Inverse transverse magneto-optical Kerr effect

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It is shown theoretically that a static in-plane magnetic field is generated in a ferromagnetic film by p-polarized light obliquely incident on the film. This phenomenon can be called the inverse transverse magneto-optical Kerr effect. The femtosecond laser pulse of peak intensity of 500 W/μm^2 generates in nickel an effective magnetic field of about 100 Oe. The value of the effective magnetic field can be increased by more than an order of magnitude at the surface plasmon-polariton resonance excited in smooth metal dielectric structures or in plasmonic crystals.

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I. INTRODUCTION

The exciting possibility of ultrafast control of a medium magnetization at the subpicosecond time scale via light was demonstrated recently.[1–3] It is of prime importance for modern magnetic storage systems demanding very large operation rates. In particular, the optical way of magnetization control is possible due to the fact that a circularly polarized light induces static magnetization in a gyrotropic medium. This phenomenon is called the inverse Faraday effect. It was theoretically predicted by Pitaevskii[4] and Pershan[5] about 50 years ago. Its experimental evidence in paramagnets was delivered in Ref. 6. The inverse Faraday effect is related to its well-known counterpart, the Faraday effect, or magnetic circular birefringence, resulting in rotation of the light polarization through a magnetic medium. In the approximation of nonabsorbing media they both are proportional to the same magneto-optical constant.[7]

It is not the only Faraday effect which was shown to have an inverse counterpart. Thus, the inverse Cotton-Mouton effect was observed recently in terbium gallium garnet crystal.[8] Due to this effect, the medium magnetization is induced in a medium by a linearly polarized light propagating in the presence of a transverse magnetic field.

Apart from the Faraday and Cotton-Mouton effects there are effects belonging to a family of magneto-optical Kerr effects. Among them the transverse magneto-optical Kerr effect (TMOKE) is of prime importance, providing an efficient tool for magnetization monitoring in different types of magnetic samples.[9,10] Furthermore, TMOKE can be used for optical reading in magnetic storage systems based on media with in-plane magnetization.

TMOKE is observed for oblique incidence of a p-polarized electromagnetic wave in the plane perpendicular to the sample magnetization.[11] It is measured by a relative change of the sample reflectivity when the sample is remagnetized. Thus TMOKE belongs to the class of the magneto-optical intensity effects in contrast to the Faraday and polar Kerr effects, which are related to the light polarization rotation. The origins of the effect are associated with the magnetization-sensitive boundary conditions at the surface of the magnetic layer. The TMOKE takes place only for absorbing media.

In analogy to the case of the Faraday effect a question arises: whether the inverse counterpart of TMOKE exists. Here we address this problem and demonstrate by rigorous solution of Maxwell's equations that this question has a positive answer. We show that the static effective magnetic field is generated in a metal ferromagnet if it is illuminated by light in the TMOKE configuration. The strength of the generated magnetic field is directly proportional to the incident intensity and is about 120 Oe for the incident light intensity of 500 W/μm^2, which approximately corresponds to the fluence of 10 mJ/cm^2 for a 100-fs laser pulse. It should be noted that a laser pulse of similar intensity (10^3 W/μm^2) was used in recent experiments on the inverse Faraday effect.[2] The inverse TMOKE can be significantly enhanced up to 5000 Oe by using plasmonic structures.

II. INVERSE TMOKE IN A SMOOTH MAGNETIC FILM

Within the macroscopic theory of magneto-optical phenomena the properties of the magnetically ordered media are defined by $\hat{\varepsilon}$ and $\hat{\mu}$ tensors. However, at the optical and near-infrared frequencies a magnetic dipole response is very weak, and the $\hat{\mu}$ tensor is close to a scalar form and can be taken to be unity.[7] Magneto-optical properties of the medium are mainly governed by the gyration vector $\mathbf{g}$, which is a function of the medium magnetization $\mathbf{M}$. For ferromagnetic crystals $g_i = a_{ij}M_j$, where tensor a_{ij} is defined by the crystallographic symmetry and $i,j = x,y,z$. In the case of an absorptive medium, the gyration vector and tensor a_{ij} become a complex-valued function of frequency: $\mathbf{g} = \mathbf{g}' + i\mathbf{g}''$, $a_{ij} = a'_{ij} + ia''_{ij}$. In the linear in magnetization approximation the $\hat{\varepsilon}$ tensor of a ferromagnet is given by

$$\varepsilon_{ij} = \varepsilon^0_{ij} - ie_{ijk}g_k, \tag{1}$$

where e_{ijk} is the Levi-Civita tensor[12] and $i,j,k = x,y,z$.

The light-induced effective magnetic field is defined by $\mathbf{H}_{\text{eff}} = -\partial U_M/\partial \mathbf{M}$, where $U_M = \frac{i}{16\pi}e_{ijk}g'_kE^*_iE_j$ is the gyrotropic part of the energy of a ferromagnetic sample illuminated by light.[2,7] Here (1) is taken into account. It leads to the following expression for $\mathbf{H}_{\text{eff}}$:

$$H^{\text{eff}}_i = -\frac{ia'_{ij}}{16\pi}e_{jkl}E_kE^*_l. \tag{2}$$

For the case of a ferromagnetic crystal with cubic symmetry (2) simplifies to

$$\mathbf{H}^{\text{eff}} = -\frac{ia'}{16\pi}[\mathbf{E}\times\mathbf{E}^*]. \tag{3}$$

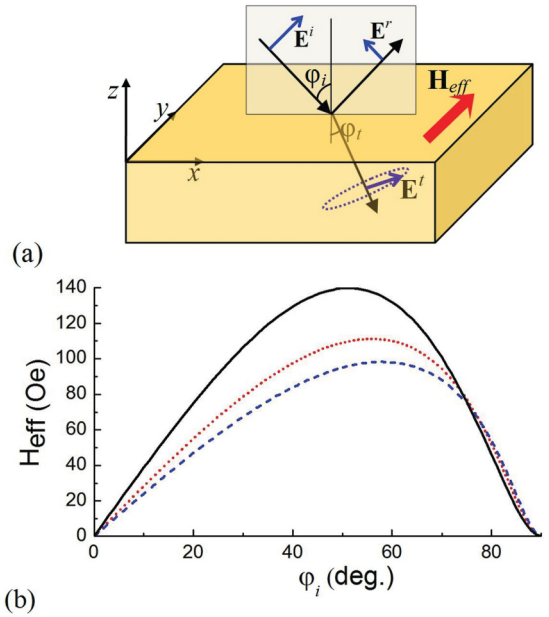

FIG. 1. (Color online) (a) Configuration for the inverse TMOKE: p-polarized light is obliquely incident on the ferromagnet film and generates an effective magnetic field H_{eff} inside the film. (b) The inverse TMOKE near the surface (at a point 5 nm in depth) of magnetic films of iron (black solid line) at $\lambda = 630$ nm, nickel (red dotted line) at $\lambda = 630$ nm, and bismuth iron garnet (blue dashed line) at $\lambda = 400$ nm vs angle of light incidence. It is assumed that the samples are illuminated with a 40-fs duration laser pulse with a peak intensity of 500 W/μm^2.

This formula is similar to the one for light-induced magnetization of paramagnets.[4] The cross product of $[\mathbf{E} \times \mathbf{E}^*]$ is not zero for elliptically polarized light, which is the ground of the inverse Faraday effect's existence. In the TMOKE configuration the incident light is linearly polarized. But due to the boundary conditions at the interface between a dielectric and a medium with absorption or with negative permittivity linearly polarized light is transformed into elliptical light, so in such a medium the quantity $[\mathbf{E} \times \mathbf{E}^*]$ is not zero. Indeed, if an electromagnetic wave with the electric field E^i is obliquely incident in the xz plane, the angle of incidence is φ, and the magnetization vector $\mathbf{M}$ is along the y axis [Fig. 1(a)], then the electric field of the electromagnetic wave inside the ferromagnet is given by[11]

$$\begin{pmatrix} E_x \\ E_z \end{pmatrix} = -E^t \begin{pmatrix} \cos\varphi_t \\ \sin\varphi_t + ig/\varepsilon\cos\varphi_t \end{pmatrix} \exp(-i\gamma z), \quad (4)$$

where $E^t = t_{12}E^i$, $t_{12} = 2\cos\varphi_i/(\tilde{n}\cos\varphi_i + \cos\varphi_t)$, φ_t is the angle defined by Snell's law $\sin\varphi_t = \tilde{n}^{-1}\sin\varphi$ with a complex refractive index of the ferromagnet $\tilde{n} = n(1 + i\kappa)$, and $\gamma = k_0\tilde{n}\cos\varphi_t$. The angle φ_t is generally complex valued. It is convenient to take $\cos\varphi_t$ in the form[13] $\cos\varphi_t = q\exp(i\delta)$, with $q = (\alpha^2 + \beta^2)^{1/4}$, $\alpha = 1 - (1 - \kappa^2)n^{-2}(1 + \kappa^2)^{-2}\sin^2\varphi_i$, $\beta = 2\kappa n^{-2}(1 + \kappa^2)^{-2}\sin^2\varphi_i$, $\tan 2\delta = \beta/\alpha$.

Equation (4) is written for p-polarized incident light (the electric field lies in the plane of incidence). It should be noted that s-polarized light (the electric field is perpendicular to the incidence plane) has only one component of the electric field in a medium and, consequently, induces no effective magnetic field (provided that weak magnetic-dipole transitions are neglected).

Substituting electromagnetic field components inside the magnetic medium defined by Eq. (4) in Eq. (3), one gets the effective magnetic field in the form

$$\mathbf{H}_{\text{eff}} = \frac{ia'|E_i|^2|t_{12}|^2\exp(2\gamma'')}{16\pi}[\sin\varphi_t(\cos\varphi_t)^* - (\sin\varphi_t)^*\cos\varphi_t]\mathbf{e}_y, \quad (5)$$

where γ'' is the imaginary part of γ and $\mathbf{e}_y$ is the unit vector along the y axis [see Fig. 1(a)]. Here we assumed that the ferromagnet has cubic crystal symmetry and retrieved only terms linear in magnetization (linear in a). Usually, the refractive index of the metal ferromagnets has rather large real and imaginary parts, so that $\cos\varphi_t \approx 1$. The vector $\mathbf{e}_y$ is perpendicular to the light incidence plane defined by the incident wave vector $\mathbf{k}_0$ and normal to the ferromagnet surface $\mathbf{N}$. Therefore it is represented by $\mathbf{e}_y = [\mathbf{k}_0 \times \mathbf{N}]/(k_0\sin\varphi)$. Taking these two points along with Snell's law into account modifies (5) as

$$\mathbf{H}_{\text{eff}} = \frac{a'|E_i|^2|t_{12}|^2\kappa\exp(2k_0n\kappa z)}{8\pi n(1 + \kappa^2)k_0}[\mathbf{k}_0 \times \mathbf{N}]. \quad (6)$$

As in the linear in a approximation g is not present in Eq. (6), and $\mathbf{H}_{\text{eff}}$ does not depend on $\mathbf{M}$ and appears in demagnetized ferromagnets and paramagnets as well. The direction of $\mathbf{H}_{\text{eff}}$ is determined by the cross product $[\mathbf{k}_0 \times \mathbf{N}]$, which means that $\mathbf{H}_{\text{eff}}$ reverses for the incident angle change from φ to $-\varphi$.

It is vivid that for the considered configuration the effective magnetic field appears only for the materials having an imaginary part of the refractive index. This means that the electromagnetic wave has to decay inside the ferromagnetic medium, which is the case if the material exhibits optical losses and/or has a metallic nature with a negative real part of the dielectric permittivity. However, if the magnetic film is sufficiently thin that light reaches its bottom face and reflects back, then the effective magnetic field does not vanish even for the medium with a purely real refractive index.

There is an important difference between inverse TMOKE and the well-known inverse Faraday effect. The inverse Faraday effect field $\mathbf{H}_{\text{eff}}$ is induced by circular polarized light and is directed along the wave vector $\mathbf{k}$. On the contrary, in accordance to Eq. (6) $\mathbf{H}_{\text{eff}}$ generated in the inverse TMOKE is oriented along the cross product of $[\mathbf{k}_0 \times \mathbf{N}]$; i.e., $\mathbf{H}_{\text{eff}}$ is perpendicular to $\mathbf{k}_0$. The latter broadens experimental possibilities for investigation of the optically induced femtosecond magnetism. Note that the difference of these effects follows from different dependences on relative orientations of $\mathbf{k}_0$ and $\mathbf{M}$ (or an external magnetic field) of the corresponding linear magneto-optical effects. The Faraday angle $\psi \sim (\mathbf{k} \cdot \mathbf{M})$, but in TMOKE $\Delta R/R \sim (\mathbf{k}_0 \cdot [\mathbf{M} \times \mathbf{N}])$, where $\Delta R/R$ is the relative change of reflection.[11,14]

The inverse TMOKE is also not related to the magnetic dichroism. Indeed, the magnetic dichroism is determined by the imaginary part of the medium gyrotropy constant, whereas it follows from Eq. (2) that the inverse TMOKE is related to the

real part of the gyrotropy and thus exists even in the medium without any absorption or dichroism. The inverse TMOKE is also quite different from the inverse Cotton-Mouton effect because the latter is even with respect to time inversion, which requires the presence of an external magnetic field to produce a magnetic torque. On the contrary the inverse TMOKE can be observed without any external magnetic field.

The H_{eff} generated by the electromagnetic field pulse in iron, nickel, and bismuth iron garnet films is shown in Fig. 1(b). The effect acquires its maximum values at an oblique incidence of about 60°. At the maxima H_{eff} is rather strong and is about 120 Oe near the film surface. For normal incidence the effect vanishes due to the absence of the E_z component in the excitation electromagnetic field. Gyration of the dielectric iron garnets is usually much smaller than the gyration of metallic ferromagnets. However, near the absorption resonance at a wavelength of about $\lambda = 370$ nm the gyration can be rather large ($g \sim 0.1$), and H_{eff} is compared to the one for ferromagnetic metals [see blue dashed curve in Fig. 1(b)].

The generated magnetic field exists only during the illumination of the sample and can be identified, for example, by its influence on **M**. Namely, if **M** is not directed along the y axis $\mathbf{H}_{\text{eff}}$ can lead to its precession around the external magnetic field. Similar to the inverse Faraday effect, magnetization dynamics can be observed experimentally in the pump-probe technique by measuring TMOKE and the Faraday effect in the probe beam.[1,2]

III. ENHANCEMENT OF THE INVERSE TMOKE IN PLASMONIC STRUCTURES

Recent progress in magnetoplasmonics demonstrated that most of the magneto-optical effects can be significantly enhanced due to excitation of surface plasmon polaritons (SPP).[14–19] Moreover, SPP-assisted magnetization of a nanohole array in noble metals was demonstrated recently by excitation of SPPs by circularly polarized light.[20] The most gain coming from the SPP generation takes place in structures with relatively low optical losses. One of the examples of such structures is a system of a structured noble metal and a magnetic dielectric operating at a light frequency far from the electronic transitions.[14,15] That is why the enhancement factor for plasmonic structures with ferromagnet metals like nickel or cobalt is rather small.[17] Nevertheless, if the structure incorporates a combination of noble and ferromagnetic metals, the SPP significance can be partly rescued.[18,19] In what follows we consider the inverse TMOKE in several plasmonic structures. The electromagnetic modeling was performed using the rigorous coupled-wave analysis (RCWA) technique.[21,22] For this technique, special factorization rules are used to improve the algorithm's convergence.[22]

In the simplest case the SPP can be excited on a smooth ferromagnetic metal surface using a prism in a Kretschmann or Otto configuration (Fig. 2).[23] This increases H_{eff} by about 4 times with respect to the nonplasmonic case. Further enhancement of the inverse TMOKE can be achieved if a periodic composite of alternating gold and nickel subwavelength stripes is considered (see inset in Fig. 2). For a wavelength of 630 nm gold and nickel permittivities have close real parts, but their imaginary parts greatly differ ($\varepsilon_{\text{Au}} = -8.9 + 1.1i$ and $\varepsilon_{\text{Ni}} = -9.2 + 14.4i$).[24] So the wavelengths of the SPPs waves at the gold and nickel surfaces are almost the same, but SPPs absorption coefficients are much different. The wavelength of SPP for the gold-nickel composite is 595 nm (at $\lambda = 630$ nm). If the period of the structure is much less compared to this value, then the gold-nickel structure acts as a kind of an effective medium. The smaller filling factor of nickel in the composite is, the larger the efficiency of the SPP excitation is.

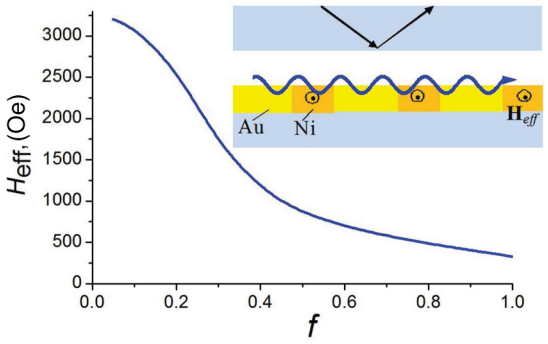

FIG. 2. (Color online) The inverse TMOKE at the SPP resonance in a Au/Ni periodic composite (shown in the inset) vs the filling factor of the nickel part f ($\lambda = 630$ nm). Effective magnetic field H_{eff} is calculated at 5 nm depth of the composite. Composite period d is 200 nm, thickness is 200 nm, and substrate is a dielectric of $\varepsilon = 5$ (lower blue region). The SPP is excited in the Otto configuration via a prism of $\varepsilon = 5$ (upper blue region) by a p-polarized laser pulse incident at 28°. Pulse peak intensity is 500 W/μm^2. Pulse duration is 40 fs.

Uniform nickel film corresponds to the filling factor $f = 1$, where f determines relative volumetric fraction of nickel in the composite. If f gets smaller, then H_{eff} increases, which

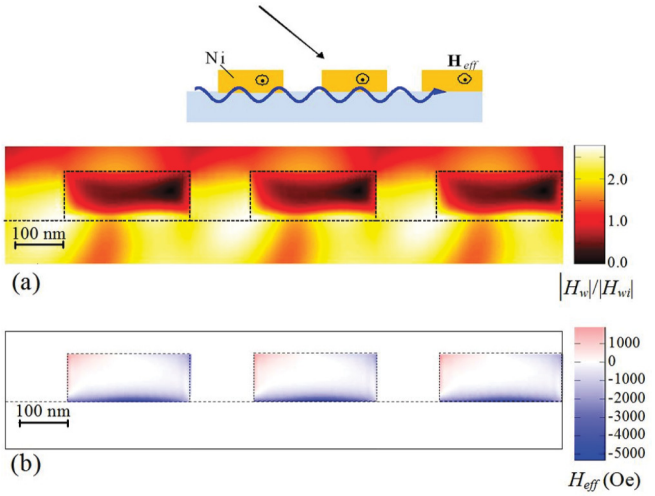

FIG. 3. (Color online) (a) Near-field distribution of the absolute value of the electromagnetic wave magnetic field $|H_w|$ in the plasmonic crystal (shown in the inset above) normalized to the magnetic field of the incident light $|H_{wi}|$. (b) Distribution of the effective magnetic field H_{eff} generated in the plasmonic crystal by the laser pulse. Three periods of the structure are shown. A laser pulse with a peak intensity of 500 W/μm^2 is p-polarized and is obliquely incident at 10°. Period d is 400 nm, slit width is 120 nm, and nickel film thickness is 100 nm.

is due to the enhancement of the SPP-assisted electromagnetic field concentration near the composite interface. The value of H_{eff} reaches 3000 Oe for very thin nickel stripes ($f < 0.1$). Consequently, the SPP introduces a significant increase of the inverse TMOKE by more than an order of magnitude.

If gold stripes are eliminated from the considered composite and the period of the composite is made comparable to the SPP wavelength, then the effects of the structure periodicity prevail, and the structure can be referred to as a plasmonic crystal. Plasmonic crystals of perforated gold and smooth iron garnet were shown recently to provide significant enhancement of TMOKE.[14] Though nickel plasmonic crystal has much larger optical losses, it can also concentrate electromagnetic energy at the SPP resonance conditions [Fig. 3(a)]. The electromagnetic energy density near the nickel-silica interface increases by an order of magnitude with respect to the one of the incident wave.

The generated effective magnetic field in the plasmonic crystal also increases and exceeds 5000 Oe near the nickel interface, which corresponds to an almost twofold further increase of H_{eff}. The prominent feature of the inverse TMOKE in plasmonic crystals is that $\mathbf{H}_{\text{eff}}$ has opposite directions in different parts of the nickel stripe cross section [shown with blue and pink colors in Fig. 3(b)]. This opens a new opportunity for the magnetization control of ferromagnetic materials.

IV. CONCLUSION

To conclude we have shown analytically and numerically that if a magnetically ordered material is obliquely illuminated with p-polarized light, then the inverse TMOKE takes place, and a static effective magnetic field is generated. It is directed perpendicularly to the incidence plane. If the laser pulse is of high intensity (of about 500 W/μm^2), H_{eff} in nickel is about 100 Oe (at $\lambda = 630$ nm). The effective magnetic field exists only during the laser pulse propagation inside the medium. It can be detected, for example, via observation of the magnetization dynamics caused by the inverse TMOKE. Since H_{eff} is determined by the near-field electromagnetic field distribution, the inverse TMOKE can be substantially enhanced at the SPP resonances providing significant electromagnetic energy concentration. Large values of the effective magnetic field generated in the inverse TMOKE can allow efficient all-optical magnetization control of magnetically ordered materials.

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[1] A. V. Kimel, A. Kirilyuk, P. A. Usachev, R. V. Pisarev, A. M. Balbashov, and Th. Rasing, Nature (London) **435**, 655 (2005).
[2] A. Kirilyuk, A. V. Kimel, and Th. Rasing, Rev. Mod. Phys. **82**, 2731 (2010).
[3] K. Vahaplar, A. M. Kalashnikova, A. V. Kimel, D. Hinzke, U. Nowak, R. Chantrell, A. Tsukamoto, A. Ithoh, A. Kirilyuk, and Th. Rasing, Phys. Rev. Lett. **103**, 117201 (2009).
[4] L. P. Pitaevskii, Sov. Phys. JETP **12**, 1008 (1961).
[5] P. S. Pershan, Phys. Rev. **130**, 919 (1963).
[6] J. P. van der Ziel, P. S. Pershan, and L. D. Malmstrom, Phys. Rev. Lett. **15**, 190 (1965).
[7] L. D. Landau, and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1984).
[8] A. Ben-Amar Baranga, R. Battesti, M. Fouché, C. Rizzo, and G. L. J. A. Rikken, Europhys. Lett. **94**, 44005 (2011).
[9] A. Chizhik, A. Zhukov, J. M. Blanco, and J. Gonzalez, J. Magn. Magn. Mater. **249**, 27 (2002).
[10] A. A. Rzhevsky, B. B. Krichevtsov, D. E. Bürgler, and C. M. Schneider, Phys. Rev. B **75**, 144416 (2007).
[11] A. K. Zvezdin, and V. A. Kotov, *Modern Magnetooptics and Magnetooptical Materials* (Institute of Physics, Bristol, 1997).
[12] G. Arfken, *Mathematical Methods for Physicists*, 3rd ed. (Academic, Orlando, FL, 1985), pp. 132–136.
[13] M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, 7th ed. (Cambridge University Press, Cambridge, 2003).
[14] V. I. Belotelov, I. A. Akimov, M. Pohl, V. A. Kotov, S. Kasture, A. S. Vengurlekar, A. V. Gopal, D. Yakovlev, A. K. Zvezdin, and M. Bayer, Nat. Nanotechnol. **6**, 370 (2011).
[15] V. I. Belotelov and A. K. Zvezdin, J. Magn. Magn. Mater. **300**, e260 (2006).
[16] V. I. Belotelov, D. A. Bykov, L. L. Doskolovich, A. N. Kalish, and A. K. Zvezdin, J. Exp. Theor. Phys. **137**, 932 (2010).
[17] J. B. Gonzalez-Diaz, A. García-Martín, G. Armelles, J. M. García-Martín, C. Clavero, A. Cebollada, R. A. Lukaszew, J. R. Skuza, D. P. Kumah, and R. Clarke, Phys. Rev. B **76**, 153402 (2007).
[18] V. Temnov, G. Armelles, U. Woggon, D. Guzatov, A. Cebollada, A. Garcia-Martin, J. M. Garcia-Martin, T. Thomay, A. Leitenstorfer, and R. Bratschitsch, Nat. Photonics **4**, 107 (2010).
[19] V. I. Belotelov, E. A. Bezus, L. L. Doskolovich, A. N. Kalish, and A.K. Zvezdin, J. Phys. Conf. Ser. **200**, 092003 (2010).
[20] I. I. Smolyaninov, C. C. Davis, V. N. Smolyaninova, D. Schaefer, J. Elliott, and A. V. Zayats, Phys. Rev. B **71**, 035425 (2005).
[21] M. G. Moharam, E. B. Grann, D. A. Pommet, and T. K. Gaylord, J. Opt. Soc. Am. A **12**, 1068 (1995).
[22] L. Li, J. Opt. A Pure Appl. Opt. **5**, 345 (2003).
[23] H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Springer, New York, 1988).
[24] M. A. Ordal, R. J. Bell, R. W. Alexander, L. L. Long, and M. R. Querry, Appl. Opt. **24**, 4493 (1985).