Nonlinear magneto-optical diffraction from periodic domain structures in magnetic films

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The nonlinear optical diffraction in magnetic films with a laminar domain structure and Bloch-type domain walls is investigated for both s and p polarization of incident light. It is shown that the contribution of magnetic domains and domain walls to the nonlinear diffraction can be separated by a polarization analysis of the scattered light. © 1999 American Institute of Physics.

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In the last few years new nonlinear optical methods have been explored to investigate magnetic films and multilayers. 1–4 Recently the observation of labyrinthlike magnetic domain structures in chromium oxide Cr2O3, 5 yttrium–iron garnets (YIG) Y3Fe5O12, 6 and yttrium–manganese–oxide YMnO3 7 via magnetically induced optical second harmonic generation (MSHG) was reported. Results of the theoretical investigations of MSHG on magnetic domains (MDs) and domain walls (DWs) were published in Refs. 8–10.

It is well known that laminar (one-dimensional) periodic domain structures appear in magnetic thin films under the influence of an internal magnetic field H0 directed perpendicularly to the film. Because the magnetic domain sizes are comparable to the wavelengths of the fundamental and second harmonic light one should expect the appearance of linear and nonlinear diffraction from such a domain structure. Generally speaking, a periodic domain structure can be presented as a diffraction grating which modulates the linear as well as the nonlinear magneto-optical susceptibilities. As a result, MSHG will be sensitive to the existence of a periodic domain structure and nonlinear magneto-optical diffraction (at the second harmonic frequency) can arise. The linear diffraction from laminar magnetic domain structures was investigated in numerous publications (see, for example, Ref. 11 and the monograph in Ref. 12), but so far, the nonlinear diffraction has not been considered. On the other hand, SHG and nonlinear diffraction in ferroelectric films with a laminar domain structure, needlelike ferroelectric domains and periodically poled ferroelectrics were studied both theoretically and experimentally starting from 1968 13 (see also Refs. 14 and 15, and some recent publications 16–20). Recently the second harmonic imaging of ferroelectric DWs was reported. 21–23

Nonlinear magneto-optical investigations of magnetic films and structures have several advantages in comparison to their linear equivalents. First, the nonlinear magneto-optical response allows us to obtain information about the magnetization at surfaces and buried interfaces. 3 Second, as was shown in experiments with YIG films, 6 with nonlinear magneto-optics it is possible to observe peculiarities of domain structures which are absent in the usual linear optical response. Third, nonlinear magneto-optics yields totally new effects like the observation of antiferromagnetic domains 5 and a transversal nonlinear magneto-optical effect linear in the magnetization. 24 Therefore, it should be expected that nonlinear magneto-optical diffraction will allow us to get more detailed information about periodic domain structures as well as about contributions of the domain walls to the nonlinear magneto-optical response.

The aim of this letter is to show the possibility of the observation of the nonlinear magneto-optical diffraction in magnetic films with a laminar periodic magnetic domain structure.

Let us consider the following geometry: a laminar domain structure with Bloch-type DWs is located in the XY plane and the Z axis is perpendicular to the film. The domains are then oriented along the X axis and form a regular structure along the Y axis with a period D

\[ D = d_1 + d_2 + 2d_{DW}, \]  

(1)

where d1 and d2 are the widths of the MDs with reversed magnetization directions and dDW is the width of the DWs,
where }k\text{ light will be determined by }E_{2}\text{ and diffracted (at the frequency }2\omega\text{) light are shown in inset.}

The directions to observe diffracted second harmonic light will be determined by

\[ k_{2\omega}\sin\phi_{2\omega,n} = k_{\omega}\sin\phi_{\omega} + NQ, \]

respectively. Equation (6) is the nonlinear analog of Bragg’s law for a three-wave interaction.\textsuperscript{14,15} From Eq. (6) it follows that the diffraction order }N\text{ can be determined by the relation

\[ N < \frac{2D}{\lambda_{\omega}} \left( \frac{n_{2\omega}}{n_{\omega}} - \sin \phi_{\omega} \right), \]

where }n_{\omega}\text{ and }n_{2\omega}\text{ are the refractive indices at the fundamental and second harmonic frequencies.}

For YIG films, which were studied in Ref. 6, the average sizes of MDs and DWs were equal to

\[ d_{+} = d_{-} = 2 \mu m, \quad d_{DW} \approx 0.1 \mu m. \]

For an incident light beam with }\lambda_{\omega}\text{ = 0.775 }\mu m\text{ (Ti:sapphire laser) and }\phi_{\omega}\text{ = 45°, we conclude from Eq. (7) that it would be possible to observe three nonlinear diffraction orders at the following angles (see Fig. 1):

\[ \phi_{2\omega,1} = 45°, \quad \phi_{2\omega,2} = 63.06°, \quad \phi_{2\omega,3} = 79.67°. \]

Using our results of Ref. 9, we can now find the contribution from the different terms in Eq. (4) to the nonlinear polarization for }s\text{ and }p\text{ out polarizations.

(1) }s\text{-polarized incident light, i.e., }E(\omega) = [E_s(\omega), 0, 0]:

\[ P_x^{NL}(2\omega) = \chi_{xxz}^{(m)} \frac{dM_Z}{dy} E_y^{2}(\omega), \quad P_y^{NL}(2\omega) = \chi_{xzy}^{(m)} M_x^{2} E_y(\omega), \quad P_z^{NL}(2\omega) = \chi_{zzz}^{(m)} M_x^{2} E_y^{2}(\omega). \]

Equation (9) corresponds to the }s\text{-polarized nonlinear polarization and describes the contribution of DWs (via the magnetization gradient), whereas Eqs. (10) and (11) give the }p\text{-polarized output. However, the }p\text{-polarized nonlinear polarization is determined by a nonmagnetic contribution [first term in Eq. (11)] and by both MDs (terms linear and quadratic in }M_Z\text{) and DWs (all magnetically dependent terms, because the magnetization vector in Bloch-type DWs contains }M_X\text{ and }M_Z\text{ components).

(2) }p\text{-polarized incident light, i.e., }E(\omega) = [0,E_s(\omega),E_s(\omega)]:

\[ P_x^{NL}(2\omega) = \left[ \chi_{xyz}^{(m)} M_Z + \frac{dM_Z}{dy} \right] E_y^{2}(\omega), \quad P_y^{NL}(2\omega) = \chi_{zxz}^{(m)} M_x^{2} E_y(\omega), \quad P_z^{NL}(2\omega) = \chi_{zzz}^{(m)} M_x^{2} E_y^{2}(\omega). \]

In contrast to Eq. (9), it follows from Eq. (12) that not only DWs, but also MDs will contribute (via term proportional to }M_Z\text{) to the }s\text{-polarized second harmonic radiation for }p\text{-polarized incident light. This will lead to a situation where the contribution of MDs is large enough to essentially determine the }p\text{-polarized nonlinear polarization in the }s\text{-polarized light (see Eq. (12)).

FIG. 1. Schematic image of magnetic film with a laminar domain structure. Arrows in magnetic domains and domain walls indicate the orientation of magnetization. Directions of incident (at the frequency }\omega\text{) and diffracted (at the frequency }2\omega\text{) light are shown in inset.

The directions to observe diffracted second harmonic light will be determined by

\[ k_{2\omega}\sin\phi_{2\omega,n} = k_{\omega}\sin\phi_{\omega} + NQ, \]

where }k_{2\omega}\text{ and }k_{\omega}\text{ are the wave numbers of second harmonic and incident light, }\phi_{\omega}\text{ and }\phi_{2\omega,n}\text{ are the angle of incidence and the angle of the }N\text{th order second harmonic diffraction,
mental geometry $s(\omega) \rightarrow s(2\omega)$ it should be possible to detect diffracted second harmonic radiation which is induced by Bloch-type DWs only.

Because the widths of MDs and the period of a laminar domain structure are very sensitive to an external magnetic field $H_0$, there exists the possibility to magnetically control the diffracted second harmonic radiation. As was shown in Ref. 26, at $H_0 > 0.4\pi M_s$ ($M_s$ is the saturation magnetization), the period $D$ and the width of the positive domain $d_+$ (in which the magnetization is oriented parallel to $H_0$) rapidly increase nonlinearly (approximately quadratically) with $H_0$, whereas the width of the negative domain $d_-$ decreases much more slowly (though also nonlinearly). Thus, the angles which determine the nonlinear diffraction maxima $\phi_{2\omega,N}$ in Eq. (6) will change as well. For $H_0 > 4\pi M_s$ the magnetic film will transit to the uniform magnetic state and for the geometry $s(\omega) \rightarrow s(2\omega)$ second harmonic radiation will disappear.

We would like to note that for ferroelectrics the situation is very similar. Recently, an analysis of the selection rules for the nonlinear polarization in ferroelectric crystals with DWs was made in Ref. 22. However, the authors of this article only took into account the nonlinear susceptibility tensor components which correspond to the domains. For a complete description of the DW contributions to the SHG for the geometry $s(\omega) \rightarrow s(2\omega)$, the magnetic film will transit to the uniform magnetic state and for the geometry $s(\omega) \rightarrow s(2\omega)$ second harmonic radiation will disappear.

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