Magneto-Optic Responses of Plasmonic Nanostructure Assemblies

Marc Bourgeois
Schatz Group
IRG 3 Meeting: May 2017

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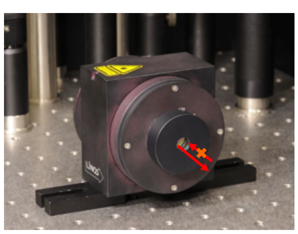
Motivation

Magneto – optic effects allow light polarization, transmission, and reflection to be controlled with an external magnetic field

Non-Reciprocal Devices



Magneto-Optical Storage

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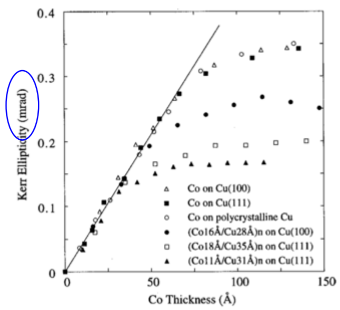
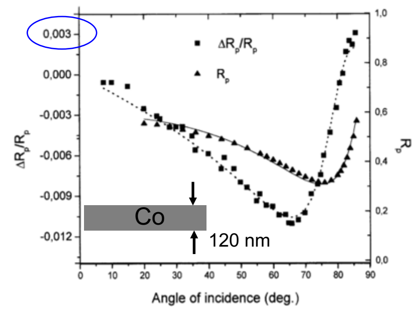
Wikipedia: Magneto-Optical Drive, Optical Isolator

Motivation

Polarization Modulation



Intensity Modulation



Challenges: High losses and low magneto-optic coupling

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Qiu, Z. Q.; Bader, S. D. Rev. Sci. Instrum. **71**. (2000).

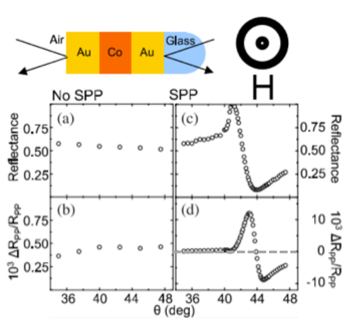
Penfolf, C. … Souche, Y. Journal of Magnetism and Magnetic Materials **242**. (2002).

Magneto-Plasmonics

Goal

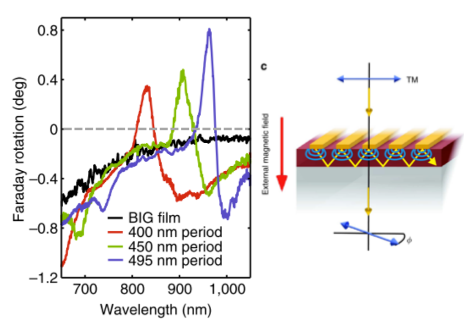
Leverage strong light-matter interaction and field enhancement from plasmonic materials to enhance magneto-optic coupling

SPP Coupling



~ 3X enhancement

Diffractive Coupling



~ 8.9X enhancement

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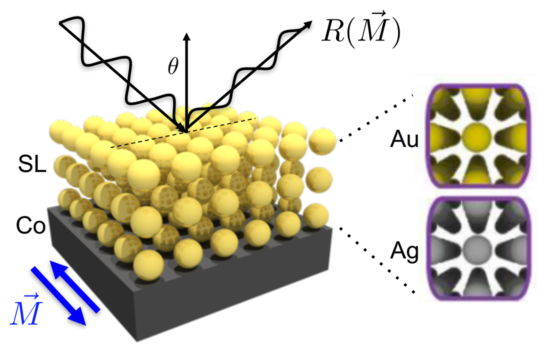
González-Díaz, J. B. … Clarke, R. Phys. Rev. B. **76**. (2007).

Chin, J. Y. … Geissen, H. Nat. Commun. **4**. (2013).

Magneto-Optics with Plasmonic Superlattices



TMOKE Figure of Merit:

$$\delta = \frac{R(+\vec{M}) - R(-\vec{M})}{R(+\vec{M}) + R(-\vec{M})}$$

Superlattice optical properties tunable with:

- NP material
- Volume fraction
- NP ordering: bimetallic vs. alloy

Ross, M. B., **Bourgeois, M. R.**, Mirkin, C. A., Schatz, G. C. J. Phys. Chem. Lett. **7**. (2016).

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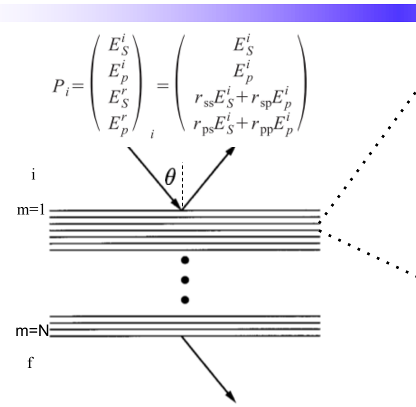
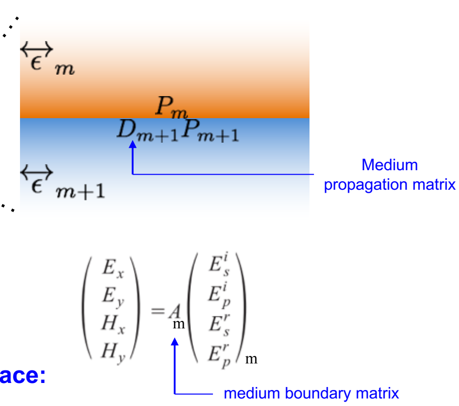
Fresnel Transfer Matrix Method





Boundary Condition at the mth Interface:

$$\hat{n}_{12} \times (\vec{E}_2 - \vec{E}_1) = 0$$
$$\hat{n}_{12} \times (\vec{H}_2 - \vec{H}_1) = 0$$

$$\Rightarrow \quad A_m P_m = A_{m+1} D_{m+1} P_{m+1}$$

Qiu, Z. Q.; Bader, S. D. Rev. Sci. Instrum. **71**. (2000).

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Fresnel Transfer Matrix Method

Re-applying the boundary condition at each interface:

$$A_i P_i = A_1 D_1 P_1 = A_1 D_1 A_1^{-1} A_1 P_1$$

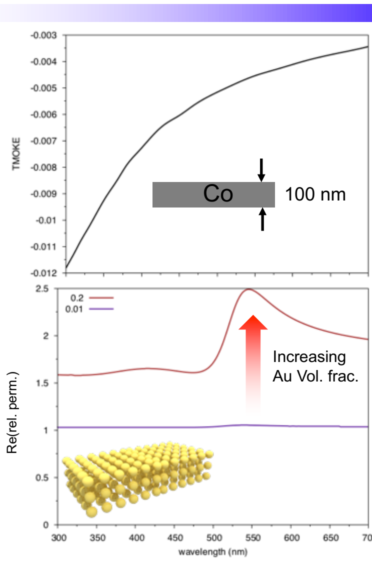
$$= A_1 D_1 A_1^{-1} A_2 D_2 P_2 \quad = \ldots = \prod_{m=1}^{N} (A_m D_m A_m^{-1}) A_f P_f.$$

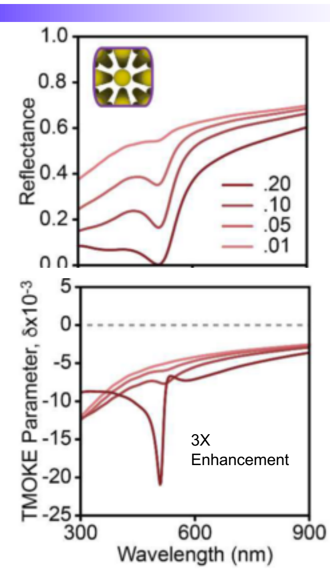
$$P_i = T P_f \qquad T = A_i^{-1} \prod_{m=1}^{N} (A_m D_m A_m^{-1}) A_f \equiv \begin{pmatrix} G & H \\ I & J \end{pmatrix}$$

$$G^{-1} = \begin{pmatrix} t_{ss} t_{sp} \\ t_{ps} t_{pp} \end{pmatrix} \text{ and } IG^{-1} = \begin{pmatrix} r_{ss} r_{sp} \\ r_{ps} r_{pp} \end{pmatrix}. \quad \Rightarrow \quad \delta = \frac{R(+\vec{M}) - R(-\vec{M})}{R(+\vec{M}) + R(-\vec{M})}$$

Qiu, Z. Q.; Bader, S. D. Rev. Sci. Instrum. **71**. (2000).

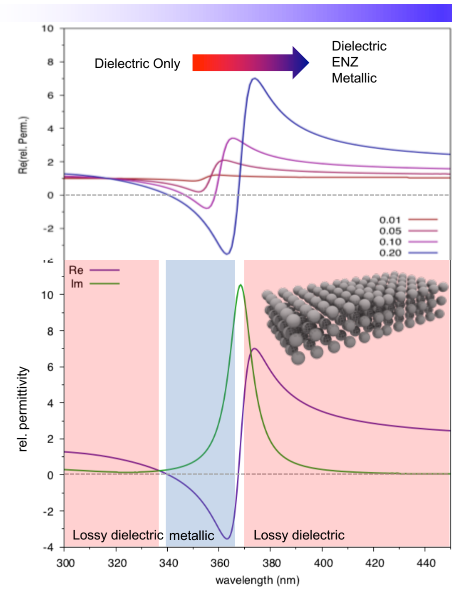
AuNP Superlattice: Lossy Dielectric

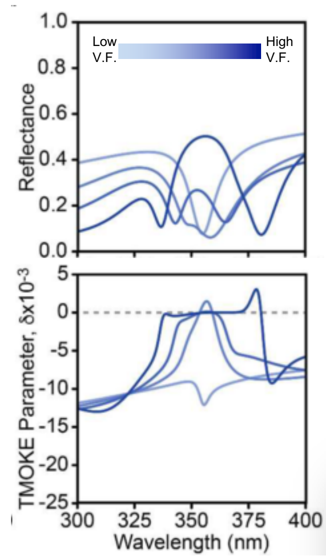




Ross, M. B., **Bourgeois, M. R.**, Mirkin, C. A., Schatz, G. C. J. Phys. Chem. Lett. **7**. (2016).

AgNP Superlattice: Role of Material Regimes





Ross, M. B., **Bourgeois, M. R.**, Mirkin, C. A., Schatz, G. C. J. Phys. Chem. Lett. **7**. (2016).

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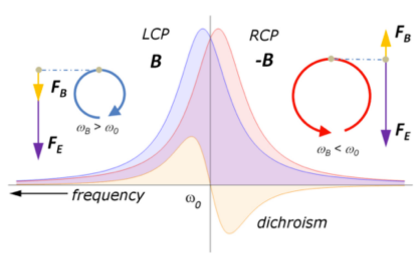
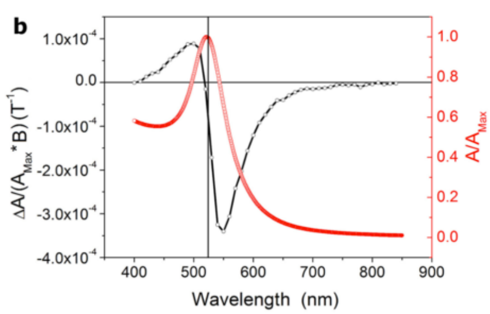
Plasmonic NPs Exhibit Magneto-Optic Response





$$m\frac{\mathrm{d}v}{\mathrm{d}t} + \gamma m v = -e\mathbf{E} - e\mathbf{v} \times \mathbf{B}$$

Quasi-static dipole polarizability:

$$\alpha_B(\omega) = -\frac{\pi D^3}{2}\frac{(\varepsilon(\omega) - \varepsilon_m) + (f(\omega) - f_m)B}{(\varepsilon(\omega) + 2\varepsilon_m) + (f(\omega) - f_m)B} \quad ; \qquad f(\omega) = -\frac{e^3 N}{m^2\omega}\frac{(\gamma - i\omega)^2}{\epsilon(\gamma^2 + \omega^2)^2}$$

Pineider, F. … Sangregorio, C. Nano Lett. **13**. (2013).

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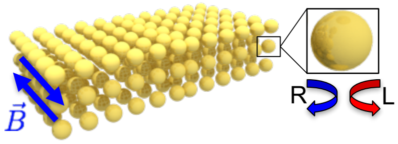
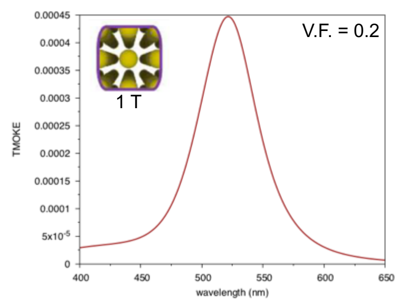
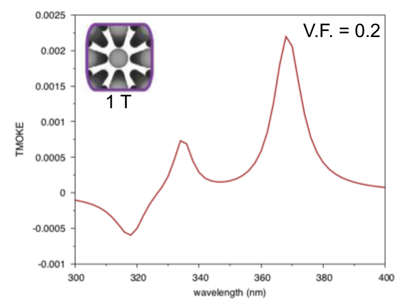
Magnetic Response of Plasmonic Superlattice



$$\overleftrightarrow{\epsilon} = \epsilon \begin{bmatrix} 1 & if(\omega)B_z & -if(\omega)B_y \\ -if(\omega)B_z & 1 & if(\omega)B_x \\ f(\omega)B_y & -if(\omega)B_x & 1 \end{bmatrix}$$

$$(\overleftrightarrow{\epsilon}_{eff} - \epsilon_h \overleftrightarrow{I})(\overleftrightarrow{\epsilon}_{eff} + 2\epsilon_h \overleftrightarrow{I})^{-1} = f(\overleftrightarrow{\epsilon} - \epsilon_h \overleftrightarrow{I})(\overleftrightarrow{\epsilon} + 2\epsilon_h \overleftrightarrow{I})^{-1}$$





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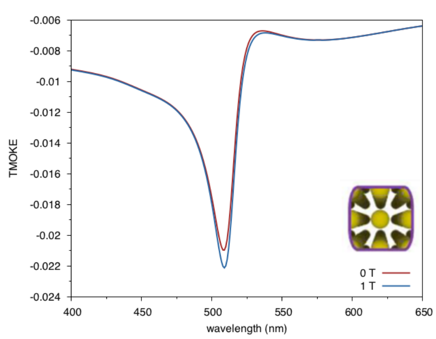
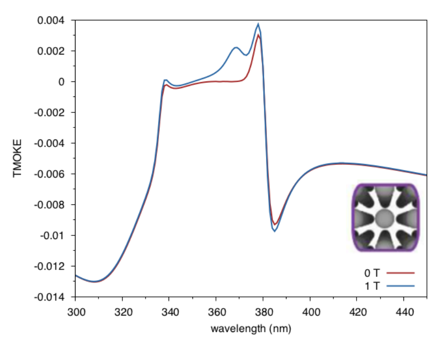
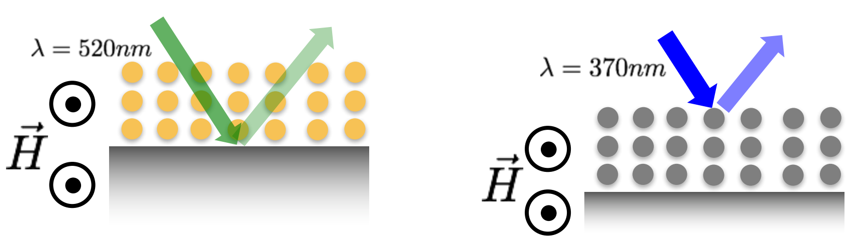
Corrected Response of Co-SL Multilayers







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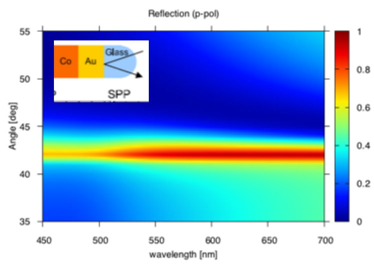
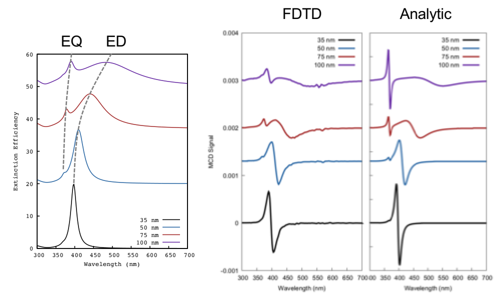
Future Directions

Angle-Dependent Superlattice TMOKE



- Excite SPP at SL interface
- Angle-dependent TMOKE

Beyond the Dipole Approximation

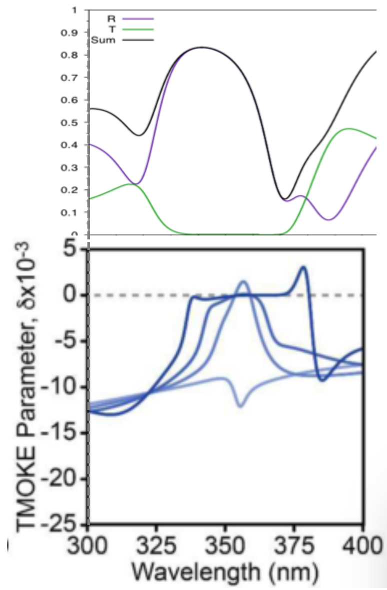


- Include size-dependent effects on plasmonic response
- Magneto-optic response of quadrupolar modes

Summary and Conclusions

- **Primary challenges**
  - Large losses
  - Weak magneto-optic coupling
- **Addressing challenges with magneto-plasmonics**
  - Interfacing traditional magnetic materials with noble metal assemblies
- **TMOKE response of Co – plasmonic superlattice multilayers**
  - AuNP SL properties dominated by absorption: ~ 3.5X TMOKE enhancement
  - AgNP SLs exhibit more complex TMOKE response due to different material regimes
  - SL properties tunable with plasmonic material, volume fraction, and ordering
- **Further investigation**
  - Nanoparticle shape/composition (core-shell and anisotropic NPs)
  - Going beyond the quasi-static dipole model
  - Permittivity engineering for tailored SPP propagation

Supplemental Slide



Ag SL only

Ag SL + Co

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