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Rapid Note

Optical properties of multilayer structures

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Abstract. This paper describes the magneto-optical effects of metallic multilayers under the condition of total internal reflection. In the framework of the Green's dyadic technique, we present numerical simulations which account for the variation of the magneto-optical signal with the angle of incidence. The Attenuated Total Reflection (ATR) has become a new technique of characterization for thin films. We show, in this paper, optical effects due to a slight variation of the indice of refraction for thin dielectric films in reflection by the reflectivity and the Kerr rotation spectra of an optimized system. In transmission, this variation is brought to the fore by the near-field intensity spectra.

PACS. 78.20.Ci Optical constants (including refractive index, complex dielectric constant, absorption, reflection and transmission coefficients, emissivity) – 78.20.Ls Magnetooptical effects – 78.66.-w Optical properties of specific thin films, surfaces, and low-dimensional structures

The surface plasmon resonance [1,2] of thin metallic and magnetic films [3] increases the magneto-optical Kerr signals [4] in the far-field. Optical effects using the Ag plasmon resonance were brought to the fore [5] in the reflectivity for linear polarized waves in experimental devices involving anisotropic dielectric layers in the far-field [6]. Moreover, a Photon Scanning Tunneling Microscope (PSTM) device can detect a surface mode in transmission by a dielectric fiber tip [7,8] in the near-field spectra [9,10] illuminating the sample in total internal reflection.

We show, in this paper, ATR methods by studying the effects associated to a slight variation of indice of refraction for thin dielectric films in the far-field spectra by the analysis of reflectivity and Kerr rotation. We underline the role of resonance phenomena in a trilayer Au/Co/Au structure. This resonance occurs at an angle close to the critical one for total reflection when a surface plasmon is excited. The numerical method used for these calculations is based on the Green's dyadic technique [11,12]. The films are illuminated through the substrate at 633 nm beyond the critical angle.

The two polarization modes TE and TM are considered for the incident electric field associated to the laser beam. In the TE mode, the incident electric field is perpendicular to the plane of incidence (s-polarization) whereas this field is parallel to it in the TM mode (p-polarization). We used the optical data of Au and Co in reference [13] and the non-diagonal magneto-optical coefficients of Co from reference [14]. Near-field studies are also performed by the analysis of the transmitted intensity associated to the total electric field. For ultra-thin films or multilayers, the magnetization vector may have components perpendicular to the film plane (polar component) and in this plane (longitudinal component).

Here for simplicity, we will consider pure polar configuration and we therefore assume that the films are uniformely magnetized. The films must be in a magnetic single-domain state. This can sometimes be obtained in a remanent state or by saturating the films by applying an external static magnetic field (perpendicular to the film plane). The structure of the permittivity tensor is then described in the linear regime by:

$$\varepsilon_{\text{polar}} = \begin{pmatrix} \alpha & \beta & 0 \\ -\beta & \alpha & 0 \\ 0 & 0 & \alpha \end{pmatrix}. \tag{1}$$

The complex coefficient β is smaller than the diagonal terms of the tensor. The non-diagonal elements transform an incident linear polarized wave into elliptic reflected and transmitted waves. We use the Co as a generic example of magneto-optical material. The case of the polar magnetization will be considered alone because longitudinal magnetization produces signals which are one order of magnitude weaker. The polar magnetization corresponds to an applied static magnetic field which is perpendicular

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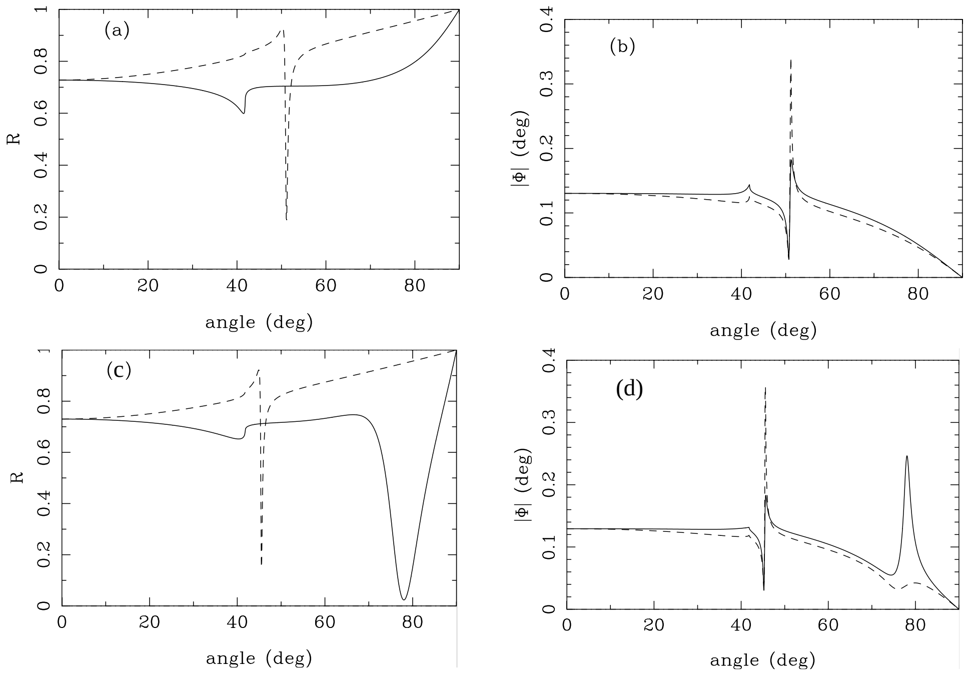

Fig. 1. For $\lambda = 633$ nm, in the case of SiO_2, (a) variation of the reflectivity as a function of the angle of incidence for both TM (solid line) and TE (dashed line), (b) variation of the module $|\Phi|$ as a function of the angle of incidence for both TM (solid line) and TE (dashed line). In the case of MgF_2, (a) variation of the reflectivity as a function of the angle of incidence for both TM (solid line) and TE (dashed line), (b) variation of the module $|\Phi|$ as a function of the angle of incidence for both TM (solid line) and TE (dashed line).

to the interfaces. For $\lambda = 633$ nm, Co has the following coefficients: $\alpha = -12.3 + \mathrm{i}\,18.4$ and $\beta = -0.4 - \mathrm{i}\,0.1$. For Au, $\alpha = -11.6 + \mathrm{i}\,1.2$ and $\beta = 0$ because Au is a non-magnetic material. We use MgF_2 and SiO_2 for dielectric materials. MgF_2 ($\alpha = 1.9$) and SiO_2 ($\alpha = 2.25$) are isotropic materials. Moreover, MgF_2 has an indice of refraction close to the SiO_2 one.

We will study the optimization of a trilayer Au/Co/Au in order to obtain a sharp plasmon resonance [15,16] in the reflectivity. The optimized trilayer system is composed by a 2 nm gold film thickness which we set on a glass substrate, we cover it by a 3 nm of Co film thickness and above a 45 nm of Au is deposited, this allows to protect the magneto-optical material. These thicknesses were chosen to optimize the sharp surface plasmon resonance in the TM mode. Moreover, the first Au layer is needed to give a better adherence to the Co layer growth. It gives a high reflectivity level since the lightwave will first illuminate the gold layer in total reflection.

The second Au layer leads to the excitation of the surface plasmon resonance. This multilayer structure is the basis for the deposition of thin dielectric films for which we vary slightly the indice of refraction. We will examine how behave the Kerr rotation module $|\Phi|$ and the reflectivity R as a function of the angle of incidence in order to show the effects of a slight variation of the indice of refraction related to a similar dielectric film thickness covering the Au/Co/Au structure.

In our approach, we display the magneto-optical aspect of the structure which shows the anisotropy and low indice of refraction variations for dielectric film cover on a surface plasmon resonance structure. The Kerr effect and the reflectivity will confirm the variation of the indice of refraction in the far-field. By addition to an isotropic 200 nm dielectric film thickness on the previous multilayer structure of the preceding section, we will create interferences in the dielectric layer and therefore, angle shifts occur in both Kerr rotation and reflectivity as a function of the angle of incidence (Figs. 1a–d).

Our aim was to complete the energetic aspect by the Kerr rotation behaviors of the system. A slight variation of indice of refraction involves that further modes appear in the reflectivity curve as a function of the angle of incidence for the system under the condition of total reflection. We can see that the Kerr effect shows drastical variations as a function of the angle of incidence (Figs. 1b, d). We can see a drastical decrease of the reflectivity in the TE mode due to the eigen modes of the system and particularly, to the interferences in the dielectric layer according to the angle of incidence for both SiO_2 at 52° (Fig. 1a) and MgF_2 at 46° (Fig. 1c). We can notice that, for MgF_2, a sharp dip occurs in the TM mode at 78° (Fig. 1c) whereas it does not appear in the case of SiO_2 (Fig. 1a).

Thus, a slight variation of indice of refraction of the dielectric layer deposited on a metallic structure involves different behaviors in the reflectivity curve as a function of the angle of incidence and therefore, in the Kerr effect where further peaks appear at 45.5° and 78° for the TM mode and at 45.5° for the TE mode in the case of MgF_2 (Fig. 1d). The same effect can be seen for

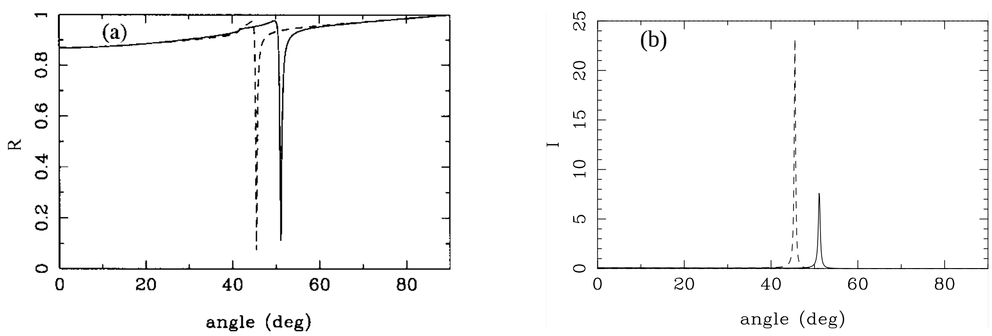

Fig. 2. For $\lambda = 633$ nm, (a) reflectivity for the TE mode, (b) transmitted intensity detected at 400 nm of the substrate in the TE mode for the case of SiO_2 (solid line) and of MgF_2 (dashed line) as a function of the angle of incidence.

SiO_2 (Fig. 1b) where peaks occur at 52.5° for both TM and TE modes. We can also notice that the intensity level for the Kerr rotation is the same in the case if MgF_2 (Fig. 1d) and of SiO_2 (Fig. 1b) because the indices of refraction of these materials are similar. We can see that further dips appear in the Kerr effect (Figs. 1b, d) at 50.5° in the case of SiO_2 for both modes and at 45° in the case of MgF_2 compared to the reflectivity curves as a function of the angle of incidence (Figs. 1a, c) for both TE and TM modes. These effects are due to the virtuals modes.

Therefore, we can see that the magneto-optical Kerr effect varies due to the presence of a dielectric film and particularly to its indice of refraction. This far-field method allows to complete the reflectivity analysis by the Kerr rotation one because an increase of the Kerr effect was brought to the fore around the eigen modes of the system (surface plasmon resonance and interferometric modes in a dielectric cavity).

It is now important to characterize a slight variation of indice of refraction in the near-field optics spectra thanks to a PSTM configuration. It is possible to frustrate the electric field close to the structure thanks to an optical fiber tip used in conventional near-field microscopes in transmission. The eigen modes of the system are materialized, in this case, by intensity peaks. They are detected when a mode is excited and this one creates an increase of the electric field at the interfaces.

The method described above allows to determine accurately the indice of refraction of a dielectric layer cover by the evolution of the reflectivity and of the Kerr rotation in the far-field. The excitation of the surface plasmon resonance creates a strong increase of the electric field on a metal/air interface.

We can thus work in transmission in order to observe the evolution of the intensity detected by the frustration of the total electric field by an optical fiber tip beyond the critical angle around the plasmon excitation. It is thus possible, thanks to a classical PSTM configuration, to frustrate the electric field scattered by the multilayer structure in order to observe the increase of the total electric field in transmission when the excitation of a surface mode occurs by varying the angle of incidence in the near-field optics.

Moreover, a slight variation of indice of refraction for a dielectric film cover will involve angular shifts and also increases or decreases of the amplitudes associated to the intensity peaks in this configuration. We have chosen to set 50 nm of Au on a glass substrate, the gold layer is recovered by 200 nm of MgF_2 or SiO_2. We will only study the TE mode. This slight variation of indice of refraction will induce different behaviors in both reflectivity and transmitted intensity. Experimentally, the transmitted intensity is brought to the fore by the frustration of the evanescent field scattered by the system thanks to an optical fiber tip in the PSTM configuration beyond the critical angle. Indeed, the gold plasmon resonance mode creates a surface mode in the system.

The addition of a dielectric film thickness creates further eigen modes which appear in the system for both polarization modes. These eigen modes, due to the interferences in the dielectric cavity, are characterized in the far-field by the reflectivity (Fig. 2a) at 45° in the case of MgF_2 an at 52° in the case of SiO_2 by strong dips for the TE mode.

However, in the near-field optics, the total transmitted electric field show sharp peaks for the same angles relative to the strong decreases of the reflectivity curves (Fig. 2b). These peaks which correspond to the eigen modes angles appear in the intensity detected in transmission as a function of the angle of incidence at the same ones where decreases of the reflectivity occur as a function of the angle of incidence (Fig. 2a). This shows another way for the detection of eigen modes by the near-field optics analysis.

As a comparison, we can notice that a slight variation of indice of refraction induces angular shifts for the dips in the reflectivity as a function of the angle of incidence (Fig. 2a) but also in the transmitted intensity in the near-field (Fig. 2b), it is thus possible to bring to the fore, thanks to a PSTM configuration, angular shifts which are related to the eigen modes of the system and also to slight variations of indices of refraction for dielectric film cover (MgF_2 and SiO_2).

Moreover, further peaks appear in the transmitted intensity around 42° (Fig. 2b), these effects are due to the critical angle as we saw in the preceding section for the Kerr rotation spectra. The sharp plasmon resonance of gold leads to thin angular widths for the peaks in transmission and the dips in reflection.

If we replace gold by an absorbing material such as cobalt or nickel, the surface plasmon resonances would appear for thiner metallic films and the absorption would widen the eigen modes due to the presence of the dielectric layer and thus, it will give weaker peaks in the near-field optics and also weaker dips in the far-field.

In fact, by the detection far-field/near-field, the absorption of metallic and/or dielectric materials is brought to the fore. Thanks to this method, variations of indice of refraction and the absorption can be determined in the near-field and far-field detection.

Using a numerical application of the Green's dyadic technique, the Kerr rotation spectra have been carefully studied beyond the critical angle for total reflection. We showed the evolutions of both energy and rotation of polarization as a function of the angle of incidence in order to examine and analyze the effects when eigen modes occur in the system. Turning to the optimization of a Au/Co/Au trilayer, the eigen modes of the system were used in the far-field in order to determine slight variations of indice of refraction for thin dielectric films. The same approach was realized in the near-field by computations of the intensity scattered by the multilayer system.

These methods are able to show accurately a variation of indice of refraction in near and far-field studies for a fixed dielectric film thickness.

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