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Magneto-Optical Kerr Effect in Conical Diffraction Geometry of Micron-Size Fe_3Si Wire Array

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Abstract— **Magneto-optical Kerr effect for micron-size ferromagnetic Fe_3Si wires deposited on silicon substrate was investigated in conical diffraction geometry with TM polarized light and applied magnetic field parallel to the plane of incidence. The diffracted intensities were found to be dependent on the orientation of the magnetization vector as with the transverse Kerr effect. The amplitude of the hysteresis loops depends on both the order numbers and the angle of incidence. A model based on the dipole light re-emission qualitatively interprets the experimental data.**

Index Terms— **Array of ferromagnetic wires, conical diffraction, dipole re-emission, magneto-optical Kerr effect.**

I. INTRODUCTION

The investigation of physical properties of the micron and submicron magnetic structures is of great interest for both fundamental and applied physics. For magneto-optics, an array of magnetic wires leads to diffraction phenomena due to the spatial period of the sample. The studies of magneto-optical Kerr effects (MOKE) in such diffraction geometry can provide information on the domain structure [1]-[3] as well as new features of 1D homogeneous and inhomogeneous magnetic gratings [4]-[7]. Optical and magneto-optical properties of magnetic patterned structures are coupled through the diffraction phenomena, and an enhancement of the magneto-optical contrast has been demonstrated on an array of magnetic wires [8]. Furthermore, the diffraction allows to observe re-emission of the light due to the magnetically induced component of the electric dipoles. These events could be the first step of a new branch of applied optics such as diffractive magneto-optics. However, in all the works mentioned above, magnetic gratings were measured in *usual diffraction* configuration, where the plane containing the wave vector of the incident wave and the normal to the mean grating surface coincided with the plane perpendicular to the grating grooves (Fig. 1a). In this case the wave vectors of the diffracted orders are all located in the plane of incidence. If the incident wave vector is out of the main section of the grating, the propagating directions of the diffracted orders form a cone with its axis parallel to the grating grooves (Fig. 1b). This configuration is known as *conical diffraction* geometry. In the present paper, we demonstrate the results of MOKE measurements in the conical diffraction geometry for amorphous Fe_3Si micron-size wires. An interpretation based on the optical interference between the light re-emitted by the usual “Fresnel” type electric dipoles and the magnetically induced ones is proposed.

II. EXPERIMENTAL

The sample with an array of rectangular amorphous Fe_3Si

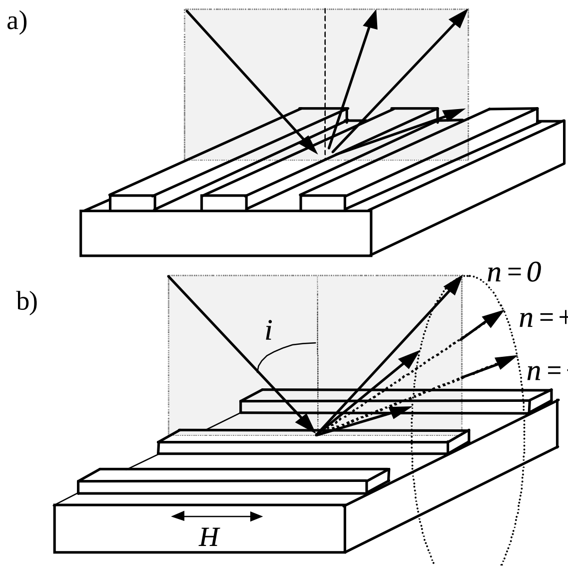

Fig. 1 Two configurations of diffraction: a) Usual diffraction (previous studies): all the diffracted beams are located in the same scattering plane. b) Conical diffraction (present paper): the diffracted beams form a cone with its axis parallel to the grooves. Incident light is TM-polarized. An external magnetic field is applied along the wires direction.

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wires 0.9 µm wide and 75 nm thick was prepared on a silicon wafer substrate by DC magnetron sputtering and optical microlithography methods. The quality of the sample was checked by scanning electron (SEM) and atomic force (AFM) microscopies. The period is 3.5 µm and the total area of the sample 10 mm x 10 mm. Amorphous Fe_3Si is a soft ferromagnetic material with a significant magneto-optical response in the visible wavelength range. The sample possesses the in-plane uniaxial anisotropy with easy direction along the wire and the coercive field is 15 mT. The light source is an intensity modulated collimated laser diode (λ = 670 nm, P = 3 mW) equipped with a p-(or TM) oriented dichroic polarizer. The detection system includes a silicon photodiode operating in photoconductive mode connected to a lock-in amplifier. The sample is placed within the gap of an electromagnet whose magnetic field is parallel to the wires axis. It has to be noticed that no analyzer is used to measure the relative change $\Delta I_n/I_n$ in intensity of various diffraction orders n during magnetization reversal. The sample, electromagnet and detector are mounted on a 3-circle rotating goniometer, allowing measurements in the diffracted beams for different angles of incidence. The power supply of the electromagnet is controlled by a low-frequency generator. The MOKE measurements were performed for the particular case of the conical diffraction by assuming that the principal plane of the light scattering is parallel to the magnetic wires as schematically shown in Fig. 1b. A PC computer monitors the magneto-optical signal delivered by the lock-in amplifier as a function of the applied magnetic field for each diffraction order.

III. Results and Discussion

The diffracted beams lean on a conical surface whose apex is common with the incident beam. Their wave vector components can be described by the diffraction grating equation [9]. Geometry of the experimental arrangement corresponds to the configuration of longitudinal MOKE where no change in the reflected light intensity can be expected when the magnetization is reversed. The measurement made for the zeroth order specularly reflected beam exhibits the rotation of the polarization plane without changing the light intensity. The diffracted beams show quite different behavior. Remarked is that, the intensity of the diffracted beams depends on the magnetization of the sample. Hereafter, we will discuss only on the results of diffracted intensity variation. It should be noted that the polarization was difficult to measure because the change in the incident angle affects the polarization state due to the optical property of the grating independent of the magneto-optical effects. The diffraction grating in conical mounting is known to act as a retarder [10].

Figure 2 represents the measured intensities I_n normalized by the incident light intensity I_{inc} and the relative changes $\Delta I_n/I_n$ for the n^{th} orders (n = 1, 2, 3) as a function of the angle of incidence i. The $\Delta I_n/I_n$ decreases when n goes from 1 to 3,

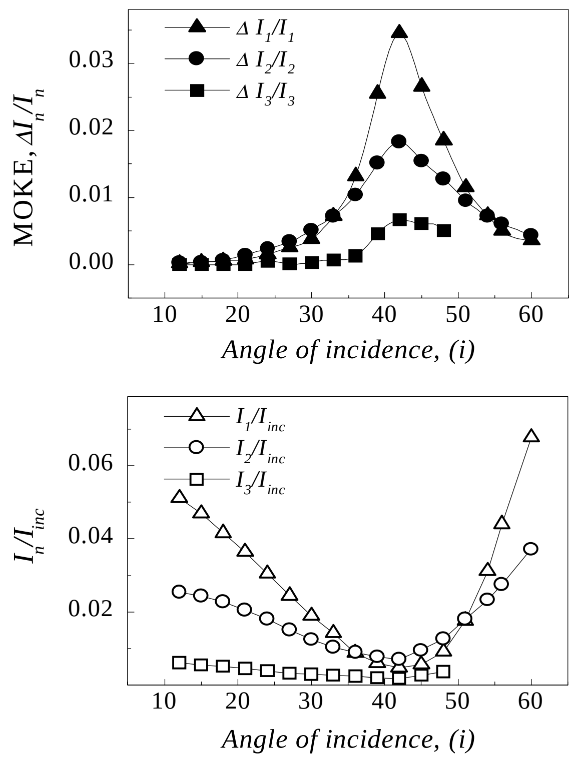

Fig. 2 Intensities I_n/I_{inc} and the relative change $\Delta I_n/I_n$ for different diffraction orders n as a function of the angle of incidence ι.

i.e. the angle between the direction of the diffracted beam and the principal plane increases. The $\Delta I_n/I_n$ takes maximum (0.035, 0.019 and 0.007 for the *1st*, *2nd* and *3rd* orders respectively), when the corresponding I_n/I_{inc} reaches the minimum value. These values are comparable with the maximum of 0.019 for the transverse MOKE for Fe_3Si. Though the magneto-optical behavior of diffracted beams appears as a variation of light intensity, it can not be considered as a transverse MOKE because the magnetization and the incident wave vector are in the same plane and the polarization state is changed when a magnetic field is applied.

As a preliminary approach, the observed magneto-optical features can be simply interpreted by considering re-emission of the light due to the induced dipoles. The induced dipole can be decomposed into two components. The first one, with a large amplitude, emits the normal Fresnel light and is parallel to the electric field vector of the incident light, while the second one, with a small amplitude, is due to the spin-orbital contribution acting as an effective axial field [11] and is perpendicular to the plane containing the electric and magnetization vectors. The detector receives the light resulting from interference between both emitted waves. The minimum light intensity corresponds to the principal angle of refraction. The magneto-optical effect is thus greatest when the contrast between both amplitudes reaches the maximum. This occurs for the first diffraction order, as it is closer to the direction normal to the dipole. The value of magneto-optical effect could be increased by adjusting the period to a larger value, which should decrease the angle between specular reflected order and diffracted beams. The width and height of the grooves, and appropriate choice of the material, should give equal amplitude for the both re-emitting components.

In the case of transverse MOKE, both induced dipoles are located in the principal scattering plane. Therefore the effect appears only through the variation of phase and intensity of the reflected light. The polarization properties are changed when there is a component of magnetization vector in the scattering plane (longitudinal or polar MOKE) and induced dipoles are therefore located in the perpendicular plane. Previous experiments on the magnetic relief grating [3, 4] and the calculation based on the perturbation approximation to the Rayleigh method [4, 6] shows that the magneto-optical effects in usual diffraction geometry can be classified into the surface MOKE. The experimental results obtained in the conical diffraction cannot be interpreted by using the same approach as the diffracted beams are no longer located within the same plane. The novelty is that for an observer placed out of the principal scattering plane there are two non vanishing components of the magnetically induced dipole; the one is located in the plane of scattering and another is perpendicular to this plane. The coupling of the light modes propagating in magnetic material leads to the simultaneous change of intensity and polarization of the diffracted light that is never observed in the usual diffraction or specular reflection geometry with the magnetization vector parallel or perpendicular to scattering plane. However, the similar coupling of magneto-optical effects may be achieved by applying an external field at some angle from the principal plane of scattering.

Magneto-optical effects are useful for characterization of magnetic materials at laboratory. They provide informations about the magnetization process (anisotropy, coercive field, surface contribution, *etc*.). But changes induced by the magnetization reversal are rather small and methods able to enhance contrast are welcome. Among these, diffraction by a magnetic grating allows more interesting viewpoints than in the usual specular geometry and can be used to plot 3D directional diagram of magnetically induced dipole light re-emission as a function of the magnetic symmetry of the sample. Moreover, thanks to the dispersive properties of gratings, they could be used for separating various energetical contributions.

CONCLUSION

The conical diffraction of a TM polarized light by an inhomogeneous grating made of ferromagnetic wires on a non magnetic substrate reveals the diffracted light intensity variation when magnetization is reversed along the wires. The relative change in intensity $\Delta I_n/I_n$ decreases when the order number increases. A qualitative explanation based on dipoles light re-emission agrees with together polarization state at the maximum $\Delta I_n/I_n$ and the change of the effect with the order number.

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