Electromagnetooptical effect in yttrium garnet ferrite, $Y_3Fe_5O_{12}$

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A rotation of the polarization plane of light has been observed in yttrium garnet ferrite when magnetic and electric fields are applied to the crystal along the light propagation direction (an electromagnetooptical effect). The effect is of odd parity in the magnetic field and of even parity and quadratic in the electric field.

A magnetoelectric effect was first discovered experimentally in the antiferromagnet[1] Cr_2O_3 in 1960 and has since been observed in many other materials (some of which are cited in Ref. 2). All studies of the magnetoelectric effect which have been carried out to date have used the low-frequency or rf range, aside from one reported observation of a linear magnetoelectric effect in Cr_2O_3 at an optical wavelength,[3] $\lambda = 0.6328$ μm. We think that extending the magnetoelectric studies to the optical range is of both theoretical and experimental interest, since it might be possible to reach a better understanding of the nature of the effect. A substantial resonant intensification of the effect can be expected near electronic transitions and near a fundamental absorption edge. By choosing a suitable measurement frequency, it might be possible to distinguish the contributions of various magnetic sublattices to the magnetoelectric effect; this distinction cannot be made in the low-frequency or rf range. These considerations motivated the present study of the magnetoelectric effect in the optical range in yttrium garnet ferrite, $Y_3Fe_5O_{12}$ (YIG). Since the garnet ferrites exhibit a rather large Faraday magnetooptic effect ($a^F \sim 10^2$–10^3 deg/cm), and advanced polarimetric methods[4] make it possible to measure the rotation of the polarization plane with a high sensitivity and a high accuracy, we have studied the electromagnetooptical susceptibility, which is manifested in changes in the Faraday effect when an electric field is applied to the crystal.

The experimental arrangement is shown in Fig. 1. The optical part of the apparatus contains an LG-126 helium-neon laser (1), a polarizer (2), a calibration Faraday cell (3), the test crystal (5), which is in a magnet (4), and an analyzer (a beam-splitting prism) (6). The comparison system for measuring the signal (7) includes two photomul-

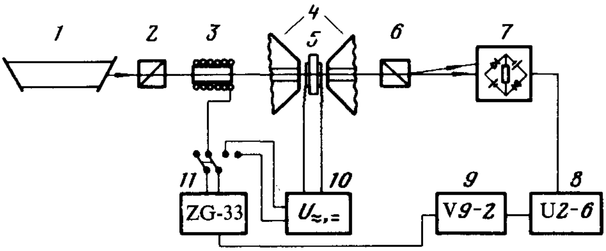

FIG. 1. Experimental arrangement for measuring the electromagnetooptical effect.

tipliers; the signal is amplified by a narrow-band amplifier (8) and measured by a synchronous detector (9). The sample is in the gap of an electromagnet (4); both the magnetic and electric fields are applied along the light propagation direction: **K**||**H**||**E**. The electric field is applied to semitransparent electrodes. A special circuit (10) makes it possible to apply a static electric field (up to 1.1 kV) and an alternating field (up to 2 kV) to the sample either separately or simultaneously. The $Y_3Fe_5O_{12}$ samples are plane-parallel wafers with the (100), (111), and (110) orientations, ranging in thickness from 50 to 800 μm. The sensitivity of the apparatus to changes in the rotation of the polarization plane is limited by the noise of the light source, to $\Delta\alpha = \pm 0.05''$ under favorable conditions. The measurements are carried out at room temperature, $T = 295$ K.

In the disordered region, the structure of the yttrium garnet ferrite is described by the point group $m3m1'$; below $T = 559$ K its magnetic structure is determined by the direction and strength of the external magnetic field.[5] Since the structure of this garnet has a center of inversion, in contrast with that of Cr_2O_3, the linear magnetoelectric effect is forbidden in garnet ferrites; only effects of second and higher even order in the electric field can occur. As in the case of the low-frequency magnetoelectric effect,[5] we can expect the following changes in the Faraday effect when static and alternating electric fields are applied to the crystal[1)]:

$$\delta\alpha^{\mathrm{EMO}} = \beta^{\mathrm{EMO}} \, (E_1 + E_2 \sin \omega t)^2 = \beta^{\mathrm{EMO}} \, \Big(E_1^2 + \frac{E_2^2}{2} + 2E_1E_2 \sin\omega t - \frac{E_2^2}{2} \cos 2\omega \Big). \tag{1}$$

When the conditions are chosen appropriately, an electromagnetooptical signal can thus appear at both the first and second harmonics of the alternating electric field.

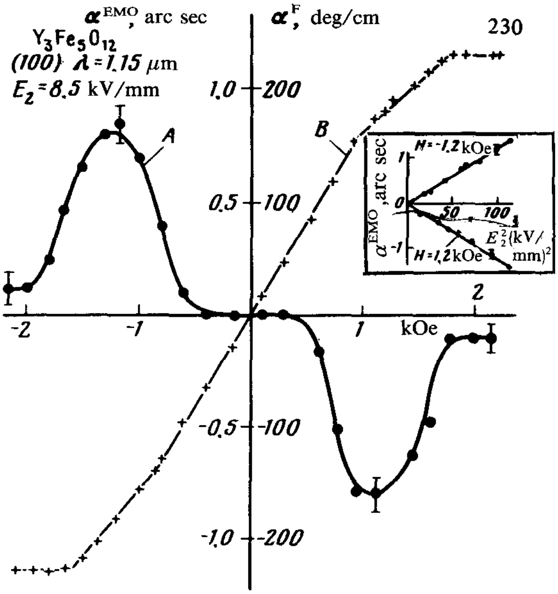

FIG. 2. A—α^{EMO} versus the magnetic field for a crystal 248 μm thick at the second harmonic; B—field dependence of the Faraday effect; inset—dependence of α^{EMO} on E_2^2 for two values of the magnetic field.

Figure 2 shows the results of our experimental study of a (100) yttrium garnet ferrite wafer 248 μm thick in an alternating electric field. The signal (curve A) is observed at the second harmonic of the field. The phase of the signal typically changes upon a change in the sign of the magnetizing field. This result is evidence that the observed effect is of odd parity in the magnetization and of even parity in the external electric field. Also shown in this figure is the field dependence of the Faraday effect (curve B). The inset shows the signal (at two values of the magnetic field) versus the square of the electric field; this dependence is linear.

It should be noted that the electromagnetooptical signal is also observed at field values above magnetic saturation, i.e., in the region in which the magnetoelectric effect does not occur in measurements at low frequencies. This result is evidence that in the optical region there is an additional mechanism for the electromagnetooptical interaction. When the crystal is saturated along the [001] axis, its magnetic symmetry ($4\bar{m}$mm) allows a magnetoelectric interaction of the (HE^2) type.

Some other experiments were carried out while static and alternating fields were applied simultaneously to the crystal. Under these conditions, according to (1), we would expect a signal to appear at the first harmonic of the alternating electric field. This signal was in fact observed, and, in agreement with (1), the height of this signal depends linearly on the static field (E_1) and on the alternating field (E_2)—including a change in the sign of the phase of the signal upon a change in the sign of the static electric field (Fig. 3). A change in the phase of the signal is also observed when the direction of the magnetic field is changed. The curve of the signal level versus the magnetic field at constant values of E_1 and E_2 is analogous to curve A in Fig. 2.

Working from the results of the two types of experiments, we determined the electromagnetooptical coefficients for yttrium garnet ferrite at the wavelength 1.15 μm and for a field $H = 1.2$ kOe; the results from the two types of experiments turned out to be the same, 1.2×10^{-14} deg·m/V^2. If we assume that the electromagnetooptical

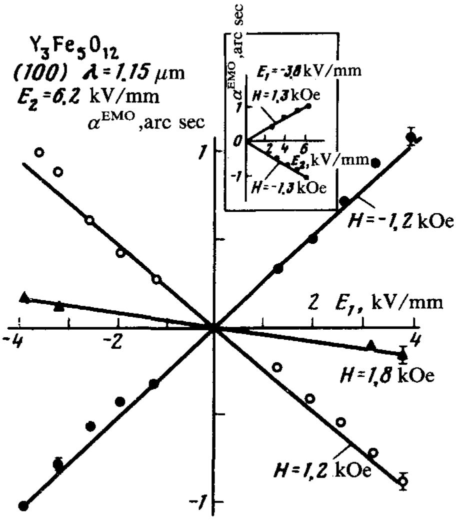

FIG. 3. α^{EMO} versus E_2 for a crystal 248 μm thick at the first harmonic for various values of the magnetic field; the inset shows the E_2 dependence of α^{EMO} for $E_1 = 3.8$ kV/mm for two values of the magnetic field.

effect is determined entirely by the magnetoelectric effect, then by knowing the saturation magnetization of yttrium garnet ferrite and the magnitude of the Faraday effect we can determine the magnetoelectric coefficient. It turns out to be -8.1×10^{-20} Wb/V^2 (-1.4×10^{-6} in Gaussian units), slightly above the value of β^{ME} given in Ref. 5.

The basic result of the present study is the observation of a rotation of the polarization plane of light in yttrium garnet ferrite caused by the simultaneous application of magnetic and electric fields to the crystal. The physical nature of this phenomenon is determined by both the magnetoelectric effect and some additional mechanism, which apparently involves changes in the magnetooptical coefficients in an electric field.

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[1)] Since the Faraday effect is proportional to the magnetization M, i.e., since $\alpha^{\mathrm{F}} = \mathrm{A}m$, the expression for β^{EMO} can be written $\beta^{\mathrm{EMO}} = (\partial^2 A/\partial E^2)m + A\beta^{\mathrm{ME}}$, where A is the magnetooptical coefficient, and β^{ME} is the magnetoelectric coefficient.

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