ELECTRO-MAGNETO-OPTICAL EFFECTS ON LOCAL AREAS OF FERRITE-GARNET FILMS

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The electro-magneto-optical (EMO) effect from separate magnetic domains is investigated in the epitaxial films of yttrium-ferrite-garnet with the simultaneous visual control over the film domain structure. The existence of local EMO effects from separate domains and from the sites with a domain wall is shown. The differences between the effects from a multidomain area of a film and local effects are revealed. It is shown that a value of the intradomain EMO effect for a domain magnetized along the applied magnetic field is decreased drastically in the magnetization stage connected with vanishing the domains with opposite signs of magnetization. In a homogeneously magnetized film, the EMO effect is practically absent. It is concluded that an electric field does not practically modify the film magnetization, and the local EMO effects are connected with the influence of the electric field on the magnetic anisotropy parameter of studied films.

The interest in the research of a behavior of magneto-ordered substances in an electric field has considerably increased after the opening of the magneto-electric (ME) effect in crystals of antiferromagnetic Cr_2O_3 by Astrov [1]. One of the methods of the researches of ME phenomena is the electro-magneto-optical (EMO) effect [2] which consists in the registration of changes in the angle of a light polarization plane rotation in a magnetic field under the action of an external electric (E) field simultaneously applied to a crystal.

Earlier, the observations of both the EMO effect [2] squared in the E-field in yttrium-ferrite-garnet (YFG) single crystals and the effect linear in the E-field in YFG films were reported [3]. The last effect is forbidden for the centrosymmetrical cubic crystal structure of YFG. In [4], the EMO effect squared in the E-field in thin films of YFG was revealed at the sounding of a multidomain site of a film with a laser beam. The EMO signal received in such a way was considered as some average light polarization plane rotation in the sounded area.

The goal of this study was a further experimental investigation of the EMO effect in ferrite garnets, in particular, EMO effects at local sites [the domain or the area of domain walls (DW)] on ferrite - garnet films. The measurements were conducted simultaneously with the visual observation of the sites of a film that were scanned with a laser beam. Such a statement of the problem is caused by the fact that a change of magnetooptical characteristics under the action of an external electric field E can take place both in the multidomain and one-domain cases. But, taking into account that the effect can be proportional not only to H (or M), but also to magnetic induction B_{loc}, a change of magnetooptical characteristics under the action of an electric field E will not be the same in different domains. Thus, at the local optical sounding of a film, the Faraday rotation angle of the light polarization plane which passes through a separate domain will be proportional to $\alpha_{\text{F}} \sim a_1 M + a_2 B_{\text{loc}}$, where $B_{\text{loc}} = H_{\text{int}} + 4\pi M$ and H_{int} is the internal magnetic field intensity in the domain under study that differs from the applied external field taking into account the demagnetization field [5].

Experimental Setting

The scheme of a laser polarimeter is considered in [4] in detail. To the scheme, we added a round diaphragm with a diameter of about 0.25 mm, which allowed us to separate sites of the film whose diameter is about 3 microns; the acousto-optical modulator; a translucent mirror for the formation of a light beam which is used for visual supervisions, and a polarizing microscope for carrying out the visual supervision over the domain structure of a sample. Such a scheme allows us to

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conduct the measurements of light polarization plane rotation angles $\alpha_{\rm EMO}$ that are the results of the action of magnetic H and electric E fields on the sample. A variable voltage $U_\sim$ of up to 2 kV was put on to the samples at a frequency of 800 Hz. The research was carried out simultaneously at the basic ω and doubled 2ω frequencies of the electric field using a helium — neon laser (λ = 0.63 microns). The sensitivity of the setup in the measurements of polarization plane rotations was about 0.05 angular seconds. Experiments were carried out at room temperature in the geometry **H** || **E** || **k**, where **k** is a wave vector of light, on ferrite — garnets samples. The magneto-optical measurements preliminary carried out for these samples with visualization of the domain structure have shown that the typical thickness of the films was about 7 microns, and the width of domains at a zero magnetic field was about 15 microns. Thus, separating a site 3 microns in diameter with a diaphragm, we can conduct the research in individual domains, but cannot investigate the sites which are located inside a DW. Th measuring setup allows us to separate the film site through which a DW passes by dividing it on equal, or not equal parts.

Experimental Results

Earlier, we revealed the EMO effect squared in the electric field in ferrite-garnet films during the sounding of rather big sites of a sample with a laser beam [4]. The results make it possible to conclude that at least some of the film's sites have centrosymmetric structure which is typical of monocrystalline ferrite-garnet [2]. The specified experiments were conducted without visual supervision. In this case, we investigated the film sites which can cover several magnetic domains. The improvement of the experimental setup allows us to carry out not the "averaged" and poorly informative measurements of light polarization plane rotations in H and E fields, but to study local EMO effects from separate domains and the sites of a film which contain DWs with carrying out the visual supervision.

In Fig. 1, the experimental dependence of $\alpha_{\rm EMO}$ on the magnetic field intensity at the central site of a separate domain whose volume decreases with the growth of H is given along with the results of the visual supervision for several points. It is seen that the dependence basically differs from the results earlier derived by us [4]. It is possible to underline the following essential differences:

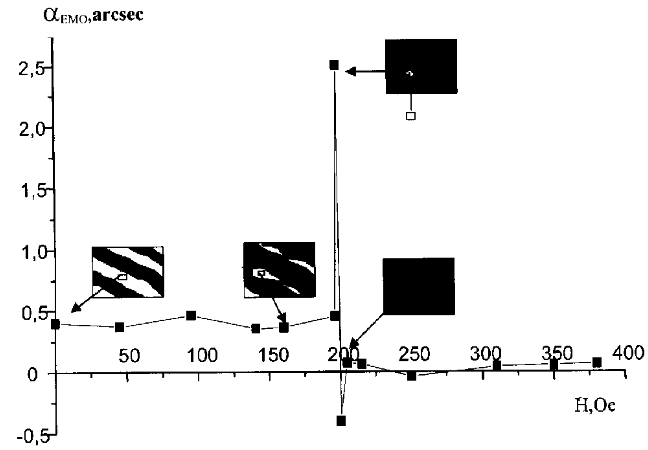

Fig. 1. Dependence of the EMO effect on H for a domain whose volume decreases with increase in the magnetic field H

1) At H = 0, the EMO effect is observed in the domain.

2) The EMO effect in the domain almost is not changed in a wide range of changes of the magnetic field, while the sounded area is confidently within the scope of the domain at a sufficient distance from its borders.

3) In the region of the maximum EMO effect from a multidomain site, the "one-domain" effect from a domain whose volume decreases is drastically grows. In this case, the residual area of the domain is commensurable with the sounded area, and, at the maximum values of the effect, a DW also gets in the sounded area. Upon the research of the EMO effects in a separate domain, the measurements were carried out in such a way when the sounding point was moved all the time to be in the residual area of the researched domain. If the sounding point is not displaced, the effect periodically change a sign on the opposite one due to the displacement of a DW in a magnetic field and as a result of the replacement of the domain with the opposite direction of magnetization M to the sounded area.

4) In the fields of transition to the mode of magnetic saturation, the value of the EMO effect is smoothly decreased to zero for multidomain sites, whereas the effect has sharply decreased to values close to zero for a separate domain. In this case, the domain whose volume is decreased has disappeared. Therefore, the further sounding took place in the area with a homogeneous magnetization of the opposite direction.

Having changed the direction of the field **H** to opposite and considered the central area of a domain whose volume now grows with H (that is, the distance between the sounding site and a DW increases all the time), we have also revealed the EMO effect (Fig. 2) in a zero magnetic field and on the section of the curve

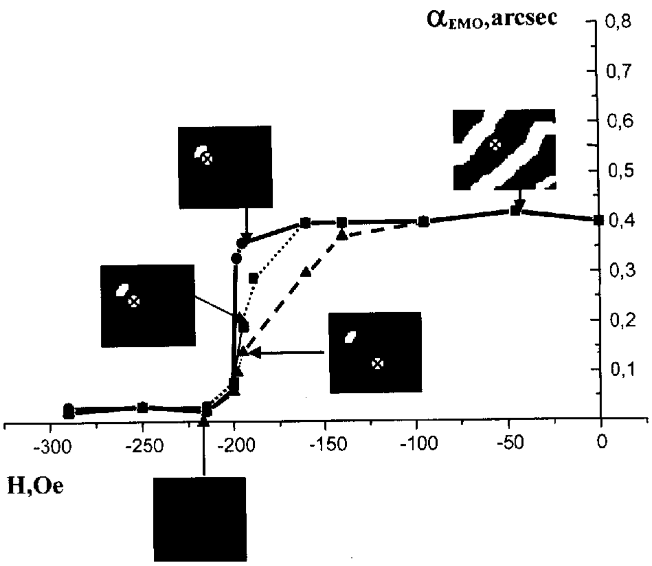

Fig. 2. Dependence of the EMO effect on H for a domain whose volume increase with the magnetic field H

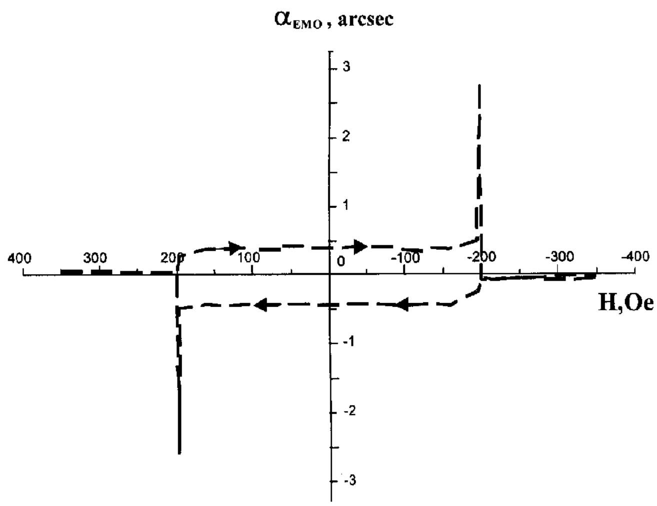

Fig. 3. Complete cycle of the qualitative dependence of the EMO-effect on H in a domain

of magnetization where there are the displacements of DWs. At the transition to the mode of rotation of the magnetization for other, next domains, the effect also drastically decreases. For the saturated sample, we observe not the increase of the EMO effect, but, vice verse, its sharp falling practically to zero. As can be seen from the plots in Fig. 2, the dependence of $\alpha_{\rm EMO}$ on H is essentially changed at the scanning of different sites of the considered domain with a laser beam in the H-field region $H \approx 150 \div 200$ Oe. So, in particular, the measurements with the displacement of a laser beam along a site of a residual domain (which comes nearer to a collapse) without "clinging" the DW (Fig. 2) gave the $\alpha_{\rm EMO}(H)$ dependence which has a narrow area of the sharp reduction. During the removal of a probing beam from the residual domain whose sign is opposite to the researched domain, the gradual expansion of the area with the $\alpha_{\rm EMO}$ dependence on H is observed. The farther a laser beam from the residual domain, the smoother is the dependence on H. Such a difference in the dependences on H is probably connected to the changes of demagnetizing fields, as a result of the features of the formation of demagnetizing fields in thin films. It is worth noting that the Faraday effect on the probed site of a film feels not only magnetization M of this site which is not changed, but also the average macroscopic field $H_{\rm int}$ which depends on demagnetizing fields. Namely this component of the Faraday effect is modulated by the applied variable electric field E.

Thus, for a separate domain, the essential dependence of the EMO signal on H is observed only in the narrow area of values of the magnetic field H. The experiments like this for the adjacent domains gave quite close results (with regard for the sign of the domain), which allows one to reproduce, at least qualitative, a full cycle of the dependence of the EMO effect on H from the saturation "–" to the saturation "+" and in the opposite direction for the measurement conditions mentioned above. The corresponding qualitative dependence is shown in Fig. 3.

From the analysis of the plots in Figs. 1 and 2, it is seen that the influence of the field $E_\sim$ on the magnetic state of a saturated film is slight ($\alpha_{\rm EMO} \approx$ 0.08 ang.sec.). With a further increase of the field H in the scope used in the experiment, the EMO signal is not changed. The registration of the EMO signal on the central site of a domain (the area with homogeneous magnetization) has also shown the independence of the EMO effect on the external field H. But the polarization plane rotation angle is essentially greater ($\alpha_{\rm EMO} \approx$ 1 ang.sec.) in comparison to the saturated sample. Thus, the experiments considered above reveal that the external field $E_\sim$ additionally contributes to the magneto-optical Faraday effect on sites of a film with homogeneous magnetization in case where the film also contains domains with the opposite orientation. This contribution is practically absent if the whole sample is in the one-domain state. In experiments, we used the fields $H \ll 4\pi M$. That is, the influence of the field H on this site was manifested, first of all, in the reorganization of a domain structure and in the change of a local value M which mainly defines the Faraday effect. Only the

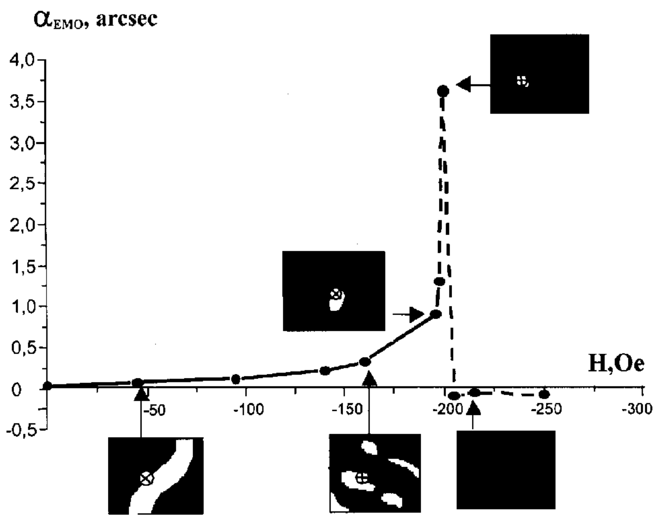

Fig. 4. Dependence of the EMO effect on H on the site of a film with a DW

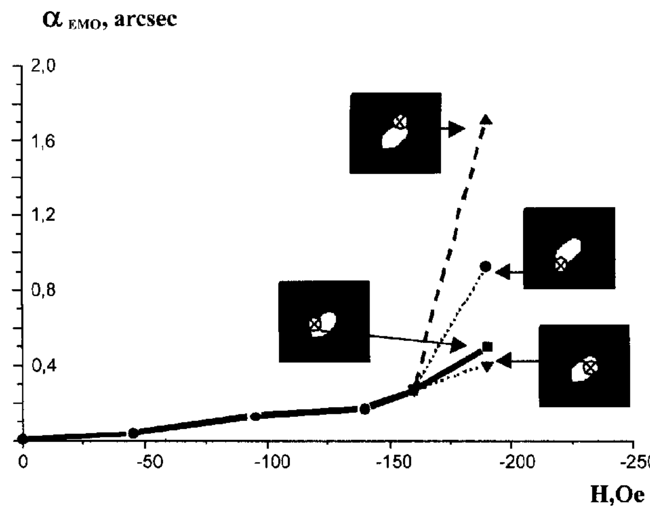

Fig. 5. Dependence of the EMO effect on H for various sites of a DW

part of the macroscopic average field H related to demagnetizing fields on a site under investigation turns out to be sensitive to the field E and to define the EMO effect and its dependence on the magnetic field.

At the same time, it is seen from the plots in Figs. 1 and 2 that the essential influence of a variable electric field $E(t)$ on the magneto-optical Faraday effect takes place for a garnet film only at the presence of a domain structure in the film, up to the magnetic saturation. Based on this fact, it is possible to foresee a possible influence of dynamic manifestations of a DW on the EMO signal under the action of external fields $E(t)$ and H. For the experimental check of the given assumption, a number of researches of EMO-manifestations was carried out on the small sites (∅ ≈3 microns) of films with a DW at different values of H, taking into account the opportunity of the scanning with a diaphragm on the surface of a film.

In Fig. 4, one of the derived dependences of the EMO effect on H is shown. It is seen from the plot that $\alpha_{\rm EMO}$ from the site with a DW in the absence of an external magnetic influence is close to zero (but it is not zero). In the range of H from 10 to 150—160 Oe (as seen from Fig. 1, the redistribution of domain's volumes occurs in this range), we observe the EMO effect whose value increase approximately linearly with the magnetic field H. In the range of H from 170 up to 190 Oe, a sharp increase of the influence of the field $E_{\sim}$ on the magnetic state of the studied site was observed. The further observation of a DW was not carried out with regard for that the diameter of a domain in the mentioned fields (∼2 microns) becomes commensurable to the spatial resolution of the optical part of the experimental setup (the dashed line in Fig. 4 is the total signal upon the film transition to the saturated state). Thus, the given experiment demonstrates the essential dependence of an EMO signal on the external field H in the presence of a DW in the sounded area. Possible "activators" of the given effect in the considered geometry of the experiment ($\mathbf{E} \parallel \mathbf{H} \parallel \mathbf{k}$) are the movement of a DW caused by the electric field and a change of the internal structure of a DW [6] in external fields H and E.

In Fig. 5, we present the results of the scanning of different sites of a DW with a diaphragm for the considered domain at H = 190 Oe. It is seen from the plot that the sharp increase of an EMO signal occurs not at all sites of the DW. This means that the maximum of an EMO signal is a manifestation of the probing beam getting into the place of fastening the DW of a precollapsing domain on a defect.

Similar measurements on the adjacent domains have shown a qualitative agreement of the results with the dependences presented in Figs. 1—5. One difference lies in that we failed to register the sharp increase of an EMO signal at the domain site with a DW in a precollapsing domain in the case of several domains, which can explained by the fact that a probing laser beam does not hit a pinning place of the given DW on a defect. When the conditions of similar experiments were changed so that the geometry $\mathbf{H} \parallel \mathbf{E} \parallel \mathbf{k}$ was used, no manifestations of the EMO effect were registered on a film site with a DW.

Thus, the totality of the revealed features of the EMO effect in thin YFG films allows us to conclude that the magnetization M that mainly defines the light polarization plane rotation is not changed under the action of the E field. The positions of domain walls are "breathing" especially in the precollapsing state of a domain which has decreased at the applied magnetic field H around the point of pinning. This "breathing" of a DW influences the magneto-optical Faraday effect due to its proportionality to the average magnetic induction B in the observed area, and the expression for B along with $4\pi M$ includes the average internal magnetic field H_{int}. The last depends on the demagnetizing fields sensitive (in the case of a thin ferrimagnetic film) to the arrangement of domain borders in a neighborhood of the observed area.

The described situation can be understood if we take into consideration that the average sizes of domains usually are inversely proportional to a certain degree of the constant of magnetic anisotropy [7]. Thus, DWs will "breathe" at a constant magnetization M in the case where the electric field E changes the magnetic anisotropy of a film [8]. Our conclusion about the determining role of an anisotropy change in the EMO effect is coordinated with the known statements about that the field E transforms the anisotropy in the ME effect in ferrite garnets.

In the expression for the thermodynamic potential of ferrite, the contribution, which describes the anisotropy and is the lowest by the degree of magnetization, is proportional to M_z^2. That means that the component of the ME effect, which is responsible for the observed effect, must be squared in M or in B. The discussed effects are quadratic in E. So, it becomes clear that the components of the ME effect which are proportional to E^2B^2 or E^2M^2 are responsible for the E-field modulation of a magnetic anisotropy. This leads to the "breathing" of DWs, which causes, in turn, the observed EMO effects.

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ЕЛЕКТРОМАГНІТООПТИЧНІ ЕФЕКТИ НА ЛОКАЛЬНИХ ДІЛЯНКАХ ФЕРИТ-ГРАНАТОВИХ ПЛІВОК

В.Є. Короновський

Р е з ю м е

В епітаксіальних плівках ітрійферит-гранатів досліджувався електромагнітооптичний (ЕМО) ефект від окремих доменів з проведенням візуальних спостережень за доменною структурою. Показано існування локальних ЕМО-ефектів від окремих доменів та ділянок з доменною стінкою (ДС). Виявлено принципові відмінності між ЕМО-ефектами від багатодоменної ділянки плівки та локальними ефектами. Розглянуто вплив доменної стінки на величину ЕМО-ефекту в різних режимах намагнічування.