Optical-waveguide measurement of the optical-frequency magnetic permeability in epitaxial iron garnet films

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The gyromagnetic and gyroelectric components of the Faraday rotation have been measured separately in epitaxial iron garnet films by an optical-waveguide method at wavelength $\lambda = 1.15$ μm. The good agreement between the results and theoretical predictions confirms that the Faraday rotation in the near-IR range in iron garnets is bigyrotropic.

1. INTRODUCTION

The Faraday effect (the rotation of the polarization plane of an electromagnetic wave) in a dielectric may stem from either the interaction between the electric field of the wave and the electric dipole moment of the medium (the gyroelectric mechanism) or the interaction between the magnetic field of the wave and the magnetic moment (the gyromagnetic mechanism). The component of the Faraday effect which results from the gyroelectric mechanism dominates in the UV and visible parts of the spectrum. Faraday observed a rotation of this type in the visible range in borosilicate lead glass.[1] Gyromagnetic rotation, on the other hand, was first observed in the microwave range in manganese salts.[2]

Since the gyroelectric component of the rotation is dominated by electric dipole transitions which occur in the UV region, the gyroelectric component falls off rapidly with increasing wavelength in the visible and near-IR regions. The gyromagnetic component, on the other hand, is essentially independent of the frequency in the visible and near-IR regions. These features permit the two rotation mechanisms to be distinguished quantitatively. This resolution has been carried out for molecular oxygen,[3] iron garnets,[4] and doped EuTe (Ref. 5). Although there is no question that the data allow the mechanisms to be distinguished in this way (see Ref. 6, for example), it seems to us that measurement methods of a more direct nature are required in order to confirm conclusions drawn about the presence of a gyromagnetic component in the optical part of the spectrum. One such method, proposed in Ref. 7, has been used to distinguish the rotation mechanisms in iron.[8] That method, however, is valid for materials with a fairly strong absorption, since in the absence of absorption the change in the intensity of the reflected light during magnetization of the sample is erased. For example, even when this method is modified, as in Ref. 9, it was not found possible to measure the magnetic permeability for cobalt. We believe that an optical-waveguide measurement method would be useful for verifying the ideas of Refs. 3–8 (Ref. 10). This method would make it possible to distinguish the gyroelectric and gyromagnetic components in the transparency region of ferromagnetic materials.

This method requires a thin film (with a thickness on the order of the wavelength of the light) of the substance of interest. The film serves as an optical waveguide. Some preliminary experiments carried out on an epitaxial iron garnet film of rather complicated composition revealed that it was possible to separate the gyroelectric and gyromagnetic components of the Faraday effect by this method.[11] In the present paper we are reporting experimental data on epitaxial iron garnet films of a simpler composition. The simpler composition adds to the reliability with which the ideas of Refs. 3–8 are confirmed.

The experiment is performed as follows. The *TE* and *TM* waveguide modes are excited in the epitaxial film with the help of a rutile prism. An external magnetic field magnetizes the film in its plane, in the direction perpendicular to the light propagation direction in the film. When the direction of the external field is reversed, one observes and measures the change in the angle at which the beam leaves the exit prism. This angular shift is measured by a special detector which is sensitive to small displacements of the beam.

The change $\delta\beta_m$ in the effective refractive indices for the modes is related to the change $\delta\alpha_m$ in the angle at which the modes leave the prism by the well-known expression[12]

$$\delta\beta_m = n_p \cos\left[\gamma + \arcsin\left(\frac{\sin\alpha_m}{n_p}\right)\right] \frac{\cos\alpha_m}{(n_p^2 - \sin^2\alpha_m)^{1/2}}\,\delta\alpha_m, \quad (1)$$

where n_p is the refractive index of the prism for the given polarization, the given wavelength, and the given temperature; β_m is the effective refractive index for the mode of index m; γ is the prism angle; and α_m is the angle between the beam and the normal to the exit face of the prism. The change in the effective refractive indices for the modes when the magnetization of the film is parallel to the $\pm y$ axes can be expressed in terms of properties of the film material and the substrate material:[13]

$$\delta\beta_{TE_m} = \pm\beta_{TE_m}\left\langle \frac{\mu_{xz}-\mu_{zx}}{i}\mathscr{E}_m\frac{d\mathscr{E}_m}{dx}\right\rangle, \quad (2)$$

$$\delta\beta_{TM_m} = \pm\beta_{TM_m}\left\langle \frac{\varepsilon_{xz}-\varepsilon_{zx}}{i\varepsilon_0^2}\mathscr{H}_m\frac{d\mathscr{H}_m}{dx}\right\rangle, \quad (3)$$

where

$$\langle A\rangle = \int_{-\infty}^{\infty} A(x)\,dx,$$

and $\mathscr{E}_m$ and $\mathscr{H}_m$ are the amplitudes of the y components of the *TE* and *TM* modes, respectively.

The x axis of our coordinate system is chosen perpendicular to the film; the y axis lies in the plane of the film, perpendicular to the propagation direction; and the z axis

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runs along the mode propagation direction. Expressions (2) and (3) were derived in an approximation which ignores the spatial dispersion and the magnetoelectric coupling,[14] which lead to similar effects, in contrast with the distinctive effects in which we are interested. Ignoring absorption, and expanding the gyrotropic parts of the permeabilities in series in the magnetization, we find

$$\mu_{xz}-\mu_{zx}=igM_y, \tag{4}$$

$$\varepsilon_{xz}-\varepsilon_{zx}=i\xi M_y, \tag{5}$$

where M_y is a component of the magnetization, and g and ξ are magnetooptic coefficients. The values of gM_y and ξM_y were determined in the following way. For measurements of the spectrum of the waveguide modes, i.e., of the angles α_m, we calculated effective refractive indices β_m for the modes and determined the thickness and refractive index of the film. From these results, we calculated the field overlap integrals which appear in (2) and (3). It can be seen from (1)–(5) that by measuring the changes in the angles when the magnetization of the film parallel to the y axis is reversed one can determine the values of gM_y and ξM_y.

Measurements of the changes in the angles with the help of the *TE* mode make it possible to determine the gyromagnetic component gM_y, while the *TM* mode makes it possible to determine the gyroelectric component ξM_y.

2. EXPERIMENTAL PROCEDURE

Measurements were carried out on four films grown by liquid-phase epitaxy on gallium–gadolinium garnet substrates in the {111} orientation. Films 1, 2, and 3 had the composition $Y_3Fe_{3.88}Sc_{0.68}Ga_{0.44}O_{12}$; film 4 had the composition $Y_3Fe_{3.79}Sc_{0.58}Ga_{0.63}O_{12}$.

These films have an easy-plane magnetic anisotropy, and their magnetization can easily be reversed by weak fields. In the experiments we used an oscillating magnetic field, produced by Helmholtz coils, with a strength up to 30 Oe, which corresponds to complete magnetic saturation. The field was directed along the y axis (Fig. 1) and changed direction at a frequency of 1000 Hz. The waveguide modes were excited by a He–Ne laser at a wavelength of 1.15 μm with the help of a rutile prism. The device for sensing small displacements of the beam is a system consisting of a mirror

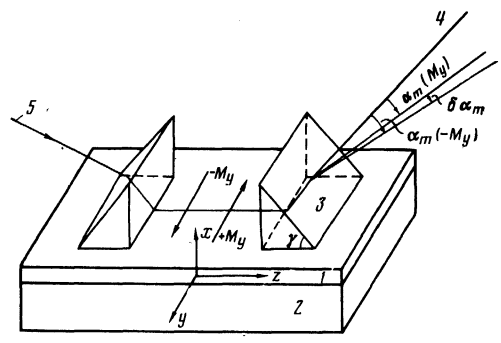

FIG. 1. Experimental layout. The beam paths are shown for the two directions of the magnetization. 1—Film; 2—substrate; 3—rutile prism with an angle $\gamma = 54°33'12''$; 4—normal to the prism face; 5—laser beam.

prism, which splits the waveguide mode emerging from the film into two beams, and two photodiodes, connected in opposite directions and tuned to these two beams. If the mode emerging from the film is split strictly in half by the prism, there is a null current at the detector output. If there is an angular deviation of the mode from this position, a signal current appears at this output. After the detector has been calibrated for the mode of interest with the help of a goniometer and a microvoltmeter, the angular displacement of a mode emerging from the film can be determined from the height of the signal. Adjustment of the optical contact of the exit prism made it possible to shape the emerging beam in such a way that the signal at the detector output remained linear for angular displacements of the mode of tens of arc seconds. The angular displacements which we measured were on the order of a hundredth of an arcsecond, so the calibration was precise.

The signal component due to the Voigt effect quadratic in the magnetization had a doubled frequency and was separated from the main signal with a synchronous detector. The experimental errors were 8–10%, due primarily to the noise of the He–Ne laser and the nonideal shape of the exiting beam.

From the measured mode spectra we determined the film properties, shown in Table I, and the overlap integrals which appear in Eqs. (2) and (3). In films 1, 2, and 4 we

TABLE I. Properties of the films.

Film	$4\pi I_S$, Гс	T_C, K	d, μm	n_f^{TE}	n_f^{TM}	β_{TE_1}	β_{TE_2}	β_{TE_3}
1	445	339	2,92	2,1125	2,1140	2,0770	2,0281	1,9621
2	430	337	3,85	2,1122	2,1137	2,0937	2,0711	2,0395
3	430	336	1,96	2,1097	2,1112	2,0489	1,9761	–
4	610	361	2,65	2,1151	2,1159	2,0770	2,0282	1,9621

Film	β_{TE_4}	β_{TE_5}	β_{TM_1}	β_{TM_2}	β_{TM_3}	β_{TM_4}	β_{TM_5}
1	–	–	2,0751	2,0235	1,9560	–	–
2	1,9988	1,9512	2,0938	2,0700	2,0367	1,9943	1,9468
3	–	–	2,0431	1,9646	–	–	–
4	–	–	2,0751	2,0235	1,9560	–	–

$4\pi I_S$—Saturation magnetization; d—thickness; T_C—Curie temperature, n^{TE} and n^{TM}—refractive indices at $\lambda = 1.15\,\mu$m for the *TE* and *TM* modes; β_{TE}, β_{TM}—effective refractive indices for the modes.

TABLE II. Experimental results.

Film	Mode	$\delta\beta_{TE}$, 10^{-7}	$\delta\beta_{TM}$, 20^{-7}	θ_F^{μ}, deg/cm	θ_F^{ε}, deg/cm	$\theta_F^{\mu_{theo}}$, deg/cm	$\theta_{F_{tot}}$, deg/cm
1	2	0,623	2,250	14	41		
	3	1,186	4,100	14,5	42,5	15,79	48
2	3	0,588	1,780	12	34		
	4	0,867	2,750	12	33	15,15	44
	5	1,060	4,062	12	32		
3	1	1,250	3,470	14	39		
	2	1,790	7,220	12	42	15,43	–
4	1	0,552	2,082	19	54		
	2	1,300	5,210	19	56	21,7	67
	3	2,170	8,680	19,5	53,5		

$\delta\beta_{TE}$, $\delta\beta_{TM}$—Changes in the effective refractive indices for the modes; θ_F^{μ}, θ_F^{ε}—gyromagnetic and gyroelectric components, respectively, of the Faraday effect; $\theta_F^{\mu_{theo}}$—gyromagnetic rotation calculated from the magnetization; $\theta_{F_{tot}}$—measured total rotation (gyroelectric plus gyromagnetic).

measured the total Faraday effect (gyromagnetic plus gyroelectric) through a *TE–TM* waveguide-mode conversion. We measured the mode conversion coefficient as a function of the distance between the prisms.[10] The results of these measurements agree within the experimental error with measurements of the Faraday effect by the method described above. The results of these measurements are shown in Table II. It was not possible to measure the total Faraday effect in film 3 because of the poor phase matching of the *TE* and *TM* modes. The film magnetization was measured on a PAR-M159 vibration magnetometer. The results are shown in Table I.

From the solution of the Landau–Lifshitz equation for frequencies much higher than the magnetic-resonance frequency, one finds a relationship between the gyromagnetic Faraday effect and the magnetization of the film:[15]

$$\theta_F^{\mu}=2\pi\frac{\varepsilon^{1/2}}{c}\gamma I_s, \tag{6}$$

where

$$\gamma=g\frac{e}{2mc}.$$

The difference between the g-factors of the iron sublattices in the iron garnet is beyond the accuracy θ_F^{μ} of these measurements, so we assume $g\approx 2$.

Table II shows values of the rotation calculated from expression (6). These results agree well with the rotation values found experimentally. In contrast with an experiment carried out on a film with the composition $(YbPr)_3(FeGa)_5O_{12}$ (Ref. 11), the gyroelectric and gyromagnetic components of the Faraday effect are comparable in this case.

3. CONCLUSION

In summary, we have reported a study of the behavior of optical waveguide modes in an equatorial geometry. It has been shown that the angular displacement of the *TE* and *TM* modes can be interpreted as resulting from an interaction of the magnetic and electric fields respectively of the electromagnetic wave with the medium. Adopting this interpretation of the experiments, we have calculated the corresponding components of the magnetic permeability tensor and the dielectric tensor. The magnitude of the permeability turned out to agree well with theoretical predictions.

Taken together, the results of this study confirm that the Faraday effect is of a bigyrotropic nature in iron garnets in the IR range, as was first suggested by Krinchik and Chetkin in Ref. 7.

From the application standpoint, the effects observed here must be taken into account in the development of nonreciprocal integrated-optics devices (rectifiers, circulators, etc.). For example, the existence of a gyrotropic component of the permeability tensor would make it possible in principle to develop devices of this sort for the *TE* polarization.

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