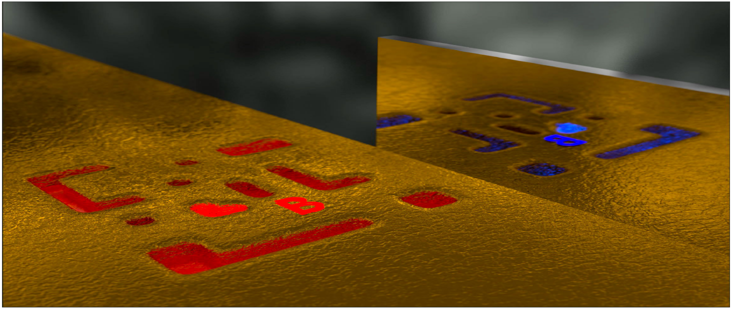
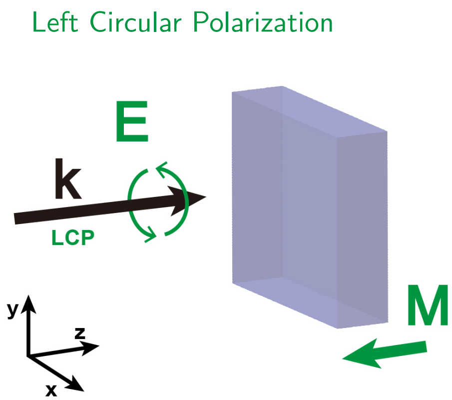
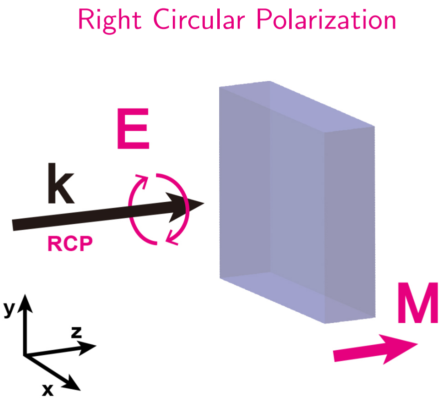
A Chiral Inverse Faraday Effect Mediated by an Inverse-designed Plasmonic Antenna



Ye Mou, Xingyu Yang, Bruno Gallas, Mathieu Mivelle*

Institut des NanoSciences de Paris - Sorbonne Université - CNRS


Left Circular Polarization
E
k
LCP
y
z
x
M


Right Circular Polarization
E
k
RCP
y
z
x
M

Origine of IFE in noble metals

Drift current J

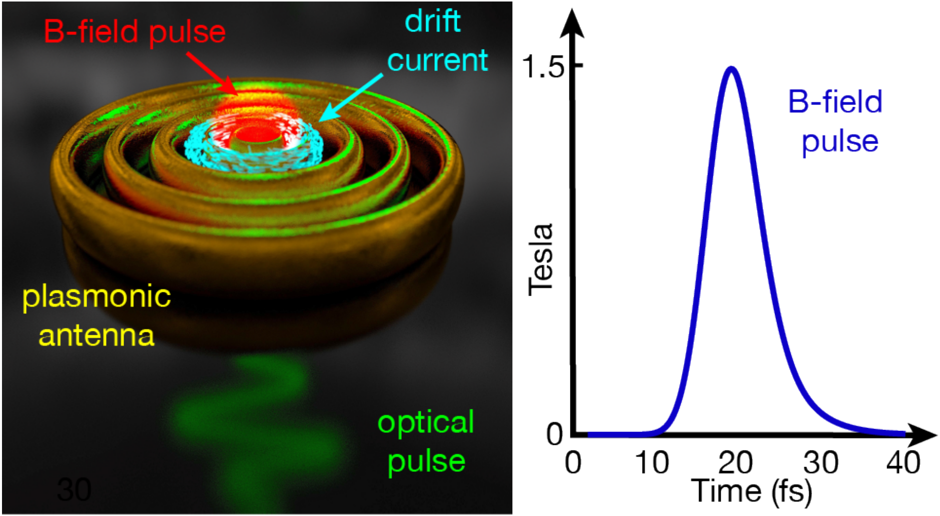
$$\langle \boldsymbol{J} \rangle = \langle e\delta n \boldsymbol{v} \rangle = \frac{1}{2en} \mathrm{Re}\left\{ \left(-\frac{\nabla \cdot (\sigma_\omega \boldsymbol{E})}{i\omega} \right) \cdot (\sigma_\omega \boldsymbol{E})^* \right\}$$

- δn: Oscillating part of electron density (continuity equation)
- $\boldsymbol{v}$: Velocity of the charges (approximation)
- σ_ω: Dynamic conductivity of the metal ($\sigma_\omega = i\omega\epsilon_0(\epsilon - 1)$)
- e: Charge of the electron ($e < 0$) and n: charge density at rest

R. Hertel, J. Magn. Magn. Mater (2006)

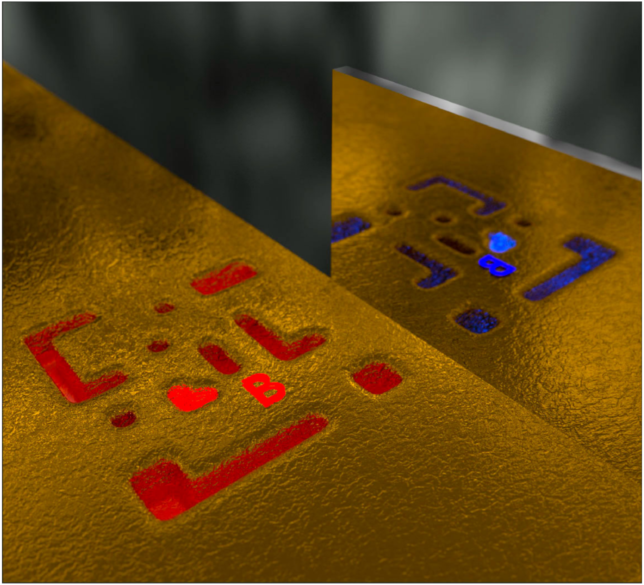
Stationary magnetic field B

$$\boldsymbol{B(r)} = \frac{\mu_0}{4\pi} \iiint_V \frac{(\boldsymbol{J}\, dV) \times \boldsymbol{r}'}{|\boldsymbol{r}'|^3} \quad (Biot\text{–}Savart\ law)$$

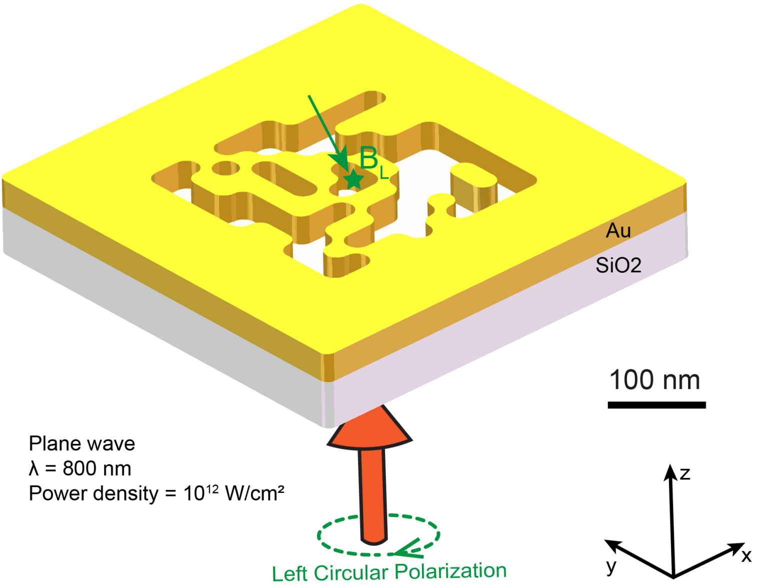


Yang, Xingyu et al. ACS Nano (2022)

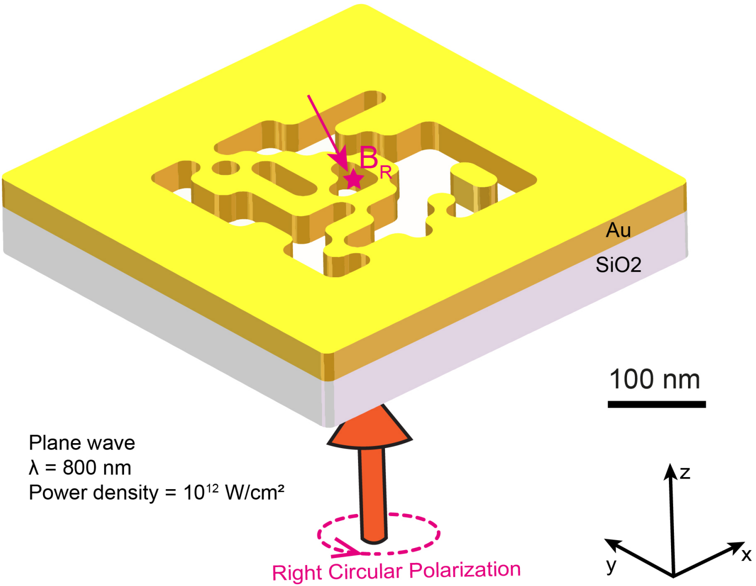
A chiral inverse Faraday effect

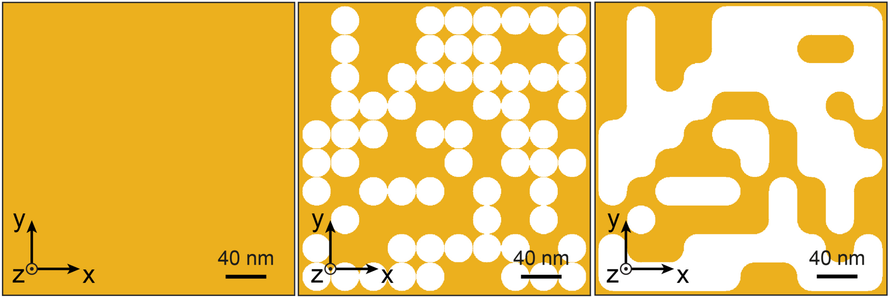


Inverse-designed plasmonic antenna under LCP



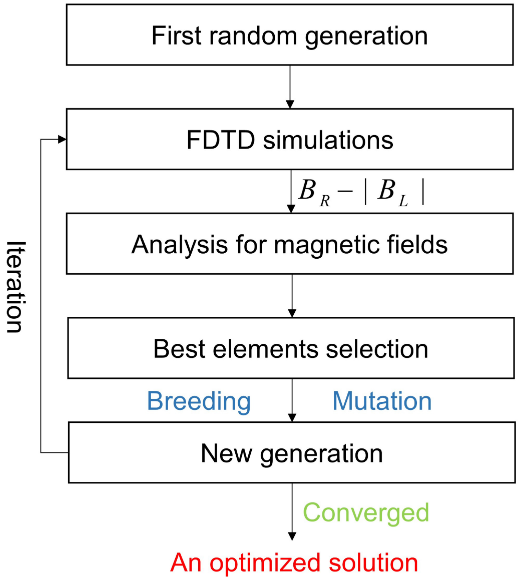
Inverse-designed plasmonic antenna under RCP





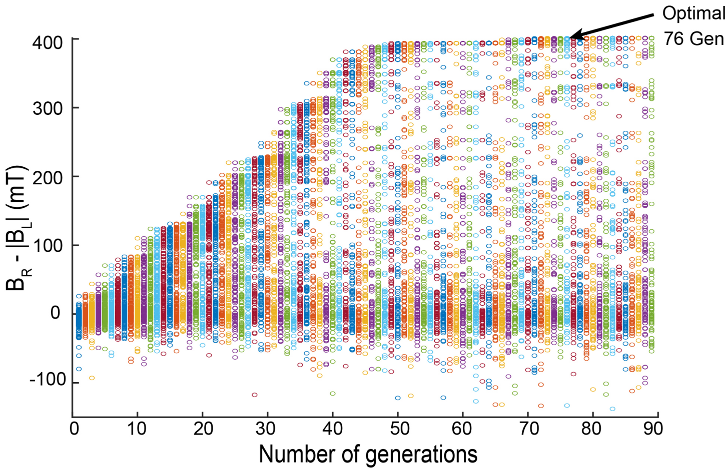
Bonod, Nicolas et al. Advanced Optical Materials (2019)

GA optimization

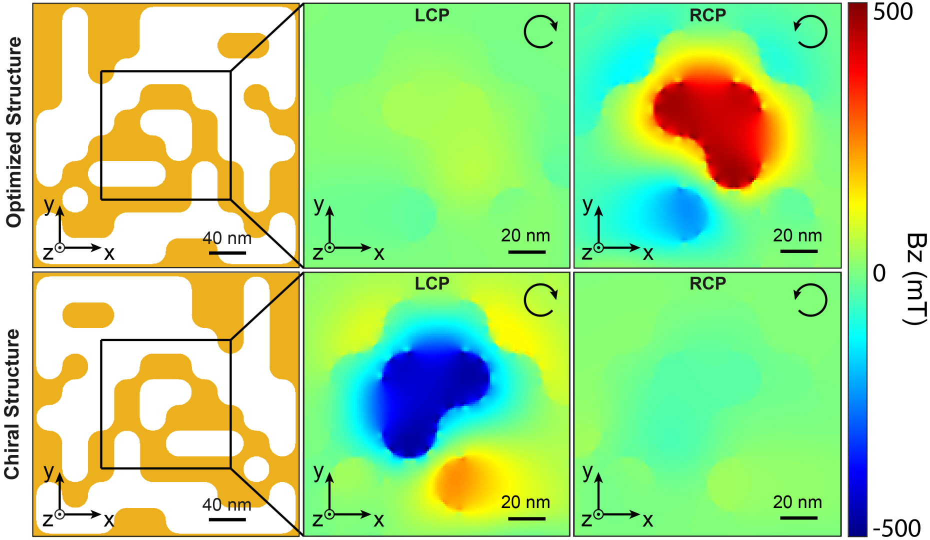


Objective function

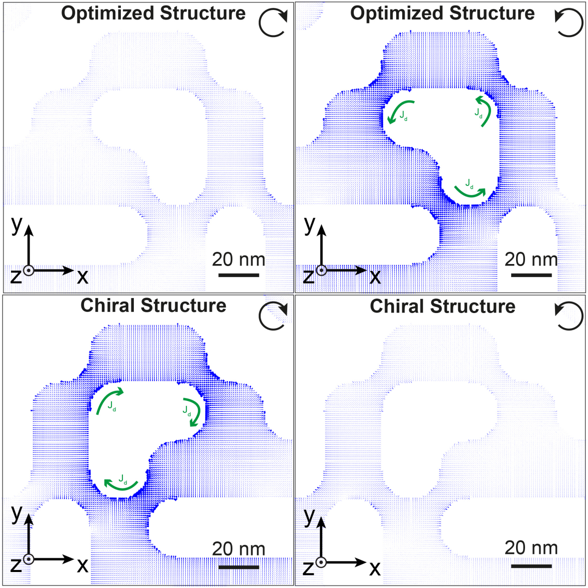
$\max B_R - |B_L|$



Stationary magnetic field - $\mathbf{B}_z$



The distributions of drift currents

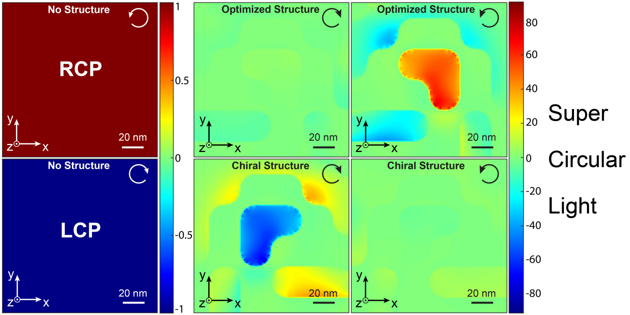


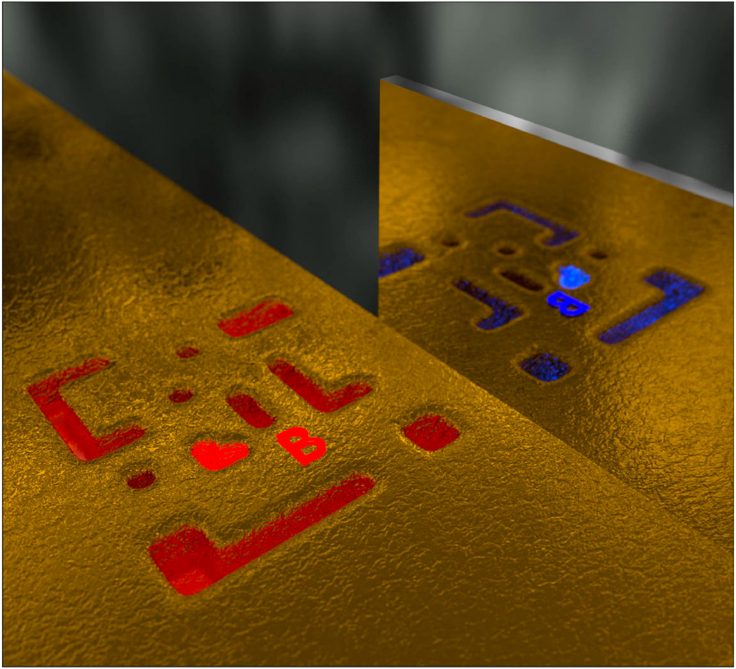
Spin density

$$\boldsymbol{s} = \frac{1}{|\boldsymbol{E}_0|^2} Im(\boldsymbol{E}^* \times \boldsymbol{E})$$

- $\mathbf{s}_z = 0 \rightarrow$ Linear Polarization; $\mathbf{s}_z \neq 0 \rightarrow$ Elliptical Polarization

Martin Neugebauer, et al. Science Advances (2019)




B
B

Magnetic NanoLight Group at INSP, Sorbonne Université

Mathieu Mivelle

CNRS Researcher

Bruno Gallas

CNRS Researcher

Xingyu Yang

PhD Student (TY)

Ye Mou

PhD Student (SY)

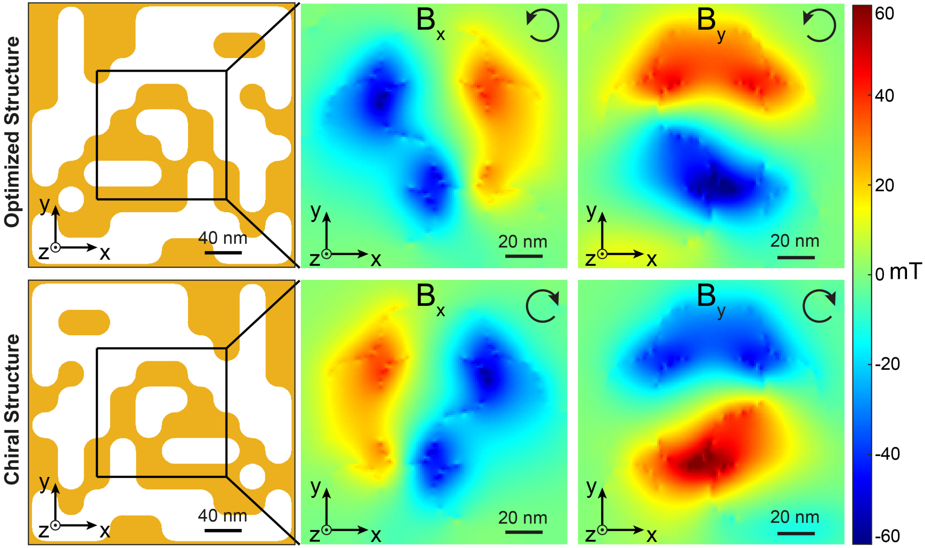
École doctorale 564 - Physique en Île-de-France

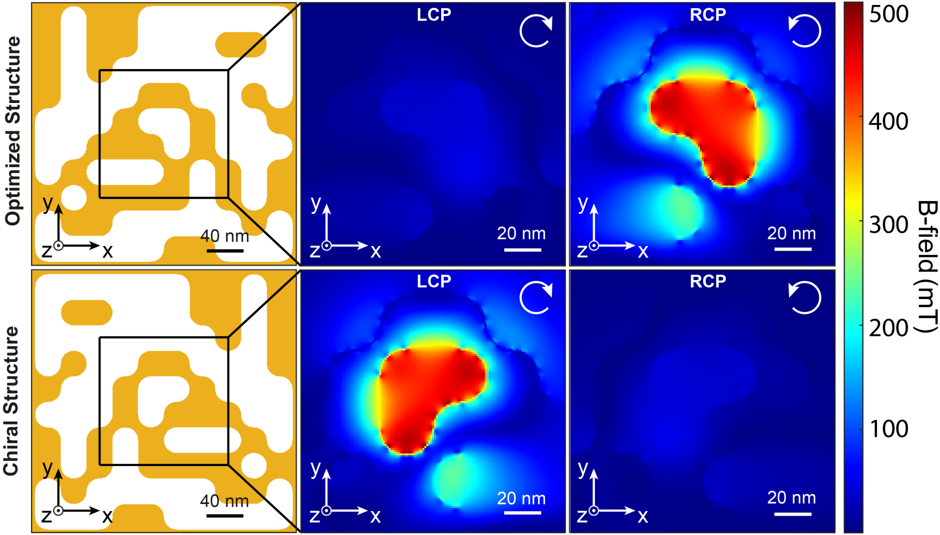
Thanks for your attention!

Q & A

Annex

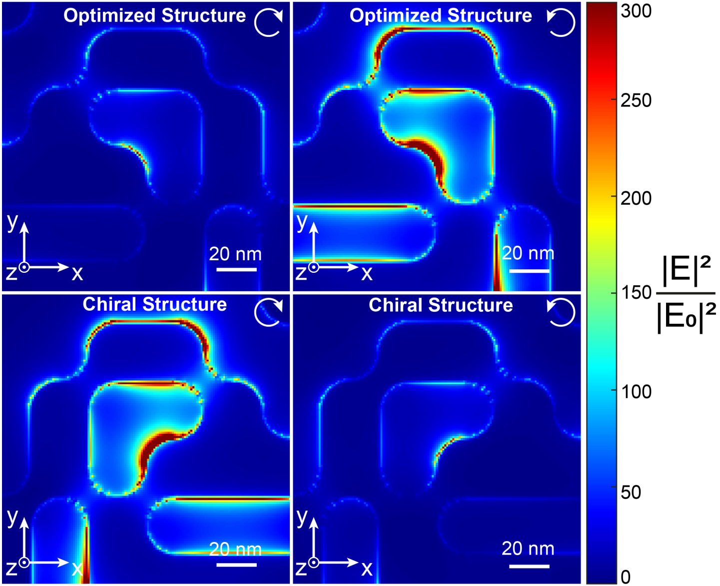
Stationary magnetic field - $\mathbf{B}_x$ and $\mathbf{B}_y$



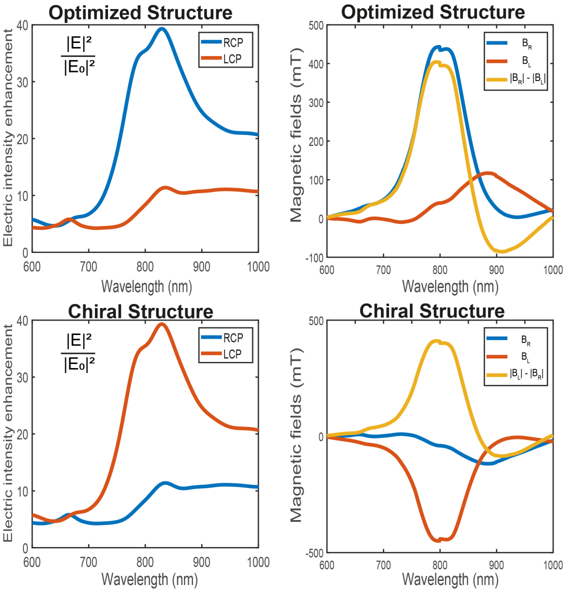


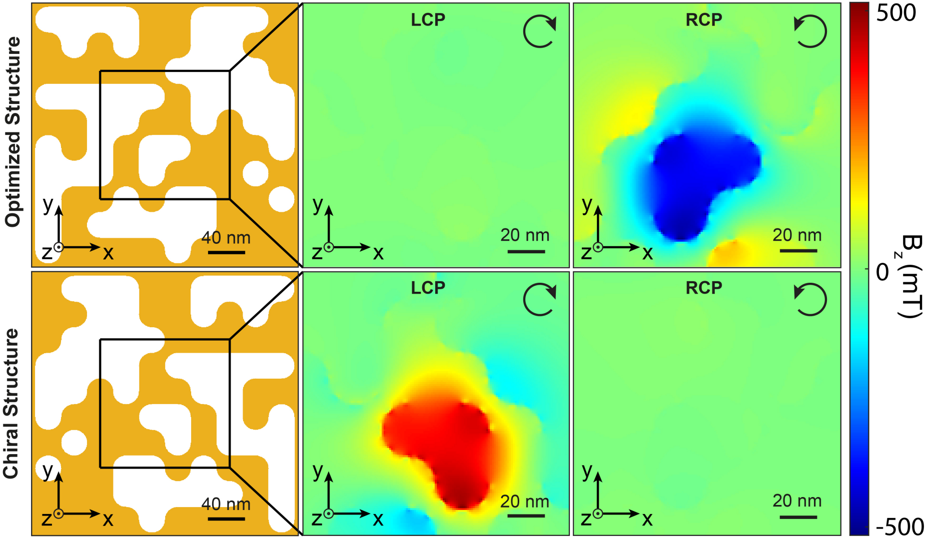
Optimized Structure
Chiral Structure
LCP
RCP
LCP
RCP
40 nm
40 nm
20 nm
20 nm
20 nm
20 nm
y
x
z
500
400
300
200
100
B-field (mT)

Electric intensity enhancement



Spectral response




Optimized Structure
Chiral Structure
LCP
RCP
LCP
RCP
40 nm
20 nm
20 nm
40 nm
20 nm
20 nm
y
x
z
500
0
-500
B_z (mT)

Why do we need magnetic fields?

- Data storage
- Magnetic Resonance Imaging (MRI)
- Magnetic actuators

Magnetic fields

All these applications use magnetic fields of different magnitudes which are produced over different temporal and spatial scales.

Stationary Magnetic Field

Electric current density : $\boldsymbol{J} = en\boldsymbol{v}$
Electron density n can be decomposed into two parts:

$$n = \langle n \rangle + \delta n$$

where $\langle n \rangle$ is constant electron density, δn is osillating part of n due to HF field ($\propto e^{i\omega t}$).

Electric current density

$$\boldsymbol{J} = e \langle n \rangle \boldsymbol{v} + e\delta n\boldsymbol{v}$$

Time average

$$\langle \boldsymbol{J} \rangle = \langle e \langle n \rangle \boldsymbol{v} \rangle + \langle e \delta n \boldsymbol{v} \rangle$$

Where the time average of conductive part $\langle e \langle n \rangle \boldsymbol{v} \rangle = 0$ due to $\boldsymbol{v} \propto e^{i\omega t}$

Drift current

$$\langle \boldsymbol{J} \rangle = \langle e \delta n \boldsymbol{v} \rangle$$

With two unknowns:

- δn
- $\boldsymbol{v}$

Oscillating part of electron density δn

The continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \boldsymbol{J} = 0 \ (\rho = ne) \rightarrow \frac{\partial n}{\partial t} + \frac{1}{e} \nabla \cdot \boldsymbol{J} = 0$$

Electron density

$$n = -\frac{1}{ie\omega} \nabla \cdot \boldsymbol{J} + n_0 = n_0 + \delta n$$

Oscillating part of electron density

$$\delta n = -\frac{1}{ie\omega} \nabla \cdot \boldsymbol{J}$$

Velocity of charges $\boldsymbol{v}$

First approximation

$$\boldsymbol{J} = e\langle n\rangle \boldsymbol{v} + e\delta n\boldsymbol{v} \approx e\langle n\rangle \boldsymbol{v}$$

$$(\langle n\rangle \gg \delta n)$$

$$\boldsymbol{J} = e\langle n\rangle \boldsymbol{v} = \sigma_\omega \boldsymbol{E}$$

Where σ_ω is dynamic conductivity with $\sigma_\omega = i\omega\epsilon_0(\epsilon - 1)$

Velocity of the charges

$$\boldsymbol{v} = \frac{i\omega\epsilon_0(\epsilon - 1)\boldsymbol{E}}{e\langle n\rangle}$$

N. Bonod, S. Bidault, G. W. Burr, and M. Mivelle.
Evolutionary Optimization of All-Dielectric Magnetic Nanoantennas.
Advanced Optical Materials, 0(0):1900121, Mar. 2019.

O. H.-C. Cheng, D. H. Son, and M. Sheldon.
Light-induced magnetism in plasmonic gold nanoparticles.
Nature Photonics, 14(6):365–368, Jun 2020.

R. Hertel.
Theory of the inverse Faraday effect in metals.
Journal of Magnetism and Magnetic Materials, 303(1):L1–L4, Aug. 2006.

R. Hertel and M. Fähnle.
Macroscopic drift current in the inverse faraday effect.
Phys. Rev. B, 91:020411, Jan 2015.

A. Nadarajah and M. T. Sheldon.
Optoelectronic phenomena in gold metal nanostructures due to the inverse faraday effect.
Opt. Express, 25(11):12753–12764, May 2017.

X. Yang, Y. Mou, B. Gallas, A. Maitre, L. Coolen, and M. Mivelle.
Tesla-range femtosecond pulses of stationary magnetic field, optically generated at the nanoscale in a plasmonic antenna.
ACS Nano, 16(1):386–393, 2022.
PMID: 34962766.

X. Yang, Y. Mou, H. Zapata, B. Reynier, B. Gallas, and M. Mivelle.
An inverse faraday effect through linear polarized light, 2022.