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Inverse Faraday Effect in Plasmonic Films

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Abstract—It is shown that the inverse Faraday effect appears in the case of surface plasmon polariton propagation near a metal/paramagnetic interface. The inverse Faraday effect in nanostructured periodically perforated metal–dielectric films increases because of the excitation of surface plasmon polaritons. In this case, a stationary magnetic field is amplified by more than an order of magnitude compared to the case of a smooth paramagnetic film. The distribution of an electromagnetic field is sensitive to the wavelength and the angle of incidence, which allows one to effectively control the local magnetization that arises due to the inverse Faraday effect.

Keywords: inverse Faraday effect, magnetooptics, surface plasmon polaritons, plasmonic structure

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INTRODUCTION

The inverse Faraday effect (IFE), which is seen in the appearance of constant magnetization in a medium where elliptically polarized electromagnetic (EM) waves propagate, is of high interest. The first experiments on the observation of the IFE occurred in 1965 [1]. However, this caused special interest only after the appearance of powerful lasers and, consequently, of the practical possibility to effectively apply the IFE. In particular, it is possible to record information optically on magnetic carriers; this method is based on the IFE [2–4].

The inverse Faraday effect in solid bodies is connected with the Direct Faraday effect (rotation of a plane of polarization of EM radiation that propagates in a substance along the force lines of a constant magnetic field passing through this substance). The following expression is correct for the angle of Faraday rotation (in the direct effect): [4]

$$b \sim V|\mathbf{H}_{\text{ext}}|d, \tag{1}$$

where d is the path passed by an EM wave in the substance, $\mathbf{H}_{\text{ext}}$ is the value of the external magnetic field, and V is the Verde constant defined by a material's properties; the proportionality coefficient depends on the used system of units.

The following expression is true for magnetization of a sample appearing during the IFE [4–6]

$$\mathbf{M} \sim V[\mathbf{E}\mathbf{E}^*], \tag{2}$$

where $\mathbf{E}$ is the intensity of an external electric field in complex meaning and an asterix indicates complex conjugation.

Both (1) and (2) imply that the direct and inverse Faraday effects are connected, since they are defined by the constant V. As well, (2) implies that the magnetization gained depends on radiation polarization during the passage of an EM wave through the sample: magnetization is maximal for circular polarization and equals zero for linear polarization. In addition, IFE is quadratic by the amplitude of the electric field of a wave. Consequently IFE is proportional to the intensity of the external field, which has been confirmed experimentally [7].

1. THE IFE DURING THE PROPAGATION OF SURFACE PLASMON POLARITONS

Expression (2) implies that the IFE requires a nonzero vector product $[\mathbf{E}\mathbf{E}^*]$ and amplification of the intensity of the external electric field. These two conditions are true in surface plasmon polaritons (SPPs), which are electromagnetic waves localized near the interface of a metal and a dielectric. The magnetic field in such a wave is perpendicular to the propagation direction. At the same time, unlike volumetric EM waves, SPPs have a nonzero projection of the intensity vector of the electric field in the propagation direction. As well, the component directed along the border of the media and the component perpendicular to this border are displaced with respect to each other in phase by $\pi/2$ for the electric field [8, 9]. Consequently, even for single SPPs the module $[\mathbf{E}\mathbf{E}^*]$ is not zero and is constant in time. At the same time, the vector of magnetization gained by the sample belongs to the surface parallel to the interface of the media. In addition, the intensity of the EM field is amplified upon

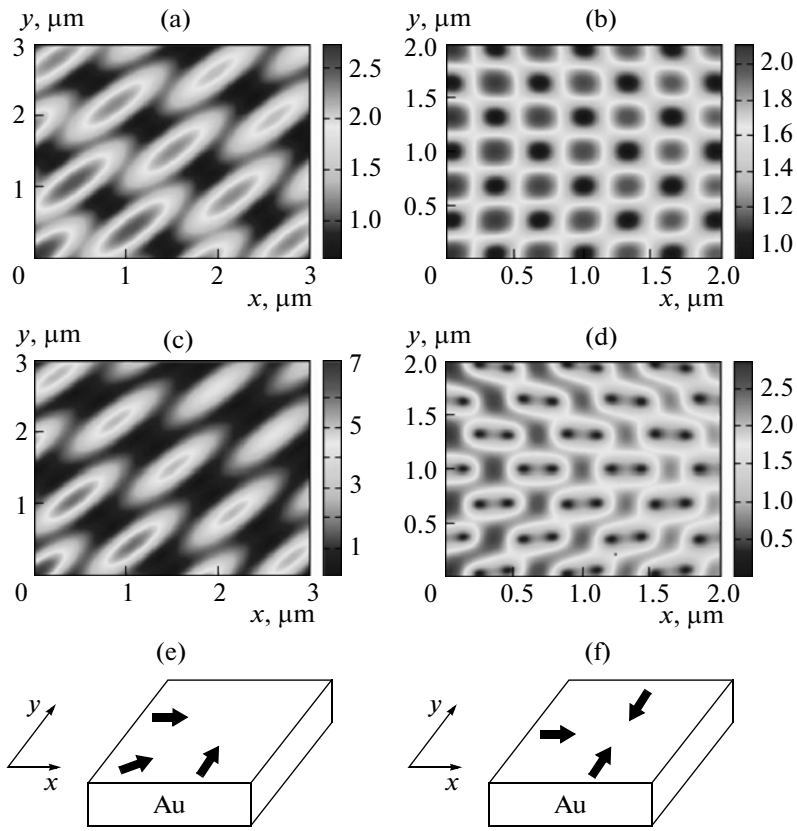

Fig. 1. Distribution of (**EE***) a, b and module [**EE***] c, d on the air/gold interface (both magnitudes are normalized to their values at propagation of the same SPP): a, b at propagation of three SPPs with wave vectors directed as shown in e; b, and d during the propagation of three SPPs with wave vectors directed as shown in f.

SPP excitation due to its localization in a thin interface layer [8–10]. In this way, both conditions are fulfilled for amplification of the IFE during excitation of a single SPP.

As well as the case of propagation of a single SPP, changes of the module [**EE***] in cases when two or more SPPs are excited on the media interface have also been investigated. Figure 1 shows the distributions of the module [**EE***] at propagation of three SPPs with wave vectors directed at different angles to each other (amplitudes of EM field and frequencies of SPP were accepted to be equal).

The distributions in Figure 1 imply that due to the interference of several SPPs a redistribution of the EM field occurs and the product [**EE***] is not constant along the entire surface. Local changes in the intensity of the electric field along the interface are observed as well (Figs. 1a and 1b). Due to the attenuation of SPPs, the resulting distribution of the field has local maxima of different values. The vector [**EE***] (and consequently magnetization gained by the sample as a result of IFE) does not belong to the surface parallel to the media interface; it has a component that is perpendicular to it.

2. THE IFE IN PLASMONIC FILMS

Surface plasmon polaritons can be excited only under certain conditions, in particular in the presence of periodic structures on a surface [8]. Two types of Plasmonic films have been considered in the present work: (I), a dielectric perforated film on the surface of a metal layer sprayed on the substrate (Fig. 2a); (II) a perforated metal film sprayed directly on a smooth substrate (Fig. 2b). For observation of the IFE the dielectric must have a nonzero value of the Verde constant; therefore, a paramagnetic was selected as the material of the semi-infinite substrate for the investigation.

It is necessary to emphasize that it is two-dimensional periodic films that present practical interest, since it is not possible to achieve high amplification of the IFE in structures that are periodic in one direction. This is connected with the fact that a one-dimensional subwave lattice affects the elliptically polarized wave as a polarizer, which suppresses the IFE.

In order to amplify the electric field inside of the substrate the SPPs must be localized near the interface of the paramagnetic and metal. The SPPs can be "horizontal," i.e., propagate along the horizontal metal–paramagnetic interface or the "vertical," i.e., excite on

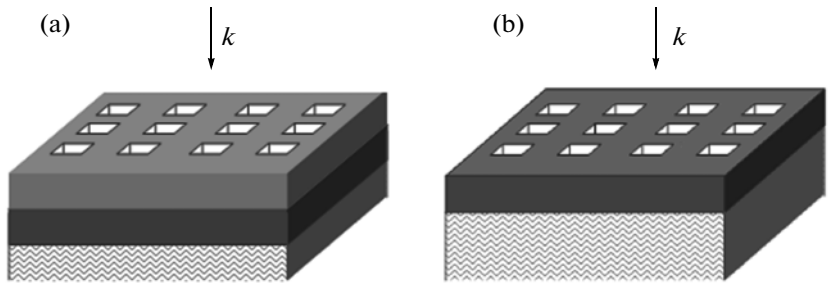

Fig. 2. Plasmonic films under consideration: a, perforated dielectric/metal/paramagnetic; b, perforated metal/paramagnetic. Circularly polarized EM wave falls from the top perpendicular to the surface of the perforated layer.

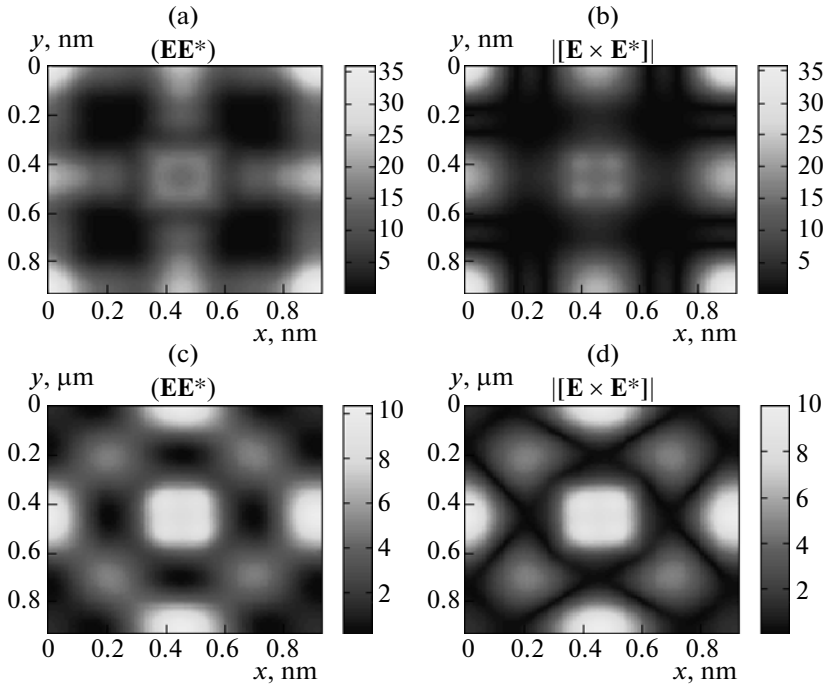

Fig. 3. Distribution of (**EE***) (a, c) and module [**EE***] (b, d) at a depth of 10 nm in a paramagnetic during passage of light through structure of type I (Figure 2a) (both magnitudes are normalized to their values in the absence of the plasmonic layer; one period of the lattice is shown and the hole is located in the center). Parameters of the structure: the dielectric constant of the paramagnetic is 2.56, $d = 924$ nm, $r = 236$ nm, $h_{gr} = 260$ nm, $h = 70$. a, b, the wavelength is 616 nm; c, d, the wavelength is 778 nm.

the walls of holes. The type of excited SPP depends on the wavelength of the incident EM radiation and the geometric parameters of the structure, viz., the lattice period d, its thickness h_{gr}, the thickness of the smooth metal layer h (for the structure in Fig. 2a), and the hole size r. For example, the excitation conditions of a horizontal SPP can be derived from the conditions of phase synchronism: $\mathbf{k} = \mathbf{k}_{\parallel}^{(i)} + \mathbf{G}$, where $\mathbf{k}$ is the wave number of a SPP, $\mathbf{k}_{\parallel}^{(i)}$, is the component of the wave vector of incident light parallel to the interface, and $\mathbf{G}$ is the vector of inverse lattice.

For simulating the distribution of an electromagnetic field in a plasmonic structure with a two-dimensional periodicity it is necessary to use special numerical methods. In this work, the rigorous coupled wave analysis (RCWA) generalized for gyrotropic media has been used. Special factorization rules for improving convergence of the method [11] have also been used.

In the mathematical simulation, the normal incidence of EM radiation with circular polarization was considered. The dielectric constants of paramagnetic and dielectric were accepted as being equal. Calculations were performed for two values of dielectric constant: 2.56 (Fig. 3) and 5.5 (Fig. 4). Silver was selected as the metal, its dielectric constant is taken from [12]. Figure 3 shows calculation results for the distribution of the intensity of the electric field and its value $[E_I E^*]$ for a perforated lattice of type (I) at different wavelengths. Both magnitudes are normalized to their values in the absence of the upper plasmonic layer.

It can be seen from Fig. 3 that the distribution of the field in the sample differs for the same structure at different wavelengths of incident radiation. In this case

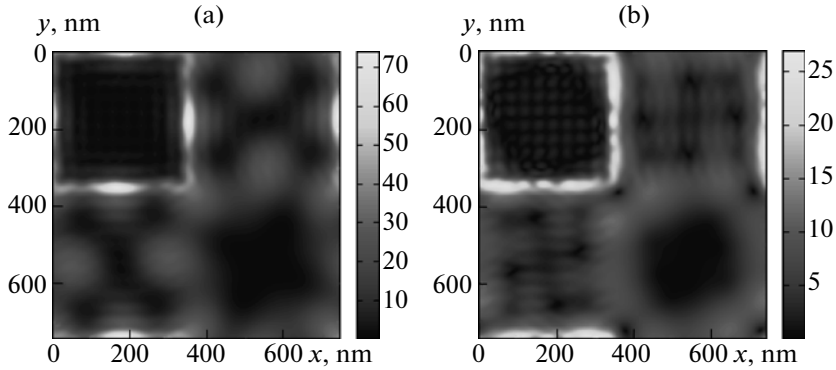

Fig. 4. Distribution of (**EE***) (a) and module [**EE***] (b) at a depth of 10 nm in the paramagnetic during passage of light through structures of type II (Fig. 2b) (both magnitudes are normalized to their values in the absence of the plasmonic layer; one period of the lattice is shown and the hole is located in the upper left corner). Parameters of the structure: the permittivity of the paramagnetic is 5.5, $d = 743$ nm, $r = 345$ nm, $h_{gr} = 151$ nm, $h = 70$; the wavelength is 855 nm.

the field is concentrated in small volumes near the surface of the paramagnetic with a diameter of 100–200 nm.

However, in both cases the intensity of the electric field and module [**EE***] in local maxima is amplified 10–35 times as compared with the case of the smooth surface. It is important to note that the distribution of the field in the paramagnetic depends on the wavelength and/or incidence angle of light. This allows one to control the local distribution of the field and to adjust the local magnetization of the medium via IFE at spatial scales much less than the wavelength of incident light. This is necessary for optical recording of super-high-density information at high rates in magnetic memory devices. Such a method was experimentally demonstrated for a non-plasmonic system in [3, 4].

A plasmon structure composed of perforated metal sprayed on a smooth paramagnetic allows one to obtain local amplification of an EM field for a hole size on the order of a half period and during excitation of "vertical" SPPs (Fig. 4).

Locally, the intensity of the field is amplified up to 70 times and the module [**EE***] is amplified up to 25 times. In the case where perforated metal is sprayed directly on a smooth paramagnetic, distribution of the field near the interface has the same shape as the distribution of holes in metal (holes are located in the upper left corner of the figure).

CONCLUSIONS

The IFE occurs during the propagation of surface plasmon polaritons along the metal-paramagnetic interface. The interference from several surface plasmon polaritons leads to local amplification of the IFE. The IFE can be amplified 10–35 times in plasmonic films in localized regions with sizes of about 100 nm. The intensity of the electric field increases locally with magnetization. At the same time, the maxima of its intensity are located in the IFE amplification regions. This leads to local heating of the paramagnetic and lowers the magnetization threshold. The location of the local amplification of a magnetic field can be adjusted by changing the wavelength or angle of the incidence of an EM wave. This is important for possible applications of the IFE, such as optical recording of information on magnetic carriers.

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