Permeability of a transparent magnetic insulator at optical frequencies. An experimental study

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The nondiagonal components of the dielectric and magnetic tensors of garnet ferrite of the composition $(YbPr)_3(FeGa)_5O_{12}$ were measured directly by the method of waveguide propagation of light.

One of the curious aspects of the optics of magnetically ordered insulators which is not completely clear is the permeability at optical frequencies. A viewpoint has been developed in Refs. 1 and 2, according to which the non-negligible permeability of garnet ferrites in their transparency region can contribute to the Faraday rotation which reaches several tens of degrees per centimeter. The physical meaning of the permeability at the optical frequencies and the relevance of its introduction were discussed extensively in Refs. 4 and 5.

Since the nondiagonal components of the dielectric tensor ϵ and the magnetic tensor μ are additive contributions to the volume effects which were analyzed in Refs. 1 and 2 and which, in particular, is the Faraday effect, these components can be distinguished by using certain models. It was shown in Ref. 3 that in the phenomenological theory of the magnetic resonance, the Faraday rotation associated with the magnetic tensor μ does not depend on the frequency over a broad range of frequencies above the resonant frequency. Because of this property, the authors of Refs. 1 and 2 were able to link the experimentally observed, frequency-independent Faraday effect with the magnetic tensor.

However, there has been, to the best of our knowledge, no direct experimental confirmation of the presence of a magnetic tensor in transparent ferromagnets.

The contributions can be distinguished when light propagates in an inhomogeneous medium, for example, in the case of a waveguide propagation of light in a thin magnetic film. This method was used by us here. The physical principles upon which the waveguide method is based have been analyzed in detail in Refs. 4 and 5. Here we will briefly summarize this method.

A light in the form of normal *TE* and *TM* modes can propagate in a thin garnet ferrite film (O_h symmetry) grown on a substrate with a lower refractive index. We assume that the x axis is perpendicular to the film plane and that the light propagates along the z axis. The y components of the fields of these modes (ignoring the magnetization) can then be described by the relations

$$\begin{aligned} E_y(x, z, t) &= \mathcal{E}(x) \exp(iN_e z - i\omega t), \\ H_y(x, z, t) &= \mathcal{H}(x) \exp(iN_h z - i\omega t), \end{aligned} \tag{1}$$

where N_e and N_h are the effective refractive indices of the TE and TM modes, respectively. If the magnetization is directed along the y axis, and if its effect on the mode fields is taken into account, relations (1) will not change in first approximation of the nondiagonal components of ϵ and μ, but the constants N_e and N_h will acquire the following increments:

$$\delta N_e = iN_e(\mu_{xz} - \mu_{zx}) \int \mathcal{E}(x) \frac{d\mathcal{E}(x)}{dx}\, dx,$$

$$\delta N_h = i\frac{N_h}{n_f^4}(\epsilon_{xz} - \epsilon_{zx}) \int \mathcal{H}(x) \frac{d\mathcal{H}(x)}{dx}\, dx, \tag{2}$$

where n_f is the refractive index of the film.

In the absence of losses, the parts of the ϵ and μ tensors linear with respect to the magnetization are antisymmetric and purely imaginary: $\epsilon^a_{ik} = if_e e_{iks} M_s$ and $\mu^a_{ik} = if_m e_{iks} M_s$. If the magnetization vector $\mathbf{M}$ is directed along the y axis, we would have $\delta N_e \sim f_m M_y$ and $\delta N_h \sim f_e M_y$. As can be seen from these relations, the increments of the effective refractive indices reverse their sign when the sign of M_y changes. The nondiagonal components of the ϵ and μ tensors can thus be clearly determined by measuring δN_e and δN_h during magnetic reversal of the film along the y axis. We call attention to the fact that since this effect is linear with respect to magnetization, it can easily be distinguished from the Voigt effect, which is quadratic in magnetization and which can also contribute to a change in N_e and N_h.

The measurements were carried out using a $(\text{YbPr})_3(\text{FeGa})_5\text{O}_{12}$ film grown epitaxially on a gadolinium-gallium garnet substrate with a $\{111\}$ orientation and "easy plane" magnetic anisotropy. The wavelength of light is 1.15 μm. Rutile prisms were used to introduce and remove the light. Measurement of the mode spectra in a given film showed that seven TE modes and seven TM modes can propagate in it. The refractive indices $n_f^{TE} = 2.17538$ and $n_f^{TM} = 2.17700$ and the film thickness $W = 3.82$ μm were determined from the mode spectrum. These values were used to calculate the overlap integrals of the mode fields in (2). The difference in the refractive indices of TE and TM modes stems principally from the stress in the film, which gives rise to optical anisotropy due to the photoelastic effect.[4] The film was then placed in an alternating magnetic field ($f = 2500$ Hz) directed along the y axis and the changes in N_e and N_h for the modes with indices $k = 4,5,6$ were determined alternately by using a special device which is sensitive to slight deviations of the beam. We then determined

TABLE I.

k	N_e	N_h	$\delta N_e \times 10^7$	$\delta N_h \times 10^7$	θ_F^e(°/cm)	θ_F^m(°/cm)
4	2.0609	2.0572	0.68	20.8	− 399.9	14.2
5	2.0093	2.0042	1.24	32.5	− 405.6	18.6
6	1.9481	1.9461	1.12	36.6	− 404.9	14.3

from Eqs. (2) the imaginary parts of the nondiagonal components of the ϵ and μ tensors and found the specific Faraday rotation corresponding to these components. The values obtained by us are presented in Table I. The gyroelectric and gyromagnetic parts of the Faraday effect determined in this manner have different signs.

This experiment can be described in principle by introducing the effective dielectric tensor[6] $\epsilon_{ik}(\mathbf{r},\mathbf{r}',\omega)$ which contains two independent parameters f_e and f_m. A description of this sort, however, would introduce unjustifiable complications, since such a tensor has peculiarities of the δ-function type at the film boundaries, which is equivalent to the introduction of a surface current (which is associated with f_m).

In summary, we have shown that a waveguide propagation of light in epitaxial garnet ferrite films makes it possible to accurately measure the nondiagonal components of the dielectric and magnetic tensors and that the nondiagonal components of the magnetic tensor are nonvanishing in the optical frequency range.

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