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Light-induced flexoantiferomagnetic effect in centroantisymmetric antiferromagnets

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It is shown that an inhomogeneous circularly polarized light wave induces components of the antiferromagnetism vector in centroantisymmetric antiferromagnets; a narrow beam of light can create a skyrmion. The analysis of the possibility of practical use of the predicted effects is carried out.

Keywords: optomagnetic effect, polyharmonic light field, light-induced magnetic field, centroantisymmetric antiferromagnet, circularly polarized light wave, flexoantiferromagnetic effect.

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Due to nonlinear magnetoelectric effect the light waves in magnetic-ordered media can create constant effective magnetic field, as well as change an exchange field, anisotropy and sublattice magnetization field [1–5]. From quantum point of view the light field changes the energy spectrum (nonlinear Stark effect) and energy levels occupation degree, resulting in variation of exchange and spin-orbital interaction and, as a result, change of value and direction of magnetization vectors. According to currently adopted terminology, there are optomagnetic [4] and photomagnetic [6] effects. The first ones appear in the magnetic transparent region, while the seconds ones — in absorption region, where under light exposure the electrons are thrown to conductivity band and to local energy levels. Optomagnetic effects, caused by virtual excitation of electrons, are characterized with small relaxation time and for observation require higher light intensity, as opposed to photomagnetic, that have higher relaxation time and are observed at much lower light intensity.

Consideration of magnetic symmetry allowed to predict and discover the new phenomena, consisting in light waves capability to create magnetoelectric, magnetostriction, magnetocaloric, galvanomagnetic and thermogalvanomagnetic effects, induce spontaneous and orientational phase transitions of the first and second order, create dissipative flows and related summarized forces [4–10].

Light-induced (LI) magnetic fields can make the significant changes of sublattices magnetization vectors orientation [3–16], while near points of static and (or) dynamic stability loss, for instance, at phase transitions, these changes will be significant, and in hysteresis area they can be memorized.

Polyharmonic light field creates both constant and variable effective fields [5]. If difference of harmonic frequencies of LI variable fields is within the area of ferromagnetic or antiferromagnetic resonance, the magnetization precession is excited and dynamic phase transitions or spin echo are observed [8]. Wave numbers of LI variable fields depend on direction of harmonics distribution and lie within wide ranges from sum to difference of wave numbers for cocurrent and opposite harmonics respectively. Velocity of such LI waves can exceed velocity of spin waves at antiferromagnetic resonance, that can be used for their amplification and generation of coherent radiation of terahertz range.

LI magnetic fields have advantages compared to „regular“ magnetic fields and elastic stress fields, since they are localized within light beam, allows realization as small duration wave packet, do not cause electromagnetic interference, depending on polarization the LI fields appear as a magnetic field or elastic stress, can be constant or permanent at frequencies in the antiferromagnetic resonance region [5].

In technologies the optomagnetic effects in antiferromagnets can be used for information writing in the area of magnetic hysteresis (particularly, near homogeneous and non-homogeneous magnetic phase transition of the 1st order), for creation and destruction of cylindrical magnetic domains, for Bloch lines control, for spin waves amplification, for creation of local magnetic potentials of the specified size (in resonators, wave guides, lattices, optomagnetic „tweezers“ etc.), including comparable with light wave length, for creation of spin-polarized electric current. Fast action of many of the above mentioned operations can be adjusted to half-period of free precession, that is about 10^{-11} s for antiferromagnets.

Light propagation in magnets is a self-consistent process, since the light wave changes the sublattices magnetization vectors, that, in its turn, impacts the light wave parameters. Particularly, magnetooptical solitons can be observed, as well as self-focusing and appearance of magnetooptical channels [5], therefore optomagnetic effects are observed at short light path lengths, where amplitude and polarization of waves are changed insignificantly.

In this work the LI optoflexoantiferromagnetic effect is examined similar to flexoantiferromagnetic [17,18].

The time-average medium energy density in a light field at low absorption and low time dispersion takes the form

$$w_{ml} = (1/16\pi)\varepsilon_{ij}E_iE_j^*, \tag{1}$$

where ε_{ij} — components of dielectric permeability tensor, and E_i — components of complex electric field of a light wave [19].

Separating the symmetric and antisymmetric components we find that

$$w_{ml} = \varepsilon_{ij}^{(s)}T_{ij}^{(s)} - \mathbf{gG}, \tag{2}$$

where $\varepsilon_{ij}^{(s)}$ is a symmetric part of dielectric permeability tensor, $T_{ij}^{(s)} = (1/32\pi)(E_iE_j^* + E_i^*E_j)$ is symmetric part of „light stress"tensor, $\mathbf{g}$ is gyration vector, $\mathbf{G} = (i/16\pi)[\mathbf{E}^*\mathbf{E}]$ is effective „magnetic field". Considering, that in general for antiferromagnet

$$g_k = \alpha_{kl}L_l + \alpha'_{kl}M_l + \eta_{klm}^{(l)}\frac{\partial L_l}{\partial x_m} + \eta_{klm}^{(m)}\frac{\partial M_l}{\partial x_m}\dots, \tag{3}$$

$$\varepsilon_{ij}^{(s)} = \varepsilon_{ij}^{(0)} + \beta_{ijkl}L_kL_l + \beta_{ijk\ln}^{(1)}L_k\frac{\partial L_l}{\partial x_n} + \beta_{ijkl}^{(2)}M_kL_l$$
$$+ \beta_{ijl\ln}^{(3)}M_k\frac{\partial L_l}{\partial x_n} + \beta_{ijkl}^{(4)}M_kM_l, \tag{4}$$

where $\mathbf{L}$ and $\mathbf{M}$ are vectors of antiferromagnetism and ferromagnetism, we find that in centroantisymmetric antiferromagnets with symmetry of $\bar{3}'m'$ (Cr_2O_3 type) the expression (2) reduces to

$$w_{ml} = -\eta_1^{(l)}\left[+\left(\frac{\partial L_x}{\partial x} - \frac{\partial L_y}{\partial y}\right)G_x + \left(\frac{\partial L_x}{\partial y} - \frac{\partial L_y}{\partial x}\right)G_y\right]$$
$$- \eta_2^{(l)}\left(\frac{\partial L_y}{\partial z}G_x - \frac{\partial L_x}{\partial z}G_y\right) - \eta_3^{(l)}\left(\frac{\partial L_z}{\partial x}G_y - \frac{\partial L_y}{\partial z}G_x\right)$$
$$- \eta_4^{(l)}\left(\frac{\partial L_x}{\partial y} - \frac{\partial L_y}{\partial x}\right)G_z - \alpha'_1(M_xG_x + M_yG_y)$$
$$- \alpha'_3M_zG_z + \beta_{12}T_{ii}^{(s)}L^2 + (\beta_{11} - \beta_{22})(T_{11}^{(s)}L_x^2 + T_{22}^{(s)}L_y^2$$
$$+ T_{33}^{(s)}L_z^2) + \beta_{44}(T_{23}^{(s)}L_yL_z + T_{31}^{(s)}L_zL_x + T_{12}^{(s)}L_xL_y). \tag{5}$$

By symmetry, there are no first and fourth components in (3) and third and fourth in (4), while two last components in (4) were not considered due to low value compared to the second one.

Total energy density of antiferromagnet for boundless medium in the absence of external magnetic field is given with expression $w = w_0 + w_m + w_{ml}$, where w_0 is energy of the main homogeneous state,

$$w_M = (1/2)\Big[a_1^{(l)}\mathbf{L}^2 + a_1^{(m)}\mathbf{M}^2 + a_1^{(\ln)}(\partial\mathbf{L}/\partial x_i)^2$$
$$+ a_2^{(l)}L_z^2 + a_2^{(m)}M_z^2 + a_2^{(\ln}(\partial L_z/\partial x_i)^2\Big]$$
$$- \eta_1^{(m)}\left[M_x\left(\frac{\partial L_x}{\partial x} - \frac{\partial L_y}{\partial y}\right) - M_y\left(\frac{\partial L_x}{\partial y} + \frac{\partial L_y}{\partial x}\right)\right]$$
$$- \eta_2^{(m)}\left(M_x\frac{\partial L_y}{\partial z} - M_y\frac{\partial L_x}{\partial z}\right) - \eta_3^{(m)}\left(M_y\frac{\partial L_z}{\partial x}\right.$$
$$\left. - M_x\frac{\partial L_z}{\partial y}\right) - \eta_4^{(m)}M_z\left(\frac{\partial L_x}{\partial y} - \frac{\partial L_y}{\partial y}\right) \tag{6}$$

— energy, induced by external fields in quadratic approximation.

From (5) and (6) it follows that the light field shifts the Neel point, renormalizes the anisotropy constants, creates the effective magnetic field, anisotropy field and results in existence of optoflexoantiferromagnetic effect.

Requiring $\delta w/d\mathbf{M} = 0$, $\delta w/d\mathbf{L} = 0$, we solve the state equation

$$M_x = \eta_1^{(m)\prime}\left(\frac{\partial L_x}{\partial x} - \frac{\partial L_y}{\partial y}\right) + \eta_2^{(m)\prime}\frac{\partial L_y}{\partial z} - \eta_3^{(m)\prime}\frac{\partial L_z}{\partial y} + \chi_\perp^{(l)}G_x,$$
$$M_y = -\eta_1^{(m)\prime}\left(\frac{\partial L_x}{\partial y} + \frac{\partial L_y}{\partial x}\right) - \eta_2^{(m)\prime}\frac{\partial L_x}{\partial z} + \eta_3^{(m)\prime}\frac{\partial L_z}{\partial x} + \chi_\perp^{(l)}G_y,$$
$$M_z = \eta_4^{(m)\prime}\left(\frac{\partial L_x}{\partial y} - \frac{\partial L_y}{\partial x}\right) + \chi_\parallel^{(l)}G_z,$$
$$\alpha_{11}^{(l)}L_x + a_{12}^{(l)}L_y + a_{13}^{(l)}L_z - a_1^{(\ln)}\Delta L_x =$$
$$- \eta_1^{(m)}\left(\frac{\partial M_x}{\partial x} - \frac{\partial M_y}{\partial y}\right) - \eta_4^{(m)}\frac{\partial M_z}{\partial y} + \eta_2^{(m)}\frac{\partial M_y}{\partial z}$$
$$- \eta_1^{(l)}\left(\frac{\partial G_x}{\partial x} - \frac{\partial G_y}{\partial y}\right) - \eta_4^{(l)}\frac{\partial G_z}{\partial y} + \eta_2^{(l)}\frac{\partial G_y}{\partial z},$$
$$\alpha_{12}^{(l)}L_x + a_{22}^{(l)}L_y + a_{13}^{(l)}L_z - a_1^{(\ln)}\Delta L_y =$$
$$\eta_1^{(m)}\left(\frac{\partial M_x}{\partial y} + \frac{\partial M_y}{\partial x}\right) + \eta_4^{(m)}\frac{\partial M_z}{\partial x} - \eta_2^{(m)}\frac{\partial M_x}{\partial z}$$
$$+ \eta_1^{(l)}\left(\frac{\partial G_x}{\partial y} + \frac{\partial G_y}{\partial x}\right) + \eta_4^{(l)}\frac{\partial G_z}{\partial x} - \eta_2^{(l)}\frac{\partial G_x}{\partial z},$$
$$\alpha_{13}^{(l)}L_x + a_{22}^{(l)}L_y + a_{33}^{(l)}L_z - a_{12}^{(\ln)}\Delta L_z =$$
$$\eta_3^{(m)}\left(\frac{\partial M_x}{\partial y} - \frac{\partial M_y}{\partial x}\right) + \eta_3^{(l)}\left(\frac{\partial G_x}{\partial y} - \frac{\partial G_y}{\partial x}\right), \tag{7}$$
$$\eta_n^{(m)\prime} = \eta_n^{(m)}/a_1^{(m)},\ \chi_\perp = 1/a_1^{(m)},\ \chi_\perp^{(l)} = \alpha'_1/a_1^{(m)},$$
$$\chi_\parallel = 1/(a_1^{(m)} + a_2^{(m)}),\ \chi_\parallel^{(l)} = \alpha'_3/(a_1^{(m)} + a_2^{(m)}),$$
$$a_\mu^{(l)} = a_1^{(l)} + \delta_{3i}a_2^{(l)} + 2\beta_{12}T_{ii}^{(s)} + 2(\beta_{11} - \beta_{12})T_\mu^{(s)},$$
$$\mu = 11, 22, 33,\ a_{ij}^{(l)} = \beta_{44}T_{ij}^{(s)},$$

where $a_{12}^{(\mathrm{ln})} = a_1^{(\mathrm{ln})} + a_2^{(\mathrm{ln})}$.

It is seen, that magnetization appearance in the examined case is caused by discontinuities of antiferromagnetic vector, i.e. there is a flexoantiferromagnetic effect, different from weak ferromagnetism, at which the magnetism exists at homogeneous distribution of antiferromagnetic vector [20,21].

In centroantisymmetric antiferromagnets there is no weak ferromagnetism and flexoantiferromagnetic effect is not masked. Circularly polarized component of the light field brings magnetism ($M \propto G$), while linearly polarized component changes the module and direction of antiferromagnetism vector (optomagnetic effect). Besides, non-homogeneous circularly polarized light component brings the components of vector of antiferromagnetism $L_i = n_{ijk}\partial G_j/\partial x_K$, i.e. there is an optoflexoantiferromagnetic effect. Considering low components in (4), the discontinuities of the linearly polarized light field will also bring components of antiferromagnetic vector.

Substitution of the expressions for M_i into three last equations of system (7) allows to define components of L_i. Without external magnetic field the components, related to $\mathbf{M}$, will be proportional to squares of constants $\eta_i^{(m)}\eta_j^{(m)}$ and $\eta_i^{(m)}\alpha'_j$, and they may be neglected at the first approximation. Besides, considering the order size of the light wave lengths the components, caused by non-homogeneous exchange interaction, will also be negligible. In this case for circularly polarized wave, propagating along the axis of symmetry with $E_y = -iE_x$, we have

$$L_x = -(\eta_4^l/a_{11}^{(l)})\frac{\partial G_z}{\partial y},\ L_y = (\eta_4^l/a_{11}^{(l)})\frac{\partial G_z}{\partial x},\ L_z = 0, \quad (8)$$

where

$$a_{11}^{(l)} = a_1^{(l)} + [(\beta_{11} + \beta_{12})|E_x|^2/16\pi],\ G_z = |E_x|^2/8\pi.$$

In light beam the electric field intensity has the maximum on the axis and drops to zero with removing from it. Therefore, the components L_x and L_y disappear on the axis and outside the beam, reaching the maximum values in points with the highest gradient of the light field intensity, creating the skyrmion. The light field with Gauss distribution $|E_x|^2 = |E|_0^2\exp(-\rho^2/\rho_0^2)$ induces the component L_φ, tangential to circle and having the module

$$L_\varphi(\eta_4^{(l)}/|a_{11}^{(l)}|)(|E|_0^2 8\pi)(2\rho/\rho_0^2)\exp(-\rho^2/\rho_0^2),$$

where $\rho^2 = x^2 + y^2$.

Magnetization component, linear by material constant, is defined with expression $M_z = \chi_{\parallel}^{(l)} G_z$. Using (8), from the first and second equations of system (7) the values of M_x and M_y can be defined, and these values substitution into the third equation of system (7) allows to get in the second approximation the value and other LI components

$$L_z = c_0[8x(3y^2 - x^2)/\rho_0^6]\exp(-\rho^2/\rho_0^2),$$

where

$$c_0(\eta_3^{(m)}\eta_1^{(m)}\eta_4^{(l)}/a_1^{(l)}a_1^{(m)}a_3^{(l)})|E_0|^2/8\pi.$$

It should be noted, that light beams can create various topological magnetic features. Particularly, this is relating to circularly polarized light field, that renormalizes the constant of homogeneous exchange, creates additional effective magnetic field, easy-axis or easy-plane anisotropy. If in easy-plane or easy-axis magnet the light brings easy-axis or easy-plane LI anisotropy, then the magnetization vectors in the beam come out of the plane or shift from the axis, creating a magnetic vortex, that can contain various phases [4]. Spiral light beam creates the skyrmion [22]. These magnetic features are based on known effects, unlike the skyrmion, described in this work and caused by optoflexoantiferromagnetic effect.

The main result of this work is a theoretical justification of the fact, that influence of non-homogeneous circularly or linearly polarized light waves on centroassymetric antiferromagnets induces appearance of earlier unknown effects, that can be used for defect detection, controlled change of parameters of such media, that are widely used in spintronics [23,24]. Light control has some undoubtful advantages over other methods, since it is local, remote and remains efficiency even when using ultrashort pulses [13,14]. However, it should be noted, that such method improvement by means of light intensity increase results in rise of side effects, particularly to magnet heating. Therefore, currently there is a search of alternative methods of efficiency improvement for optomagnetic effects, particularly the inverse Faraday effect [25].

Almost complete lack of required experimental data currently prevents from numerical evaluation of material constants, included in the equation (3) and defining the value of flexoantiferromagnetic effect and possibility of its observing. What is, however, reassuring is that the authors of works [26,27], who observed the new unilateral optical phenomena in antiferromagnet Cr_2O_3 in electrical $\mathbf{E}_\mathrm{O}$ field, related possibility of their existence with presence of the component $\eta_{klm}^{(e)}L_l E_m^{(0)}$ in the gyrotropic part of the medium energy density, while this component coincides in terms of structure and symmetry with the third member of the equation (3), specifically $\eta_{klm}^{(l)}\frac{\partial L_l}{\partial x_m}$. When using the narrow light beams the gradient $\mathbf{L}$ can create the effect similar to $\mathbf{E}_\mathrm{O}$.

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Conflict of interest

The authors declare that they have no conflict of interest.

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