

Non linear electromagneto-optical effect in epitaxial films of yttrium iron garnet

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The magneto-electric effect has been studied both in multidomain areas and in local areas of single domains in epitaxial films of yttrium iron garnet using optical polarimetry method. The effect has been revealed to met a square law with respect to electric field and its magnetic field dependences have been investigated. Local effects from single magnetic domains have been registered and it has been found that those are defined by local distributions of magnetic induction in the probing points. It has been shown that the film magnetization remains unchanged due to application of an external electric field, and the revealed features of magnetic field dependences are caused by the domain film structure sensitivity to changes in magnetic anisotropy induced by an external electric field.

Методом оптической поляриметрии исследован магнитоэлектрический эффект как на многодоменных участках так и в локальных областях отдельных доменов эпитаксиальных пленок иттрий-феррит-гранатов. Выявлен квадратичный по электрическому полю эффект, исследованы его магнитополевые зависимости. Зарегистрированы локальные эффекты от отдельных магнитных доменов и показано, что они определяются локальными распределениями магнитной индукции в точках зондирования. Показано, что намагниченность пленки под действием внешнего электрического поля не изменяется, а выявленные особенности магнитополевых зависимостей обусловлены чувствительностью доменной структуры пленки к изменениям магнитной анизотропии, которые вызваны внешним электрическим полем.

The effect of magnetic state change of a solid under the action of an electric field predicted by Dzyaloshinsky, i.e., the magneto-electric effect (MEE), has been first revealed experimentally in Cr_2O_3 antiferromagnetic crystals, when an alternating magnetic moment arising in a sample subjected to an electric field was registered [1]. The first observation of the MEE in single crystals of yttrium iron garnet (YIG) was reported by O'Dell [2]. Now, numerous materials with MEE have been investigated [3–6]. In this work, presented are the MEE study results using optical polarimetry for epitaxial YIG films. The method consists in registration of changes in the light polarization plane rotation (Faraday rotation) due to an electric field applied to the crystal, that is referred to as "electro-magneto-optical effect" (EMOE) [7, 8].

The investigated epitaxial YIG films (five films) were deposited on a (111) type $Gd_3Ga_5O_{12}$ substrate of about 600 μm thickness. A preliminary magneto-optical investigation of the samples with visualization of the domain structure has shown that typical film thickness was about 7 μm, the domain width, about 15 μm at $H = 0$ and the domain wall width, about 0.5 μm. The domain magnetization was normal to the film plane. The experimental setup is a combination of a high-sensitive laser polarimeter and a polarizing microscope [9,10]. A variable voltage $U_{\sim}$ of 800 Hz frequency (ω) and up to 2 kV amplitude was applied to the sample. One optically transparent electrodes was placed on the YIG film surface while the other one, under the substrate. Assuming the static permittivities of the YIG and $Gd_3Ga_5O_{12}$ to be approximately the same, the applied ac field amplitude in the YIG film can be estimated to be 3.3 kV/cm. The experimental setup makes it possible to measure linear, $\alpha_{EMO}^{(\omega)}$, and non-linear, $\alpha_{EMO}^{(2\omega)}$, components of the electric field induced changes of the Faraday rotation. The measurements were done at the multidomain ares of a film and at single domain areas or at small areas that contained domain walls (DW). The ω and 2ω components of the angle changes correspond to the EMOE linear and quadratic with respect to electric field, respectively. A He–Ne laser (λ = 0.63 μm) was used. The setup includes a semi-transparent mirror to form a light beam which was used for visual inspection of the domain structure using a polarizing microscope. Such a scheme allows to measure both the rotation angle of light polarization plane in the magnetic field (**H**) and its change, α_{EMO}, caused by the electric field (**E**) applied to the sample. The polarization plane rotation measurement sensitivity was about 0.05 arc seconds (sec. arc). Experiments were carried out at room temperature in the **H** ‖ **E** ‖ **k** ‖ **n** geometry, where **k** is the light wave vector; **n**, normal to the surface vector.

Taking into account the center-symmetrical garnet structure, the MEE in ferrite garnets must be proportional to E^2, the effect linear with respect to the electric field being forbidden [2]. It is revealed experimentally by us that there is the quadratic EMOE law with respect to electric field in researched YIG films, although only linear (forbidden) EMOE [8] for YIG films was reported before. In Fig. 1, the dependence of α_{EMO} value on magnetic field is presented at probing of a multidomain film site by a laser beam. The effect was observed at electric field frequency of 2ω. In the inset in Fig. 1, the field dependence of magneto-optical Faraday effect (FE) is shown. When analyzing the presented dependences, it is seen that for epitaxial YIG film EMOE is absent at **H** = 0. In a magnetic field, the film magnetic state change under the electric field action has been revealed depending on **H**. Comparing the obtained plot with FE field dependence for the same sample (Fig. 1, inset), it is seen that the maximal influence of the electric field on the film magnetic state (α_{EMO} ~ 8 sec.arc) gets at the magnetization rotation area (area II in the inset to Fig. 1). In fields **H** > 220 Oe, i.e. at the film magnetic saturation, α_{EMO} decreases to the values close to zero, and at

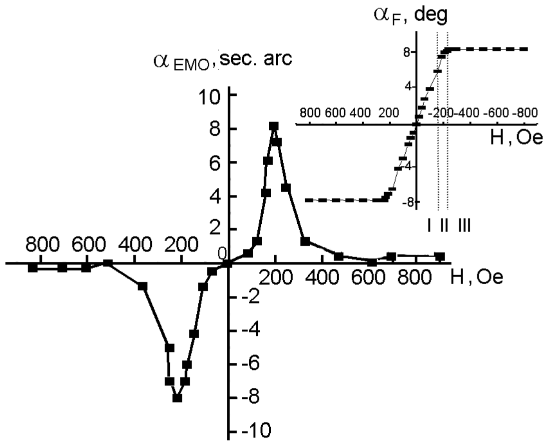

Fig. 1. Magnetic field dependence EMOE at optical probing of multidomain site of YIG film in geometry **H** ‖ **E** ‖ **k** ‖ *n*, where **k** is a light wave vector, **n** — normal to the surface vector. On the insert — the field dependence FE of a film in geometry **H** ‖ **k**.

further increase of magnetic field, the effect is not registered. It is typical of the obtained dependences that the change of signal phase at sign reversal of the external magnetic field. The researches conducted in **H** ⊥**E** ‖ **k** geometry have also shown a quadratic dependence of the EMOE. The ME coefficient corresponding to maximal EMOE has a value $\alpha_{ME} = 10^{-5}$.

The experiments specified above were carried out without any visual observations. The film areas were studied that could cover some domains and an average EMO signal from the optical probing area was considered. But the change of magneto-optical characteristics induced by an electric field may occur not only in a multidomain case, but also within a single domain, i.e. the measured effect may be proportional not only to **H** but also to $\mathbf{B}_{loc} = \mathbf{H}_{int} + 4\pi\mathbf{M}$ ($\mathbf{B}_{loc}$ is magnetic induction; $\mathbf{H}_{int}$, an internal magnetic field). Accordingly, the change of magneto-optical characteristics due to *E*-field may differ in different domains. Taking this into account, we have conducted a number of experiments to research EMOE from single domains with visual observations of domain structure. The use of a round diaphragm of about 0.25 mm diameter in our experimental setup made it possible to allocate the sites of a film of about 3 μm in diameter. Due to such allocating, we could measure the effect in single domain areas or in areas containing a DW.

Fig. 2 shows the magnetic-field dependences of EMOE measured in a central area

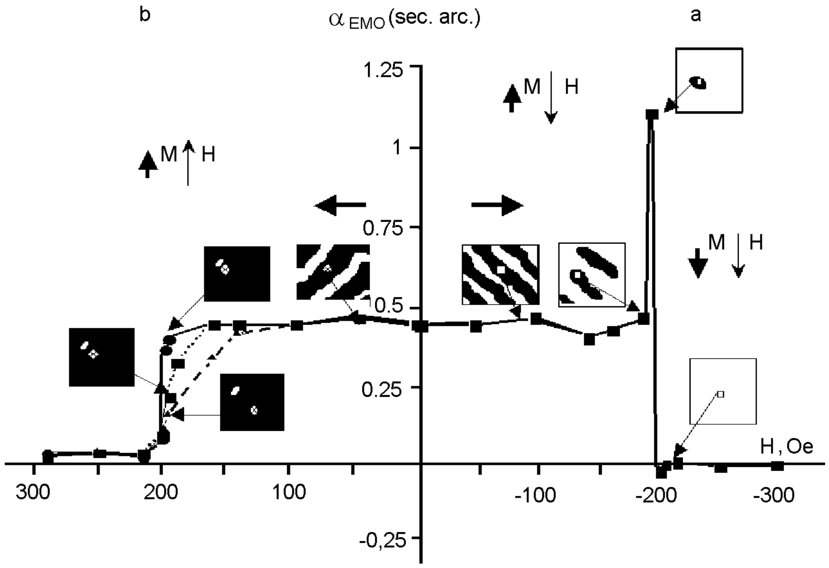

Fig. 2. Magnetic-field dependencies of EMOE measured on the domain, which decrease (a) or increase (b) their volume with growth of the magnetic field value, correspondingly. The positive and negative signs of the magnetic field correspond to the field direction along and opposite to magnetization in the domain under observation. The insertions present a view of a domain structure in region of observation. The sketches on the Figure show the mutual orientations of and vectors for the different magnetic field regions.

of a domain, the volume thereof decreasing (a) or increasing (b) as the magnetic field value increases or decreases, respectively. The results of visual observations for several points are presented. As is seen from the plots, EMOE at zero magnetic field is apparent (α_{EMO}≈0.45 s.arc) unlike the multidomain case. We explain that distinction by mutual compensation of the effects from single domains with the opposite signs getting into the probing zone of a multidomain area. The effect value in the domain remains practically constant in a wide **H** range (from −170 Oe up to +170 Oe). Perhaps a sudden change of α_{EMO} value at **H** = −190 Oe (Fig. 2a) is connected with the influence of domain boundary "breathing" in electric field for the domain which is in a pre-collapse state [10]. A specific attention should be given to Fig. 2b, where magnetic field dependences at probing with a laser beam (at fixed **H** values) of different zones in the domain (with volume increasing at given direction **H**) essentially differ in the character of α_{EMO} value changes in fields **H**≈150−200 Oe. This is a result of demagnetization field changes, since the Faraday rotation, α_F, of the light passeing through a single domain is proportional to $a_1 M_{loc} + a_2 B_{loc}$ (M_{loc} is local magnetization, a_1 and a_2 are certain coefficients). Here, $\mathbf{B}_{loc.} = \mathbf{H}_{int.loc.} + 4\pi\mathbf{M}_{loc}$ is local magnetic induction value and $\mathbf{H}_{int.loc.} = \mathbf{H}_{ext} - \mathbf{H}_{demag.}$, where $\mathbf{H}_{demag.}$ is the demagnetization field. Thus, the FE in the observed zone responses not only to magnetization **M** of this zone which practically does not change (what is evidenced by the EMOE value which is close to zero in the area of magnetic saturation, Fig. 2), but also to the macroscopical average field $\mathbf{H}_{int}$, that depends on demagnetization fields. It is just this FE component that is modulated by the variable electric field. That is, in fields **H** <<|4π**M**, the influence of **H** is defined first of all by reorganization of domain structure and by changing of local **M** value, which mainly defines EF. In this case, only a part of macroscopical average field **H** in the researched area connected with demagnetization fields appeared to be sensitive to the electric field. It is just that part that has defined the EMOE and its magnetic field dependence.

Thus, an essential influence of an alternating electric field on magneto-optical FE in YIG films is manifested only at presence of domain structure in the film. The applied external electric field modulates the factors depending on the arrangement and configuration of domain walls. The specified factors at constant **M** are defined by anisotropy characteristics, i.e. the described features of the *E*-field influence on magnetic state of YIG are possible to explain by changing of the film magnetic anisotropy in the electric field.

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Нелінійний електромагнітооптичний ефект в епітаксійних плівках ітрій-ферит-гранатів

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Методом оптичної поляриметрії досліджено магнітоелектричний ефект як на багатодоменних ділянках, так і в локальних областях окремих доменів епітаксійних плівок ітрій-ферит-гранатів. Виявлено квадратичний за електричним полем ефект, досліджено його магнітопольові залежності. Зареєстровано локальні ефекти на окремих магнітних доменах і показано, що вони визначаються локальними розподілами магнітної індукції у точках зондування. Показано, що намагніченість плівки під дією зовнішнього електричного поля не змінюється, а виявлені особливості магнітопольових залежностей обумовлені чутливістю доменної структури плівки до змін магнітної анізотропії, викликаних зовнішнім електричним полем.