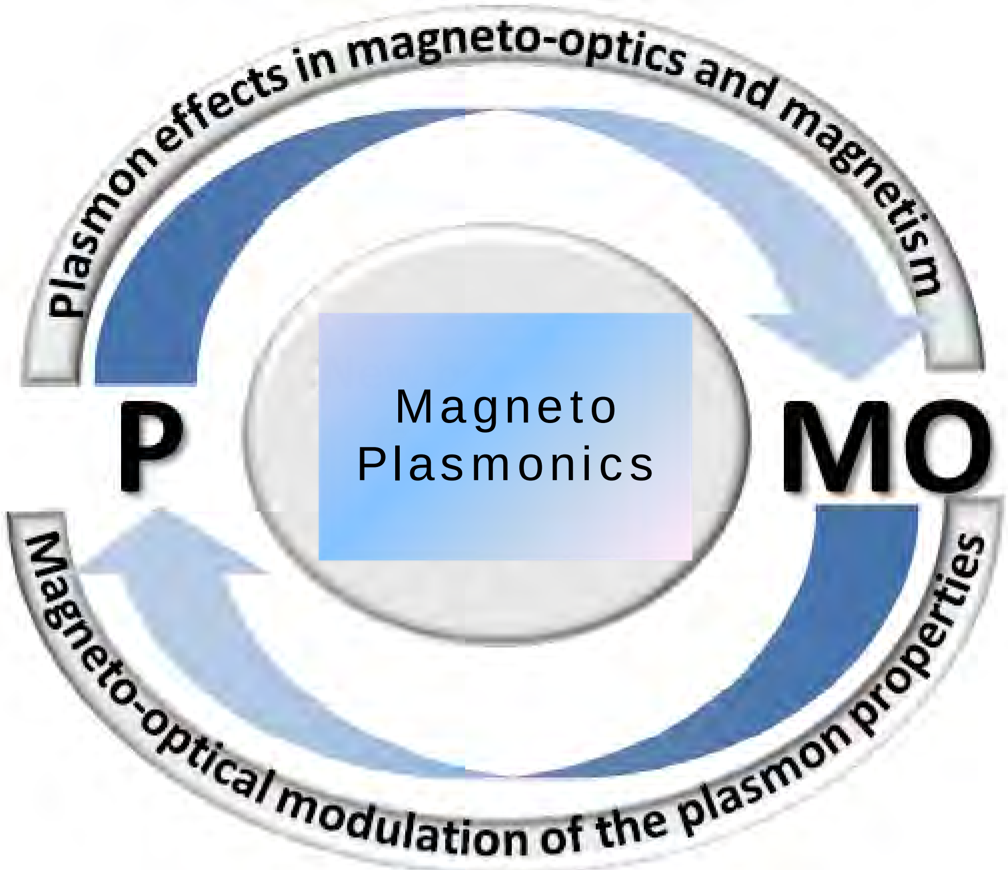
Plasmon effects in MO properties:

ENHANCED MO ACTIVITY



MO activity basically proportional to the EM field intensity at the MO active componet*.

$$|\Phi|(z) \propto \iint_{S(|\varepsilon_{MO}|\neq 0)} |\varepsilon_{MO}(x,y)|\, \mathcal{E}_s(z,x,y)\,\mathcal{E}_p(z,x,y)\,dx\,dy$$

GOAL: Exploit light harvesting properties of plasmonic systems to maximize the EM field at the MO layer!!!

* thin film approximation

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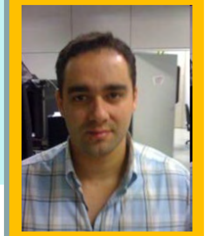
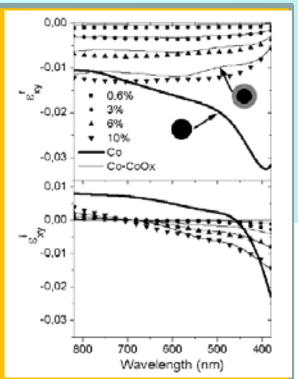
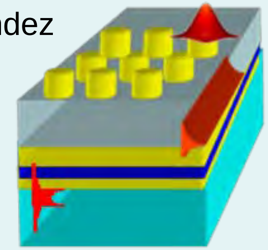


R.Fermento



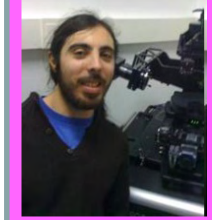
MO active dielectrics

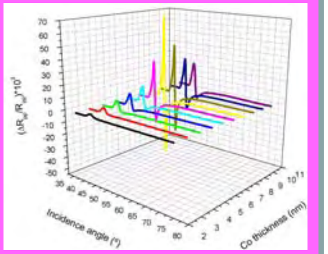
J.Fernández



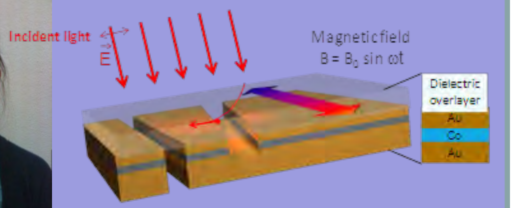
Magnetoplasmonic Activity in Systems with Localized and Extended Surface Plasmons

E. Ferreiro





MO and SPP k modulation in continuous layers



D.Martin

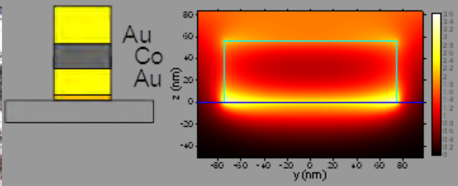
Magnetoplasmon interferometry and sensing applications

N. Sousa (Col. MoLE group @ UAM)

B. Caballero (Col. Cuevas group @ UAM)

Theoretical developments
NS. Coupled diplole method
BC. Scattering Matrix Techniques

EM field distribution in nanodiscs

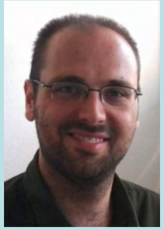


Colloidal lithography

D.Meneses

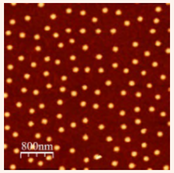
A.Vitrey

Near field studies of magnetoplasmonic structures



A.Kaidatzis

PLasmon
ASsisted
MAgnetic
Recording

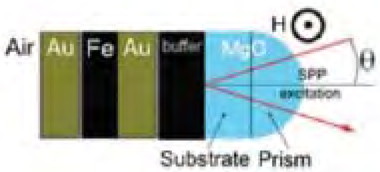


J.C.Banthí

Metal-dielectric magnetoplasmonic nanoresonators

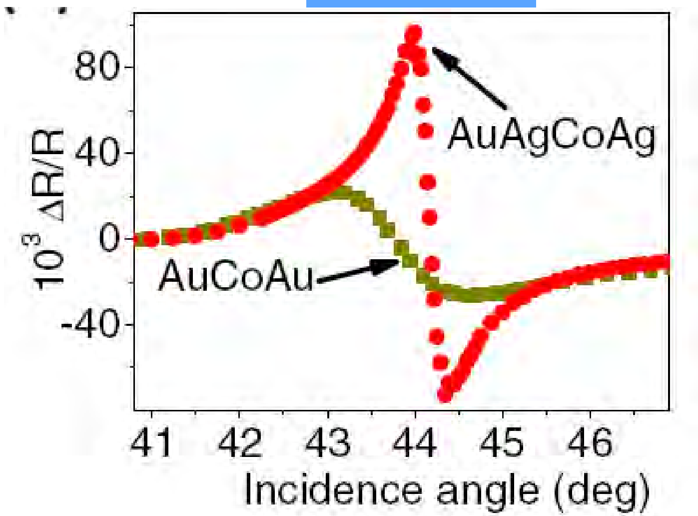
HTTP://WWW.IMM-CNM.CSIC.ES/MAGNETOPLASMONICS

Magnetoplasmonic effects in systems with propagating plasmons

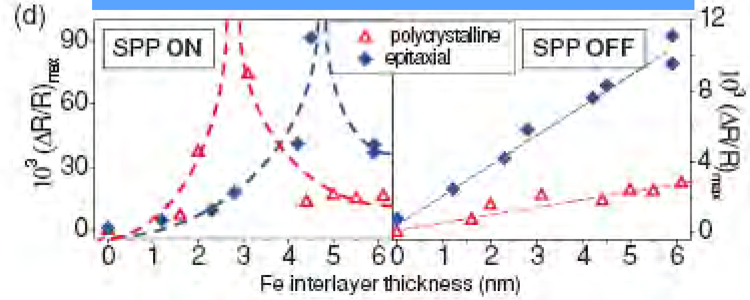


Enhanced MO activity upon SPP excitation

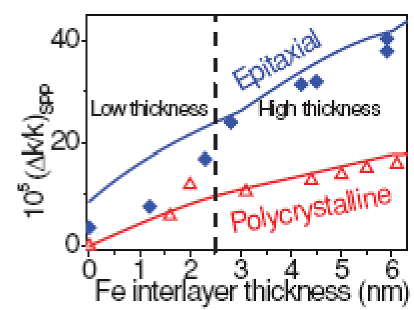
Ag vs Au



Epitaxial vs polycrystalline



Magnetic field wavevector modulation



J.B. González-Díaz et al., Physical Review B, **76** (2007) 153402.
E. Ferreiro Vila et al. IEEE Transactions on Magnetics, **44** (2008) 3303.
E.Ferreiro-Vila et al., Physical Review B, **80** (2009) 125132.
E. Ferreiro-Vila, et al., Physical Review B, **83** (2011) 205120.

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Magnetoplasmonic effects in systems with propagating plasmons

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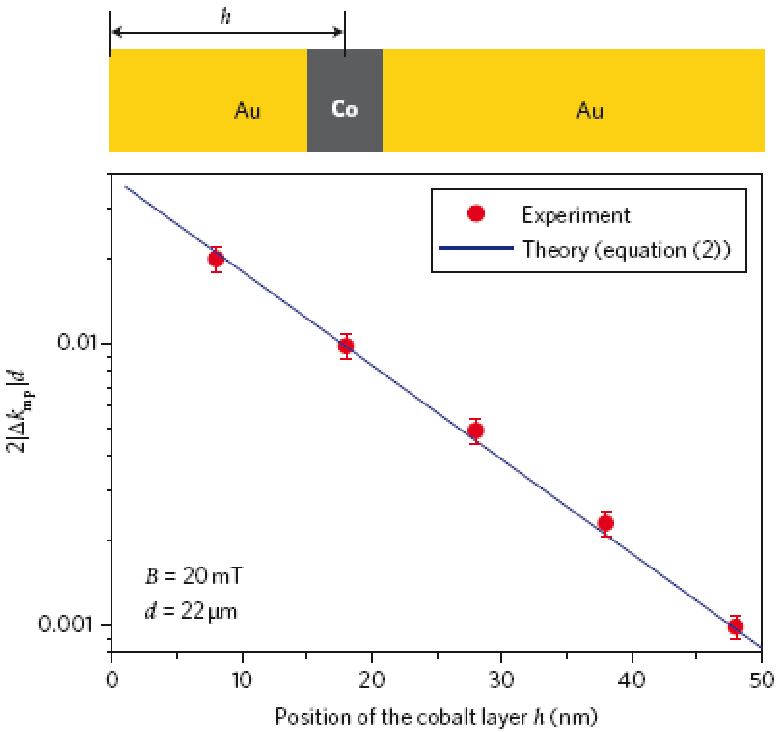
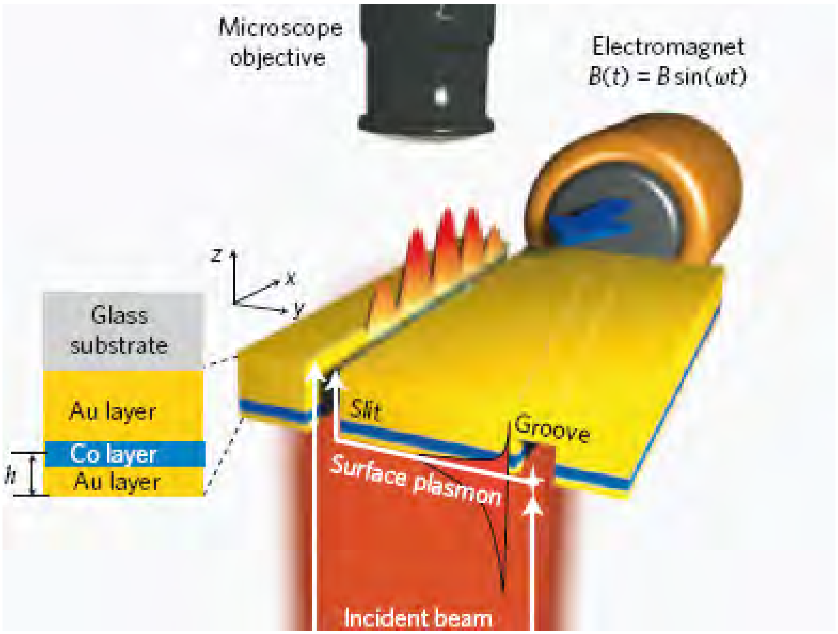
Magnetic field modulation of the SPP wavevector: Active Plasmonics

nature photonics
AIP Applied Physics Letters

Probing the EM field within a continuous gold layer





V.V. Temnov et al; Nature Photonics **4** (2010) 107
D. Martín-Becerra et al., Appl. Phys. Lett. **97**, 183114 (2010)

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Magnetoplasmonic effects in systems with propagating and localized plasmons

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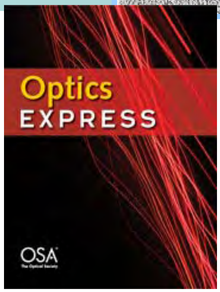

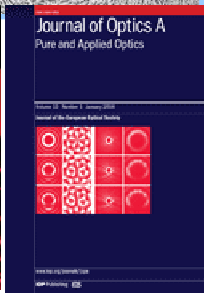

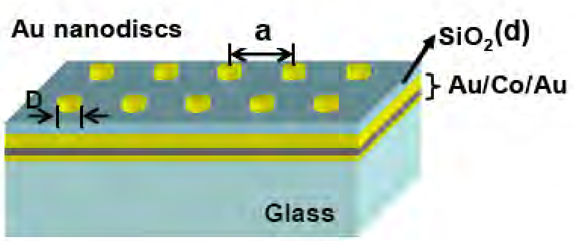

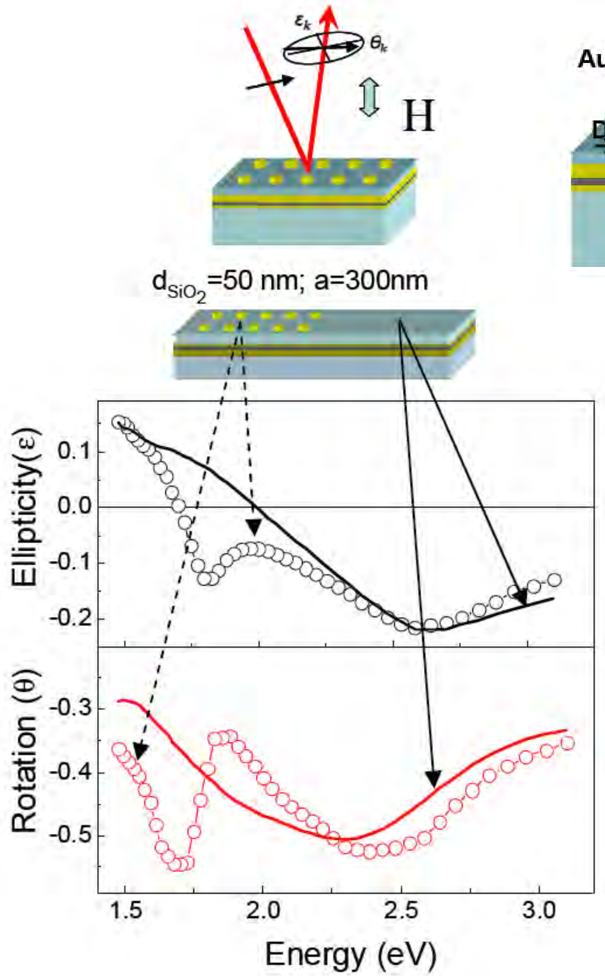

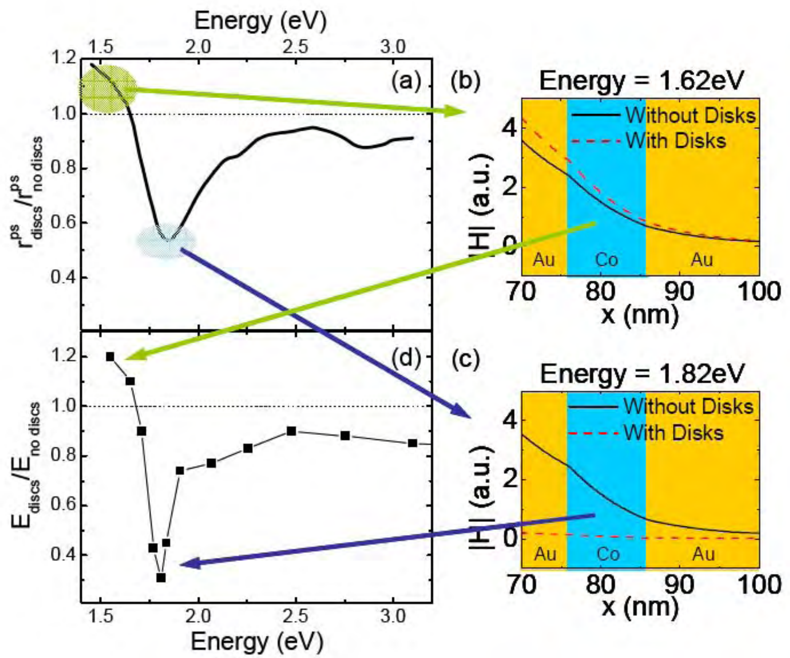

G.Armelles, et al., Optics Express, **16** (2008) 16104.
G Armelles et al., Journal of Optics A: Pure and Applied Optics, **11** (2009) 114023.

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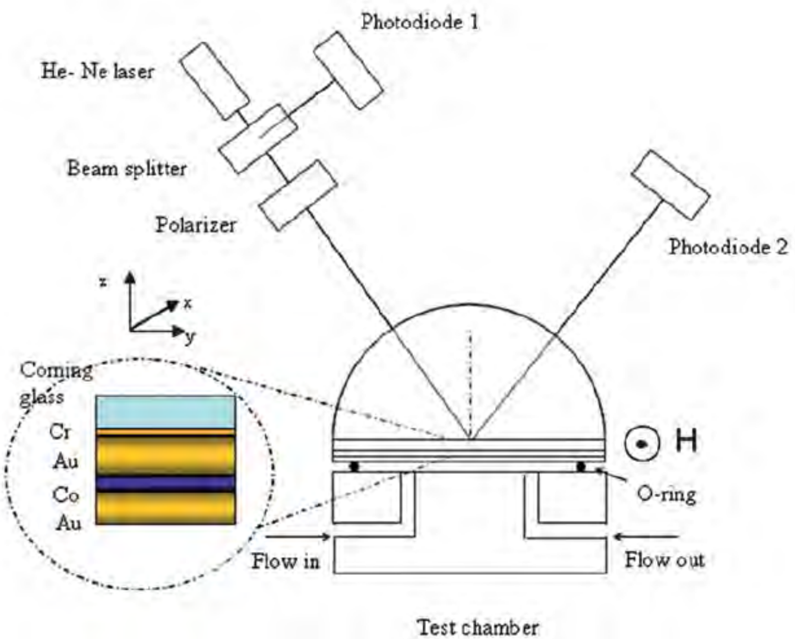
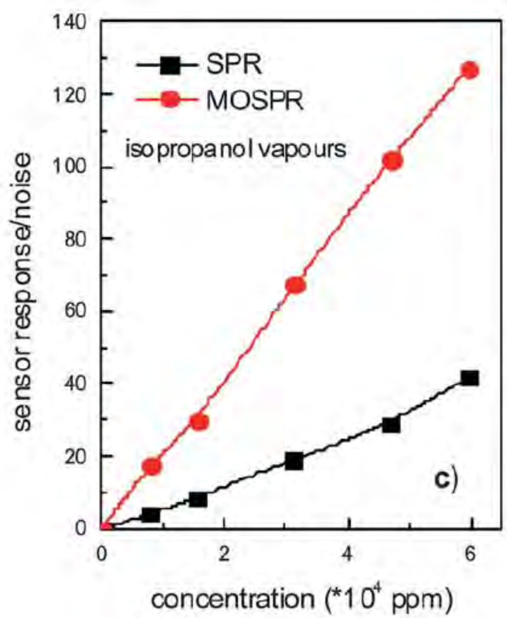
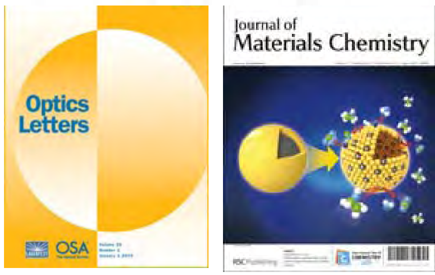
Magnetoplasmonic effects in systems with propagating plasmons

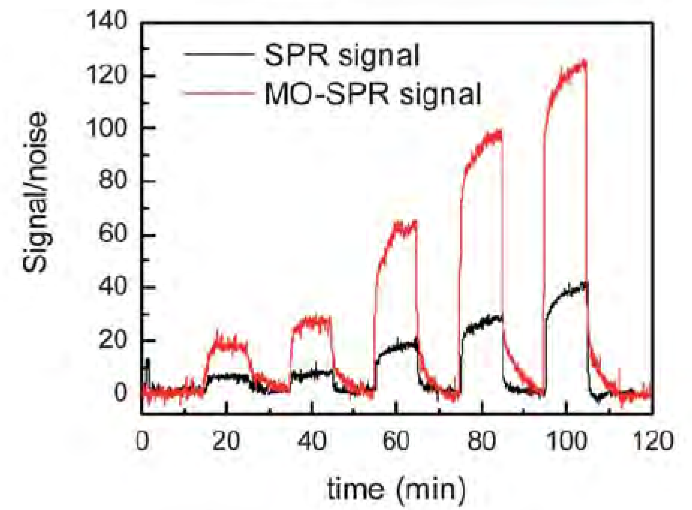
SENSING





AIP Journal of Applied Physics





B.Sepúlveda et al., Opt. Lett. **31** (2006) 1085.
D. Regatos et al., Journal of Applied Physics, **108** (2010) 054502.
M.G.Manera et al., Journal of Materials Chemistry, **21** (2011) 16049.

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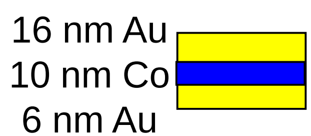
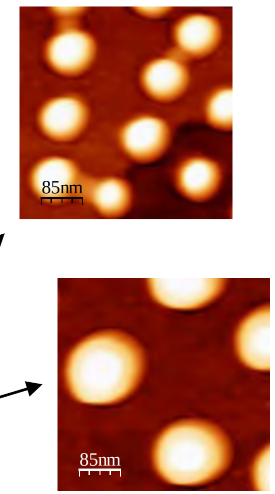
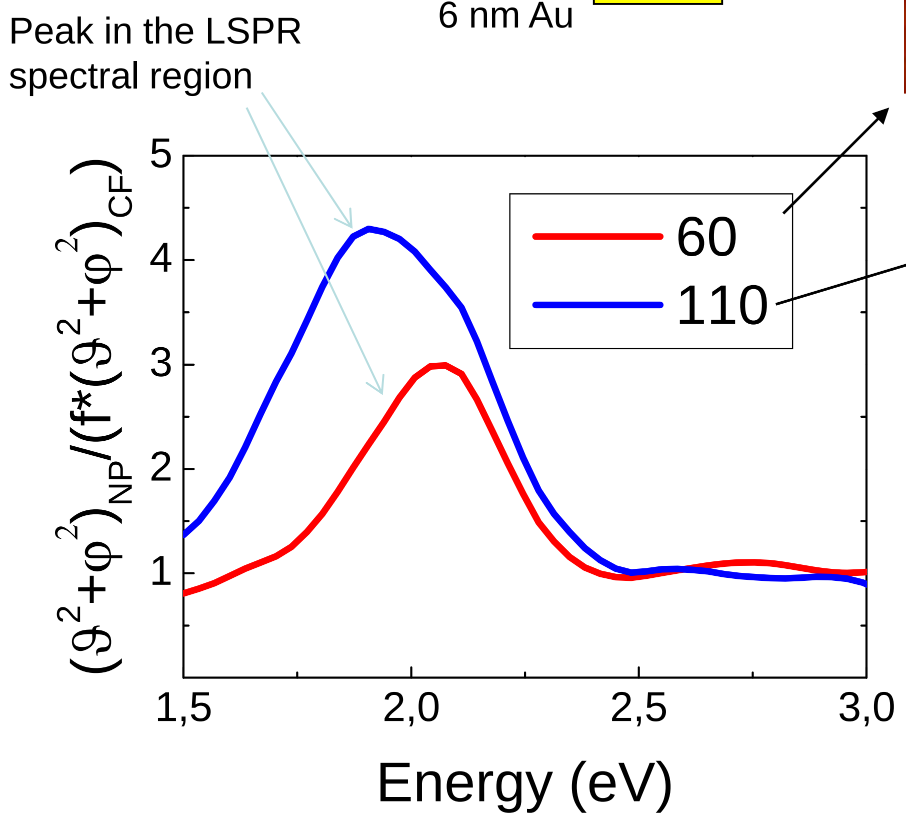
Magnetoplasmonic effects in systems with localized plasmons







LSPR excitation: strong concentration of the EM field in the nanodisc.

Enhancement of the MO activity in the LSPR spectral region with respect to continuous layer (with only 20% the amount of Co)

(J.B. González-Díaz, et al.; SMALL **4** (2008) 202)

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Magnetoplasmonic effects in systems with localized plasmons

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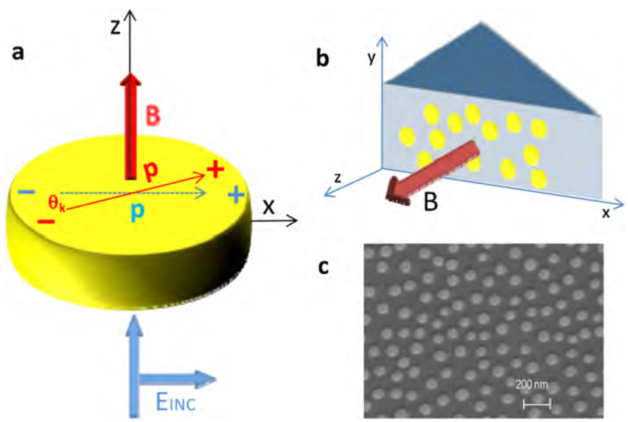
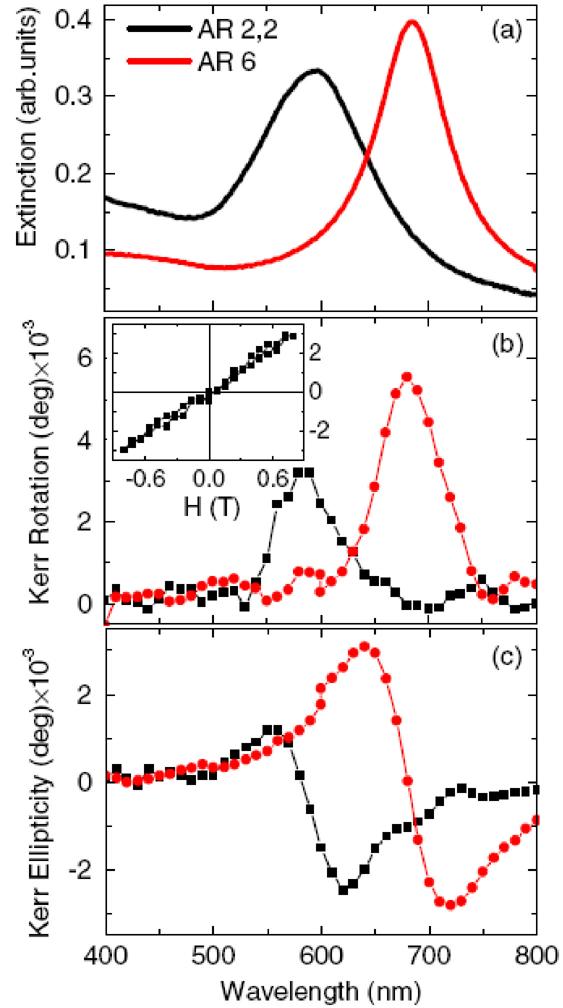
Physical Review Letters moving physics forward

MO activity of PURE Au nanodisks

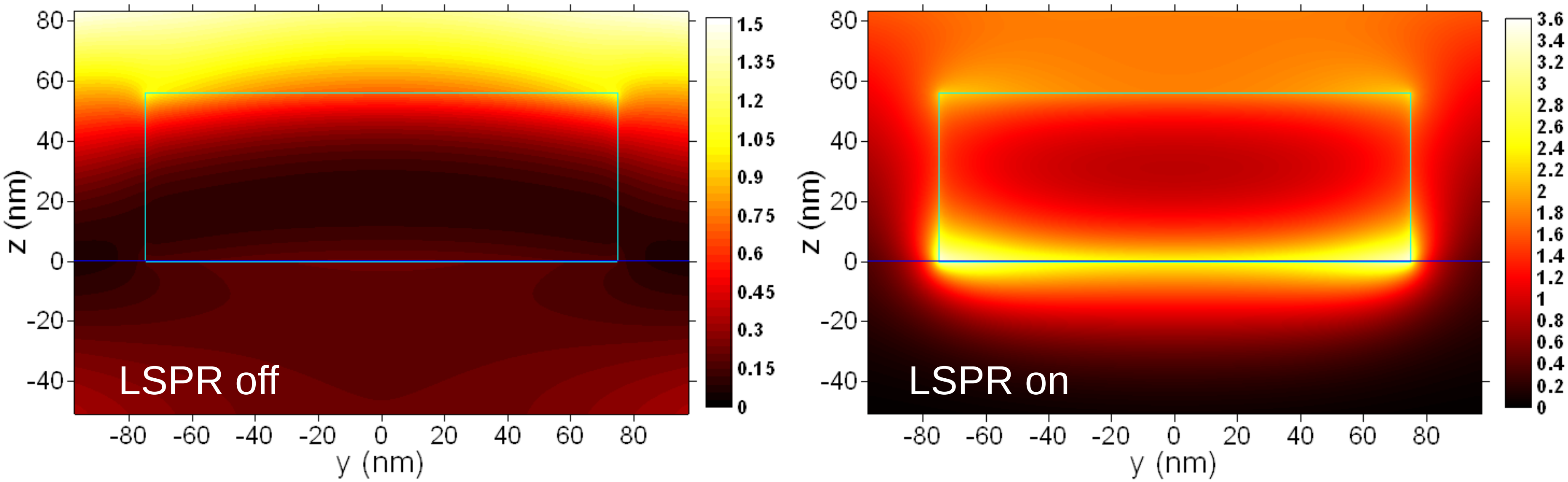




B. Sepúlveda et al., Phys. Rev. Lett. **104** (2010) 147401

Magnetoplasmonic effects in systems with localized plasmons

EM field distribution within the nanodisc



(FDTD simulations: Au disc, h = 55 nm , ϕ = 150 nm)

Vertical EM field distribution:

- "U" shaped
- varies in the nanometer scale
- asymmetric due to the presence of a substrate

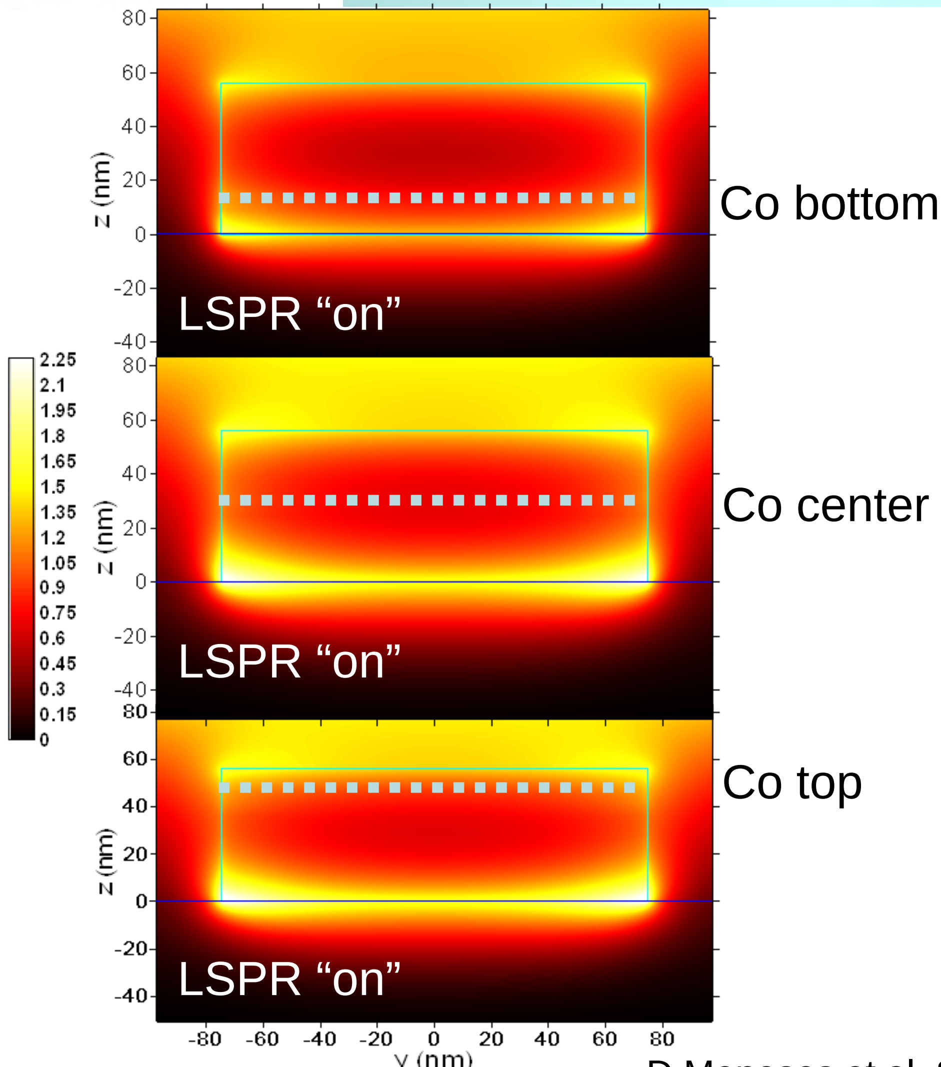
D.Meneses et al. SMALL (in press) DOI 10.1002/smll.201101060

Experimental mapping of the EM field distribution ***outside*** the nanostructure (SNOM) or extract its integrated vertical distribution (TEM-EELS)

...

but not straightforward to experimentally probe the EM field ***inside*** the nanostructure

Effect of the insertion of a 6 nm Co layer in the EM field distribution



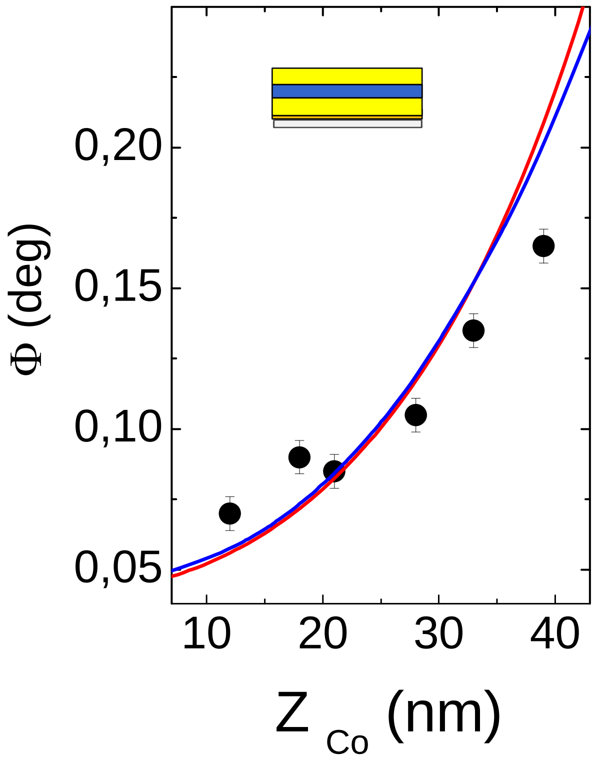
Co insertion does not vary:

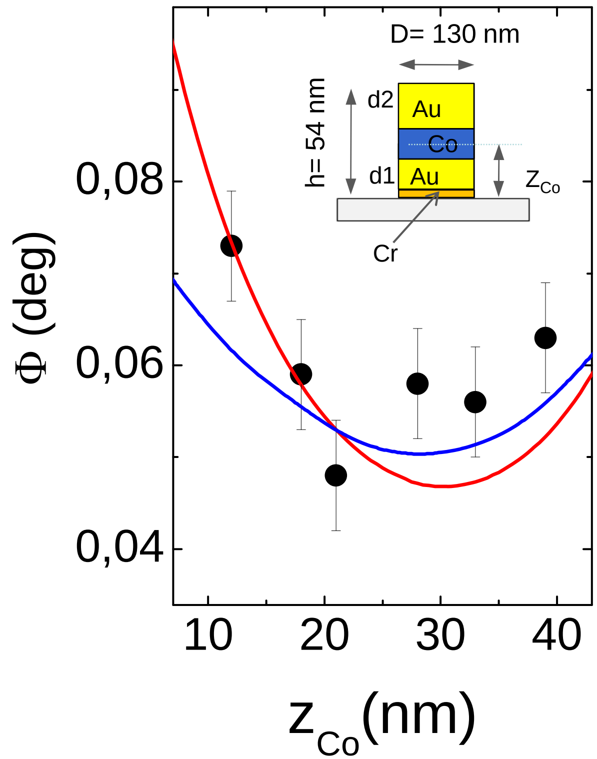
-“U” shape
-Variation in the vertical direction in the nm scale
-Substrate induced asymmetry

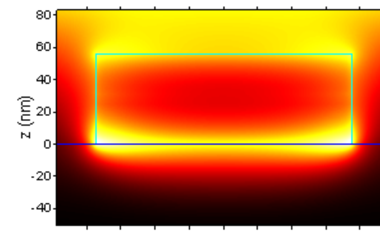
⇒ ~ Non perturbative probe

D.Meneses et al. SMALL (in press) DOI 10.1002/smll.201101060

MO activity as a function of Co position: Continuous layers vs discs







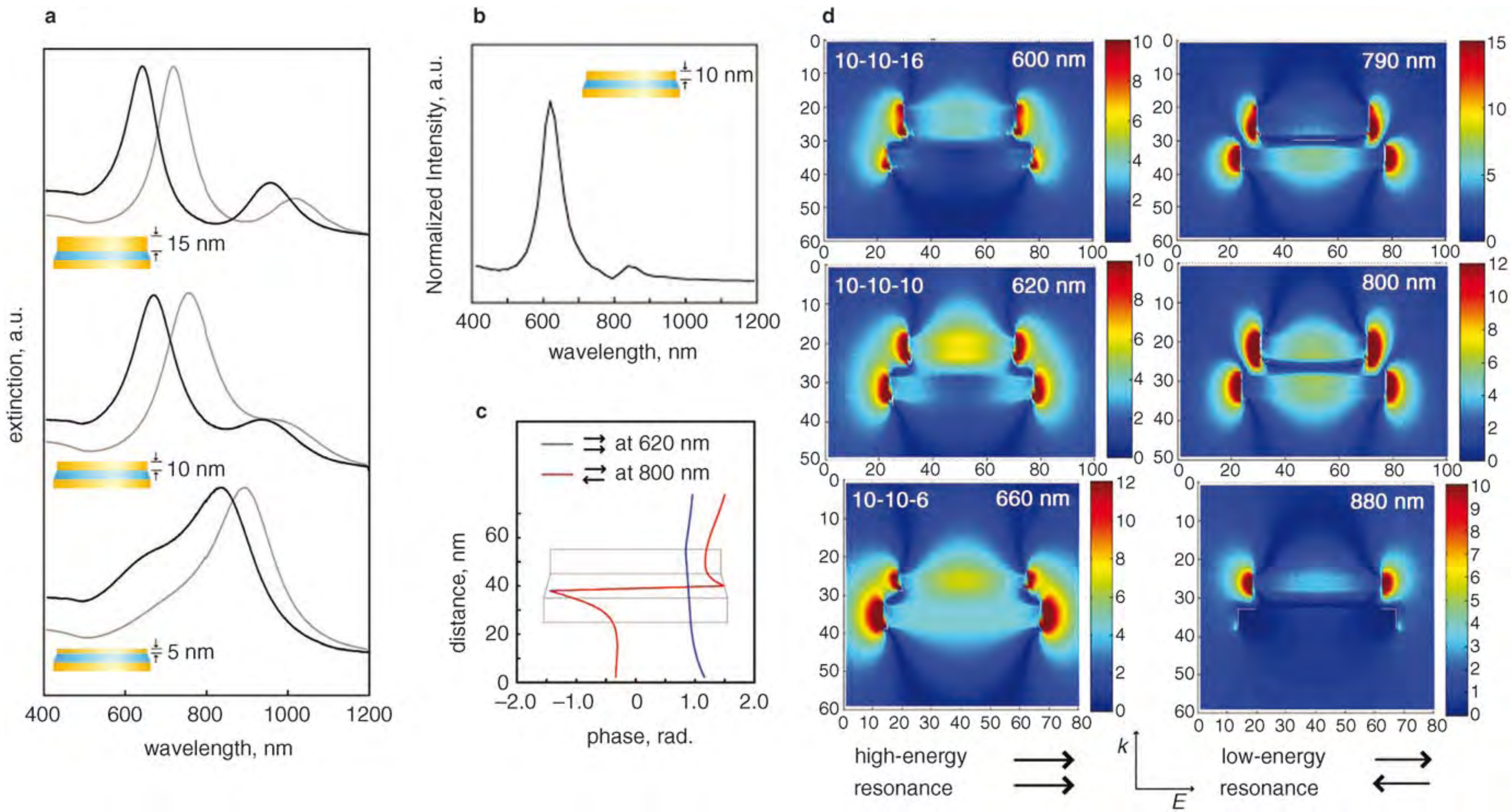
D.Meneses et al. SMALL (in press) DOI 10.1002/smll.201101060

Can we tailor/control this EM field distribution??

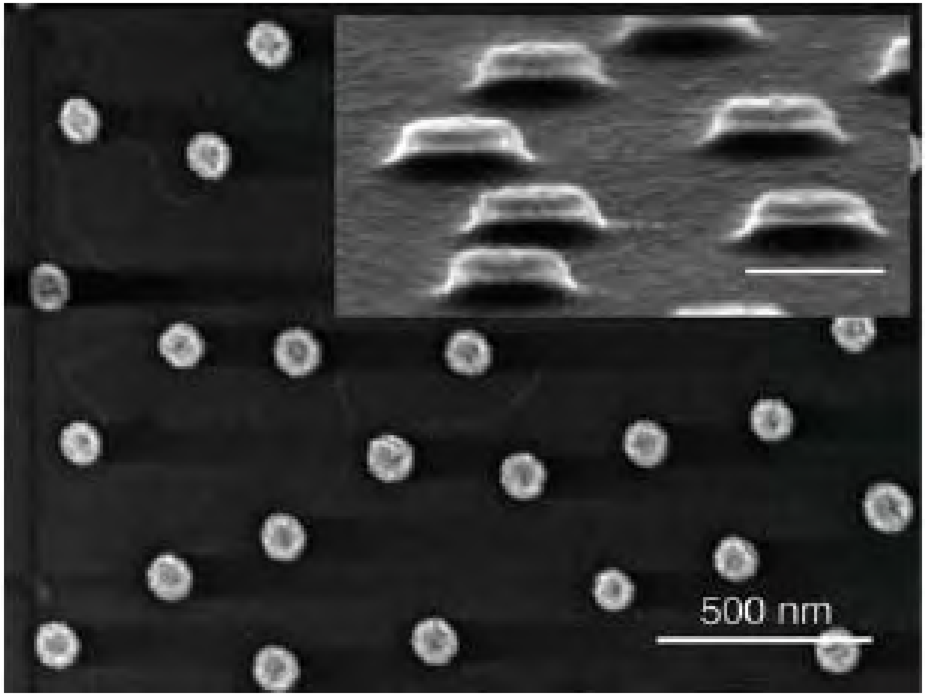
Can we maximize the EM field at the MO active component and minimize it in the others??

$\Rightarrow$ Our first approach: insertion of a dielectric layer

Metal-dielectric nanodiscs



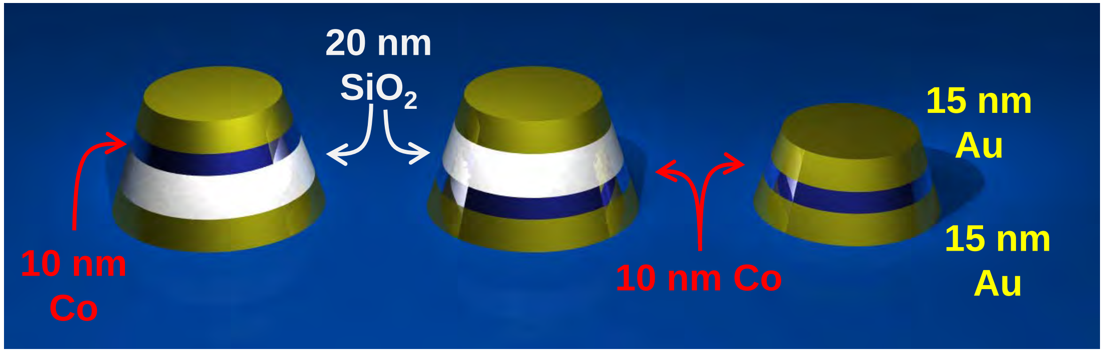
A.Dmitriev, et al. Small **3** (2007) 294



A.Dmitriev, et al. Small **3** (2007) 294

Metal-dielectric nanodiscs

Our approach: insertion of Co layer in the Metal-dielectric nanodisc



J.C.Banthí et al. Advanced Materials (accepted)

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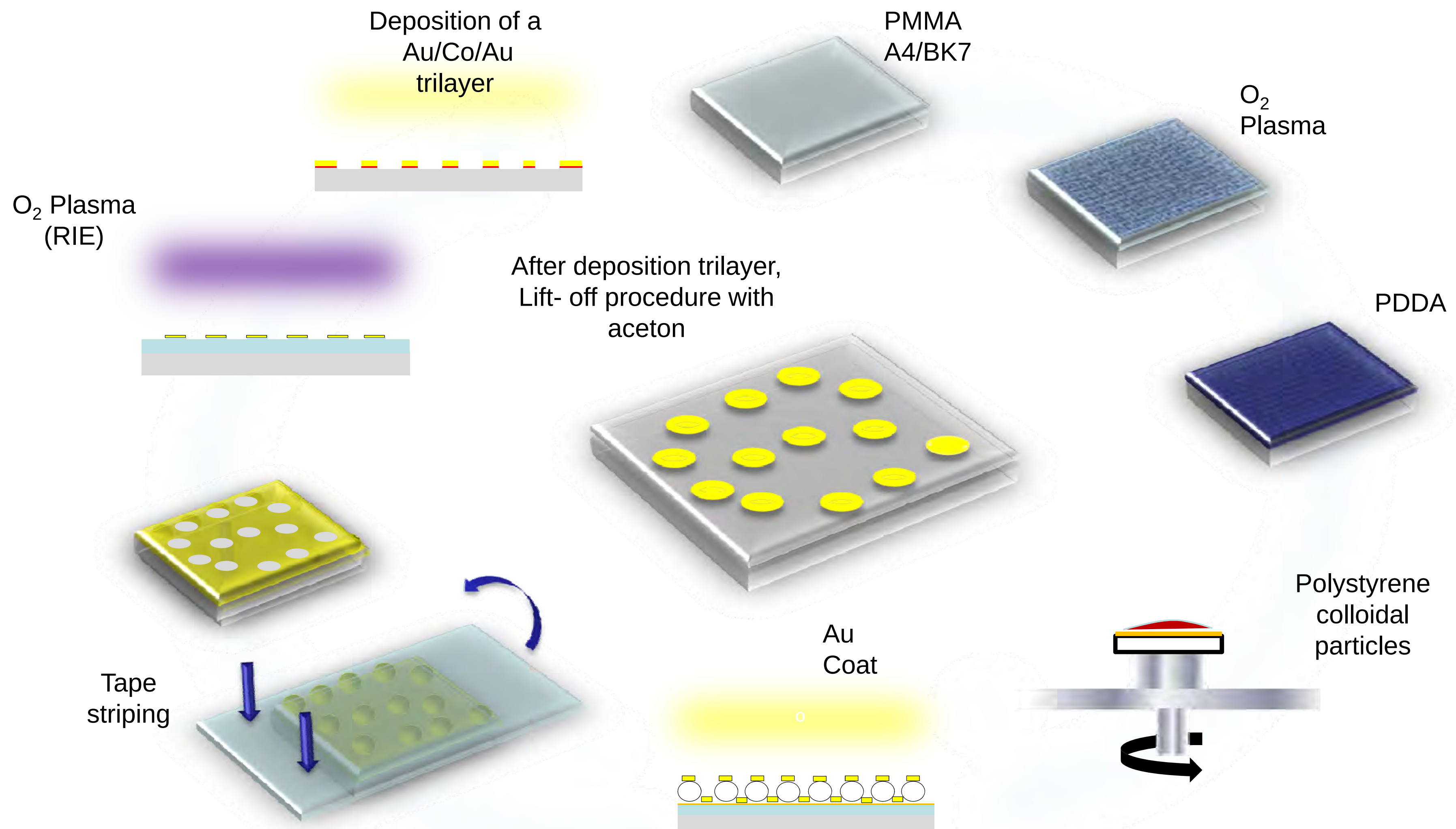
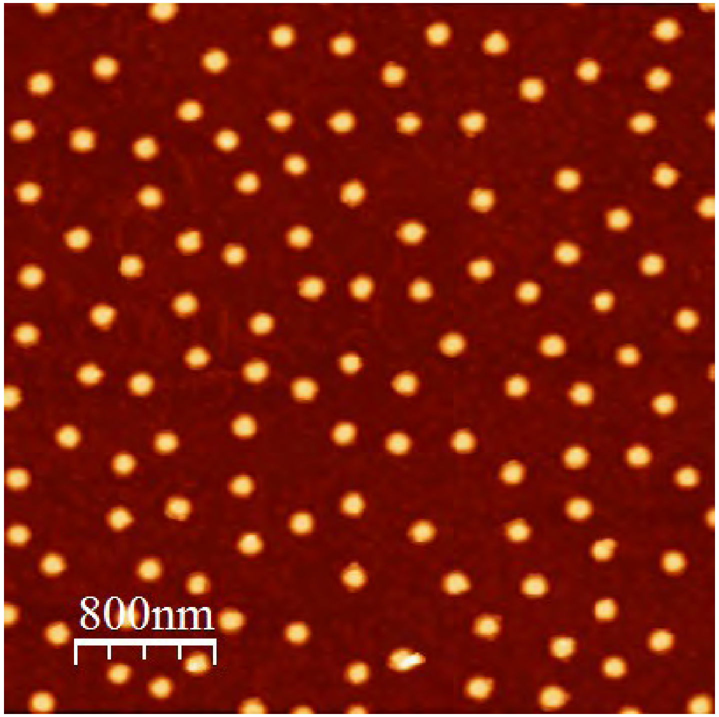
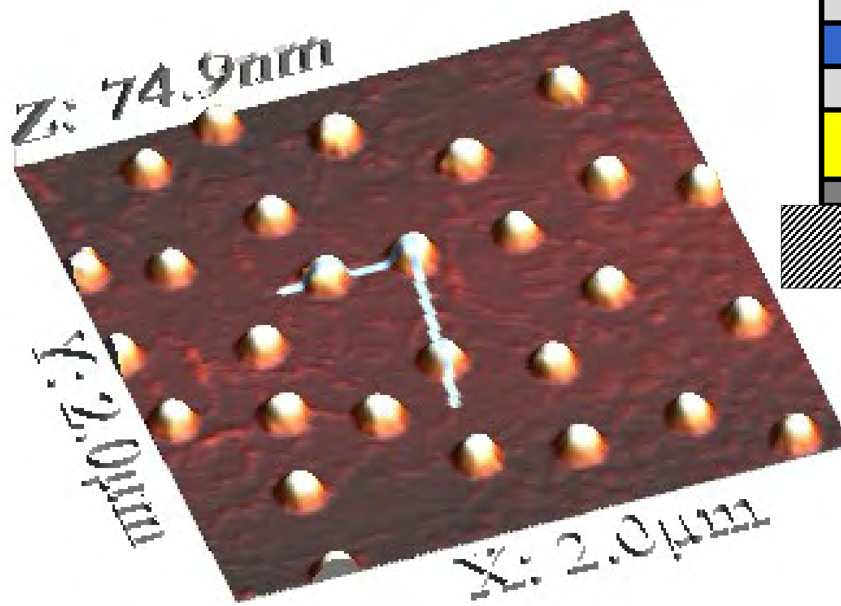
Colloidal-hole lithography process

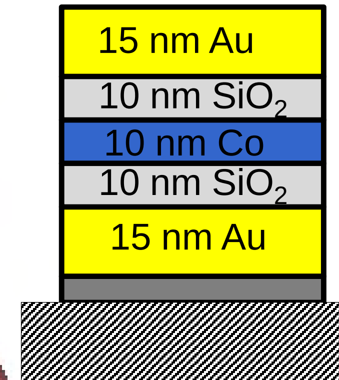


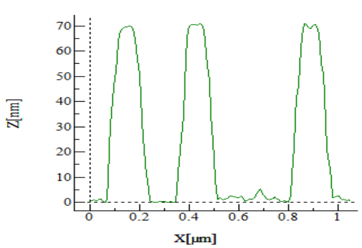
Metal-dielectric nanodiscs



Ø≈110 nm, h ≈ 68 nm







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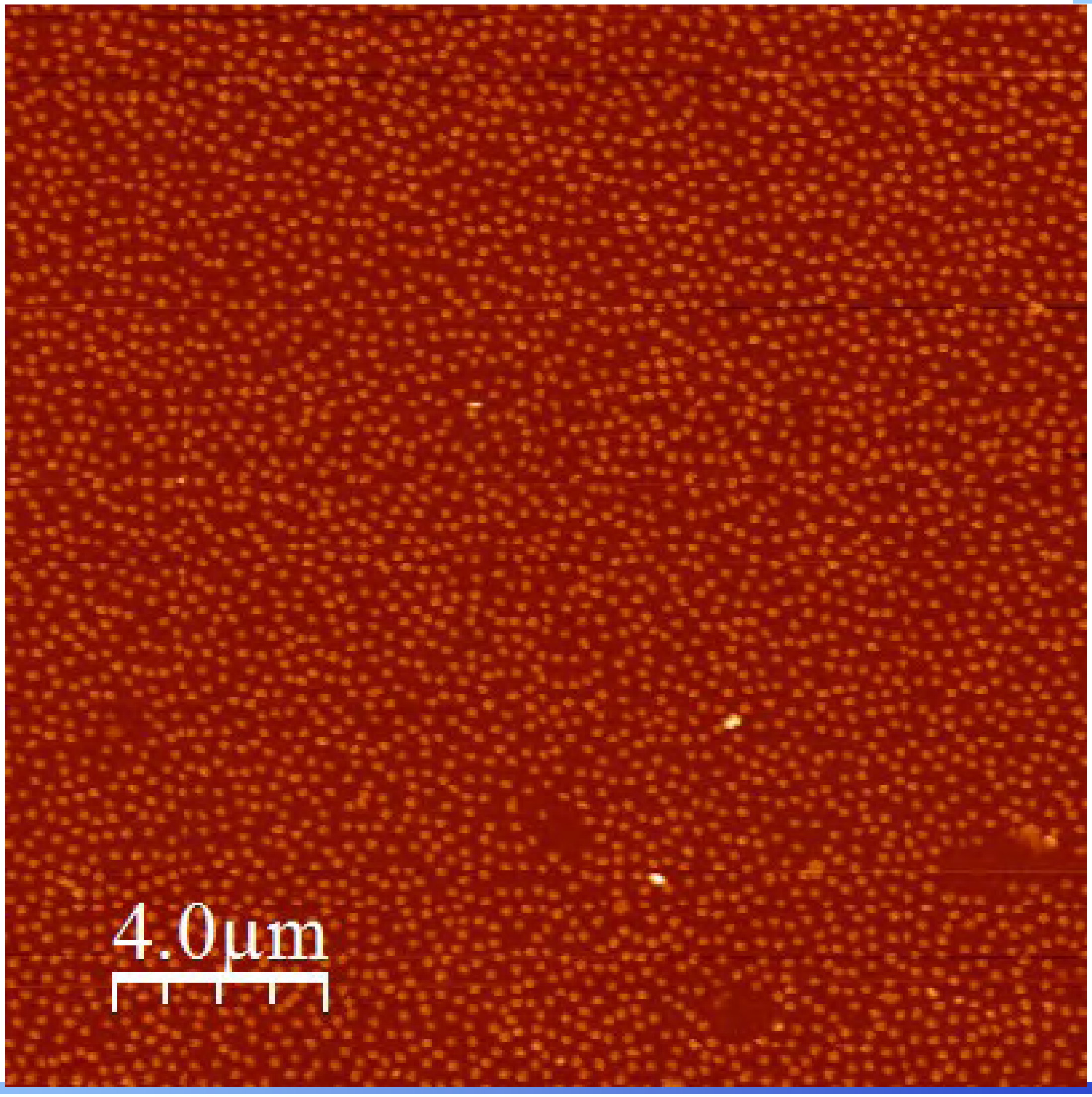
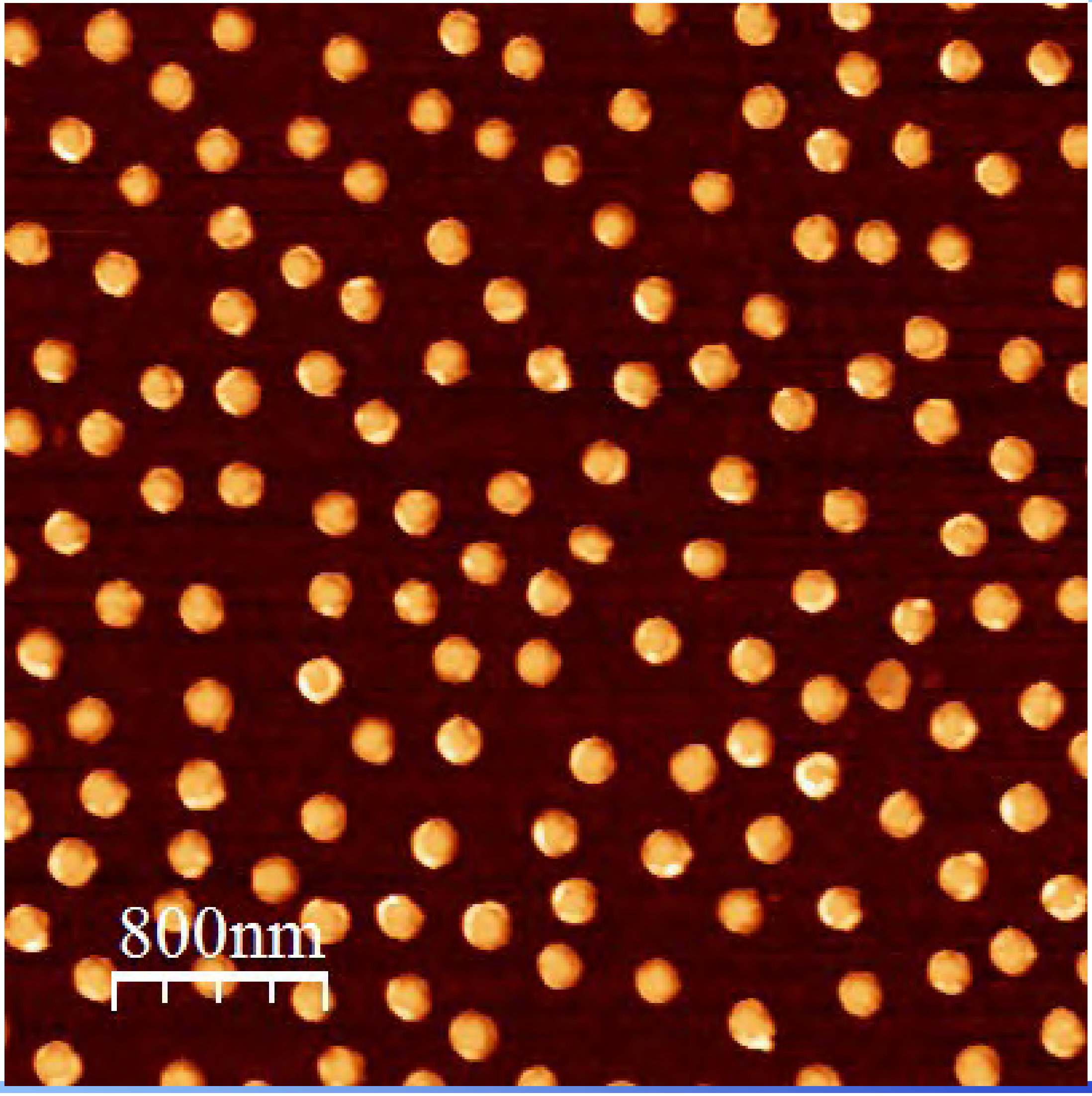
Magnetic Nanostructures MN-MP Magneto Plasmonics




800nm

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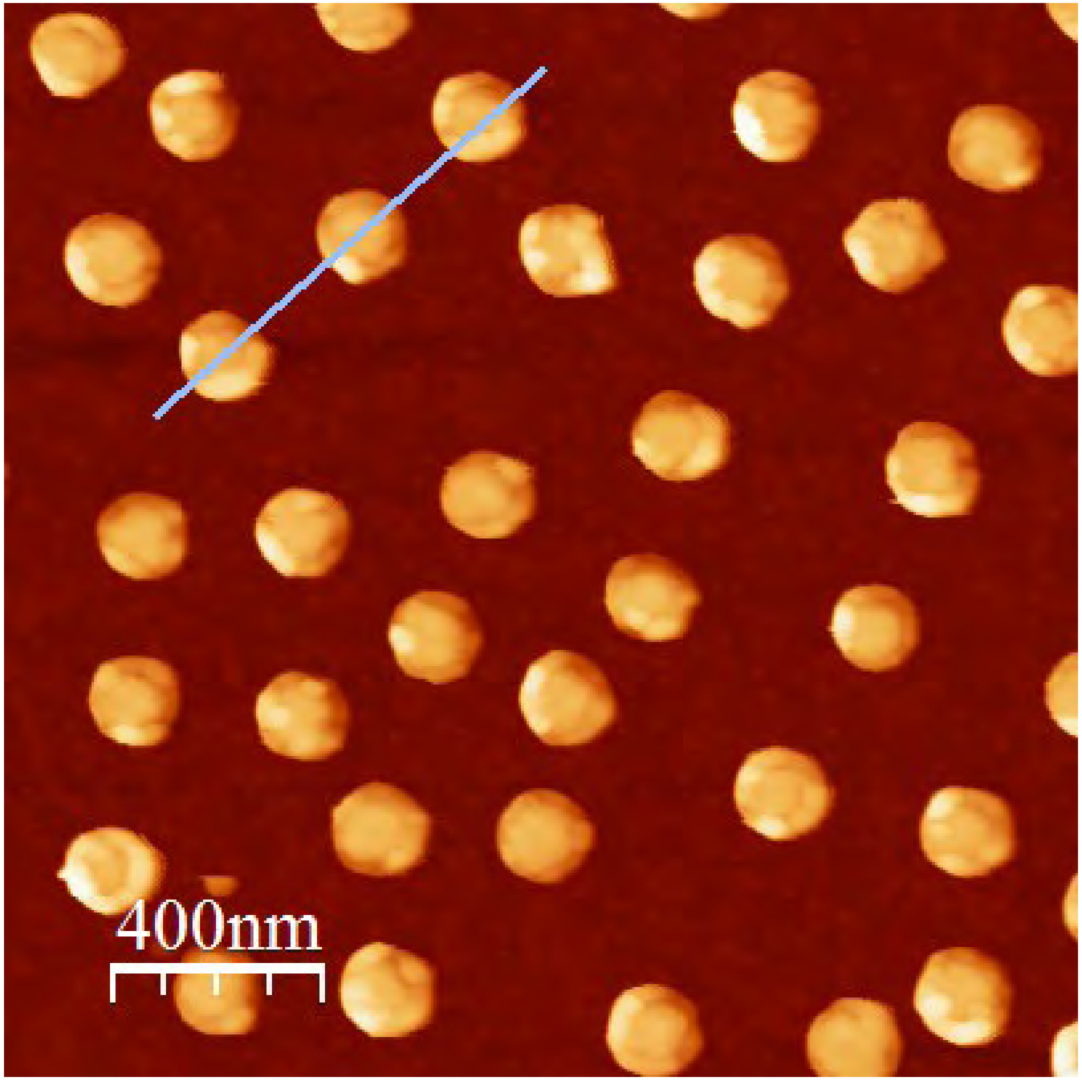
Magnetic Nanostructures MN-MP Magneto Plasmonics



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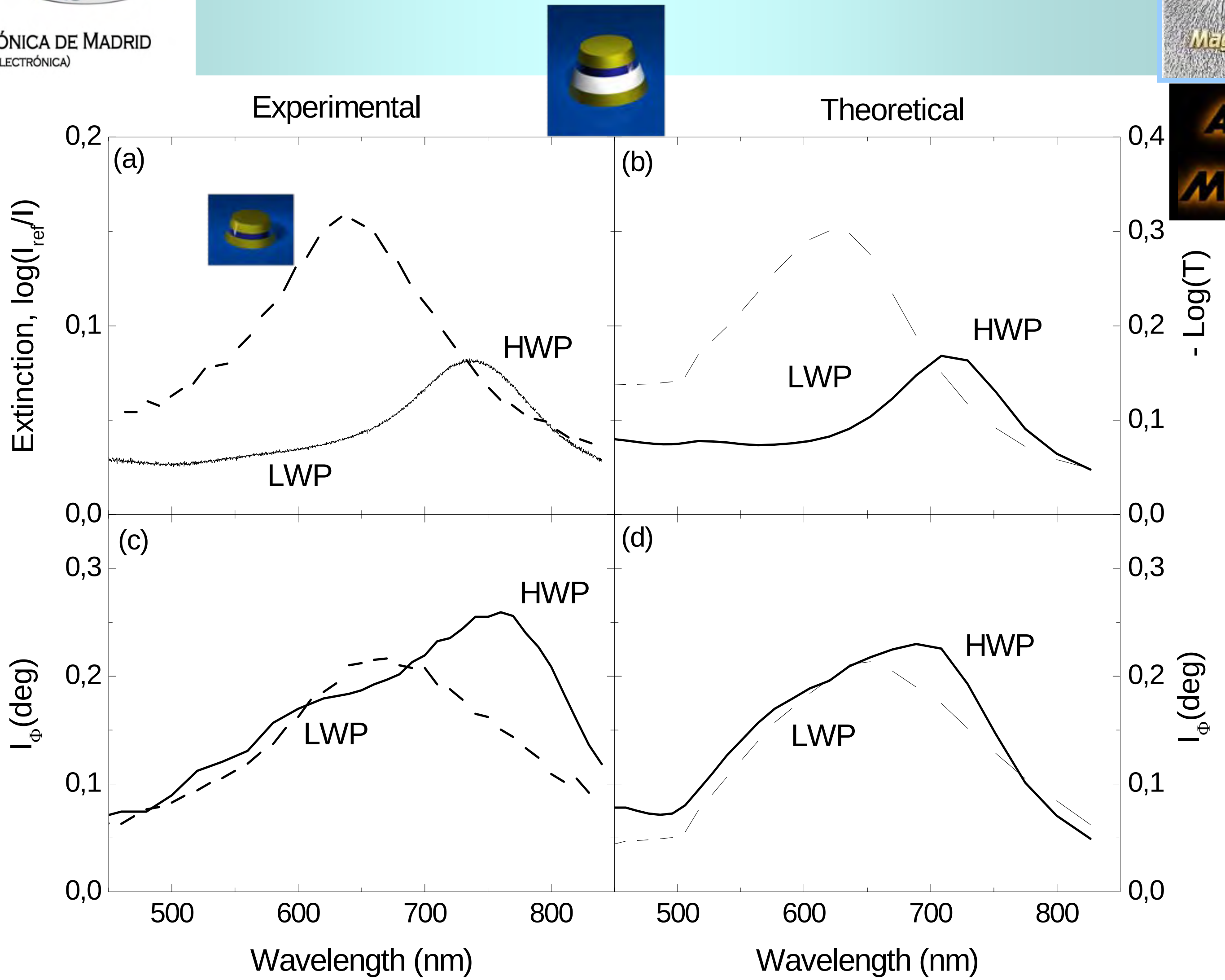
ADVANCED MATERIALS



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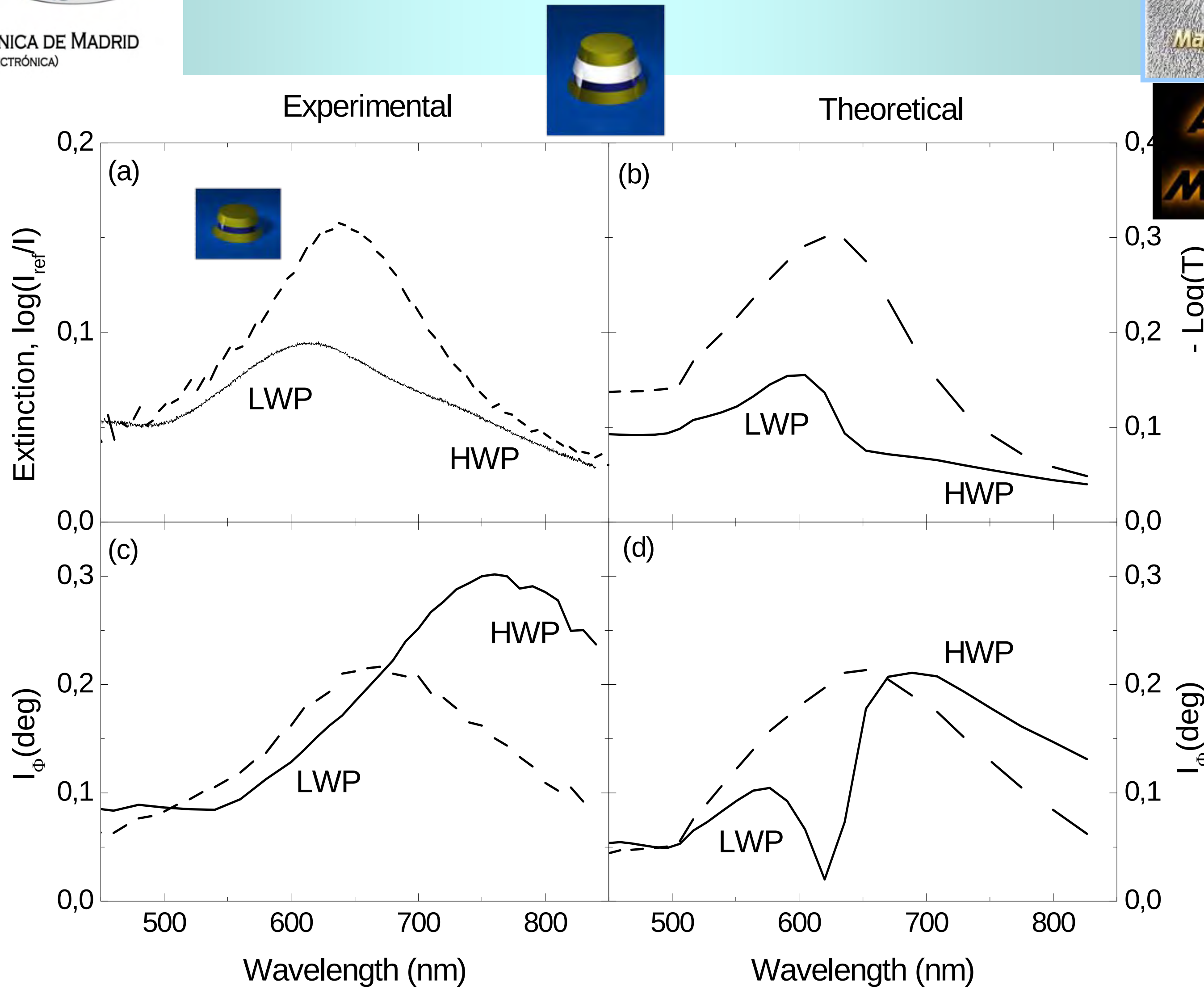
Magnetic Nanostructures
MN-MP
Magneto Plasmonics

ADVANCED MATERIALS



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HTTP://WWW.IMM-CNM.CSIC.ES/MAGNETOPLASMONICS

EM field redistribution

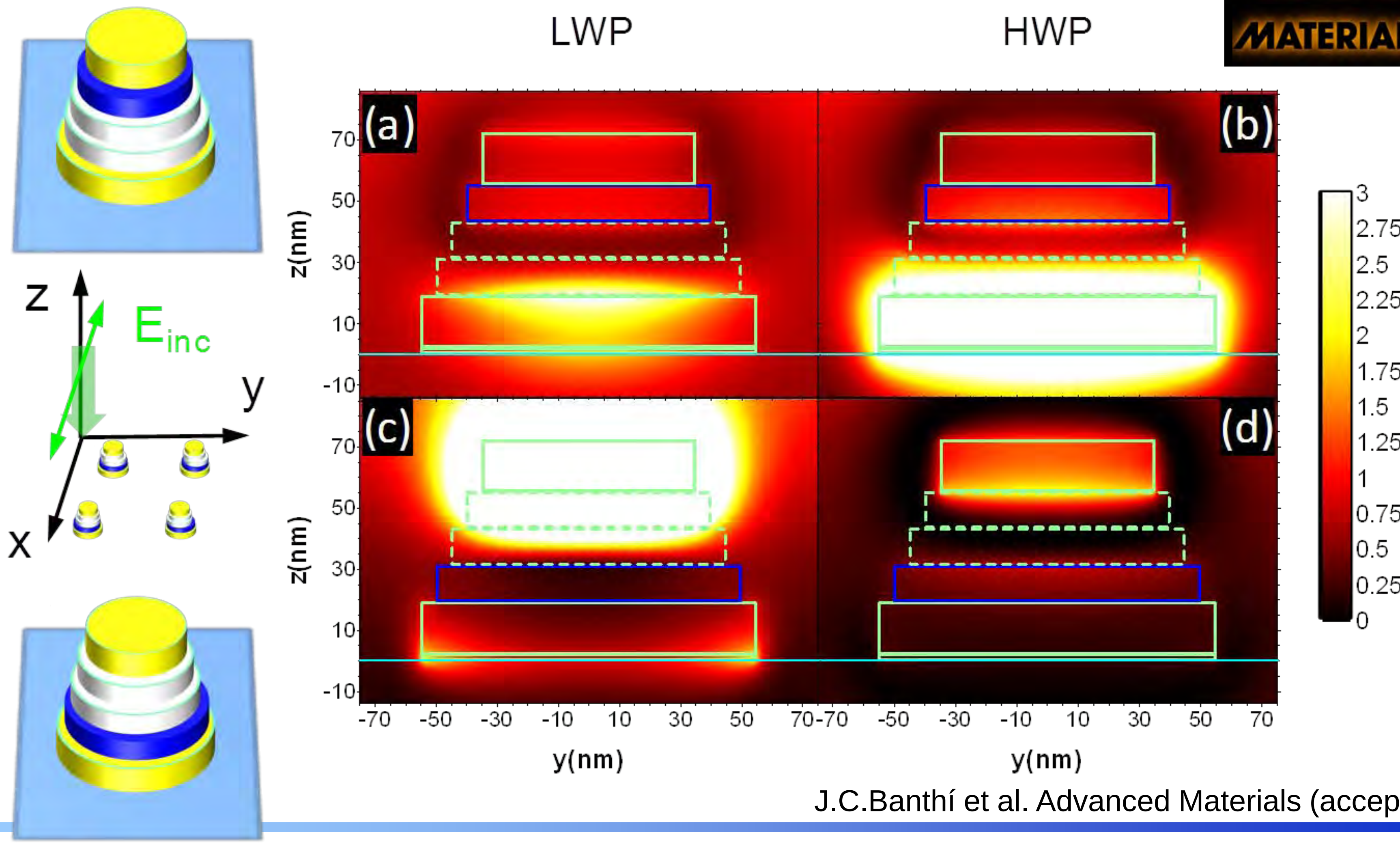

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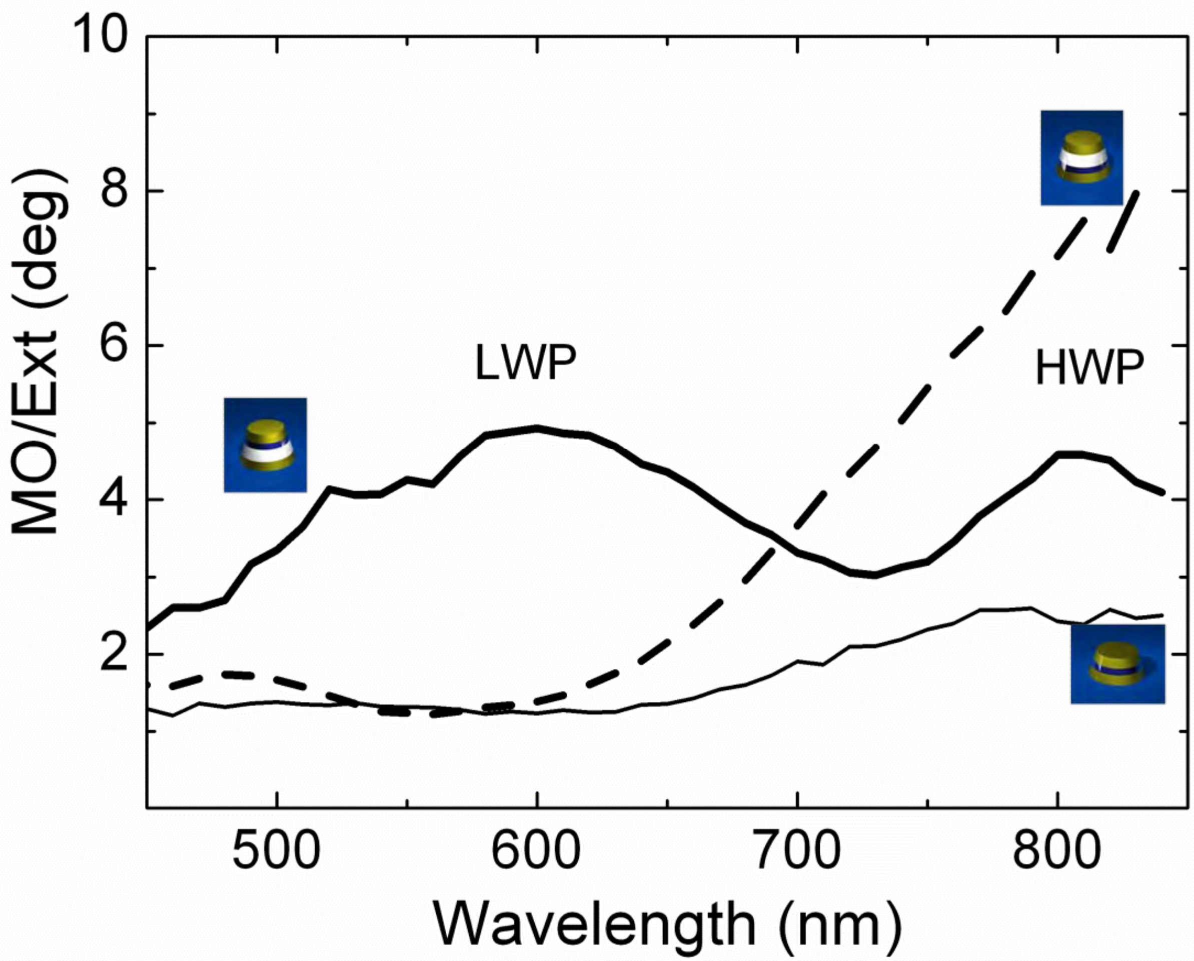
Figure of Merit:
MO activity vs optical losses

Magnetic Nanostructures
MN-MP
Magneto Plasmonics

ADVANCED MATERIALS



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Summary:

Key issue: EM field distribution.

EM field engineering by insertion of a dielectric layer
+ adequate stacking of all different layers

→Maximize the EM field at the MO active layer
→ Reduce the EM field at the non-MO layers.

<u>Large MO activity + low optical losses magnetoplasmonic system</u>