Tailoring the modulation depth in Au/Co/Au magnetoplasmonic switches

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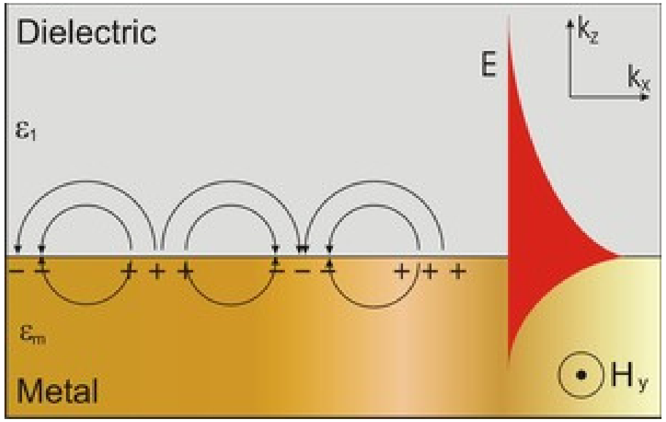
Introduction

Surface plasmon polaritons (SPP) are:

"Electromagnetic excitation (TM polarized) localized at the interface between a media with $\varepsilon_r < 0$ (metal) and a media with $\varepsilon_r > 0$ (dielectric material)"



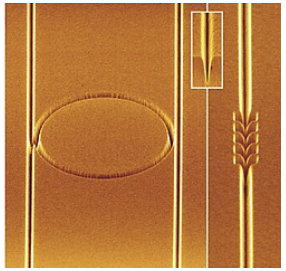
- Localization of light in subwavelength volumes, beyond the diffraction limit

→ ***Miniaturized optical devices***

Introduction

Plasmonics → one path to develop nanophotonic devices

- Passive systems widely demonstrated

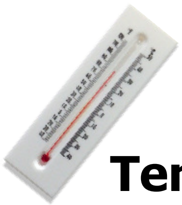


Groove based waveguides

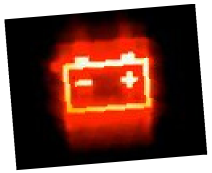
Nature **440**, 508 (2006)
Nano Lett. **7**, 880 (2007)

- **Active plasmonics** is needed to provide active components

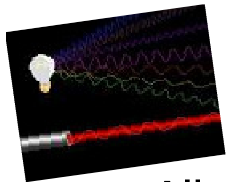
  ↳ Several proposed control agents:



Temperature
Thermo-optical materials



Voltage
PlasMOStor
Electro-optical materials

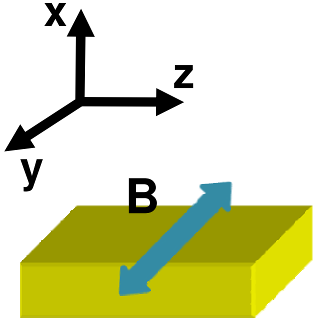


Light
All-optical modulation

- Our choice as external agent → **magnetic field**

Magnetic field effects

Effects of magnetic field on optical properties of metals (Drude):



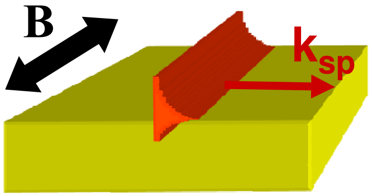
$$\begin{pmatrix} \varepsilon & 0 & \pm\varepsilon_{mo} \\ 0 & \varepsilon & 0 \\ \mp\varepsilon_{mo} & 0 & \varepsilon \end{pmatrix}$$

$$\varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + \Gamma^2} + i\frac{\omega_p^2 \Gamma}{\omega(\omega^2 + \Gamma^2)}$$

$$\varepsilon_{mo} = -\left(\frac{2\omega_p^2 \omega_c \Gamma}{\left(\omega^2 + \Gamma^2\right)^2} + i\frac{\omega_p^2 \omega_c}{\omega(\omega^2 + \Gamma^2)} \right)$$

$$\omega_c = \frac{eB}{m^*}$$

Effects of magnetic field on surface plasmon polaritons (SPP)

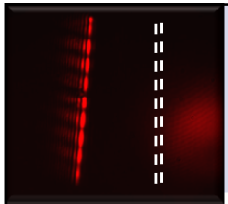


$$k_{sp} \approx \frac{\omega}{c}\sqrt{\frac{\varepsilon}{\varepsilon + 1}}\left(1 - \frac{i\varepsilon_{mo}}{(1 + \varepsilon^2)\sqrt{-\varepsilon}}\right)$$

SPP wavevector modulation

$$k_{sp} = k_{sp}^0 \left(1 + \frac{\Delta k_{sp}}{k_{sp}^0} \mathrm{B} \right)$$

R.F. Wallis *et al.*,
PRB **9**, 3424 (1974)



Magnetic field effects

Magnitude of the effects

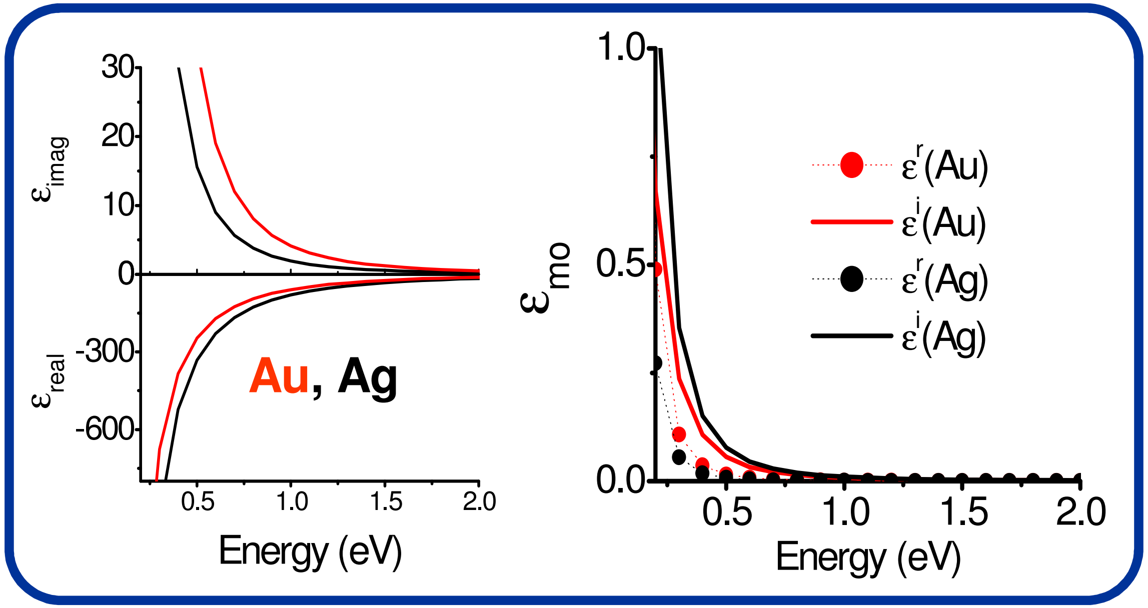
$$\varepsilon_{mo} = -\left(\frac{2\omega_p^2 \omega_c \Gamma}{\left(\omega^2 + \Gamma^2\right)^2} + i \frac{\omega_p^2 \omega_c}{\omega(\omega^2 + \Gamma^2)} \right)$$

$$\omega_c = \frac{eB}{m^*}$$ ➡ small for metals

$$\varepsilon_{mo} << \varepsilon$$

$\hbar\omega_c$= 0.115 meV (B=1 Tesla)

Plasmonic metals



SPP wavevector modulation

$$k_{sp} = k_{sp}^0 \left(1 + \frac{\Delta k_{sp}}{k_{sp}^0} \mathrm{B} \right)$$

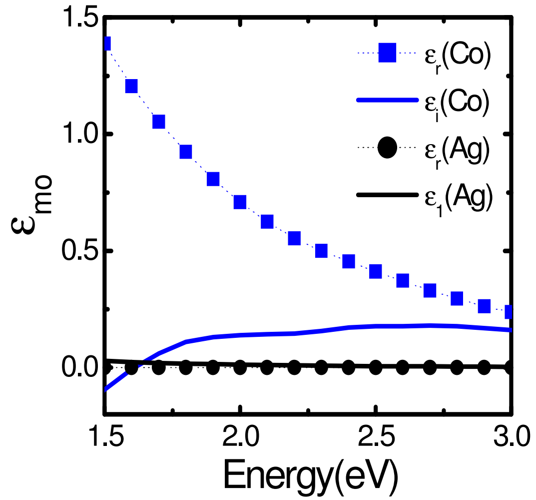
Very small effect:

Au/air, B = 1T, 1eV

$(\Delta k/k_0)\cdot B = 1{,}4\cdot 10^{-6}$

Magnetic field effects

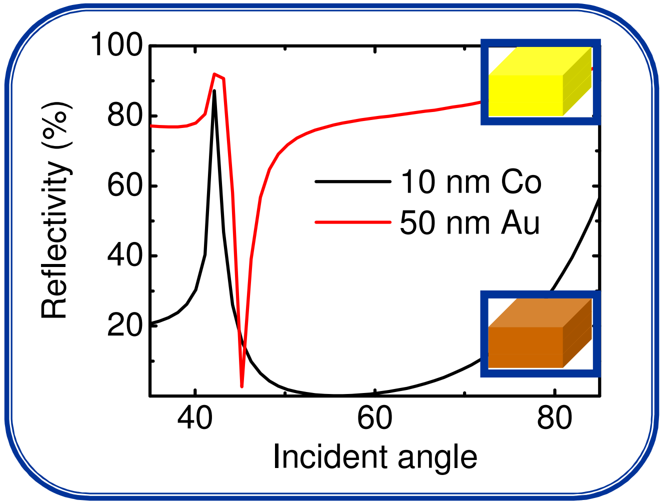
ε_{mo} in noble metals is very small → Solution: **ferromagnetic metals**



$$\varepsilon_{mo}(Co, Fe, Ni) \propto M;$$
$$\pm M \ (B \sim .005\ T)$$
$$\varepsilon_{mo}(Ag, Au) \propto B$$

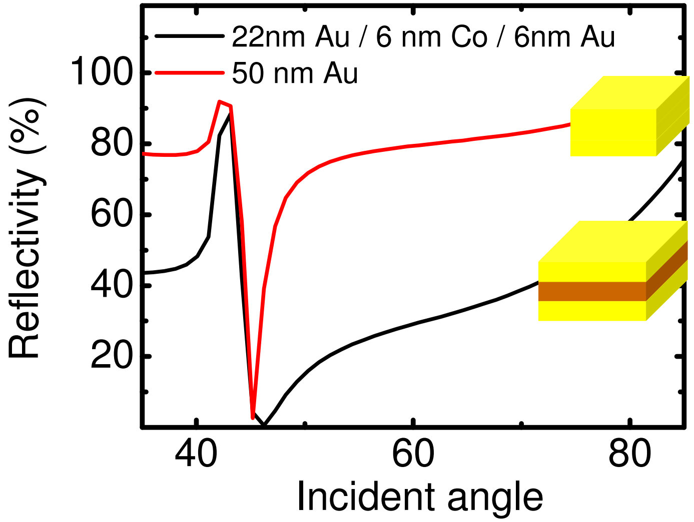
Co/air, B = 10^{-3} T, 1eV
$(\Delta k/k_0)\cdot M = 2{,}8\cdot 10^{-4}$

Ferromagnetic metals are very absorbent → very broad plasmonic resonances



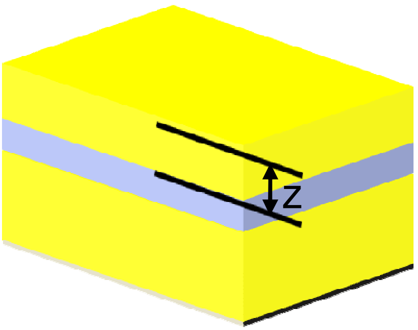
Magnetoplasmonics

Magnetoplasmonic materials: Hybrid ferromagnetic – noble metal systems



- Fair plasmonic modes
- Good MO activity

$$k_{sp} = k_{sp}^{0} \cdot \left(1 + \frac{\Delta k_{sp}}{k_{sp}^{0}} M\right)$$

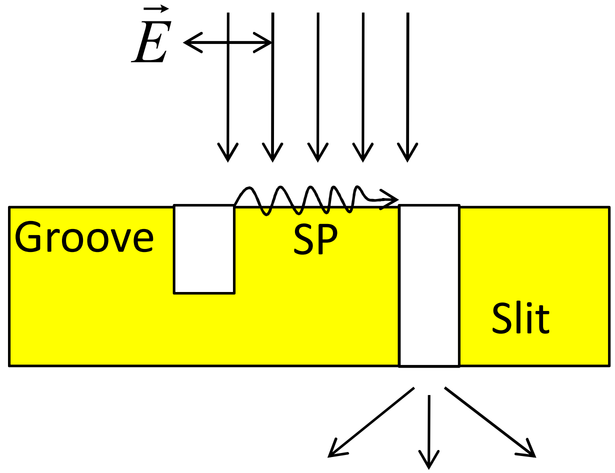


Samples:

Glass+ 2Cr+Trilayers Au/6 nm Co/Au 200nm thick

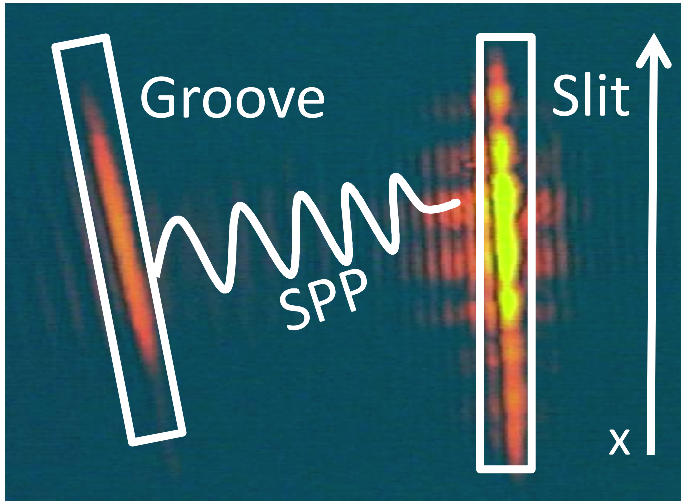
Co depth, z: 05/15/25/35/45/55 nm

Plasmonic interferometer



$I_T = I_{direct} + I_{SPP} + I_{interference}$

Tilted groove

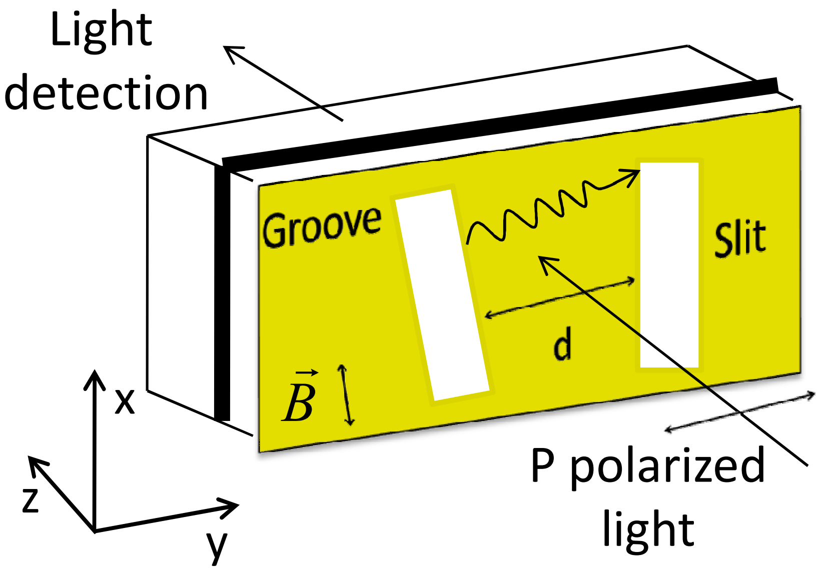


$$I = \underbrace{A^2_{np}}_{I_{direct}} + \underbrace{A^2_{sp} e^{-2k^i_{sp}\cdot d}}_{I_{SPP}} + \underbrace{2\cdot A_{np} A_{sp} \cdot e^{-k^i_{sp}\cdot d} \cdot \cos(k_{sp}{}^r \cdot d + \varphi)}_{\text{Interference term}}$$

Opt. Lett. **32**, 1235 (2007)
Opt. Express **17**, 8423 (2009)

Magnetoplasmonic interferometer

Transversal configuration



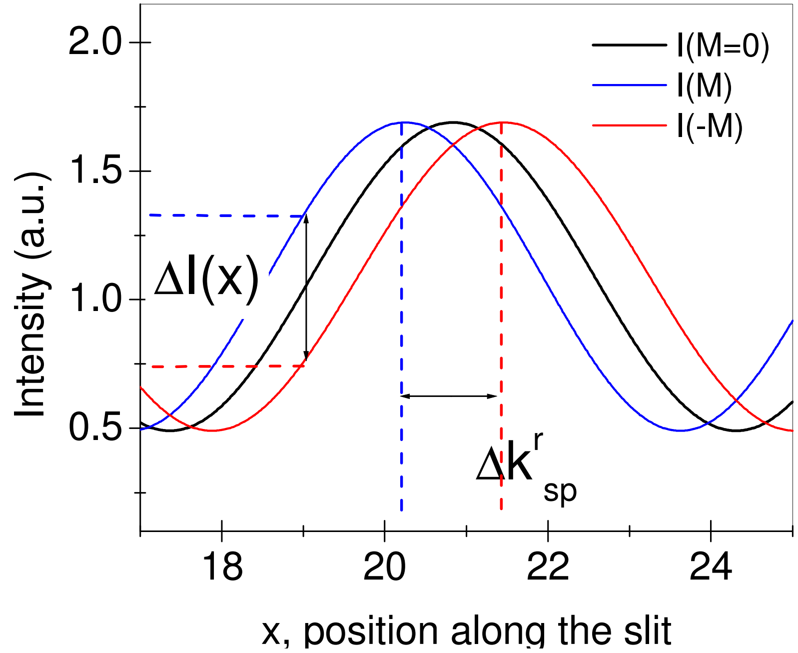
$$k_{sp}(M) = k_{sp0} \cdot \left(1 + \frac{1}{2}\Delta k_{sp}\right)$$

$$\Delta k_{sp} = k_{sp}(M) - k_{sp}(-M) \propto M$$

Δk_{sp}

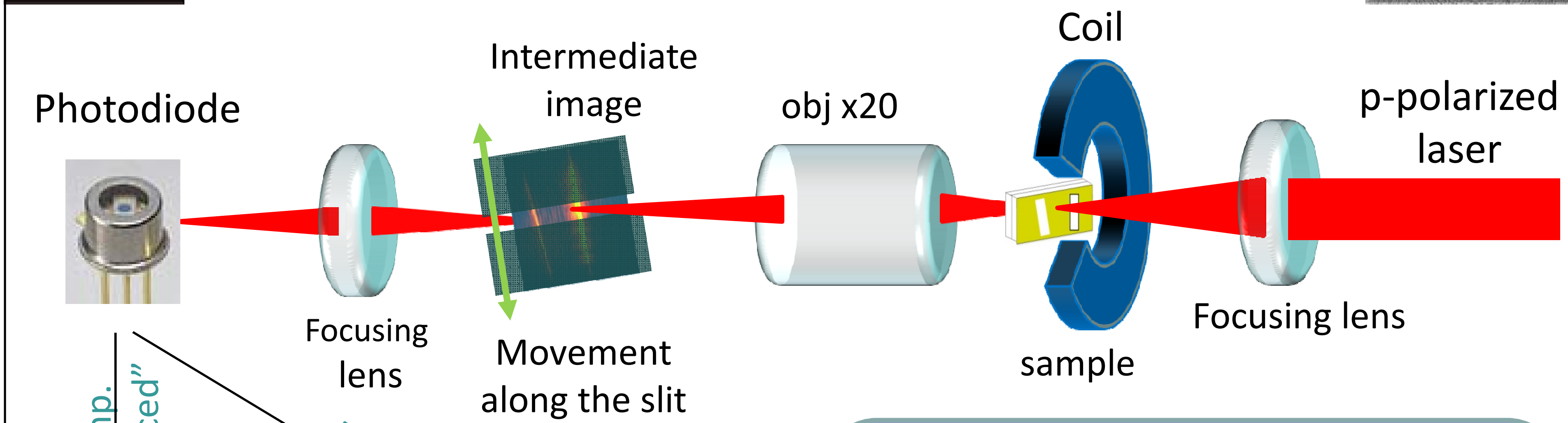
⇓

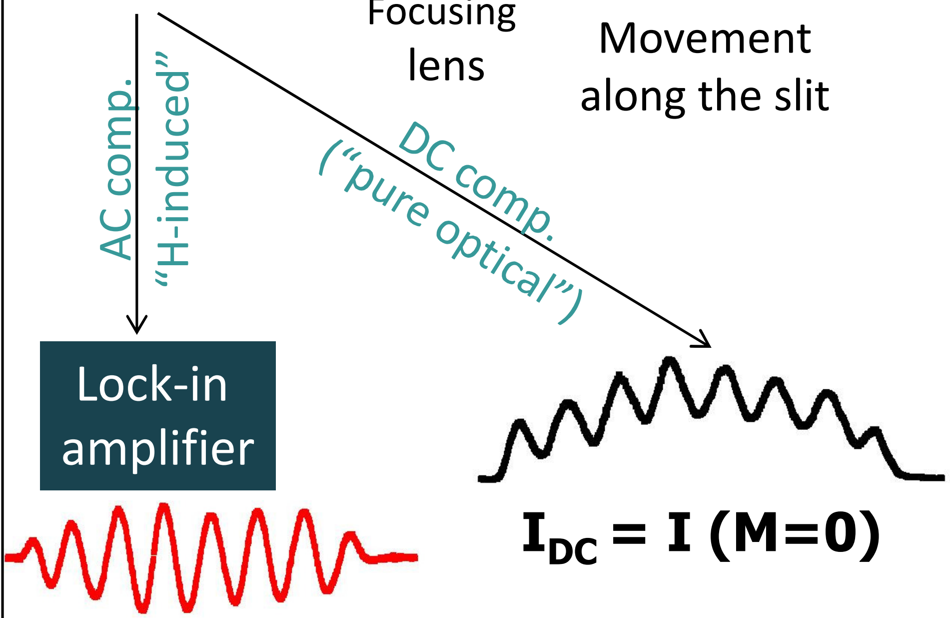
interference pattern shift



⇒ We modulate ΔI

Experimental setup





$I_{DC} = I\,(M=0)$

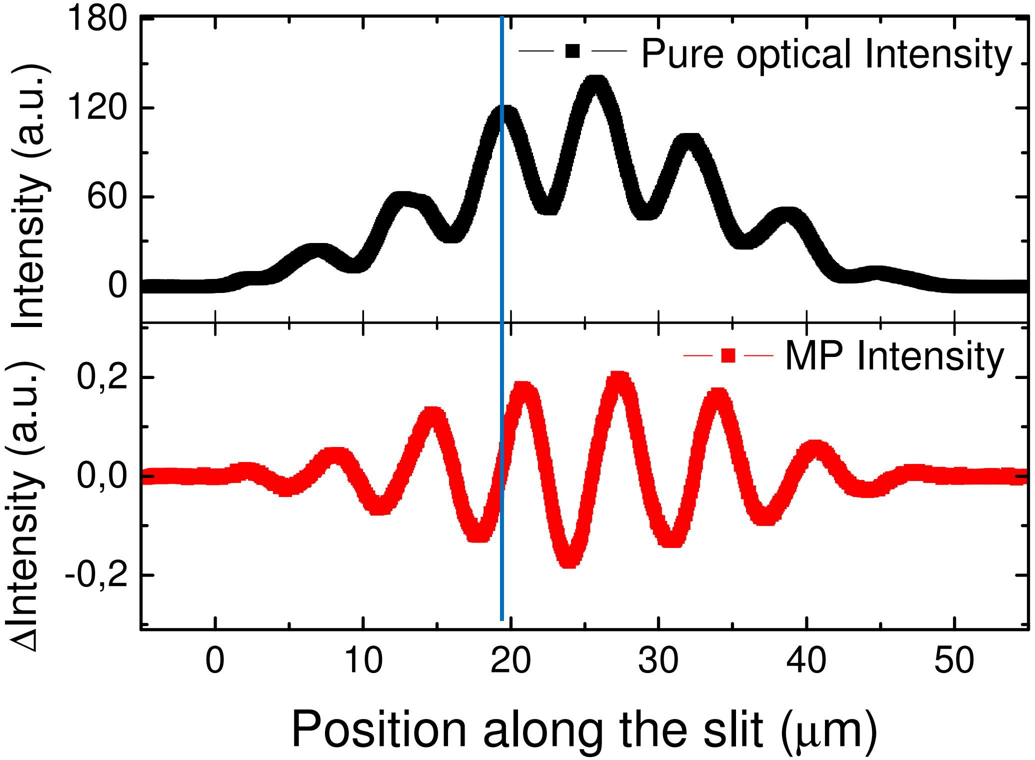
$I_{MP} = \Delta I(M) = I(M)-I(-M)$

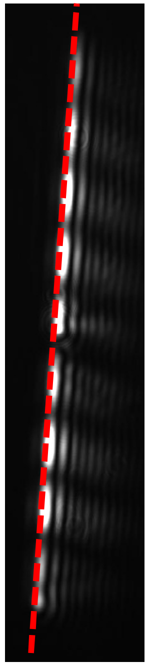
Lasers: λ=633 nm, P =30 mW
λ = 785 nm, P = 100 mW

Applied magnetic field:
B= 19 mT; f=1400 Hz

Magnetoplasmonic interferogram

$$I_{DC} = A^2_{np} + A^2_{sp} e^{-2k^i_{sp0} \cdot d} + 2 A_{np} A_{sp} e^{-k^i_{sp0} \cdot d} \cos(k_{sp0}{}^r \cdot d + \varphi)$$



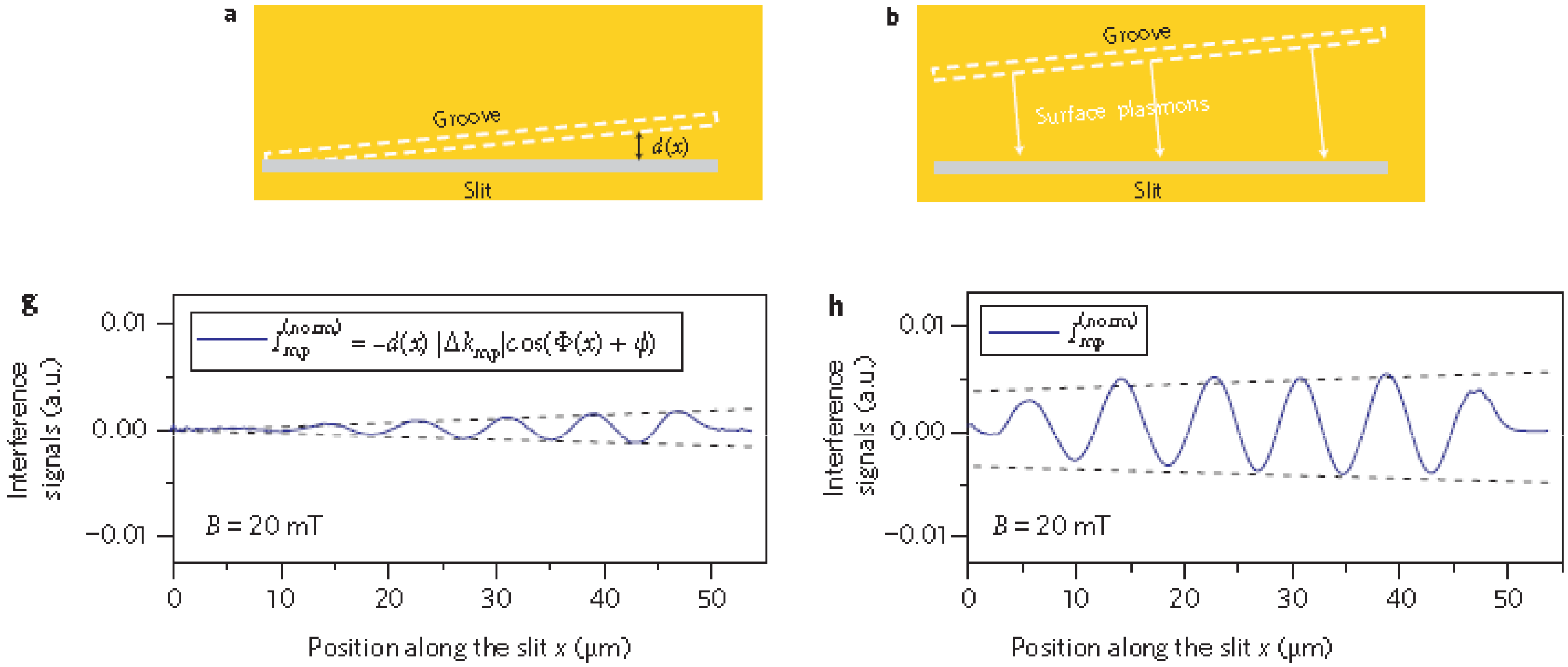


$$\frac{I_{MPContrast}}{I_{DCContrast}} \approx \Delta k_{sp} \cdot d$$

$$I_{MP} = -2\Delta k_{sp}{}^r d \, A_{sp} A_{np} e^{-k^i_{sp0} d} \sin(k_{sp0}{}^r d + \varphi)$$

Nat. Photonics **4**, 107 (2010)

Magnetoplasmonic interferogram

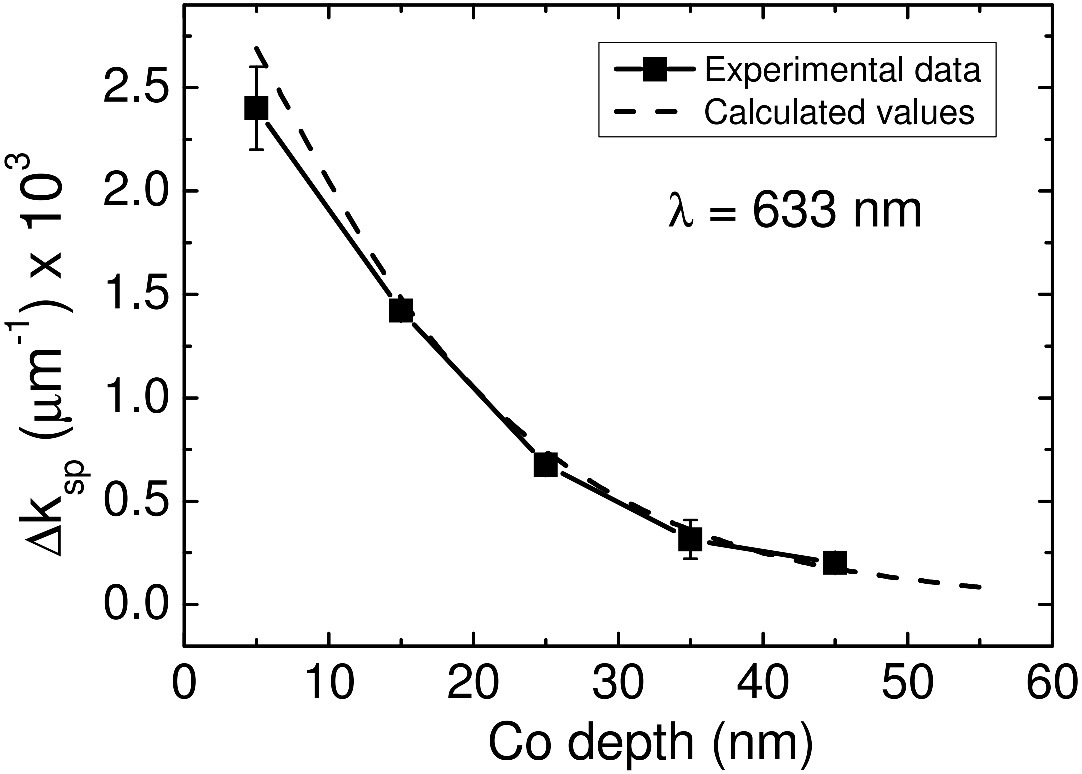


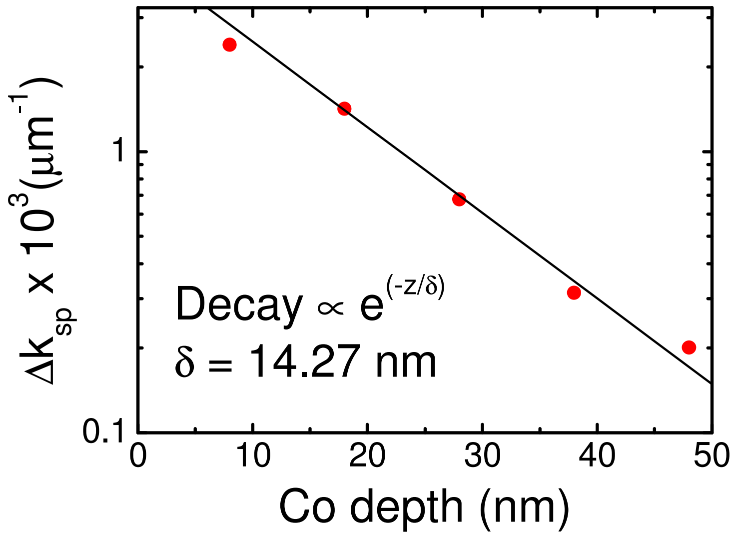
Intensity modulation → $\Delta k_{sp} \times d$

We can obtain Δk_{sp}

Nat. Photonics **4**, 107 (2010)

Evolution with Co depth

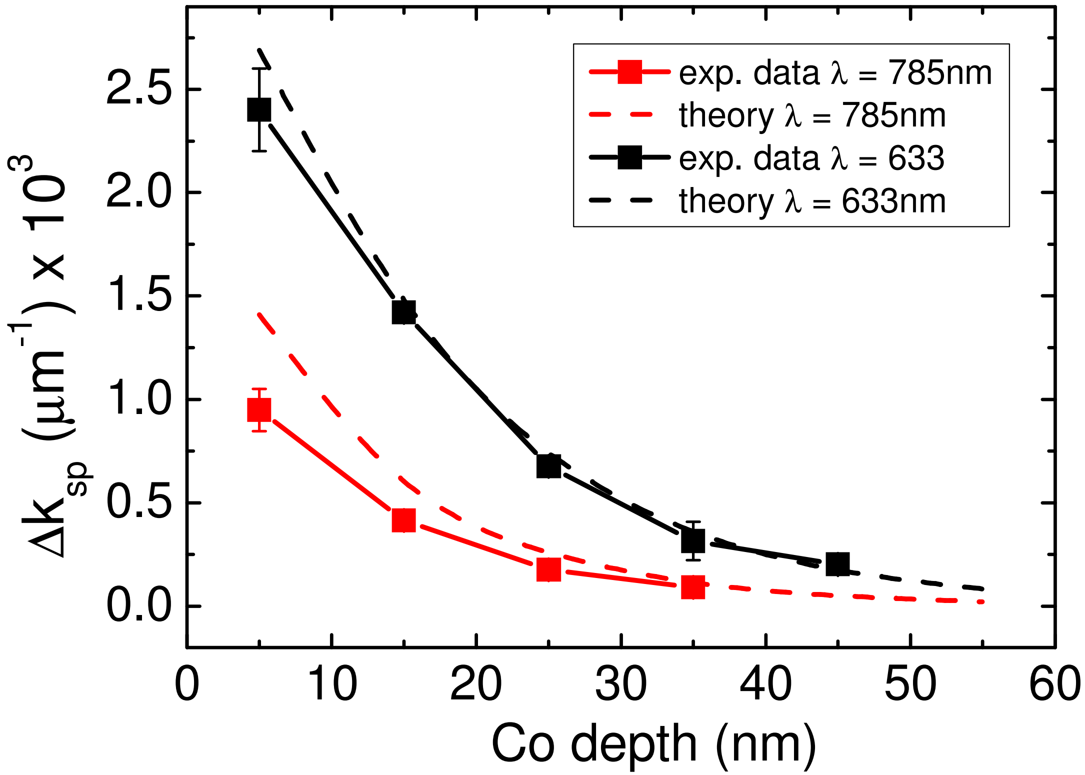


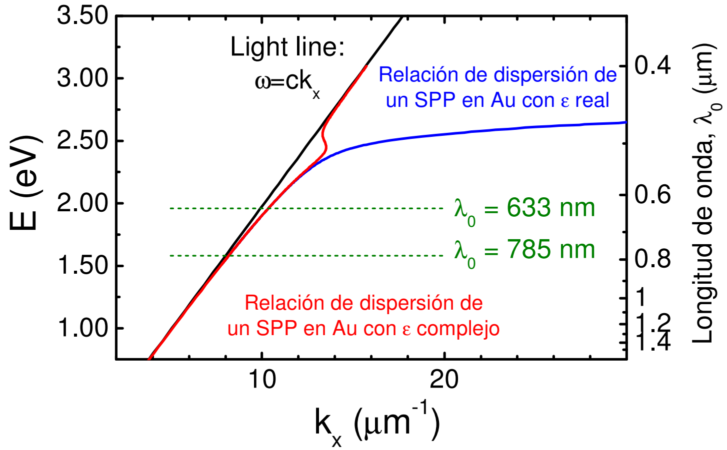


$$\Delta k_{sp} \approx \frac{2 z_{Co} (k_0 \varepsilon_d \varepsilon_{Au})^2}{(\varepsilon_d + \varepsilon_{Au})(\varepsilon^2{}_d - \varepsilon^2{}_{Au})} \frac{i \varepsilon_{yz}}{\varepsilon_{xx}} M_x e^{-z/\delta_{penetration}}$$

- k_{spp} modulation depends on the SPP field penetration depth

Wavelength dependency





- k_{spp} modulation depends on the wavelength

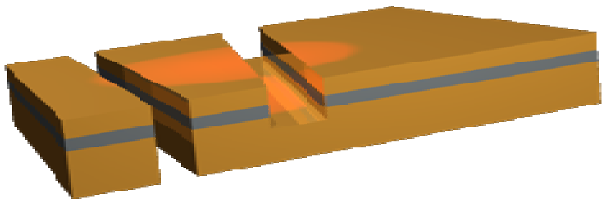
Engineering Δk_{sp}

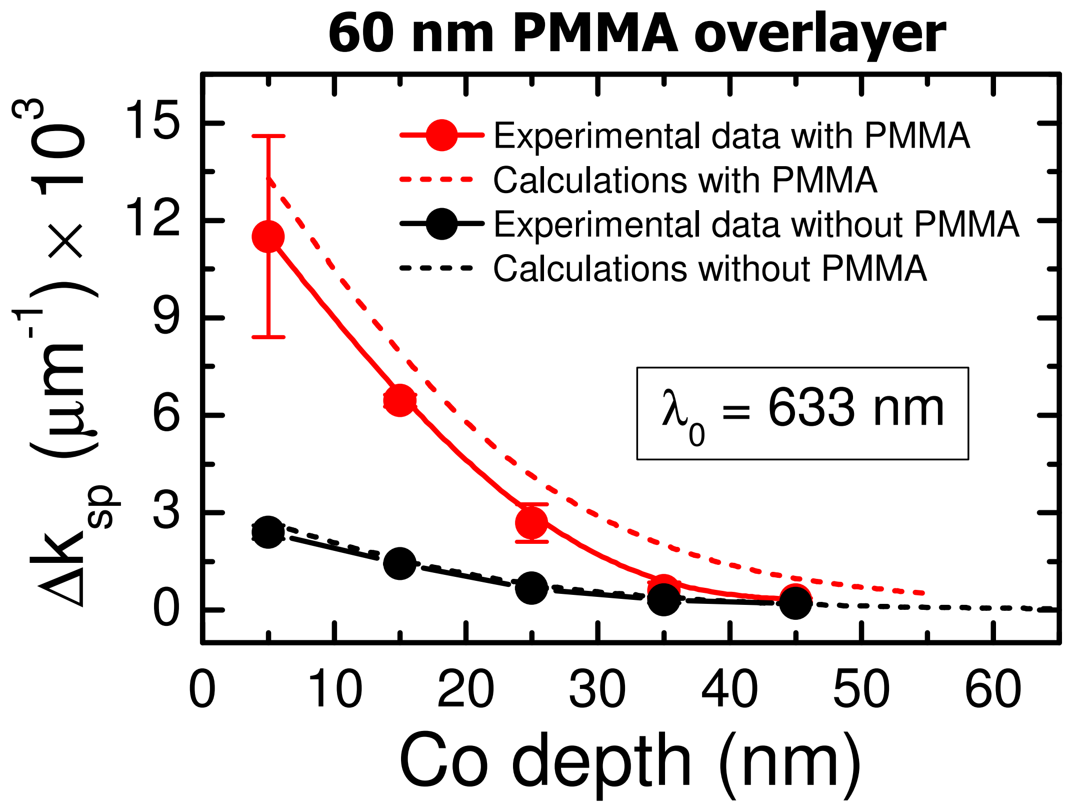
How to increase Δk^r_{SP}?

$$\Delta k_{sp} \approx \frac{2 z_{Co} (k_0 \varepsilon_d \varepsilon_{Au})^2}{(\varepsilon_d + \varepsilon_{Au})(\varepsilon^2_d - \varepsilon^2_{Au})} \frac{i\varepsilon_{yz}}{\varepsilon_{xx}} M_x e^{-z/\delta_{penetration}}$$

We can use a dielectric with a higher ε

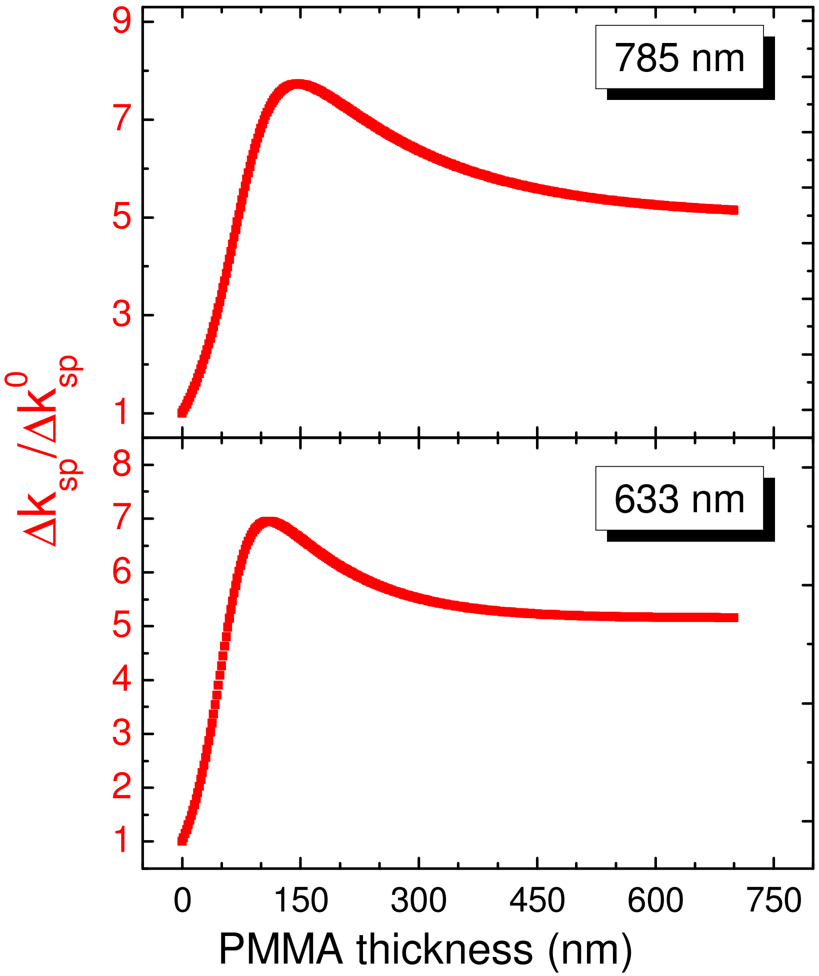
we add a thin dielectric overlayer

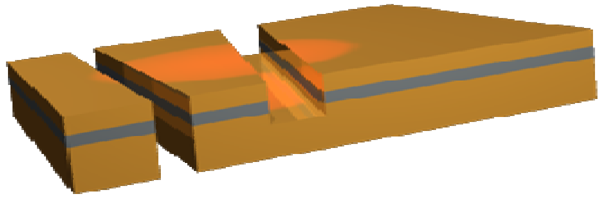




Engineering Δk_{sp}

Evolution with the dielectric thickness

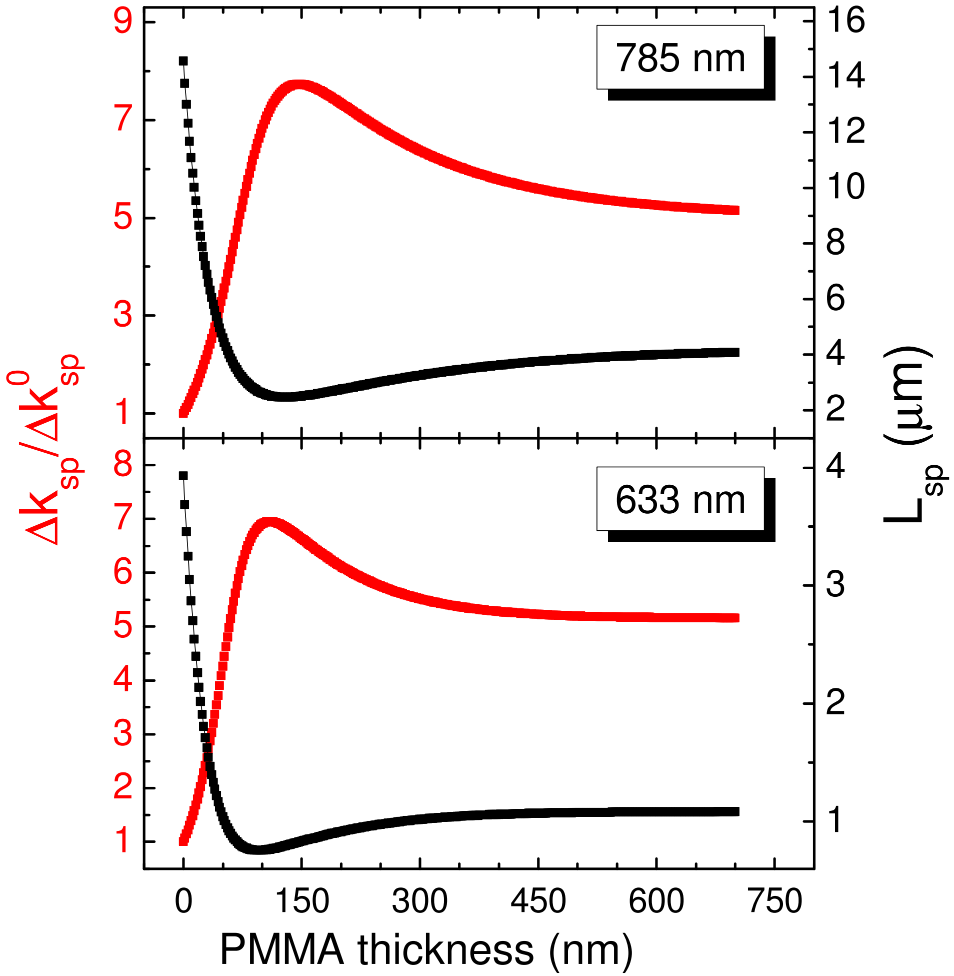


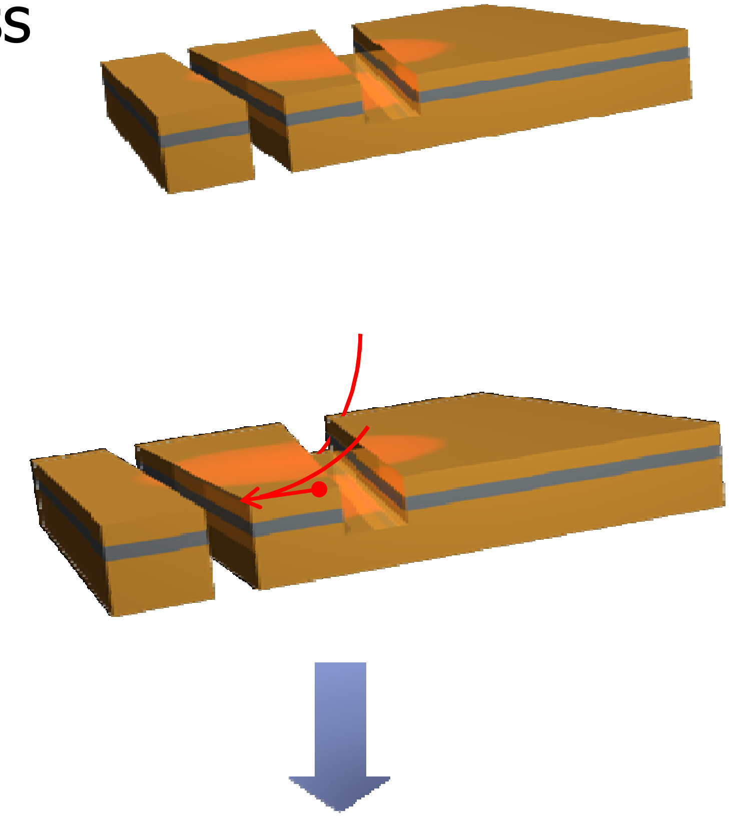


We can obtain a 8-fold enhancement of the SPP wavevector modulation depth

Engineering Δk_{sp}

Evolution with the dielectric thickness

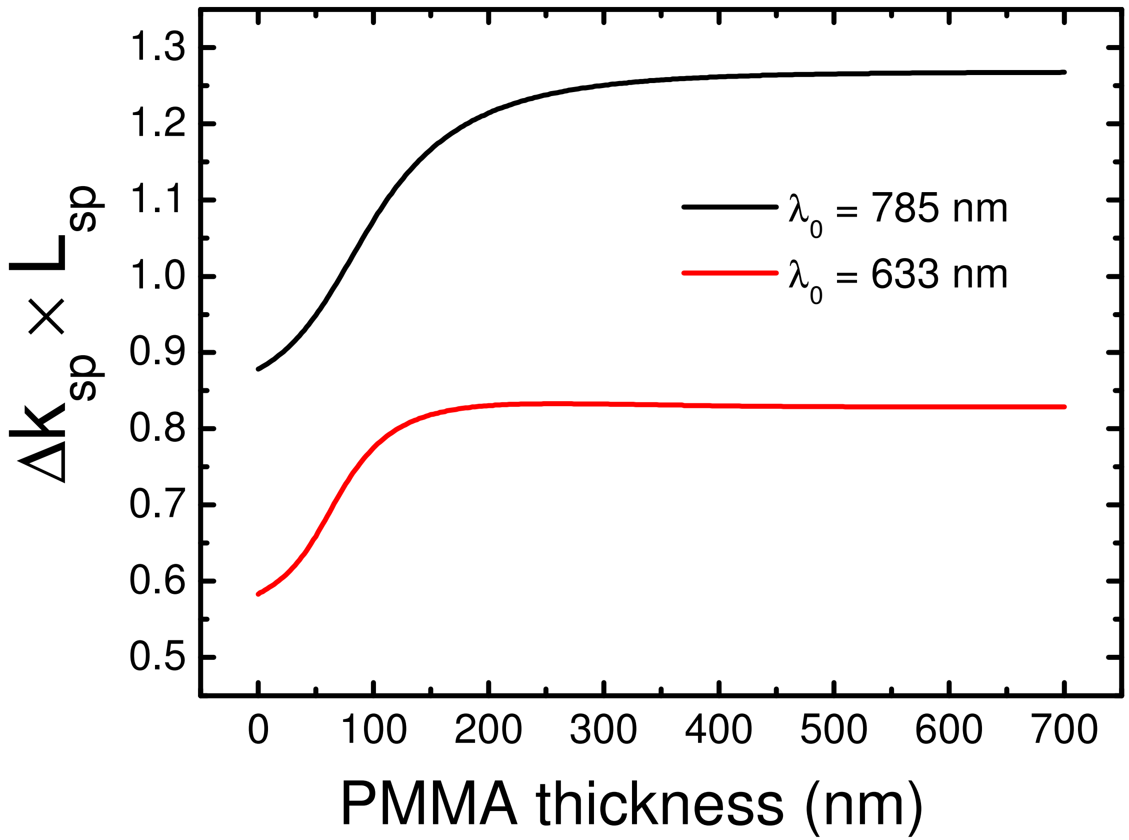




Squeezing of the plasmon in the dielectric overlayer

Engineering Δk_{sp}

Figure of merit: Δk_{sp} x L_{SP}



Conclusions

- A magnetic field induces a measurable modulation on the surface plasmon wavevector in magnetoplasmonic systems

  → Development of active plasmonic interferometers

- k_{sp} modulation can be increased up to 8 times by adding a thin dielectric overlayer, keeping a favourable figure of merit Δk_{sp} x L_{sp}

- Δk_{sp} can provide information on the plasmon field distribution

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Magplas

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Thank you very much!