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Optimized factor of merit of the magneto-optical Kerr effect of ferromagnetic thin films

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Abstract. This paper deals with the optimization of the factor of merit of the magneto-optical Kerr effect of a resonant multilayer cavity including a ferromagnetic film. This optimization is of interest in the context of optical storage technology. Using numerical simulations based on the Green's dyadic technique, we discuss a route to obtain magneto-optical multilayers with a vanishing ellipticity and factors of merit (with respect to the bulk magnetic material) larger than 3 on a broad range of wavelengths, significantly higher than the actual state of the art.

PACS. 78.20.Ls Magnetooptical effects – 85.70.Sq Magnetooptical devices – 75.50.Ss Magnetic recording materials

1 Introduction

In magneto–optical (MO) storage technology, thermomagnetic writing and magneto–optical reading require to optimize optical, thermal and magnetic functions of thin film structures based on Co–Pt multilayers or on a TbFeCo thick film [1–5]. This paper deals with the optimization of the optical function which is central when reading a MO disk.

When using MO materials for data storage, optical readout is achieved by a laser beam analyzing the magnetization, pointing in one or the opposite direction. The polarization of the incident light is rotated by a certain amount depending on the local magnetization. This rotation is detected in the reflected beam (MO Kerr effect). A properly oriented polarization analyzer filters the reflected light, thus reading 0 or 1 bit values according to the local magnetization state.

In optical readout applications, the maximal signal–to–noise ratio associated to a differential measurement of the magneto–optical Kerr effect is desired. A large signal–to–noise ratio is obtained by optimization of the Kerr rotation θ_k and of the reflectivity R. A large Kerr ellipticity ϕ_k increases the phase difference $\delta = \arctan(\frac{\phi_k}{\theta_k})$ between the two rotating field components. The detection of the state of polarization requires a minimal ϕ_k to avoid that the detected signal be in a rotating state of polarization. If ϕ_k is not vanishing, a linear polarization may be achieved by auxiliary optical devices.

The factor of merit Q used in this paper is an empiric coefficient which measures the performance of a system as compared to the one of the bulk magneto–optical material [6,7]. This factor must be greater than 1 to consider a system as optimized relatively to the bulk. Let $R_{\rm ref}$, $\theta_{k,\rm ref}$ and $\phi_{k,\rm ref}$ be the reflectivity, the Kerr rotation and the ellipticity of the *reference* bulk magneto–optical material. We use the following formula for Q which is based on the geometrical mean of the normalized (with respect to bulk) reflectivity R and Kerr signal $\theta_k^2 + \phi_k^2$.

$$Q = \frac{\sqrt{R\ (\theta_k^2 + \phi_k^2)}}{\sqrt{R_{\rm ref}\ (\theta_{k,\rm ref}^2 + \phi_{k,\rm ref}^2)}}\,.$$

According to this formula, either a low reflectivity or a weak Kerr effect disqualifies a system to operate for a magneto–optical readout purpose. A large Q that would be obtained on the basis of a large ellipticity ϕ_k implicitly requires a compensating auxiliary optical device to achieve a minimal ϕ_k before entering the output polarizer. In this paper, we directly base the optimization of Q by using a comptutational and numerical Green's dyadic technique.

A vanishing ϕ_k which avoids any additional compensating optical device is therefore required in the optimization procedure, thereby reducing the size of the complete readout system.

Several solutions have been tested to increase the factor of merit Q by exploiting an optical eigenmode. Indeed, when optical eigenmodes are sustained by a system

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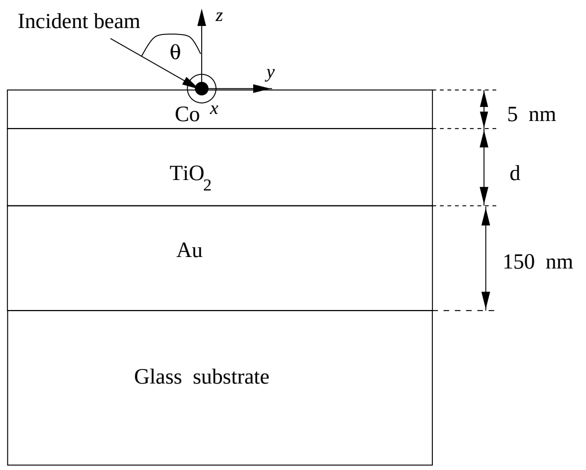

Fig. 1. Geometry of the optical device.

including a magneto–optical material, the Kerr rotation increases. A straightforward way to obtain an eigenmode of the system consists in a anti-reflection multilayer in which a magneto–optical thin film is included. Such antireflection multilayer allows to obtain a figure of merit which reaches 1.5 [8].

Another class of solutions intends to exploit surface plasmon resonances. The excitation of surface plasmon resonances [9] in the Attenuated Total Reflection (ATR) geometry [10–13] increases the Kerr signal up to 20 degrees but is associated with a very small reflectivity which is difficult to measure, giving a factor of merit around 0.7. The major problem in the concept of exploiting an optical eigenmode is that the resonance of an optical system decreases its reflectivity. Large Kerr rotations are then associated with lower reflectivities. In the most favorable cases, this counterbalance effect leads to a relatively minor enhancement of Q.

2 Optimization procedure

On the basis of the above considerations, this paper discusses a route to obtain factors of merit Q larger than 3, significantly higher for a 5 nm ferromagnetic film thickness, and still featuring vanishing ellipticities. The basic geometry of the studied multilayers appears in Figure 1. On a glass substrate are stacked a Au layer, a dielectric (TiO_2) film and a Co thin film. In order to achieve a resonant optical cavity, the 150 nm thick Au layer is characterized by a reflectivity which is the same as the one of bulk Au. The variable thickness d of the dielectric film allows to optimize optical interferences in order to work at a wavelength which corresponds to a minimum Kerr ellipticity.

We choose 5 nm for the Co film thickness which is a good compromise to achieve high Kerr rotation and reduced absorption over the range of visible wavelengths. For larger wavelengths, another value of the Co thickness should be taken as starting point of the optimization procedure (not shown here for the sake of brevity).

The numerical work is performed in the framework of the Green's dyadic technique. The adaptation of this method to cope with any anisotropic multilayers is detailed in [12]. In the simulations, we approximate that the indexes of refraction of the glass substrate and of the isotropic dielectric layer (TiO_2) do not vary as a function of the incident wavelength but the wavelength dependence of the dielectric tensors of the metallic layers is taken rigorously into account. For Au, we used the data of reference [14].

For the ferromagnetic Co, we consider a layer magnetized perpendicular (along the z direction of Fig. 1) which defines the dielectric tensor of Co as follows:

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

The wavelength dependent optical data α, β of Co are summarized in reference [12].

One must be aware that the natural magnetization state of a 5 nm thick Co film is parallel to the surface. Static fields as high as 2 T are needed to pull the magnetization out of plane. Nevertheless, the 5 nm Co film can be replaced by Co-Pt or Co-Au ultrathin multilayers, known to have strong perpendicular magnetic anisotropy, without affecting the results discussed here.

A previous work [15] showed that the Kerr rotations of such ultrathin films arranged in a multilayer stack are additive and exhibit a linear behavior as a function of the cumulated thickness of Co. This is due to the fact that multiple interferences are not sustained between ultrathin layers. Provided that the total thickness of the ferromagnetic system responsible for the Kerr rotation is much smaller than the incident wavelength, its detailed structure is not crucial for the optimization of Q since multiple interferences can not show up to significantly alter the values of R and of the Kerr signal $\theta_k^2 + \phi_k^2$. The choice of a single 5 nm thick Co layer should thus be understood as a simplification which underlines that the optimization procedure to be detailed below is essentially based on optical principles which apply to any thin ferromagnetic structure.

In the computations, a multilayer with a given d is illuminated from the air at an arbitrary fixed angle of incidence $\theta = 20$ degrees. Except from the fact that the normal incidence makes experimentally difficult to distinguish the reflected beam from the incident one, this value is not critical in the procedure described below.

For the given thickness d of the sandwiched dielectric film, varying the incident wavelength recovers the interference related to the resonant wavelength. The optical cavity mode is associated to an enhanced Kerr rotation. Inside the width of the cavity mode, we then search a wavelength featuring an acceptable reflectivity level and a vanishing ellipticity. It turns out that a vanishing ellipticity occurs systematically for the TE incident polarization (s–polarization). This is not the case for TM incident polarization (p–polarization). Focusing the procedure on the TE polarization, we can sweep d in order to optimize Q at any desired wavelength.

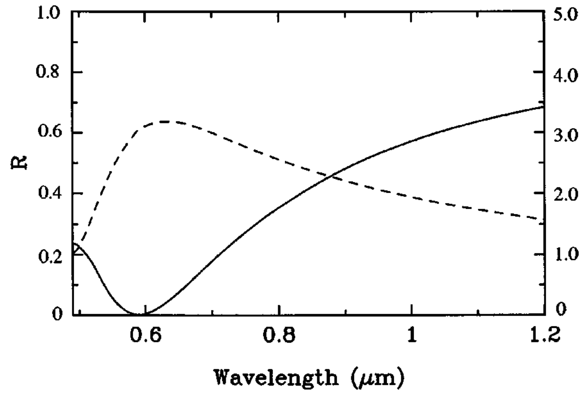

Fig. 2. For $\theta = 20$ degrees and for $d = 0.04$ μm, reflectivity (solid line) and factor of merit (dashed line) as a function of the incident wavelength.

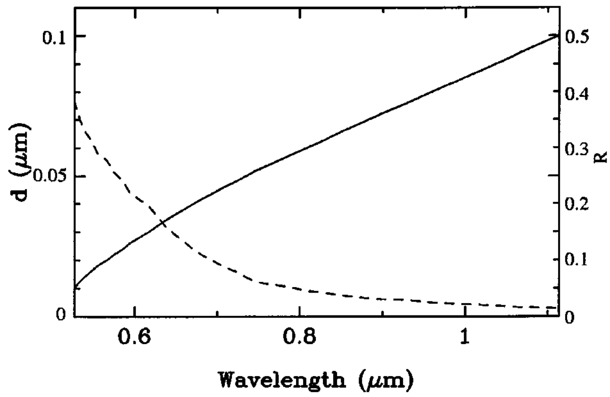

Fig. 4. For $\theta = 20$ degrees, dielectric film thickness (solid line) and reflectivity (dashed line) as a function of the wavelength for which the ellipticity vanishes.

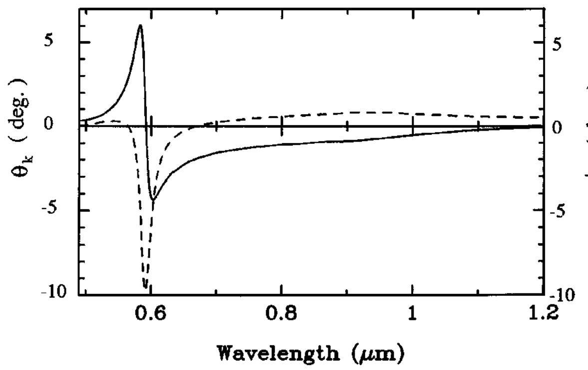

Fig. 3. For $\theta = 20$ degrees and for $d = 0.04$ μm, Kerr rotation (solid line) and ellipticity (dashed line) as a function of the incident wavelength.

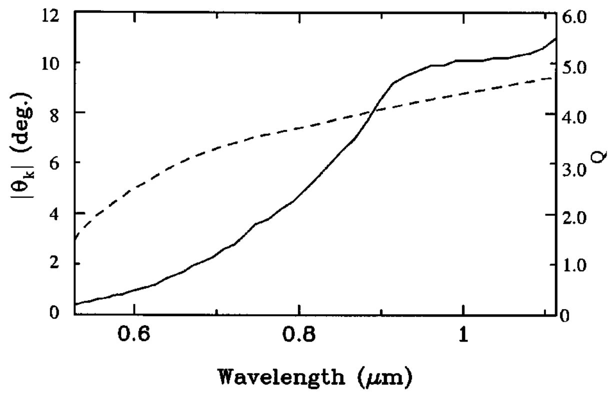

Fig. 5. For $\theta = 20$ degrees, absolute Kerr rotation (solid line) and factor of merit (dashed line) as a function of the wavelength for which the ellipticity vanishes.

We now detail the steps of this procedure on the basis of a specific example.

In Figure 2, we display the reflectivity as a function of the incident wavelength for a dielectric film thickness $d = 40$ nm. We identify an optical mode of the system at the wavelength $\lambda = 0.592$ μm where the reflectivity vanishes. Around this optical mode, we see in Figure 3 that: (1) the Kerr signal shows two extremal values at $\lambda = 0.584$ μm and $\lambda = 0.604$ μm; (2) the ellipticity vanishes at $\lambda = 0.565$ μm and $\lambda = 0.671$ μm where the reflectivity is respectively 0.025 and 0.118. Outside the width of the optical mode, all curves have a smooth behavior as a function of the incident wavelength.

We notice that for $\lambda = 0.671$ μm the factor of merit is around 3 which is a good result for this system (see Fig. 2). We have thus found a system with a high Q factor for which the ellipticity vanishes.

Similar calculations are then repeated in order to plot the dielectric film thickness and the reflectivity as a function of the wavelength for which the ellipticity vanishes (Fig. 4). On the basis of Figure 4, the Kerr rotation and the factor of merit are displayed in Figure 5 as a function of the wavelength for a vanishing ellipticity.

Each of these wavelengths is associated to a different value of d according to Figure 4. The curves of Figures 4 and 5 make possible to fix a wavelength and find the optimized dielectric film thickness d.

The analysis of both Figures 4 and 5 shows that the wavelength corresponding to the vanishing ellipticity increases for thicker d. This is in agreement with the basic behavior of interferences, just like in a Fabry–Pérot interferometer.

Also, the factor of merit and the Kerr rotation increase as a function of the wavelength. In Figure 5, the Kerr rotation increases rapidly for larger wavelengths. The step occurs for wavelengths between 800 and 1000 nm where the Kerr signal increases not only due the resonant optical mode but also due to the broad peak in the wavelength dependence of β for bulk Co.

The reflectivity decreases as a function of the wavelength but still remains acceptable for practical measurements in the visible range where the factor of merit reaches 3 at $\lambda = 0.670$ μm. Such value exceeds the current standard magneto–optical devices. Above $\lambda = 0.600$ μm, the Kerr rotation is larger than 2 degrees which is a comfortable value for application purpose.

3 Conclusion

In conclusion, this paper proposed a multilayer structure based on a resonant cavity with optimized factors of merit of the magneto-optical Kerr effect and vanishing ellipticities. Over a broad range of wavelengths, we found factors of merit larger than 3, opening a new potential to optical storage technology.

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