THE EFFECT OF A MAGNETIC FIELD ON THE FARADAY EFFECT IN IRON GARNETS

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The influence of an external magnetic field of up to 34 kOe on the Faraday effect in yttrium and holmium iron garnets is studied for wavelengths from 1 to 4 μm. The relative change in the Faraday effect in $Y_3Fe_5O_{12}$ induced by a field in the magnetic saturation range is as great as in ferromagnetic d-metals. It is shown that this anomalous effect is not related to a change in magnetization of the sample but only to the gyroelectric part of the Faraday effect. Because of the increase in the para-process susceptibility, it is possible to observe in holmium iron garnet an effect in the gyromagnetic region which is related to variation of magnetization of the holmium sublattice.

In a previous paper[1] we showed that the effect of a magnetic field on the magnetooptic Kerr effect in ferromagnetic d-metals is anomalously large, the growth of the equatorial Kerr effect in the magnetic saturation region exceeding the corresponding increase of magnetization of the sample due to the para-process susceptibility 10–40 times. Thereafter, it was shown in[2] that the Faraday effect in yttrium iron garnet (at λ = 6328 Å) varies to approximately the same degree in an external magnetic field. In the visible, the Faraday effect in this substance is mainly connected with electronic transitions in the Fe^{3+} ions. However, already $\lambda > 3$ μm, where electronic transitions are absent, the rotation of the plane of light polarization has an altogether different physical origin.[3] In this region the Faraday effect is evoked by the precession of the magnetization vector of the sample at light frequencies, and its magnitude can be calculated quantitatively on the basis of the Landau-Lifshitz theory of ferromagnetic resonance. The aim of the present work was the study of the effect of a magnetic field on the Faraday effect in iron garnets in the transition region from 1 to 4 μm, where the effect changes from gyroelectric (electronic transitions) to gyromagnetic (precession of the magnetization vector).

To measure the Faraday effect at room temperature we built the compensation apparatus schematically represented in Fig. 1. The nature of working with high magnetic fields and the necessity of registering small changes in the Faraday effect required careful screening of all electric fields, isolating the detector circuits from the electromagnet, stabilizing the light source, etc. The magnetic field was provided by an FL-2 electromagnet with a pole gap of 10 mm. The analyzer was oriented at an angle of 45° to the polarizer in order to obtain the maximum change in the intensity of the light passing through the polarizer-sample-analyzer system, due to the Faraday rotation of the plane of polarization α_F when the magnetic field was reversed. The light source was either an incandescent lamp or a globar, and the detectors were an FDK-1 silicon photodiode, an FD-1 germanium photodiode, a PbS photoresistor, and a cooled InSb photodiode. The ranges of maximum sensitivity of these detectors in combination with light filters and with the transmissivity of the sample taken into account was specified by the following wavelength intervals, at the ends of which the transmitted light intensity decreased by a half: 1 ± 0.2, 1.5 ± 0.2, 2.1 ± 0.4, and 4.5 ± 0.8 μm. The investigated samples were in the form of thin polished platelets cut from

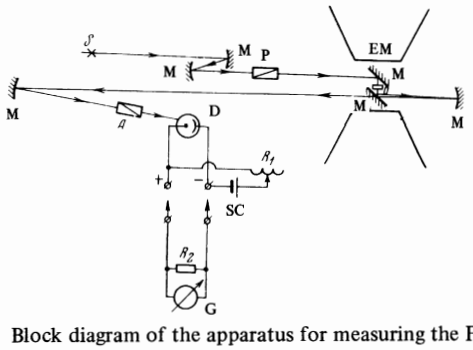

FIG. 1. Block diagram of the apparatus for measuring the Faraday effect in magnetic fields up to 34 kOe. S – light source, M – mirror, P – polarizer, EM – electromagnet, O – sample, A – analyzer, D – detector, SC – standard cell, G – M21/3 galvanometer, R_1, R_2 – variable resistors.

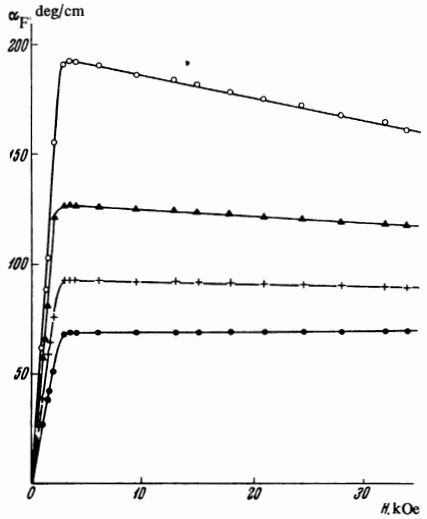

FIG. 2. Field dependence of the Faraday effect in yttrium iron garnet. The four curves correspond respectively to λ = 4.5 ± 0.8, 2.1 ± 0.4, 1.5 ± 0.2, 1.0 ± 0.2 μm (from bottom up). Sample thickness, 120 μm.

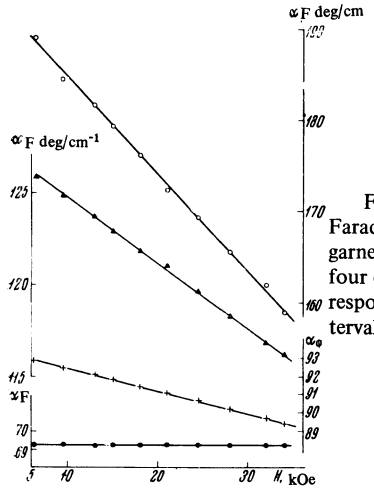

FIG. 3. Field dependence of the Faraday effect for yttrium iron garnet in the para-process region. The four curves (from bottom up) correspond to the same wavelength intervals as in Fig. 1.

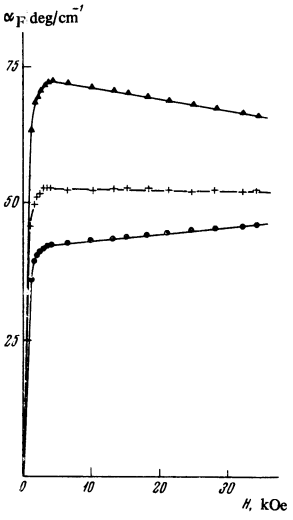

FIG. 4. Field dependence of the Faraday effect in holmium iron garnet. The three curves correspond respectively to $\lambda = 4.5 \pm 0.8$, 2.1 ± 0.4, 1.5 ± 0.2 μm (from bottom up).

single crystals of yttrium and holmium iron garnets.

The experimental curves of the dependence of the Faraday effect on the applied magnetic field for one of the samples of yttrium iron garnet are given in Fig. 2. Each experimental point represents the mean of 40 readings obtained upon reversing the magnetic field. The measurement error nowhere exceeded 0.5%. In all, we measured four samples with thicknesses 2.3 mm, 400, 120, and 75 μm (because of the low intensity of transmitted light, measurements at $\lambda = 1$ μm were not made on the sample with d = 2.3 mm). Figure 3 shows in enlarged scale the data for the yttrium iron garnet in the region of magnetic saturation, obtained by averaging the experimental values of α_F for the aforementioned four samples. The method of least squares was used to obtain the extrapolated values $\alpha_F^s = \alpha_F^{H \to 0}$, as well as the slopes of the linear portions $\xi = (1/\alpha_F^s)\,\Delta\alpha_F/\Delta H$ (see table). The error in measuring α_F is not indicated in the table, since in each case the measurement pertains to a wide wavelength interval in which α_F varies nonlinearly.

The results obtained shows that ξ decreases with increasing wavelength, and goes to zero at $\lambda = 4.5$ μm. The vanishing of ξ in this wavelength region is easily explained by considering that the gyromagnetic Faraday

Effect of a magnetic field on the Faraday effect in 1/3 Fe_5O_{12}

λ, μm	α_F^s, deg/cm^{-1}	$\xi = \frac{1}{\alpha_F^s}\frac{\Delta\alpha_F}{\Delta H}$, % kOe^{-1}	$\xi_{el}\frac{1}{\alpha_F^{el}}\frac{\Delta\alpha_\Phi}{\Delta H}$, % kOe^{-1}
1,0±0.2	195	—0,54±0,03	—0,8
1,5±0,2	128	—0,27±0,03	—0,53
2,1±0,4	94	—0,13±0,03	—0,4
4,5±0,8	69	0 ±0,03	—

effect for yttrium iron garnet is determined by the following formula[3]:

$$\alpha_F = \frac{2\pi\sqrt{\varepsilon}}{c}\gamma I_s,$$

where ϵ is the dielectric constant, γ is the gyromagnetic ratio, and I_S is the saturation magnetization. Consequently, in the given case

$$\xi_{mag} = \frac{1}{\alpha_F^s}\frac{\Delta\alpha_F}{\Delta H} = \frac{1}{I_s}\frac{\Delta I}{\Delta H} = \frac{\varkappa_p}{I_s}.$$

Using Anderson's[4] values for κ_p and I_S, we obtain $\xi_{mag} \approx 0.04\%/\text{kOe}$ for $Y_3Fe_5O_{12}$, i.e., a value that is practically at the limits of experimental error. Moreover, the residue of the gyroelectric Faraday effect in the vicinity of 4.5 μm should lead to compensation of ξ_{mag}, since ξ_{el} has a negative sign (see table). The last column of the table gives the values of $\xi_{el} = (1/\alpha_F^{el})\,\Delta\alpha_F^{el}/\Delta H$ obtained under the assumptions that $\alpha_F^s = \alpha_F^{el} + \alpha_F^{mag}$, the external magnetic field acts only on α_F^{el}, and $\alpha_F^{mag} = 63$ deg/cm and is independent of wavelength.[3] Thus, as the role of the electronic transitions becomes important, ξ increases and reaches values of the order of those for ferromagnetic d-metals. The coefficient $k_\alpha = |\xi_{el} I/\kappa|$, which characterizes the ratio of the slope of the linear portions of α_F to the slope of the magnetization in the para-process region is approximately 20 at 1 μm; therefore it is impossible to explain the experimentally observed field dependence of the Faraday effect in yttrium iron garnet by the change in magnetization.

An effect of the magnetic field on the Faraday effect directly associated with a change of magnetization in the region of magnetic saturation was found by measuring ξ in holmium iron garnet in the gyromagnetic region. In ferrite-garnets with rare-earth sublattices, κ_p increases sharply because the exchange field acting on the rare-earth sublattice is markedly smaller than interaction field of the iron sublattices. For example, for the holmium garnet $\kappa_p = (1.3 \pm 0.2) \times 10^{-4}$ cm^3/g,[1)] i.e., an order of magnitude greater than for $Y_3Fe_5O_{12}$, which should lead to a corresponding increase in ξ_{mag}. The quantity α_F in this case is determined by the following formula[3]:

$$\alpha_F = \frac{2\pi\sqrt{\varepsilon}}{c}(\gamma_1 I_1 - \gamma_2 I_2),$$

where I_1 is the total magnetization of the two iron sublattices, which we set equal to the magnetization of yttrium iron garnet, I_2 is the magnetization of the rare-earth sublattice, and γ_1 and γ_2 are the respective gyromagnetic ratios. Presuming that the susceptibility of the garnet is predominantly due to a change

[1)] The para-process susceptibility κ_p for holmium iron garnet was measured by G. A. Yarkho.

in I_2, i.e., $\kappa_p = 1.3 \times 10^{-4} = \Delta I_2/\Delta H$, and using the above formula for α_F^{mag}, we find $\xi_{mag} \approx 0.4\%/kOe$.

Figure 4 shows the experimental $\alpha_F(H)$ curves obtained on a platelet of holmium garnet 435 μm thick. The values of ξ in %/kOe calculated from the slope of the linear portions of α_F in the saturation region for $\lambda = 1.5 \pm 0.2$, 2.1 ± 0.4, and 4.5 ± 0.8 μm are equal respectively to -0.28 ± 0.03 ($\alpha_F^S = 73$ deg/cm), 0 ± 0.03 ($\alpha_F^S = 52$ deg/cm), and $+0.32 + 0.03$ ($\alpha_F^S = 42$ deg/cm). Thus, in the gyromagnetic region, ξ corresponds in sign and order of magnitude to the estimate of ξ_{mag} given above, i.e., in this case the change in the Faraday effect is actually due mainly to the change of magnetization of the holmium sublattice in the magnetic field. The too-low value of the experimental magnitude of ξ compared to the calculated value may be due to an admixture of α_F^{el}, a g-factor for Ho^{3+} that differs from the free-ion value of 1.25, as well as some uncertainty in the numerical value of κ_p. With decreasing wavelength, ξ goes to zero at 2.1 μm, and attains a value of $-0.28\%/kOe$ at 1.5 μm, i.e., inclusion of gyroelectric effects changes the sign of ξ. An important role in this is played, of course, by the iron sublattices in the holmium iron garnet, for which ξ is negative, since at temperatures above the compensation point the iron sublattices in the holmium garnet are oriented just as they are in $Y_3Fe_5O_{12}$.

The source of the anomalously large change of α_F in yttrium iron garnet in a magnetic field is still not clear even qualitatively. One may note the similar character of this anomalous change both in the ferromagnetic d-metals and in yttrium iron garnet. In both cases, the order of magnitude of ξ is the same. The negative sign of ξ in yttrium garnet (it is positive in the ferromagnetic d-metals) can be explained by the fact that the magnetization of the sublattice of the Fe^{3+} ions located at octahedral sites and giving the main contribution to α_F[5] is oriented oppositely to the external magnetic field in this wavelength region. If we start from this analogy, then it is possible to distinguish two common factors in the magnetooptics of the ferromagnetic d-metals and yttrium iron garnet: 1) spin-orbit origin of the magnetooptic effects (spin-orbit splitting of excited levels in yttrium iron garnet[6] [2)] and the effect of spin-orbit interaction on the wave functions of the d electrons in the metals[7]), 2) the decisive role of the difference in the transition intensities (oscillator strengths) for electrons with right and left spins.[3,7,8] The effect of the magnetic field on either of these factors could lead to the observed change in the magnitude of the magnetic saturation (the necessity of taking the first factor into account was mentioned in[1]).

However, there is still no theoretical treatment of magnetooptical phenomena in ferromagnets in the presence of an external magnetic field that gives a sufficiently reliable description of the state of the electrons in the ground and excited levels either for metals or ferrite-garnets, even though the analysis of the experimental facts could be of value not only for constructing a theory of magnetooptic effects but also for testing the validity of existing hypotheses about the character of the electronic states and electronic transitions in ferromagnetic 3d-dielectrics and metals.

[2)] In the magnetooptics of rare-earth ions the exchange splitting of the energy levels plays a fundamental role.[8]

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