Electromagneto-optical effects on local areas of a ferrite-garnet film

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The electromagneto-optical (EMO) effect from separate magnetic domains in the epitaxial films of yttrium-ferrite-garnet is investigated simultaneously with visual control of the film's domain structure. The local EMO effect, both from single domain sites and from the sites with a domain wall is measured. These local effects are different from the EMO from the multidomain area of a film. It was revealed unexpectedly that a local value of the EMO effect for the domain magnetized along the applied magnetic field decreased drastically in the magnetization stage connected with vanishing of the domains with opposite sign of magnetization. In the homogeneously magnetized film, the EMO effect is practically absent. It is concluded that the electric field practically does not modify the film magnetization and the local EMO effect is connected with the influence of the electric field on the magnetic anisotropy parameter of the studied film.

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Interest in the study of magneto-ordered substance behavior in an electric (E) field has increased considerably since the discovery of the magneto-electric (ME) effect in the antiferromagnetic crystals Cr_2O_3 by Astrov.[1] The first observation of the ME effect in yttrium-ferrite-garnet (YIG) was reported by O'Dell.[2] Later, the ME effect was studied in a number of papers.[3–9] One of the methods for the ME phenomena investigation deals with the registration of the changes of light polarization plane Faraday rotation under action of an E field applied to the crystal. The appearance of such changes has been termed the electromagneto-optical (EMO) effect. Throughout the paper, we shall refer to this effect as EMOE.[10]

The ME and EMO effects that are linearly dependent on the E field are forbidden for the centrosymmetric cubic crystal structure of YIG. In earlier studies, only square-law EMOE was observed in YIG single crystals.[10] Nevertheless, the linear EMOE was reported in Refs. 11 for a YIG film. In Ref. 12,13, the square law on the E-field EMOE was revealed in thin YIG films. Measurements were done at a multidomain site of the thin film with use of a laser beam. The EMO signal obtained in such a way was interpreted as the result of averaging of the light polarization plane rotation on the probed area.

The goal of the present study was a further experimental investigation of EMOE in ferrite garnets. In particular, we investigated this effect on local sites. The measurement data obtained from single domain sites are compared with those obtained from the sites that contained domain walls (DW). The measurements of the EMOE were carried out simultaneously with a visual observation of the domain structure of the film. The changes of the magneto-optical characteristics in the different magnetic domains under E field action were not the same. The Faraday rotation of the light, α_F, which passes through a single domain, is proportional to $a_1 M_{loc} + a_2 B_{loc}$. There, M_{loc} is local magnetization, a_1 and a_2 are some coefficients, $B_{loc.} = H_{int.loc.} + 4\pi M_{loc}$ is the local value of the magnetic induction, and $H_{int.loc.} = H_{ext} - H_{demag}$. The demagnetization field H_{demag}, which generally depends on the average magnetization, in the case of a multidomain thin film will be additionally not uniform. As a result, the EMOE picture from the one-domain sample area must be more detailed and informative than an averaged one in the multidomain case.

The investigated YIG films were deposited on the $Gd_3Ga_5O_{12}$ substrates with a thickness of about 600 μm. Preliminary magneto-optical investigation of the samples with visualization of the domain structure has shown that the typical thickness of the films was about 7 μm, the width of domains was about 15 μm at $H=0$, and the domain-wall width was about 0.5 μm. The domain's magnetization was normal to the film plane.

The experimental setup consists of a combination of a high-sensitive laser polarimeter and a polarizing microscope. The use of a round diaphragm with a diameter of about 0.25 mm allowed us to allocate the sites of a film of about 3 μm in diameter. Due to such allocating we could carry out measurements on single domain sites, or on sites containing a domain wall.

A variable voltage $U_\sim$ with frequency (ω) of 800 Hz and amplitude up to 2 kV was applied to the sample. One of the optically transparent electrodes was placed on the YIG film surface and the other one was placed under the substrate. If we assume that the static permittivities of the YIG and $Gd_3Ga_5O_{12}$ are approximately the same, we can estimate the amplitude of the applied ac E field in the YIG film as 3.3 kV/cm. The experimental setup allowed us to carry out measurements of linear, $\alpha_{EMO}^{(\omega)}$, and nonlinear, $\alpha_{EMO}^{(2\omega)}$, components of the electric-field-induced changes of the Faraday rotation. Measurements could be done on single domain areas or on small areas that contained DW. The ω and 2ω components of the angle changes correspond to the linear and square law on electric field EMOE, respectively.

The setup includes a semitransparent mirror to form a light beam, which was used for visual inspection of the domain structure with the help of a polarizing microscope.

Such a scheme allows us to carry out measurements of both an angle of light polarization plane rotation in the magnetic field and a changing of it, α_{EMO}, caused by action of the electric field on the sample. A He-Ne laser ($\lambda = 0.63$ μm) was used. The sensitivity of measurements of polarization plane

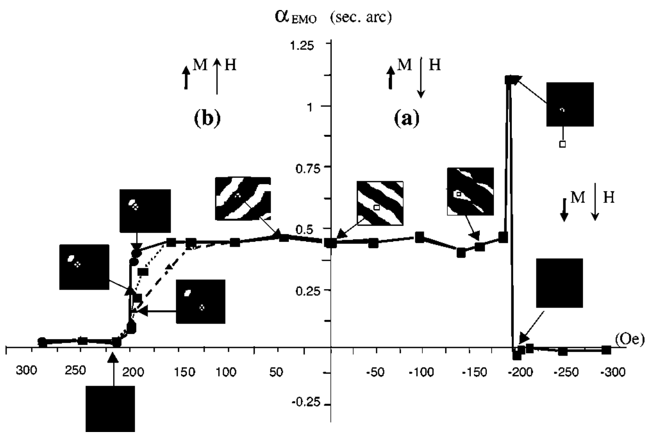

FIG. 1. Magnetic-field dependencies of EMOE measured on the domains, which decrease (a) or increase (b) their volume with growth of the magnetic-field value correspondingly. The positive and negative signs of the magnetic field **H** on this and further figures correspond to the field direction along and opposite to magnetization **M** in the domain under observation. The sketches on the figure show the mutual orientations of **M** and **H** vectors for the different magnetic-field regions. The insertions present a view of a domain structure in the region of observation. The squares on the right side of (a) and circles with a cross on the left one (b) mark the observation points and their sizes.

rotations was about 0.05 s of arc (sec arc). Experiments were carried out at room temperature in geometry $\mathbf{H}\|\mathbf{E}\|\mathbf{k}$, where $\mathbf{k}$ is a light wave vector.

Only the 2ω component of the EMOE signal was detected in our samples. So $\alpha_{\mathrm{EMO}}^{(2\omega)} \equiv \alpha_{\mathrm{EMO}}$. The linear EMOE was absent. The magnetic-field dependence of α_{EMO} measured in central sites of a separate domain is shown in Fig. 1. The positive sign of the magnetic field on the figure corresponds to the field orientation along the magnetization of the investigated domain. So, the right (a) and left (b) sides of the figure correspond to the H orientations opposite and along the magnetization at the observation site. Thus, the volume of domain under observation is decreasing with the growth of H absolute value or increasing with it in the cases shown on the right (a) or the left (b) sides of the figure. The results of visual inspection of the domain structure are also plotted.

We can note that the received dependence of α_{EMO} differs essentially from those reported earlier in Refs. 12,13. In those earlier papers, the EMOE from multidomain areas was investigated. We observed the following differences.

(i) At $\mathrm{H}=0$, the EMOE is nonzero at a single domain site.

(ii) The EMOE of a single domain site hardly depends on the applied magnetic field if the probing area remains securely within the domain at a sufficient distance from its borders.

(iii) For the magnetic field close to the field where the domains collapse, the EMO signal drastically increases and sharply drops practically to zero after it. In this case, the residual area of the domain is commensurable with the probing area, and the probing site will contain DWs. It is worth noting that for our study of the EMOE of the single domain sites, the probing point was being moved after each change of the dc magnetic field so that the probing area would not contain any DWs and the direction of the magnetization in the probing area would not change in all cases except the transition through the field of domain collapse.

(iv) For the large fields, the film magnetization saturates and the EMO signal sharply decreases to values close to zero. The domain whose volume decreased [Fig. 1(a)] has disappeared. Let us note that in former investigations of multidomain areas,[12,13] it was shown that the EMOE decreased up to zero in large magnetic field too. But in the cases of their investigations, this transition was more fluently due to a distribution of the domain collapse fields of the different domains.

The unexpected result was obtained in the case of domains with the magnetization direction along the applied magnetic field and it has a special interest, from our point of view. The volume of this domain grows with the increase of H [Fig. 1(b)] and its magnetization value should not be changed noticeably at the magnetic field $\mathrm{H}\approx 160$–200 Oe, which induces the transition of the YIG film to the homogeneous magnetization. Nevertheless, a drastic decrease of the α_{EMO} value takes place in this magnetic-field range [Fig. 1(b)]. No maximum was observed, though.

One can see from Fig. 1(b) that the magnetic-field dependencies of α_{EMO} in the magnetic-field region 150–200 Oe are essentially different for different locations of the probing area with respect to the DW. So, the measurements with the placement of a laser beam in the domain with magnetization along the H nearby to the "nonpinned" DW of the residual domain with opposite magnetization, which is in a state close to a collapse, reveal the $\alpha_{\mathrm{EMO}}(\mathrm{H})$ dependence, which has a narrow area of a sharp reduction of an α_{EMO} value in the H field. The displacement of the probing beam from the residual domain leads to the more gradual expansion of an area where the α_{EMO} value depends on H. The smoother character of the magnetic-field dependence α_{EMO} takes place at further deposition of a laser beam from the residual domain. Such properties of the $\alpha_{\mathrm{EMO}}(\mathrm{H})$ are probably connected to the changes of the local value of demagnetizing fields in the areas close to a residual domain due to the features of formation of demagnetizing fields in a thin film. Let us notice that the Faraday effect (FE) on the probed site of a film feels not only the magnetization M of this site, which does not change, but also feels an averaged local value of field $\mathrm{H}_{\mathrm{int}}$, which depends on the local demagnetizing fields. And, most likely, just this component of FE is modulated by the enclosed variable electric field $\mathrm{E}_{\sim}$.

Thus, for the separate domains with both signs of magnetization with respect to the H-field direction, the essential dependence of the EMO signal on H is observed only in the narrow areas of the magnetic field close to the magnetic film transition to homogeneous magnetization. The measurements carried out for the many different separated domains gave quite close results (with taking into account the sign of the domain magnetization). That allows us to define, at least qualitatively, a full cycle of magnetic-field dependence for EMOE from saturation of one sign of magnetization to saturation of the other one and in the opposite direction. The specified dependence as a qualitative figure is shown in Fig. 2 (where arrows show the direction of the magnetic-field changes in each of the measurement stages). The mutual ori-

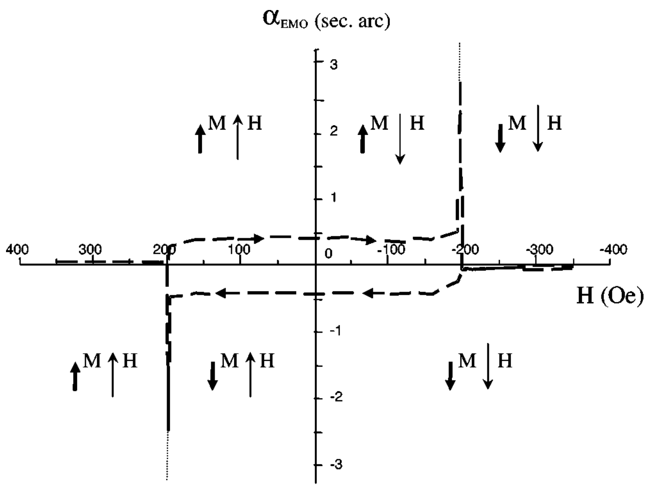

FIG. 2. The magnetic-field dependence of EMOE in a full cycle of the domain remagnetization (qualitative picture). The arrows on the curves show the path-tracing direction of the magnetic field changing. The sketches on the figure show the mutual orientations of **M** and **H** vectors for the different magnetic-field regions.

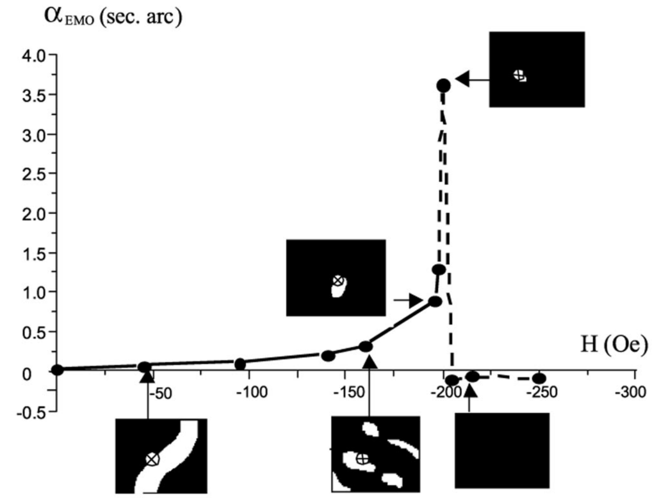

FIG. 3. The magnetic-field dependence of the EMOE measured on the film region with a domain wall in the different stage of the domain decreasing up to the full collapsing.

entations of M and H vectors for different regions of magnetic field in this cycle are shown in the figure by sketches.

One can see from Fig. 1 that the influence of the $E_\sim$ field on the saturated magnetic state of the investigated YIG film is very small $[\alpha_{EMO}=(\vec{H}/|\vec{H}|)0.05\pm0.05]$. And the variation of it with the field (in the field range of the measurements) is smaller than the measurement sensitivity of the setup. It is much smaller in comparison to the α_{EMO} value in the multidomain state ($|\alpha_{EMO}|\approx 0,42$ sec arc at $|H|<100$ Oe). Let us note that the signs of the EMO signal, which are given in Fig. 1 and later figures, are relative. In all the cases, the defined sign corresponds to the same relation of the phases of signal and of the second harmonic of an ac E field. Unfortunately, we have not determined the absolute sign of it.

The EMO signal does not change with the further increasing of field H (as the minimum in the limits of field used in our experiments). Registration of the EMO signal on the central site of the domain (area with homogeneous magnetization) has also shown an independence of EMOE from the external field H. Thus, the results of the above experiments reveal that external field $E_\sim$ noticeably contributes to the magneto-optical FE on sites of YIG film with homogeneous magnetization inside the separate domains only in the case of the simultaneous presence of domains with opposite orientations of the magnetization. The electric field practically does not influence the FE if the whole sample is in the one-domain state. Let us also note that only fields with H $\ll 4\pi$M were used in our investigation (the typical value of 4πM for YIG at room temperature is about 1700 G). That is, the influence of field H on this site was defined first of all by the reorganization of the domain structure and by the change of local corrections to the M value. So, these local corrections basically define the FE changes, and only the contribution to the macroscopically average field H_{int} depending on the local demagnetizing fields on a site under investigation turns out to be sensitive to the E field.

We already noted that the essential influence of the variable electric field E(t) on the magneto-optical FE for the YIG film takes place only in the presence of a domain structure in the film. It practically vanishes after magnetic saturation of the film. When taking this into account, one can expect an influence of DW motion (or changing of DW width) on the value of the EMO signal under the action of ac electrical and dc magnetic fields. We do not mean to discuss the role of the domain wall's oscillations, which have frequencies much higher than the frequency of our ac E field. But we would like to pay attention to the possible DW displacement or changing of DW width under E-field action. In the range of our ac E-field frequency, these processes should be quasistatic and one should not expect any frequency dependence for it. Therefore, we have not carried out any experiments for investigation of EMOE as a function of the ac E-field frequency.

For the experimental check of this hypothesis, a few of the EMO measurements at different values of the magnetic field have been carried out on small areas ($\varnothing\approx 3\ \mu$m) of the film, which include a DW. The opportunity of scanning a film surface with a diaphragm was used for it. It is clear that the value of α_{EMO} obtained in these measurements reflects a change of the average (on the light spot area) Faraday rotation of the light polarization plane due to action of the E-field.

One of the magnetic-field dependencies of EMOE that was obtained in such a way is shown in Fig. 3. One can see that the average α_{EMO} from the DW-containing area is close to zero (but not zero) in the absence of an external magnetic field. In a range of the magnetic-field change from 10 to 150–160 Oe, the α_{EMO} value was increasing approximately linearly with the magnetic field. In the range of $170<$H <190 Oe, a sharp increase of α_{EMO} was observed. Further observation was not carried out, taking into account that the linear sizes of the residual domain in the specified fields ($\sim$2 μm) become close to the diameter of the probing optical beam. The dashed line in Fig. 3 shows a total signal in the region of the film transition to the state with saturated magnetization. Thus, the given experiment shows that the

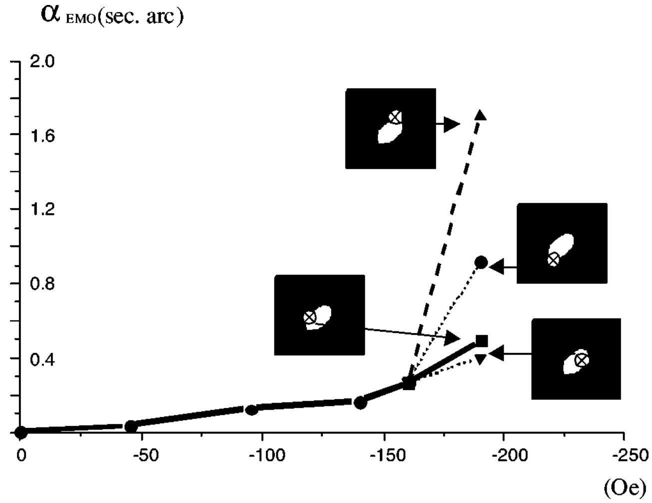

FIG. 4. The changes of the magnetic-field dependencies of EMOE for the different sites of a domain wall in the magnetic fields close to the domain collapse.

"activators" of the peculiarities of EMOE magnetic-field dependencies in the considered geometry of the experiment ($\mathbf{E}\|\mathbf{H}\|\mathbf{k}$) are DW movements caused by an electric field, and/or changes of the internal structure of DW (Ref. 14) in external magnetic field under action of the electrical fields.

The results of scanning of the different sites of DW with a diaphragm for one of the domains at the fixed H=190 Oe are presented in Fig. 4. As one can see, the sharp increase of an EMO signal occurs only at part of the DW sites. We have established by means of visual control of the domain structure that the maximum of an EMO signal corresponds to the cases of the probing beam getting into the places close to the points of DW pinning (probably on the defect) in the domain precollapse magnetic field.

Similar measurements for the neighboring domains have shown qualitative compliance of the results with the submitted ones in Figs. 1–4. The only difference is that for several domains it was not possible to register the sharp increase of an EMO signal at any region of DW in their precollapse state. One of the possible explanations of this fact may be the absence of the pinning places of the given domain DW on defects.

Thus, the set of revealed features of EMOE in our thin YIG films allows us to conclude that magnetization M, which mainly defines the light polarization plane rotations, does not change under the E-field action. At the same time, the E-field action leads to a small changing ("breathing") of domain-wall positions or theirs width. This "breathing" of DW influences the value of magneto-optical FE due to its proportionality to a local magnetic induction **B** in the testing area. The local internal magnetic field H_{int}, which along with $4\pi M$ enters into the expression for B_{loc}, depends on demagnetizing fields. In the case of a thin multidomain film, the demagnetizing field is nonhomogeneous and its local values are sensitive to an arrangement of domain borders in the surrounding testing area. The DW "breathing" influence on the local value of the demagnetizing field is especially essential in a precollapse state of the domain, which has decreased at the enclosed magnetic field H, around the point of pinning.

The reason for the DW "breathing" under the E field's action can be understood by taking into account that the average sizes of the domains are usually inversely proportional to the certain degree of a constant of magnetic anisotropy.[15] Thus, DWs will change their position and/or width at constant magnetization M in the case when an electric field E changes the value of magnetic anisotropy of the film.[16] And this E-field influence on magnetic anisotropy is responsible for a "breathing" of the DW that causes the observed EMOE. Our inference about a determinative role of anisotropy changes in the EMOE corresponds to the guess in Ref. 17 about an anisotropy change in YIG under an E-field action due to the ME interaction. In principle, changes of the crystal anisotropy may lead to changes of the Faraday rotation besides those caused by the modification of local induction due to the crystal anisotropy influence on the domain (a domain wall) structure. Apparently, those changes are less than the sensitivity of our setup.

The lowest contribution by degree of magnetization to the thermodynamic potential of ferrimagnets, which describes a magnetic anisotropy, is proportional to M_z^2. That means that the ME contribution, which is responsible for the observed effect, must be square law on M or on B. The observed EMOE in our case is quadratic on E. Thus, we should conclude that the corresponding contribution to the ME effect must be proportional to E^2B^2 or E^2M^2.

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