Optomagnetic field in nonmagnetic plasmonic nanostructures

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Abstract

Using simplified hydrodynamic model, we theoretically investigate resonant inverse Faraday effect within individual plasmonic nanostructures. Upon illumination with circularly polarized light, resonant nanostructures are shown to develop an optomagnetic field that is controllable by the helicity of the light. Given their submicron footprint, individual plasmonic nanostructures open new prospects towards ultrafast and polarization-controlled tunable magnetism on the nanoscale, thus potentially impacting large panel of application and techniques including all optical magnetization switching, spin-wave excitation and optomagnetic tweezing of nano-objects.

1. Introduction

Optically-induced magnetism has drawn considerable interest in the past years for its ability to speed up magnetic processes[1]. For example, static magnetic fields have been demonstrated to be generated in non-magnetic plasmonic (gold) nanoparticles and nano-apertures [2, 3]. Such a phenomenon has been analyzed as the result of the inverse Faraday effect [4, 5, 6]. Inverse Faraday effect in plasmonic structures can been predicted with a hydrodynamic description of the free electron gas of a metal [5, 7]. More generally, the hydrodynamic model provides reference equations for describing optical nonlinearities in plasmonic nanostructures [8, 9, 10, 11].

In the context of the hydrodynamic model, the electron fluid density n(r,t) and the electron velocity field v(r,t) satisfy Euler's equation

$$\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\tau}\mathbf{v}+\frac{e}{m}\mathbf{E}_\omega+\frac{\mu_0 e}{m}\mathbf{v}\times\mathbf{H}_\omega-\frac{\beta^2}{n}\nabla n, \quad (1)$$

And the continuity equation reads as:

$$\nabla\cdot\mathbf{j}_\omega = -e\frac{\partial n}{\partial t}, \quad (2)$$

where $\mathbf{j}_\omega = \gamma_\omega \mathbf{E}_\omega$, γ_ω is conductivity, $\mathbf{E}_\omega$ and $\mathbf{H}_\omega$ are applied fields, m is the effective electron mass, τ is the electron collision time, n is electron fluid density, $\mathbf{v}$ is electron velocity. The last term in the equation 1 is due to the electron gas pressure, with β proportional to the Fermi velocity v_F. This term describes nonlocal effects. The 3D numerical solvers of such a hydrodynamic model require computational power and are time consuming [12].

In case of smooth and slowly varying n it is possible to neglect nonlocal effects ($\beta \to 0$) and take into account only local responce [11]. This local response approximation avoids the resolution of a complex nonlocal equation [5, 6], however this approximation limits the model predictions to bulk. Prediction of surface effects become inaccurate and ambiguous due to strong variation of electron fluid density [9, 11, 13, 14]. We have developed a simplified hydrodynamic model which enables to stay within the local approximation and overcome the ambiguity at the interfaces.[15, 16]. Simplifying the hydrodynamic model required to rigorously describe optomagnetism in noble metals [17] helps leaving basic nanoparticle geometries and addressing optomagnetism in more complex 3D nanostructures usually obtained from top-down nanofabrication techniques.

2. Simplified hydrodynamic model

This method consists of defining a thin metal layer beneath interfaces, whose thickness matches Thomas-Fermi length ($\lambda_{TF} \simeq 0.1$ nm for nobel metals). This layer is considered to be a surface/interface layer, where the electron gas pressure is considered to be high. Out of this layer, in the metal bulk, the local model applies ($\beta \to 0$). Within the interface layer, the parallel component of the linear current density j_ω^T preserves whereas the normal component j_ω^N decays to zero. This additional boundary condition on j_ω^N, which is required to solve the nonlocal problem, is attributed to a neglected electron "spill-out" at interfaces [11]. The new boundary condition enables to solve the simplified hydrodynamic model in perturbation approach and find the expression for bulk and surface DC currents. It has been demonstrated that the main contributors to the optomagnetic responce are sufrace currents [2, 4, 5, 7, 15, 16, 17, 18]. The azimutal component of the surface current reads as:

$$[\mathbf{J_d^s}]_\theta = \frac{\tau}{n_0 e}\mathfrak{Re}\left[\left(1+\frac{i\gamma_0}{\omega\tau\gamma^*}\right) j_\omega^N(0^-) j_\omega^{\theta *}(0^-)\right]. \quad (3)$$

Defining ξ as the spatial coordinate normal to surfaces so that the metal bulk is located at $\xi < 0$ and the surface layer corresponds to $0 < \xi < \lambda_{TF}$, we have $\boldsymbol{j_\omega^T}(\xi) \approx \boldsymbol{j_\omega^T}(0^-)$ and $j_\omega^N = j_\omega^N(0^-)\sigma(\xi)$, where σ is a decaying function defined by $\int_0^{\lambda_{TF}} \sigma'(\xi)d\xi = -1$ where σ' is the derivative with respect to ξ [11].

3. Results

Using our simplified hydrodynamic model we have predicted the optomagnetic responce of a 50 nm-diameter and 12 nm high silver cylinder in a medium of refractive index equal to 1.45 (Fig. 1) and 70nm- inner diameter and 50nm high coaxial nanoaperture of gap size equal to 10 nm (Fig. 2). Both nanostructures are illuminated with a right-handed circularly polarized gaussian beam propagating along the axis of symmetry (Oz) of the structures.

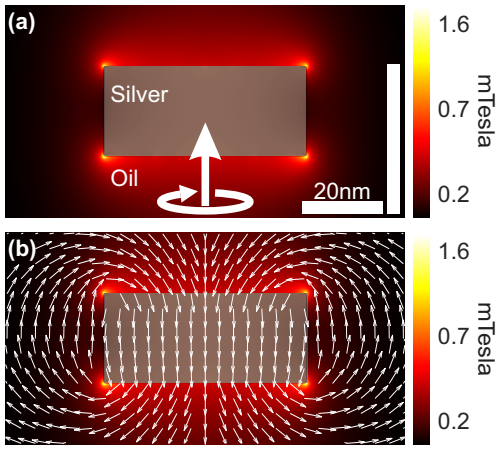

Figure 1: (a) and (b) Distributions of amplitude of the optically-induced static magnetic field in a longitudinal cross-section (x0z) of the cylyndrical plasmonic nanostructure in oil. Illumination is realized with a circularly polarized light of intensity $3.2 \cdot 10^8$ W.cm^{-2} at $\lambda = 649$nm. The local optomagnetic field orientation is represented with white arrows.

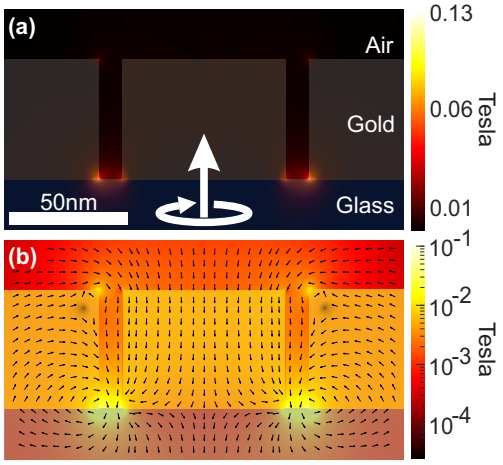

Figure 2: Distributions of amplitude of the optically-induced static magnetic field in a longitudinal cross-section (x0z) (a) linear scale (b) log scale. The nanostructure is annular nanoaperture in gold laying on glass substrate. Illumination is realized with a circularly polarized light of maximum intensity 0.5 10^{11}W.cm^{-2} at $\lambda = 800$nm. The local optomagnetic field orientation is represented with white arrows.

4. Conclusions

On the basis of the simplified hydrodynamic model of the free electron gas of a metal, we investigate the generation of an optomagnetic field (generated from the inverse Faraday effect) in plasmonic coaxial structures upon illumination with a circularly polarized light. We also show that the substrate introduces an important asymmetry of the optomagnetic response of the plasmonic nanostructure. The optomagnetism is mainly localized within the substrate, which appears to be advantageous for many applications. Optomagnetism in plasmonic nanoapertures may impact a broad field of applications and techniques including spintronics, magnonics and data storage via the development of on-chip nanoscale plasmonic-magnetic architectures. Optomagnetism may also provide new degrees of freedom in nano-object tweezing based on the combination of optomagnetic and pure optical forces.

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References

[1] Maccaferri et all. *J. Appl. Phys.*, 127(8):080903, 2020.

[2] Smolyaninov et all. *Phys. Rev. B*, 71(3):035425, 2005.

[3] Cheng et all. *Nat. Photon.*, 14(6):365–368, 2020.

[4] Nadarajah et all. *Opt. Express*, 25(11):12753–12764, 2017.

[5] Hurst et all. *Phys. Rev. B*, 98(13):134439, 2018.

[6] Sinha-Roy et all. *ACS Photonics*, 7(9):2429–2439, 2020.

[7] Yannick Lefier. PhD thesis, Université de Franche-Comté, 2016.

[8] Krasavin et all. *Laser Photonics Rev.*, 12(1):1700082, 2018.

[9] Sipe et all. *Phys. Rev. B*, 21(10):4389, 1980.

[10] Scalora et all. *Phys. Rev. A*, 82(4):043828, 2010.

[11] Ciracì et all. *Phys. Rev. B*, 85(20):201403, 2012.

[12] Morel et all. *Scientific Reports*, 11(1):1–10, 2021.

[13] Raza et all. *Phys. Rev. B*, 84(12):121412, 2011.

[14] Toscano et all. *Opt. Express*, 20(4):4176–4188, 2012.

[15] Karakhanyan et all. *Opt. Lett.*, 46(3):613–616, Feb 2021.

[16] Karakhanyan et all. *OSA Continuum*, 4(5):1598–1608, May 2021.

[17] Koshelev et all. *Phys. Rev. B*, 92(23):235426, 2015.

[18] Mondal et all. *Phys. Rev. B*, 92(10):100402, 2015.