Second Harmonic Light Scattering by the Edge Dislocation in Magnetic Crystal

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Abstract

Optical second harmonic light scattering, or hyper-Rayleigh light scattering which is characterized by the electromagnetic radiation at the double frequency of an incident light in magnetic crystal with the single straight edge dislocation have been phenomenologically investigated by adopting a nonlinear photoelastic and a nonlinear magneto-optic interactions. The polarization dependencies of the light scattered at the double frequency of an incident light for the different scattering geometries are analyzed.

1. Introduction

The methods of nonlinear magneto-optics are well developed for investigating the domains in the magnetic films [1,2]. It is well known that real crystals and films contain the structural defects, for example, the dislocations [3]. The dislocations are the sources of the long-range strain field in a crystal, or in a film [3]. This strain changes the optical properties of a crystal via photoelastic interaction [3]. In magnetic films and crystals it is the magnetoelastic (ME) interaction plays very important role [4]. For example, in a magnetic crystal with a dislocation the ME interaction leads to the formation the specific kind of domain sructure, so called dislocation domains [5]. These dislocation domains are characterized by a special distribution of magnetization around a dislocation core [5].

In this communication we consider the nonlinear elastic light scattering, or hyper-Rayleigh light scattering (HRLS) by single edge dislocation in magnetic crystal. Similar to second harmonic generation (SHG), the HRLS is characterized by the electromagnertic radiation scattered at the double frequency of incident light. The nature of the HRLS phenomenon is very close to the origin of the SHG, because both these three-photon effects are described by the quadratic nonlinear polarization. However, the radiation, corresponding to the HRLS, propagates in an arbitrary direction (non-specular scattering), while for the SHG is necessary to satisfy the phase-matching conditions[6], or specular reflection (in the case of a surfaces, or thin non-transparent films).

2. Magnetization in Crystal with Dislocation

Let us consider a cubic crystal magnetized along the Y axis without an inversion center (the point symmetry $\bar{4}3m - T_d$) with the edge dislocation oriented along the Z axis with Burgers vector $\mathbf{b} = (b, 0, 0)$. In the crystallographic coordinate basis XYZ, the dislocation strain is characterized by the following non-zero components of the strain tensor $u_{ik}(\mathbf{r})$[3]:

$$
\begin{aligned}
u_{xx}(\mathbf{r}) &= -\frac{b}{4\pi(1-\nu)}\frac{y[x^2(3-2\nu)+y^2(1-2\nu)]}{(x^2+y^2)^2}, &(1)\\
u_{yy}(\mathbf{r}) &= \frac{b}{4\pi(1-\nu)}\frac{y[x^2(1+2\nu)+y^2(1-2\nu)]}{(x^2+y^2)^2}, &(2)\\
u_{xy}(\mathbf{r}) &= \frac{b}{4\pi(1-\nu)}\frac{x(x^2-y^2)}{(x^2+y^2)^2}, &(3)
\end{aligned}
$$

where ν is the Poisson's coefficient.

As mentioned above, due the ME interaction magnetization vector $\mathbf{M}_0$ changes orientation in XY plane and additional components of magnetization can be presented in the following form [5]:

$$
\begin{aligned}
m_x(\mathbf{r}) &= \frac{bM_0}{4\pi}y[\frac{2\gamma+\pi(1-2\nu)}{2(1-\nu)}+\beta]\ln\sqrt{\frac{\alpha}{(x^2+y^2)^2}}, &(4)\\
m_y(\mathbf{r}) &= \frac{bM_0(1-2\nu)x}{2\pi(1-\nu)(x^2+y^2)^2}, &(5)
\end{aligned}
$$

where α and $\beta$are the constants of nonuniform exchange interaction and uniaxial magnetic anisotropy, respectively, and γ is the constant of ME interaction.

3. Second Harmonic Light Scattering

The second-order nonlinear optical polarization $\mathbf{P}^{NL(2)}(2\omega)$ at the double frequency of the incident light in the dipole approximation can be written in the well known form [6]:

$$P_i^{NL}(2\omega) = \chi_{ijk}^{(2)}(-2\omega:\omega,\omega)E_j(\omega)E_k(\omega), \tag{6}$$

where $\chi_{ijk}^{(2)}$ is the second-order nonlinear optical suceptibility (NOS) tensor and $\mathbf{E}(\omega)$ is the electric field of the incident light at the frequency ω. Within the phenomenological approach an influence of strain and magnetization on the second-order nonlinear polarization can be described by the nonlinear photoelastic and nonlinear magneto-optic tensors.

$$\chi_{ijk}^{(2)} = \chi_{ijk}^{(2,0)} + p_{ijklm}u_{lm} + if_{ijkl}m_l \tag{7}$$

where $\chi_{ijk}^{(2,0)}$ is the second-order NOS tensor of unstrained crystal in paramagnetic phase, p_{ijklm} is the nonlinear photoelastic tensor, and f_{ijkl} [1] is the linear on magnetization nonlinear magneto-optic tensor.

Let us determine the polarization of light scattered at the second harmonic frequency. Within the slowly varing amplitude approximation the wave equation for the second harmonic electric field can be written as [6]

$$2ik_{2\omega,l}\nabla_l E_i(2\omega,\mathbf{q}) = -\frac{\omega^2}{c^2}\chi_{ijk}^{(2)}(\mathbf{r})E_j(\omega)E_k(\omega)exp(i\mathbf{q}\cdot\mathbf{r}), \tag{8}$$

where $\mathbf{q} = 2\mathbf{k}_\omega - \mathbf{k}_{2\omega}$ is the scattering wave vector while $\mathbf{k}_\omega$ and $\mathbf{k}_{2\omega}$ are the wave vectors of the fundamental and second harmonic light, respectively. Using the infinite plane wave approximation, we obtain from Eq. (21)

$$E_l(2\omega,\mathbf{q}) = \frac{A}{V}\int_V \chi_{ijk}^{(2)}(\mathbf{r})E_j(\omega)E_k(\omega)exp(i\mathbf{q}\cdot\mathbf{r})d\mathbf{r}, \tag{9}$$

where

$$A = -\frac{i\omega}{cn_{2\omega}}.$$

The integral in Eq. (22) is taken over the interaction volume V, and $n_{2\omega}$ is the refractive index of the crystal at the second harmonic frequency.

Substituting the non-zero components of the nonlinear phootoelastic and nonlinear magneto-optic tensors for the point symmetry group $43m$ [7] and the dislocation stran tensor determined by Eqs. (18)-(20) into Eq. (22), we obtain the values of the electric fields at the second harmonic frequency for the s- and p-polarized incident light as follows:

i) $s(\omega) \rightarrow s(2\omega)$

$$E_s(2\omega, \mathbf{q}) = A[p_{yyyxy}u_{xy}(\mathbf{q}) + if_{yyyx}m_x(\mathbf{q})]E_s^2(\omega), \tag{10}$$

ii) $p(\omega) \rightarrow s(2\omega)$

$$\begin{aligned} E_s(2\omega, \mathbf{q}) \quad = \quad & A\{[p_{yxxxy}E_x^2(\omega) + p_{yzzxy}E_z^2(\omega)]u_{xy}(\mathbf{q}) \\ & +i[f_{yxxx}E_x^2(\omega) + f_{yzzx}E_z^2(\omega)]m_x(\mathbf{q})\}, \end{aligned} \tag{11}$$

iii) $s(\omega) \rightarrow p(2\omega)$

$$E_x(2\omega, \mathbf{q}) = Aif_{yyyy}m_y(\mathbf{q})E_s^2(\omega) \tag{12}$$

$$E_z(2\omega, \mathbf{q}) = A[\chi_{zyy}^{(2,0)}f(\mathbf{q}) + p_{zyyxx}u_{xx}(\mathbf{q}) + p_{zyyyy}u_{yy}(\mathbf{q})]E_s^2(\omega). \tag{13}$$

iv) $p(\omega) \rightarrow p(2\omega)$

$$\begin{aligned} E_x(2\omega, \mathbf{q}) \quad = \quad & A\{[(\chi_{xxz}^{(2,0)} + \chi_{xzx}^{(2,0)})f(\mathbf{q}) + (p_{xxzxx} + p_{xzxxx})u_{xx}(\mathbf{q}) \\ & +(p_{xxzyy} + p_{xzxyy})u_{yy}(\mathbf{q})]E_x(\omega)E_z(\omega) \\ & +i[f_{xxxy}E_x^2(\omega) + f_{xzzy}E_z^2(\omega)]m_y(\mathbf{q})\} \end{aligned} \tag{14}$$

$$\begin{aligned} E_z(2\omega, \mathbf{q}) \quad = \quad & A\{[\chi_{zxx}^{(2,0)}f(\mathbf{q}) + p_{zxxxx}u_{xx}(\mathbf{q}) + p_{zxxyy}u_{yy}(\mathbf{q})]E_x^2(\omega) \\ & +[\chi_{zzz}^{(2,0)}f(\mathbf{q}) + p_{zzzxx}u_{xx}(\mathbf{q}) + p_{zzzyy}u_{yy}(\mathbf{q})]E_z^2(\omega) \\ & +if_{zxzy}m_y(\mathbf{q})E_x(\omega)E_z(\omega)\} \end{aligned} \tag{15}$$

The Fourier transform of the dislocation strain tensor components $u_{lm}(\mathbf{q})$, magnetization vector $\mathbf{m}(\mathbf{q})$ and factor $f(\mathbf{q})$ are determined as follows:

$$u_{lm}(\mathbf{q}) \quad = \quad \frac{1}{V}\int_V u_{lm}(\mathbf{r})exp(i\mathbf{q}\cdot\mathbf{r})d\mathbf{r}, \tag{16}$$

$$\mathbf{m}(\mathbf{q}) \quad = \quad \frac{1}{V}\int_V \mathbf{m}(\mathbf{r})exp(i\mathbf{q}\cdot\mathbf{r})d\mathbf{r}, \tag{17}$$

$$f(\mathbf{q}) \quad = \quad \frac{1}{V}\int_V exp(i\mathbf{q}\cdot\mathbf{r})d\mathbf{r} = 2\frac{J_1(q_\perp R)}{q_\perp R}sinc(\frac{q_z h}{2}), \tag{18}$$

where $J_1(x)$ is the first-order Bessel function, R is the diameter of the laser spot, $q_\perp$ is the in-plane component of the scattering wave vector $\mathbf{q}$, $sinc(x) = sin(x)/x$, and h is the thickness of the crystal.

As follows from Eqs. (10)-(12), the $s-$polarized component of second harmonic radiation depends on $x-$component of magnetization which is induced by ME interction for both $s(\omega) \rightarrow s(2\omega)$ and $p(\omega) \rightarrow s(2\omega)$scattering geometries. For the p-polarized second harmonic radiation, from Eqs.(13) - (15) we obtaine that only y-component of the magnetization vector contributes to the effect for both $s(\omega) \rightarrow p(2\omega)$ and $p(\omega) \rightarrow p(2\omega)$scattering geometries.

4. Conclusions

In conculsion, we shown that magnetization-induced nonlinear light scattering is sensitive to a change of orientation of magnetization in crystal. Particularly, in magnetic crystal with dislocation ME interaction leads to the change in magnetization orientation. It is possible to observe this new magnetization component via polarization analysis of reflected light at the second harmonic frequency. As mentioned above, s-polarized second harmonic radiation depends on the $x-$component of magnetization as well as p-polarized second harmonic radiation depends on the $y-$component of magnetization. This dependence can be observe via measurements of magnetic anisotropy of second harmonic sygnal whichis determined as folows

$$A_{2_\omega}(\mathbf{M}) = \frac{I_{2\omega}(\mathbf{M}) - I_{2\omega}(-\mathbf{M})}{I_{2\omega}(\mathbf{M}) + I_{2\omega}(-\mathbf{M})}. \tag{19}$$

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