Nanotechnology **14** (2003) 239–244 PII: S0957-4484(03)54419-1

Pure magneto-optic diffraction by a periodic domain structure

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Received 26 September 2002, in final form 20 December 2002
Published 16 January 2003

Abstract
Magneto-optic diffraction by a periodic domain structure is reported. The periodic domain structure is generated in a flat ferromagnetic metal by coupling it magnetically to an array of magnetic elements. Both exchange and magnetostatic couplings are effective, creating a modulation of the magnetization, although the effect is somewhat larger for magnetostatic coupling, since it favours an antiparallel alignment of adjacent domains. Micromagnetic simulations agree qualitatively with the experimental findings.

1. Introduction

Magneto-optic Kerr effects (MOKEs) [1, 2] offer a powerful experimental tool to investigate magnetic properties of ferromagnetic materials, thin films and nanostructures. They have also provided technological landmarks in the recording technology business. Recently, great attention has been paid to the analysis of specular and non-specular MOKEs in nanostructures. These include light reflected and diffracted by regular arrays of magnetic elements [3–13] and by arrays of holes in continuous magnetic media [14–16] and scattered by rough surfaces [17] and by inhomogeneous distributions of particles [18, 19]. In particular, the diffracted MOKE has been studied predominantly on arrays of magnetic elements separated by non-magnetic spacers [3, 6–10, 12] or magnetic films over or under relief gratings [4–6, 10]. These systems involve large topographic and refractive index contrasts, and consequently large diffraction intensities, on which a small MO modulation can be measured as a function of the applied magnetic field.

The possibility of obtaining light diffraction by a flat metallic ferromagnetic thin film is demonstrated in this work. A periodic domain structure is artificially generated in a flat and optically homogeneous magnetic thin film. The local reflectivity depends on the local magnetization direction, and when the magnetization is modulated periodically the reflectivity varies accordingly. Under these circumstances, the appearance of a diffraction pattern is expected. Notably, the appearance of this diffraction pattern can be controlled by an externally applied magnetic field, being able to switch it on and off. This effect should then be considered a manifestation of pure MO diffraction, not arising from any topographic or refractive index contrast[2].

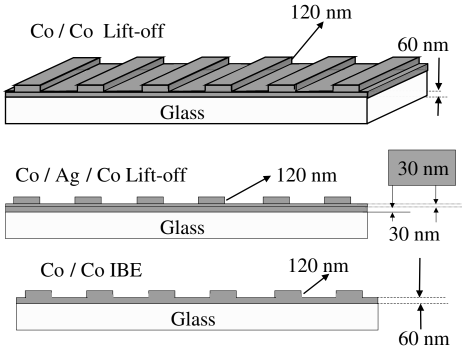

Figure 1. (a) Cobalt stripe array on a Co thin film prepared by the lift-off technique. (b) The same structure but with an intermediate Ag separation layer between the Co stripes and the continuous Co layer. (c) The same structure as (a) but fabricated by a single Co sputtering process and IBE to guarantee exchange coupling between stripes and the continuous film.

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[2] To be more accurate, the contrast does not depend on the diagonal part of the refractive index, since this work demonstrates pure MO contrast arising from the non-diagonal terms of the permittivity.

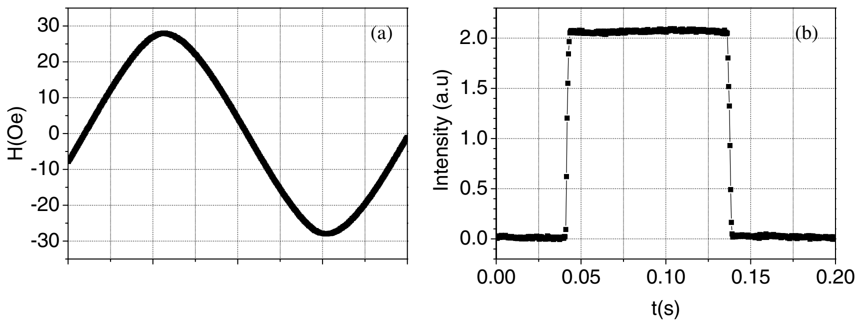

Figure 2. (a) Applied field and (b) variation of the first order MO diffracted light spot intensity in the '*Co/Co lift-off*' when light is shone on the flat side of the structure.

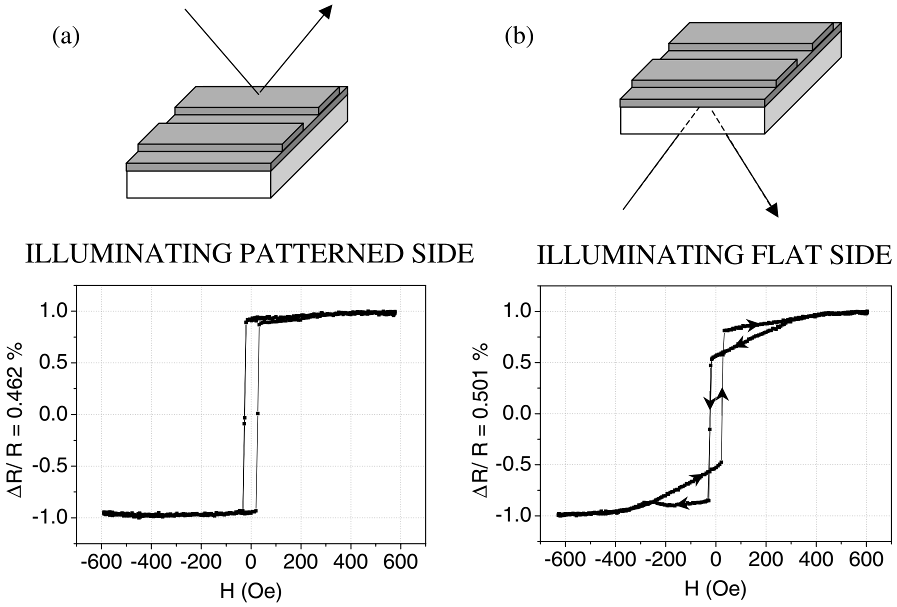

Figure 3. Transverse MOKE hysteresis loops measured on the reflected beam ($n = 0$) for the '*Co/Co lift-off* sample when light is shone on (a) the patterned side and (b) the flat side of the structure.

To our knowledge this is the first study of controlled diffraction in reflection by a flat 3d metallic thin film. However, in the context of integrated magneto-optic devices and iron-garnet wave guides developed in the 1970–1980s, there are some works where garnets are used to produce Faraday and Kerr diffraction by periodic stripe domain patterns [20–23].

2. Experimental details

The periodic magnetic domain structure is generated in a continuous Co thin film by coupling it magnetically to a microfabricated ferromagnetic Co stripe array. Initial structures (termed '*Co/Co lift-off*' in figure 1(a)) were microfabricated by optical lithography on polycrystalline Co sputtered on glass. First, a continuous layer, 60 nm thick, was grown by triode sputtering. The magnetic anisotropy of this Co is uniaxial with an anisotropy field of about 30 Oe parallel to the field used to confine the plasma during the Co sputtering. Second, an array of 120 nm thick Co stripes was fabricated on top of the previous continuous layer. This was performed by photo-resin spinning, UV patterning, developing and a second Co deposition, i.e., the standard lift-off technique [24]. The UV mask used contains different 2×1 mm^2 motifs with varying stripe width (2–100 μm) and inter stripe spacing (4–8 μm), allowing the simultaneous fabrication of arrays with different periodicities on the same sample.

Two additional control samples were fabricated (see figures 1(b) and (c)). In the first control sample a 30 nm Ag separation layer was inserted between the continuous 30 nm Co layer and the lift-off patterned Co array. This sample is termed '*Co/Ag/Co lift-off*' in figure 1(b). The second control sample was grown in a single Co sputtering process, 180 nm thick, and locally etched to a depth of 120 nm by ion beam etching (IBE) through the photo-resin mask. This sample is termed '*Co + IBE*' in figure 1(c).

MO measurements are performed with a p-polarized He–Ne laser directed towards the sample at 60° incidence. In the measurements reported here, the optic plane is parallel to the stripes. Reflected and dispersed p-polarized light are detected by a low noise, small aperture, Si photodiode and its intensity recorded at selected angles as a function of the applied magnetic field. Standard transverse MOKE hysteresis loops are recorded on light reflected both from the top patterned side and from the bottom flat glass/film interface side in order

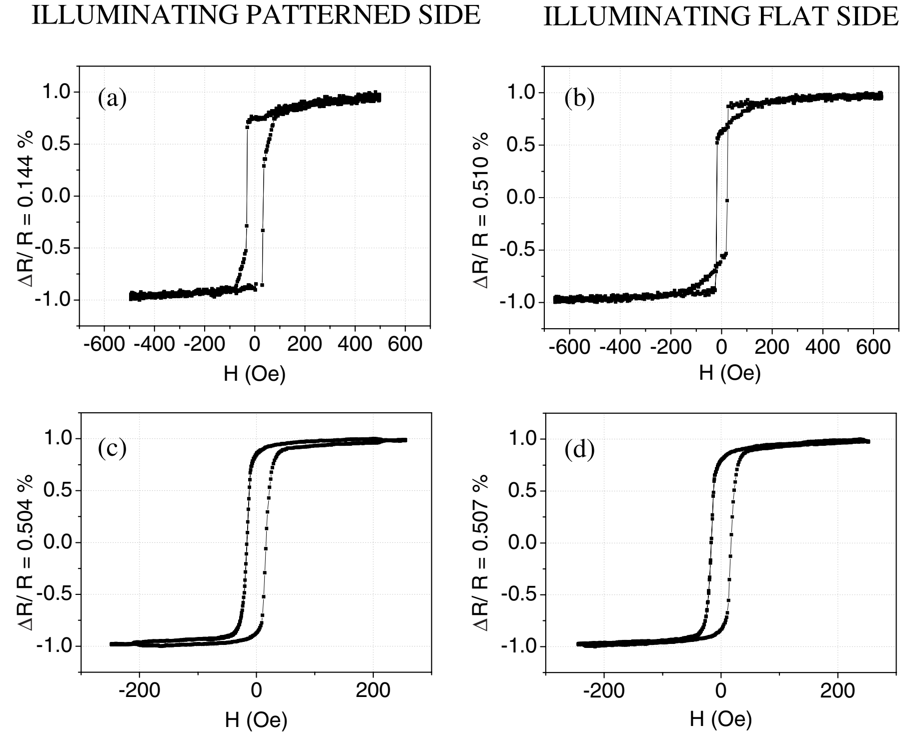

Figure 4. Transverse MOKE hysteresis loops measured on the reflected beam ($n = 0$) for (a), (b) the '*Co/Ag/Co lift-off*' sample from the patterned and flat sides, respectively, and (c), (d) the '*Co + IBE*' sample from the patterned and flat sides, respectively.

to determine their magnetic properties. A set of Helmholtz coils is used to supply a low frequency magnetic field in the plane of the sample.

A diffusive screen, placed perpendicular to the reflected beam from the flat side of the sample, helped in searching for the appearance of diffracted beams when illuminating the flat side of the structures. Once detected, the Si photodiode was used to record their intensities.

3. Results and discussion

3.1. Experimental results

All the experiments described in what follows are performed on the transverse MOKE configuration (light polarized in the plane of incidence and field applied perpendicular to that plane) and illuminating the samples either on the flat side, i.e., through the glass substrate, or on the patterned side. In the case of the '*Co/Co lift-off*' structure shown in figure 1(a), the appearance of faint but clear new diffracted light beams is observed for light impinging on the flat side of the sample and for low alternating magnetic fields applied perpendicular to the stripe long axes. The diffraction angle corresponds to the periodicity of the Co stripe array deposited on the opposite side. In figure 2, the intensity of the first order diffraction spot is displayed for a structure that had an array on the other side of stripes 8 μm wide separated by 4 μm. For low magnetic field amplitudes the diffracted intensity switches clearly on and off in phase with the applied field. This experiment shows controlled diffraction by an induced periodic domain structure.

From a theoretical point of view, classical electromagnetic theory describes accurately the interaction of light with a magnetized medium using permittivity tensors [1, 2, 25]. If the medium or the magnetization are inhomogeneous, in a scale comparable with the wavelength of light, the description is valid although in general difficult to implement. In this context, several attempts to develop a theory for the MO diffraction from a magnetic grating can be found in the literature [3, 4, 26]. A simple and general theory for the MO diffraction [27] has recently been used to model successfully the diffraction from an array of Fe microtiles [13]. In the case of a flat medium with periodic magnetization, the extension of that model supplies the following expression for the intensity of the nth diffraction spot:

$$I_n \propto \left| \int_{-T/2}^{T/2} (1 + A m_x(x)) \exp\left(\mathrm{i}\frac{n2\pi x}{T}\right) \mathrm{d}x \right|^2, \qquad (1)$$

where A is a complex parameter that depends on the dielectric tensor of the material and the angle of incidence, T is the structure period and $m_x(x)$ is the component of the magnetization perpendicular to the optic plane. This expression assumes that $m_x(x)$ is uniform in the y-direction and periodic in the x-direction, and the reflection coefficient $r_{pp}(x)$ depends only on $m_x(x)$. According to equation (1), diffracted intensity should vanish for a magnetically saturated sample and should exhibit a finite intensity for a periodic magnetic distribution.

Pure MO diffraction then means a periodic modulation of the magnetization. The periodicity is that of the stripe array deposited on the opposite side. The question remains about the kind of coupling responsible for inducing a magnetic distribution into the flat continuous layer with the periodicity of the top grating. This coupling can be of two types: through the

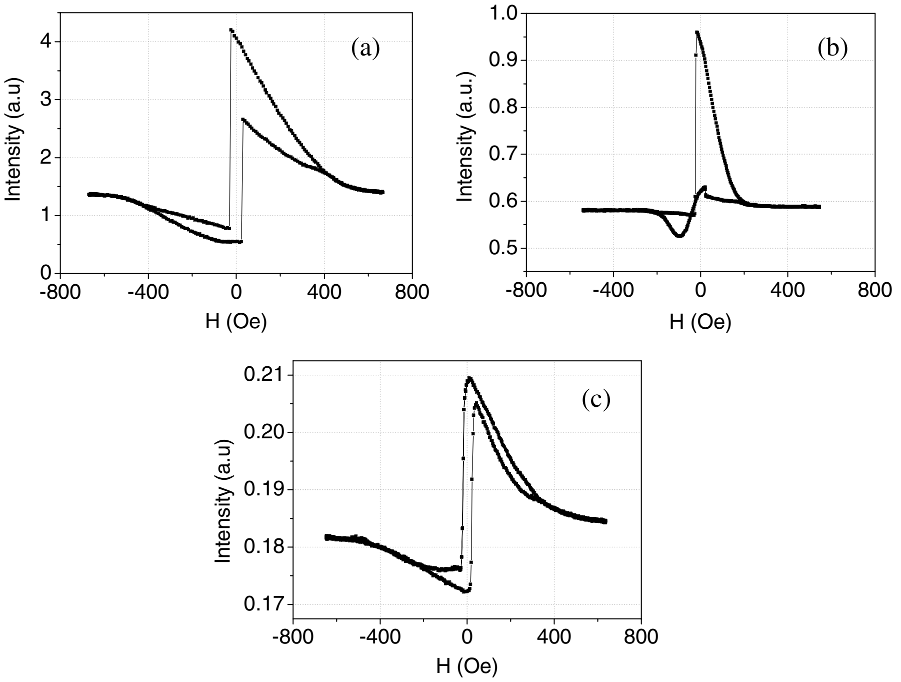

Figure 5. Diffracted intensity ($n = 1$) by the flat Co continuous layer as a function of the applied field for samples (a) '*Co/ Co lift-off*', (b) '*Co/Ag/Co lift-off*' and (c) '*Co + IBE*'.

fringe fields at the stripe edges, i.e., magnetostatic, or through interface exchange interactions.

In order to discern between these two possibilities, the magnetization processes were investigated in detail by standard MOKE for large ac field amplitudes. When an alternating magnetic field is applied perpendicular to the stripe long axis, marked differences are found in the MOKE signal corresponding to front and back reflections, as shown in figure 3 for a '*Co/Co lift-off*' structure with 8 μm period and 4 μm inter-stripe spacing. The loop obtained from the light reflected on the patterned side shows a sharp reversal at about 30 Oe, and a reduced remanence M_R/M_s close to one. On the other hand, the hysteresis loop measured on the flat side presents an almost linear decrease of the magnetization at positive fields with remanence close to 0.5, followed by a sharp reversal transition and an approach to saturation. This feature can be attributed to antiferromagnetically coupled top/bottom bilayers; i.e., there is a range of fields where magnetic domains in the continuous film are created with an antiparallel orientation to the magnetization of the Co stripe. The fact that the loops are different on either side, and that the effect is only observed for fields applied perpendicular to the stripe long axis, support this statement as well. On the other hand it is very costly energetically to form a domain wall between the stripe and the continuous layer. This would imply that the Co stripes and the Co continuous layer are exchange uncoupled in this structure.

To obtain additional evidence about the operative coupling mechanism, and to investigate the differences between exchange coupled and exchange uncoupled structures, two sets of control samples were fabricated ('*Co/Ag/Co lift-off*' and '*Co + IBE*' shown in figures 1(b) and (c), respectively). In the sample '*Co/Ag/Co lift-off*' exchange is inoperative between the Co stripes and the continuous Co layer due to the Ag layer, and in the sample '*Co + IBE*' exchange is operative between the Co stripes and the continuous Co layer due to the fabrication procedure. The hysteresis loops for these two samples are shown in figure 4. Figures 4(a) and (b) show the MOKE loops obtained when shining light on the patterned and flat sides respectively for the '*Co/Ag/Co lift-off*' sample. As observed both loops are similar to the '*Co/Co lift-off*' sample shown previously in figure 2. On the other hand, the loops for the '*Co + IBE*' sample shown in figures 4(c) and (d), for the patterned and flat sides respectively, are very similar to each other and different to the '*Co/Co lift-off*' and '*Co/Ag/Co lift-off*' ones. This is easily understood since, in the sample patterned by IBE, exchange is operative through the Co stripe/continuous Co interface and the magnetization is constant along the Co growth direction. In other words, the magnetization process is independent of the side from which you look at it.

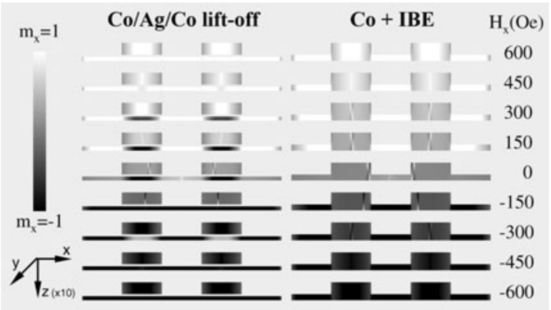

Figure 6. Results from micromagnetic calculations simulating the '*Co/Ag/Co lift-off*' and '*Co + IBE*' structures. Magnetization in the x-direction ($mx = +1$ in white, -1 in black) for different values of the applied magnetic field in the x-direction from 600 to -600 Oe. Notice that the z-scale has been magnified tenfold for clarity.

The previous experiments with the control samples show that for the '*Co/Co lift-off*' sample the Co stripes are not

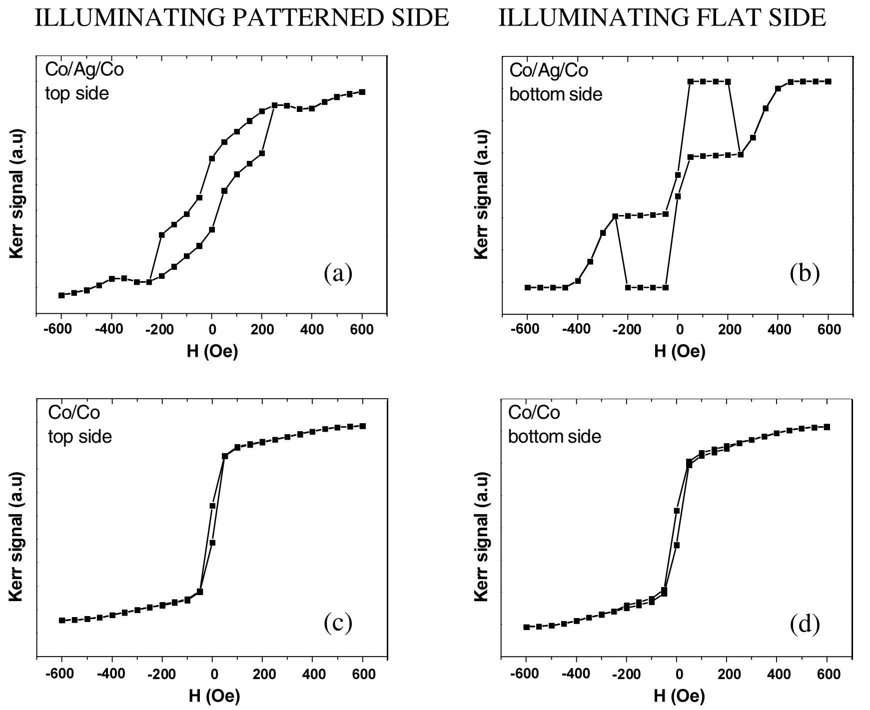

Figure 7. Simulated dependence of the reflectivity ($n = 0$) for (a), (b) '*Co/Ag/Co lift-off*' and (c), (d) '*Co + IBE*' samples. Left-hand column, patterned side incidence. Right-hand column, flat side incidence.

coupled by direct exchange with the bottom Co continuous layer. This is probably due to the formation of a thin oxide barrier during the development process of the UV resin exposed areas, just before the second Co deposition.

In figure 2 was shown the dependence, at low amplitude alternating applied magnetic fields, of the light diffracted by the flat Co continuous layer in the '*Co/Co lift-off*' sample. It behaved as a blinker at the frequency of the magnetic field. The dependence at large applied magnetic fields is shown in figure 5 for the '*Co/Co lift-off*', '*Co/Ag/Co lift-off'* and '*Co + IBE'* samples. Notice a similar dependence and a larger magnitude of the effect for the '*Co/Co lift-off*' and the '*Co/Ag/Co lift-off'* samples. This dependence is clearly different for the '*Co + IBE'* sample in agreement with the previous considerations concerning exchange coupling/decoupling of the Co stripes and Co continuous layers. However, the overall dependences are not straightforward to understand in terms of equation (1), since, besides possible small components of diffusive light producing an offset of the signal, in all the figures the intensity at saturation is above the signal at certain lower field values. This is against intuition (and equation (1)) in the sense that at magnetic saturation the diffracted light should be zero and consequently no signal should be found below that level. The explanation of this fact is currently under investigation and will be presented elsewhere. Small reflectivity changes, less than 1%, between the continuous film areas covered by stripes and those that are not can explain the observed behaviour, and preliminary experiments and calculations agree with this speculation.

3.2. Micromagnetic simulations

Micromagnetic simulations emulating the two control samples have been performed with the OOMMF 1.1b [28] code with 3D spins in a 2D mesh. The y-direction (the long stripe axis) has been considered infinite. These simulations support the main features of the experimental hysteresis loops. Figure 6 shows the x-magnetization results of simulations for the '*Co/Ag/Co lift-off*' and '*Co + IBE*' equivalent structures. Notice that, for clarity, the z-direction has been magnified tenfold. As observed, the structures are basically saturated along the applied field direction at field values of the order of 600 Oe. On reducing the field, both simulations produced ordered magnetic domain structures at the Co continuous layer, but of different kinds. When exchange between the stripe pattern and the continuous layer is inoperative ('*Co/Ag/Co lift-off*' sample), the ordered domain structure at certain field values consists of antiparallel domains due to the magnetostatic coupling between the stripes and the continuous Co layer underneath the stripe. This antiferromagnetic alignment occurs twice per loop branch. In the case of the '*Co/Co +IBE*' sample, the magnetization underneath the stripe orients parallel to the stripe long axis, due to an effective exchange interaction between the stripe and the continuous Co layer. Notice that (according to equation (1)) both samples ought to produce diffraction because a periodic $m_x(x)$ is induced. However, the field dependences of the diffracted intensities would be different for the two cases, in agreement with the experimental results presented in figure 5.

Once the magnetization of the whole structure is obtained as a function of the applied field, the expected hysteresis loops when illuminating either the patterned or the flat side can be obtained. These results are shown in figure 7 for the '*Co/Ag/Co lift-off*' and '*Co + IBE*' samples. As observed, simulations reproduce qualitatively what is observed experimentally. For the exchange-uncoupled structure '*Co/Ag/Co lift-off*', the loops on either side are different. The flat side loop reproduces (although excessively marked) the 'negative susceptibility' found in the experimental loop in figure 3(b). The simulation shows that this is due to a second antiparallel alignment between the stripe and the continuous layer under it during the loop branch. For the structure 'Co + IBE', both loops are basically equal because the magnetization the light 'sees' on both sides is the same.

4. Conclusions

In conclusion, pure and fully modulated MO diffraction by a periodic domain structure is demonstrated. The periodic magnetic distribution is obtained by coupling magnetically an array of magnetic elements to a flat and continuous ferromagnetic layer. Both, exchange and magnetostatic types of coupling are effective in creating the magnetic modulation, although the effect is somewhat larger for magnetostatic coupling, since it favours an antiparallel alignment of adjacent domains. Micromagnetic simulations agree qualitatively with the experimental findings.

Acknowledgments

The authors acknowledge Ricardo Ortega for performing some related measurements. Financial support from the European Union Hidemar project GRD1-2001-40316 is also appreciated. One of the authors (PG-M) acknowledges financial support from the Comunidad de Madrid through a post-doctoral grant. CG acknowledges financial support through the exchange programme between the CSIC—Spain and the IVIC—Venezuela and from the Spanish DGICyT (MEC) Cooperación con Iberoamérica project PB98-0464.

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