Magnetization of the paramagnet $Gd(PO_3)_3$ by light in an external field 1.6 MOe

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We measured the Faraday effect (FE) in $Gd(PO_3)_3$ at $\lambda = 6950$, 6328, and 4950 Å. It is shown that this effect is due mainly to the magnetization of the Gd^{3+} ions by the magnetic field of the light wave. By the same token, we have measured for the first time the magnetic susceptibility of a transparent magnet in the optical band.

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The concept of magnetic susceptibility of a magnetic crystal at optical frequencies was first introduced in[1] to explain the Faraday effect (FE) in iron garnets in the near infrared region. At wavelengths shorter than 3 or 4 microns, however, the gyromagnetic FE started to be masked by the more intense gyroelectric contribution due to electronic transitions in the Fe^{3+} ions of the iron sublattice. We describe below an experiment aimed at observing the magnetic susceptibility of the paramagnet $Gd(PO_3)_3$ in the optical band; we were able to detect this susceptibility because of the smallness of the gyroelectric FE, since the intense electrodipole transitions in Gd^{3+} are shifted into the far ultraviolet region, and also as a result of an analysis of the dispersion and field dependences in fields reaching 1.6 MOe.

The magnetic field was obtained in a magneto-cumulative setup of the explosive type.[2] The procedure for

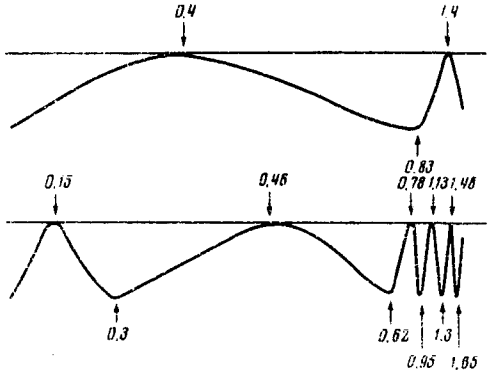

FIG. 1. Oscillograms of the FE of a sample of TF5 glass + $Gd(PO_3)_3$ at $\lambda = 6950$ Å ($l_{TF} = 3$ mm, $V_{TF} = 0.033$ min/cm-Oe, $l_{Gd} = 3.9$ mm) (upper trace) and for $\lambda = 4950$ Å ($l_{TG} = 3$ mm, $V_{TF} = 0.100$ min/cm-Oe, $l_{Gd} = 39$ mm) (lower trace). The markers indicate the intervals of θ in stops of 90°, and the numbers denote the corresponding fields in MOe.

measuring the FE in fields ~2 MOe is described in our earlier papers.[3,4] Polarized light passed through two samples: TF_5 glass with known Verdet constant, and an identical sample of TF-5 glass, on which $Gd(PO_3)_3$ was placed. The sign and magnitude of the FE in the paramagnetic glass was obtained by subtracting the angle of rotation θ of the polarization plane of the first sample from that of the second. Several explosion experiments, that duplicated one another, were performed for the wavelengths $\lambda = 6328$ Å (laser) and 6950 and 4950 Å (flash lamp and filter with $\Delta\lambda = \pm 25$ Å), at $T_0 = 258$ °K. The oscillograms of the FE of TF5 + $Gd(PO_3)_3$ for $\lambda = 6950$ and 4950 Å are shown in Fig. 1. Figure 2 shows the experimental values of the FE on $Gd(PO_3)_3$ at the indicated wavelengths as functions of the magnetic field. The accuracy with which θ was determined was ± 5 deg in strong fields and ± 1 in fields ~ 10^5 Oe.

As seen from Fig. 2, the sign of θ is positive, its dispersion dependence coincides at $H \sim 10^5$ Oe with that measured earlier in $Gd(PO_3)_3$,[6] and its characteristic field dependence indicates saturation with increasing field. The dependence of θ on H indicates unambiguously, in our opinion, that the decisive contribution is made by the magnetic permeability,

$$\theta_\mu = -\frac{2\pi\sqrt{\epsilon}\, g\,\mu_B\,\omega^2\hbar l l}{c\,(g^2\mu_B^2 H^2 - \omega^2\hbar^2)}\ \text{(rad)}, \qquad (1)$$

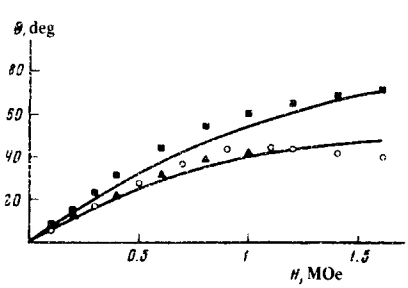

FIG. 2. Dependence of V on H at $\lambda = 4950$ (squares), 6328 (triangles), and 6950 Å (circles) for $l = 0.390$ cm. Solid lines—calculations: upper line for 4950 Å and lower line for 6950 Å ($Gd(PO_3)_3$).

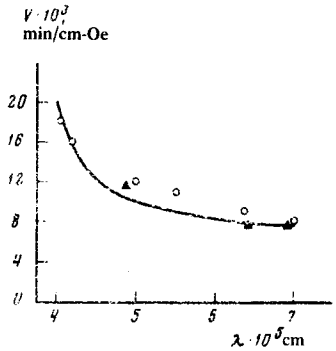

FIG. 3. Dependence of θ on λ. Circles—experimental results of[6], triangles—our data, solid curve—calculation.

where $I = Ng\,\mu_B J B_j(g\,\mu_B J H/kT)$ is the magnetic moment per unit volume, l is the length of the sample, with θ_μ positive and independent of the frequency if $g\,\mu_B H \ll \omega\hbar$, as in our case.[1,7] Two other possible contributions connected with the dielectric constant, namely diamagnetic and paramagnetic

$$\theta_g + \theta_n = \frac{\lambda^2 K_1}{(\lambda^2 - \lambda_1^2)^2}\, l H - \frac{K_2}{(\lambda^2 - \lambda_2^2)}\, l H \qquad (2)$$

cannot account for the obtained field dependence, owing to the linearity of the first term and the negative sign of the second. On the other hand, the dispersion dependence $\theta(\lambda)$ measured in[6] cannot be accounted for by θ_g alone or by θ_n alone at arbitrary λ_1 or λ_2. To explain the foregoing facts it is necessary to take into account all three contributions (1) and (2). In spite of the fact that the orbital momentum of Gd^{3+} is zero, θ_n appears as a result of the admixture of excited states to the ground state, due to the electric field of the light wave and to the "turning on" of spin-orbit interaction. The paramagnetic rotation should then be much weaker than in $Re(PO_3)_3$ glasses, where Re = Ce, Pr, Tb, etc.,[6] and coincides in order of magnitude with the diamagnetic contribution θ_n due to the ions of the matrix. Taking $K_1 = 0.526 \times 10^{-10}$ min-cm/Oe and $K_2 = 1.19K_1$, which corresponds to the estimates, $\lambda_1 = 2500$ Å, and $\lambda_2 = 2800$ Å, we can calculate both the field and dispersion relations $\theta = \theta_\mu + \theta_g + \theta_n$. We determine θ_μ from the formula

$$\theta_\mu = \frac{360\sqrt{\epsilon}\, g^2\mu_B^2 N J B_J(x)\, l}{c\hbar}\ \text{(rad)} \qquad (3)$$

with $\sqrt{\epsilon} = 2.5$, $N = 5.3 \times 10^{21}$ cm^{-3},[6] and $g = 2$. We assume that θ_n is linearly dependent on H. A comparison of the calculated and experimental results is shown in Figs. 2 and 3, from which it is seen that the agreement can be regarded as good.

It follows from the foregoing that the main contribution to the Faraday effect (on the order of 90% in fields up to 0.5 MOe) is made by the nondiagonal components $\varkappa_{xy}$ of the magnetic susceptibility. For example, the Verdet constant for $\lambda = 6950$ Å, namely 0.008 min/cm-Oe, is almost exactly equal to the 0.009 min/cm-Oe calculated from (3). In addition, the sign and the field and dispersion relations prove convincingly the connection between the FE and the high-frequency susceptibili-

ty of gadolinium glass in the magnetic field of a light wave in the visible band. This result is of fundamental significance, since it is stated in a number of theoretical papers that the concept of the quantity $\varkappa$ has no meaning whatever at optical frequencies (see, e.g., [8]).

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