JOYRNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 17, SUPPLEMENT B-I, 1962
PROCEEDINGS OF INTERNATIONAL CONFERENCE ON MAGNETISM AND CRYSTALLOGRAPHY, 1961, VOL. I

Exchange Interaction and Magneto-Optical Effects in Garnets*

G. S. KRINCHIK AND M. V. CHETKIN
Moscow State University, U.S.S.R.

The Faraday effect in infrared light was measured in yttrium, holmium, erbium and europium garnets. The Faraday effect in the region $\lambda > 4\mu$ is due to ferromagnetic and exchange resonances. An absorption band due to electric transitions between levels of the ground term of europium ions $^7F_0 \rightarrow {}^7F_6/2.04\mu$/has been observed Zeeman effect in exchange field of 2.5×10^5 Oe.

The Faraday effect has been measured in monocrystals of yttrium, holmium and erbium garnet in infrared light. In the transparency region of garnets, $4\mu < \lambda < 8\mu$, the Faraday effect has been found to be independent of light wavelength and equal to several ten degrees per centimetre for all garnets (see Table I).

The rotation of the plane of polarization in this case may be attributed to the precession of the magnetic moment of the ferrite under the action of the magnetic field of the light wave, or spin magnetic resonance.

For ferrites in which exchange resonance is of minor importance, the Faraday effect in the region $\omega \gg \omega_{res}$ may be found from the Landau-Lifshits equation (1):

$$\alpha_F^{res} = \frac{2\pi\sqrt{\varepsilon}}{c}\gamma I \text{ rad/cm} . \qquad (1)$$

where $\gamma = eg/2mc$, ε is the dielectric constant, and I is the magnetization of the ferrite.

For garnets of erbium and holmium, it is essential to take into account the effect of the exchange resonance, predicted by Kaplan and Kittel (2) and differing from zero only when the γ-factors for the ions of the magnetic "sublattices" of the ferrite are different.

From the equation for the non-diagonal component of the magnetic susceptibility tensor obtained in reference (3), provided $\omega \gg \omega_{res}, \omega_{exch.}$, we obtain:

$$\tilde{\alpha}_F^{exch} = \frac{2\pi\sqrt{\varepsilon}}{c}(\gamma_1 I_1 - \gamma_2 I_2) , \qquad (2)$$

where γ_1, γ_2, I_1 and I_2 are gyromagnetic ratios and magnetisation of two sublattices of the ferrite. The physical meaning of this equation may be derived by decomposing eq. (2) into two summands:

$$\tilde{\alpha}_F^{exch} = \alpha_F^{res} + \alpha_F^{exch} = \frac{2\pi\sqrt{\varepsilon}}{c}\left[\gamma_{eff} I - \frac{\gamma_{eff} I_1 I_2 (\gamma_1 - \gamma_2)^2}{\gamma_1 \gamma_2 I}\right] , \qquad (3)$$

where $I = I_1 - I_2$ is the resultant magnetization of the ferrite, and

$$\gamma_{eff} = \frac{I_1 - I_2}{(I_1/\gamma_1) - (I_2/\gamma_2)} .$$

The first summand is the contribution due to the conventional ferromagnetic resonance and the second, due to the exchange resonance. The signs of the rotation conditioned by the first and the second summand are different, which results from the difference in the direction of the precession of the magnetic moments (4).

Table I presents experimental values of α_F at $\lambda > 4\mu$ and values of α_F^{res} and $\tilde{\alpha}_F^{exch}$, as calculated from equations (1) and (2) at $\sqrt{\varepsilon} = 2.2$. The magnetisation of the first sublattice has been assumed to be equal to the resultant magnetisation of two iron sublattices of the ferrite (yttrium garnet). Thus, the Faraday effect in the yttrium garnet at $\lambda > 4\mu$ is caused by the ferromagnetic resonance, i.e., by the precession of the vector of spontaneous magnetisation at optical frequency. In erbium and holmium garnets, the Faraday effect is also governed by the exchange resonance, i.e., the precession of the vector of magnetisation of one sublattice in the exchange field of another sublattice. Referring to Table I, the exchange resonance in the holmium garnet reduces the Faraday effect by approximately two-thirds. Good agreement between the theoretical and experimental values seems to prove that the Faraday effect as measured in the infrared region may give a measure of γ-factors for rare-earth ions and their relation to temper-

* Read by E. I. Kondorsky.

Table I

Garnets	levels of ground term		g			T°K	I_1	I_2	α_F^{res} theor. deg/cm	α_F^{exch} theor. deg/cm	α_F exp. deg/cm
	Sublat. 1	Sublat. 2	g_1	g_2	g_{eff}						
$Y_3Fe_5O_{12}$	$^6S_{5/2}$	—	2.0	—	2.0	290	135	—	63	—	61
						77	181	—	84	—	74
$Ho_3Fe_5O_{12}$	$^6S_{5/2}$	$^5I_8$	2.0	1.25	8.5	290	135	75.8	117	41	42
$Er_3Fe_5O_{12}$	$^6S_{5/2}$	$^4I_{15/2}$	2.0	1.2	3.1	290	135	46.8	63	50	47

ature. Measurement of the ferromagnetic resonance in the UHF band does not make it possible to determine these γ-factors because of the pronounced damping of the rare-earth sublattice (5).

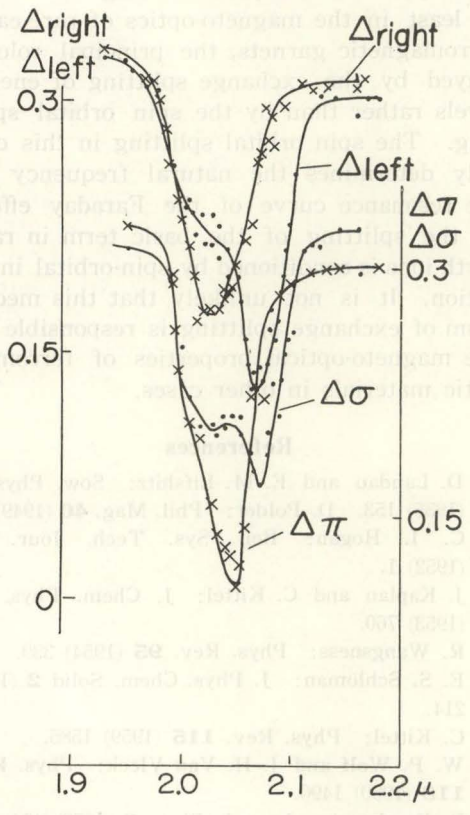

Fig. 1. Transpareney $\Delta=\frac{I_{tr}}{I_0}$ of europium garnet ($d=100\mu$) in magnetic field $\boldsymbol{H}=2000$ Oe

Δ_{right}: right-handed circularly polarised light (longitudinal observation).

Δ_{left}: left-handed circularly polarised light (longitudinal observation).

$\Delta\pi$: linearly polarised light (transverse observation, $\boldsymbol{e}\|\boldsymbol{H}$).

$\Delta\sigma$: linearly polarised light (transverse observation, $\boldsymbol{e}\perp\boldsymbol{H}$).

Apart from the effect of the exchange interaction of sublattices on the rotation of the plane of polarization of infrared light, we have also revealed the direct effect of the exchange field of iron sublattices on the absorption line of the rare-earth ion in a garnet of europium. The study involved the electron transition $^7F_0\rightarrow{}^7F_6$ at a wavelength of 2.04μ with the various orientation of the vector of magnetisation relative to the beam of light. Fig. 1 shows the observation of the above line in a magnetic field of 2,000 oersteds in circularly-polarized light (longitudinal observation) and in linearly-polarized light (transverse observation). Referring to the figure, at the attained spectral resolution of 40 cm^{-1}, the pattern resembles the Zeeman triplet with a splitting of 110cm^{-1}, corresponding to a magnetic field of several hundred thousand oersteds. It is natural to compare this field with the exchange field acting upon the ions of europium from the magnetic sublattices of iron. According to Wolf and Van Vleck (6), the strength of this field at room temperature is approximately 2.5×10^5 oersteds. Substituting $g=1.5$ and $H=2.5\times10^5$ into the equation $2\Delta E=2gJ\mu_BH$ for the complete Zeeman splitting of the level of a free ion at a given value of H gives $2\Delta E=210cm^{-1}$. If we assume that the absorption lines observed give an averaged picture of the Zeeman components displaced to the right and left, the experimental data agree reasonably well with this estimate. A comparison of curves of circular dichroism at room and nitrogen temperatures will show that the splitting of the line at 77°K is approximately 30 per cent higher than at 290°K. This observation agrees well with the assumption that the splitting has been caused by the

exchange field, as, according to Pauthenet (7), the magnetisation of iron sublattices in ferromagnetic garnets increases in proportion to the rise from room to nitrogen temperature.

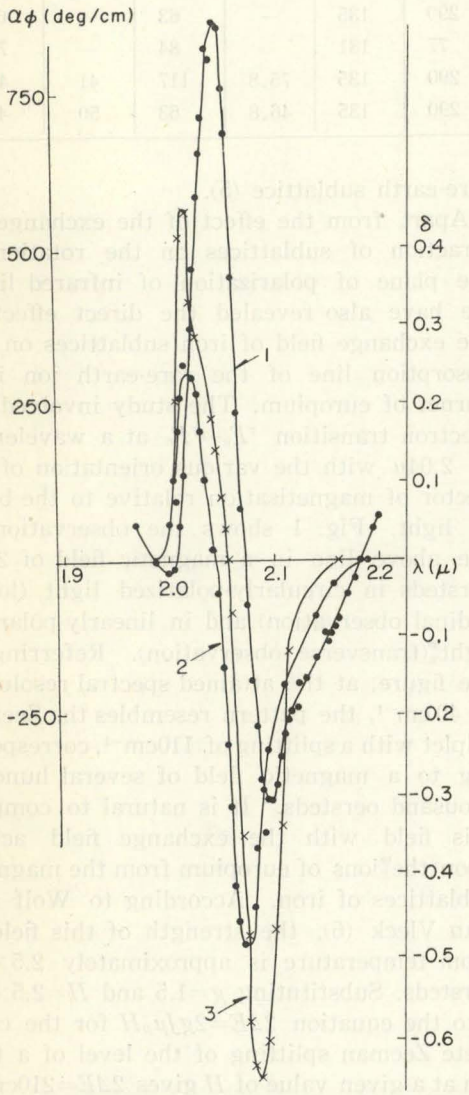

Fig. 2. The Faraday effect (1) and circular dichroism $\delta=\frac{\Delta_{right}-\Delta_{left}}{\Delta H=0}$ at room (2) and liquid nitrogen temperatures (3) in garnet of europium in region of absorption.

The results obtained seem to throw light on the physical mechanism responsible for the magneto-optical properties of ferromagnetic materials. The curve of the Faraday effect has the typically resonance appearance, as it does in other ferromagnetic garnets near absorption bands (8). In our case, however, the direct physical cause of the rotation of the plane of light polarization may be singled out. This is the exchange splitting of the excited energy level of a rare-earth ion. The exchange splitting brings about circular dichroism and double circular refraction—the difference in the absorption coefficient and refractive indices of right-handed and left-handed polarized light components and, consequently, the Faraday effect (Fig. 2). Thus, at least in the magneto-optics of rare-earth ferromagnetic garnets, the principal role is played by the exchange splitting of energy levels rather than by the spin orbital splitting. The spin orbital splitting in this case only determines the natural frequency for the resonance curve of the Faraday effect, as the splitting of the basic term in rare-earth ions is conditioned by spin-orbital interaction. It is not unlikely that this mechanism of exchange splitting is responsible for the magneto-optical properties of ferromagnetic materials in other cases.

References

1 D. Landau and E. M. Lifshitz: Sow. Phys. **8** (1935) 153. D. Polder: Phil. Mag. **40** (1949) 99. C. L. Hogan: Bell. Sys. Tech. Jour. **31** (1952) 1.
2 J. Kaplan and C. Kittel: J. Chem. Phys. **21** (1953) 760.
3 R. Wangsness: Phys. Rev. **95** (1954) 339.
4 E. S. Schlöman: J. Phys. Chem. Solid **2** (1957) 214.
5 C. Kittel: Phys. Rev. **115** (1959) 1585.
6 W. P. Wolf and J. H. Van Vleck: Phys. Rev. **118** (1960) 1490.
7 R. Pauthenet: Ann. de Phys. **3** (1959) 424.
8 G. S. Krinchik and M. V. Chetkin: JETP **40** (1961) 729; JETP **41** (1961) 673; Optika and Spectr. **11** (1961) 274.