Inverse Faraday effect in plasmonic heterostructures

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Abstract. The phenomenon of the surface plasmon assisted electromagnetic field concentration in the vicinity of the metal/dielectric interface of a periodically perforated with subwavelength holes arrays plasmonic structure is considered. An increase of the local stationary magnetic field appearing due to the inverse Faraday effect while the heterostructure is illuminated by circularly polarized light is demonstrated. The stationary magnetic field induced is more than an order of magnitude larger than the one for a uniform non-plasmonic film which implies a possibility for local control of the magnetization.

1. Introduction

The inverse Faraday effect (IFE) takes place when circularly polarized light incident on a crystal induces a magnetic moment $M$. The IFE was first predicted by Pitaevskii in 1961 [1]. Actually, the IFE is a manifestation of the fact that circularly polarized light causes an angular momentum-flux, the phenomenon usually referred to as Sadovskii effect (see review paper [2]).

If a medium is illuminated by polarized light the IFE is measured by

$$\text{IFE} = \frac{\lambda V}{2\pi c}(I_R - I_L),$$

where $V$ is Verdet constant of the medium, $\lambda$ is the light wavelength, $I_R$ and $I_L$ are intensities of right and left circularly polarized components of the incident light, respectively, in cgs units and $M$ is in Gauss per cubic centimeter. Thus, if incident light is elliptically polarized the intensities $I_R$ and $I_L$ are not equal and the medium acquires a magnetic moment and can be magnetized. The difference $I_R - I_L$ is proportional to the vector product of $E$ and its complex conjugate $E^*$:

$$I_R - I_L \sim \text{Im}(E \times E^*) \cdot (E \times E^*) = |\text{Im}(E \times E^*)|^2.$$ Consequently, the quantity $m = |\text{Im}(E \times E^*)|$ characterizes the dc magnetic field arising in the medium illuminated by light.

It is worth noticing that the IFE depends also on the Verdet constant. For a paramagnetic medium it is calculated by $V = 4\pi^2\chi/n\lambda$, where $n$ is the refraction index, $\chi$ is the material constant describing conventional Faraday effect, $\chi = g/4\pi H$, $g$ is a medium gyrotropy, and $H$ is the
external magnetic field. Hence to get high value of the IFE one need either to find a material with large Verdet constant or to make the value of $m = \Im \left( E \times E^* \right)$ inside a material as large as possible. We in what follows investigate the latter possibility.

2. Results and discussion

Let us consider a plasmonic material, i.e. a medium which sustains propagation of the surface plasmon polaritons (SPP). The SPPs are collective oscillations of free electrons plasma and electromagnetic field. They are localized at the interface between a metal and a dielectric. Recently studies of the plasmonic materials are paid much attention which is mainly due to the interesting optical phenomena related to the excitation of the SPPs such as extraordinary optical transmission [5], giant magnetooptical effects [6], and local increase of the electromagnetic field intensity [7,8]. The latter leads to much more efficient light-matter interaction and as a consequence to the enhancement of any types of the optical effects related to the electromagnetic field intensity. One of the most vivid examples of that is the substantial increase of the nonlinear effects [8].

Once the SPPs are generated the electromagnetic field intensity near the interface can be enhanced greatly. Thus, it is shown in Ref [7] that the SPP is an efficient tool for the nanolithography process with high spatial resolution since the intensity in the 50 nm interface vicinity is enhanced by as much as 50 times. Since the IFE depends on the electric field amplitudes one can assume that the SPPs can also be used for the IFE enhancement. However, this idea does not look straightforward since the IFE is defined not by intensity of the electromagnetic field, i.e. it is measured not by the scalar product of the field amplitude and its complex conjugate but by their cross product.

The SPPs are resonantly excited for example in perforated metalo-dielectric films (Fig. 1). The perforated film can be made of a dielectric diffraction grating of subwavelength period attached to a smooth metal substrate (Fig. 1 a). In order to observe the IFE the dielectric layer should have not vanishing Verdet constant. We assume it to be a paramagnetic. Otherwise, it is a metal layer which is perforated and the paramagnetic is placed directly under the grating (Fig. 1 b). Grating period is $d$, holes size is $r$, grating thickness is $h_{gr}$, and the uniform metal layer (see Fig.1a) thickness is $h$. The thickness of the paramagnetic substrate is much larger than $h_{gr}$ and $h$.

![Figure 1. Schematic of the plasmonic heterostructures: (a) perforated dielectric / metal / paramagnetic; (b) perforated metal / paramagnetic.](image)

To increase electric field amplitude inside the paramagnetic material the SPP must be localized at the interface between the paramagnetic and the metal. The SPP can be “horizontal”, i.e. travelling along the metal/dielectric interface or “vertical”, i.e. excited at the holes walls. What type of the SPP is excited depends on the geometrical parameters of the structures: grating period, thickness, and holes size. For example the conditions of the excitation of the horizontal SPPs can be estimated easily from the photon momentum conservation law: $\mathbf{k} = \mathbf{k}^{(i)} + \mathbf{G}$, where $\mathbf{k}$ is the SPP wave number, $\mathbf{k}^{(i)}$ is the interface component of the incident light wave vector $\mathbf{G}$ is the reciprocal lattice vector. The SPP wave number can be approximated with the one for uniform interface between a metal and a magnetized dielectric. If magnetization is perpendicular to the interface then the magnetic layer is described by the dielectric tensor $\varepsilon^{(m)}$ having the following nonzero components: $\varepsilon_{11} = \varepsilon_{22} = \varepsilon_{33} = \varepsilon_1$, $\varepsilon_{12} = -ig$, $\varepsilon_{21} = ig$, where $g$ is the value of medium’s gyration. Perpendicular
magnetization causes a leakage of the SPP, however as $g$ is much smaller than $\varepsilon_1$ its influence on the SPP’s wave number is negligible and thus the SPP wave number can be approximated by a well known formula

$$\kappa = k_0 \sqrt{\varepsilon_1 \varepsilon_2 / (\varepsilon_1 + \varepsilon_2)} ,$$

where $k_0$ is the vacuum wave number and $\varepsilon_2$ is the dielectric constant of the metal.

In order to model electromagnetic field distribution in the multilayer of two-dimensional periodic arrays of holes special numerical techniques are necessary. In this paper we present the numerical results obtained by the rigorous coupled waves analysis (RCWA) extended to the instance of gyrotropic materials [9]. At this, special factorization rules are used for the improvement of the algorithm’s convergence.

At the numerical modeling normal incidence of the circularly polarized light is assumed. Permittivities of the paramagnetic and dielectric are taken to be equal. Their values are indicated in captions to Fig. 2 and 3. Permittivity of the metal is equal to the one of silver [10]. Figure 2 represents electromagnetic field intensity $I$ and the value of $m$ across the paramagnetic layer for two perforated films of the first type. Both quantities are normalized on their values for a single paramagnetic film without the plasmonic upper layer.

![Image](image_url)

**Figure 2.** Contour plots (a), (c) for $I$ and (b), (d) for $m$ at 10 nm depth inside the paramagnetic across a unit lattice normalized on their values for a single paramagnetic film without plasmonic upper layer. A grating is of the first type (see Fig. 1 a): (a), (b) paramagnetic permittivity is 2.56, $d=924$ nm, $r=236$ nm, $h_{gr}=260$ nm, $h=70$ nm; (c), (d) paramagnetic permittivity is 5.5, $d=533$ nm, $r=272$ nm, $h_{gr}=147$ nm, $h=57$ nm; $\lambda$ is 550 nm corresponding to the excitation of SPP by the 3-rd transmitted diffraction order (the hole is in the center of the unit cell).

It is evident from Fig. 2 that the field distribution patterns are drastically different for two gratings of the first type. This is due to the fact that the complex amplitude of a diffraction order giving birth to the SPP has different ratio to the amplitudes of the lower diffraction orders. Thus, in the case of the structures modeled in Fig. 2, the SPPs are excited by the 3-rd transmitted diffraction orders. When the complex amplitudes of other transmitted orders (zeroth, first and second orders) are negligible comparing to the amplitude of the order corresponding to the SPP, the formed pattern is regular (Fig. 2 a,b). Otherwise, the pattern becomes rather complex (Fig. 2 c,d). In the latter case the maximum field concentration takes place in several small spots of diameter of about 20-40 nm in the paramagnetic.

Nevertheless, in both cases the intensity of the local maxima reaches 10-50 times increase and the enhancement factor of $m$ is of the same order. It is very important to note here that the field distribution can be varied by changing light wavelength or/and angle of incidence. It opens a possibility to locally control field distribution and, consequently, to affect locally the medium magnetization via the IFE. At this, the scale of the influence would be much smaller than the wavelength which is vital for an optical data recording at ultra high density and very fast rates. The latter was demonstrated experimentally for non-plasmonic systems in Ref. [3].
Figure 3. Contour plots (a) for $\vec{I}$ and (b) for $\vec{m}$ at 10 nm depth inside the paramagnetic across a unit lattice normalised on their values for a single paramagnetic film without plasmonic upper layer. A grating is of the second type (see Fig. 1 b), paramagnetic permittivity is $5.5$, $d=743$ nm, $r=345$ nm, $h_{gr}=151$ nm; wavelength is 855 nm which is close to the SPP the 2-nd diffraction order in transmission. The hole is in the upper left quarter of the unit cell.

Plasmonic structures of perforated metal onto a smooth paramagnetic give even larger enhancement factors if the holes size is large and SPPs anomalies are excited (Fig. 3). The field intensity is increased locally by 70 times, while the induced dc magnetic field parameter $m$ is increased by 25 times. In the case of metal gratings lying onto the paramagnetic the near field distribution mimics the holes contours more closely (the hole is in the upper left quarter of the unit cell).

3. Conclusion

We investigated the electromagnetic field distribution near the metal/dielectric interface of the plasmonic perforated films. The IFE is found to be locally increased by 10-50 times to the order of magnitude at the spatial scale of several tens of nanometers. In addition to that the electromagnetic field intensity is got increased as well and the maxima of the intensity are usually very close to the maxima of the induced magnetic field. It leads to much more efficient influence of light on the medium around these spots as several impact mechanisms are enhanced: magnetic, thermal and energetic. Thus if the medium is magnetized it can be locally switched by means of incident circularly polarized light of moderate energy. Moreover, the loci of the enhanced dc magnetic field can be changed by shifting light wavelength or incidence angle. It is very important for possible applications related for example to the magnetization switching and magnetic data recording at record densities and rates.

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