Acousto-optic modulation in hematite

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(Submitted 4 November 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 1, 31–34 (5 January 1982)

Observations of an acoustic modulation of optical birefringence in hematite are reported. The modulation of the dielectric function in fields $H \lesssim 1$ kOe is caused primarily by spatially inhomogeneous, high-frequency oscillations of the magnetic moments that accompany acoustic waves.

PACS numbers: 78.20.Hp, 78.20.Fm

Hematite in its magnetically ordered state is an optically biaxial crystal with principal dielectric axes determined by the orientation of the magnetic moments.[1,2] As acoustic waves propagate in this crystal, they cause an oscillation of the magnetization which in turn causes spatially inhomogeneous, high-frequency oscillations of the dielectric axes. This acousto-optic modulation mechanism can be expected to be particularly important in the easy-plane, weakly ferromagnetic phase of hematite, because of the strong mutual effects of the elastic and magnetic subsystems which are characteristic of antiferromagnets exhibiting an easy-plane anisotropy.[3–6] [In magnetic fields $H \lesssim 1$ kOe, the amplitude of the angular deviation (ϕ) of the antiferromagnetic vector **l** from its equilibrium direction reaches values on the order of 0.1 rad at relatively small strain levels in the acoustic waves, $\hat{u} \sim 10^{-6}$.] A modulation of the optical birefringence caused by oscillations of the dielectric axes has been observed experimentally at antiferromagnetic resonance in the compound $CoCO_3$, which is isomorphic with hematite.[7]

The magnetic contribution to the dielectric function can be described by[2,8]

$$\Delta\hat{\epsilon}_M = \mathbf{l}\hat{\eta}\mathbf{l}\,. \tag{1}$$

Solving the equation of motion for the antiferromagnetism vector[6] in the first approximation in the acoustic-strain amplitudes, we find the following equation, which describes the magnetoacoustic modulation of the birefringence:

$$\Delta\hat{\epsilon}_{ME} = \hat{\eta}_2\left(\frac{2H_E}{M_0}\right)\frac{\hat{B}_2}{(\omega_{s0}/\gamma)^2}\,\hat{u}, \tag{2}$$

where $\omega_{s0} = \gamma\sqrt{H(H+H_D) + 2H_E H_{ms}}$ is the frequency of the antiferromagnetic resonance,[4] and $\hat{\eta}_2$ and $\hat{B}_2$ are elements of the magnetooptic and magnetostriction tensors, respectively. An estimate, shows that $\Delta\hat{\epsilon}_{ME}$ at $H \lesssim 1$kOe (using the values of η found in Ref. 2) is more than an order of magnitude higher than the contribution from the photoelastic effect proper, which occurs in the paramagnetic phase. The contribution of this magnetophotoelastic effect decreases with increasing magnetic field H at a given strain amplitude, and there is no change in $\Delta\hat{\epsilon}$ with increasing H at a constant amplitude of the magnetic oscillations caused by the strain [see Eq. (1)]. Another feature of this effect [which is not incorporated in the linearized equations in (2)] is

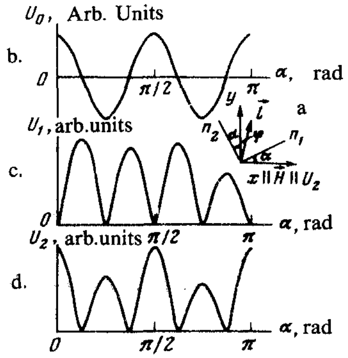

FIG. 1. Intensity of the transmitted light as a function of the angle between the polarization vector of the incident light and the twofold axis. a—Experimental geometry (n_1 and n_2 are the axes of the polarizer and of the analyzer); b—constant component of the signal; c—signal component at ω_1; d—signal component at $2\omega_1$.

that it reaches saturation at strain levels $\hat{u} \sim 10^{-5}$ ($\phi \sim 1$ rad), because of a limitation on the dynamic changes of the projection of the vector $\mathbf{l}(|\mathbf{l}| \cong 1)$ and thus a limitation on $\Delta\hat{\epsilon}_M$ [see Eq. (1)]. Experimentally, the modulation was observed from the change in the intensity of light transmitted through a polarizer crossed with an analyzer bracketing the hematite sample when the acoustic waves were excited. The experimental geometry is shown in Fig. 1a. The light source is a laser with a wavelength $\lambda = 1.15$ μm. The sample is a disk with a plane oriented perpendicular to the threefold axis (C_3), with a diameter of 5.5 mm, and with a thickness $d = 0.35$ *mm*. The C_3 axis is oriented parallel to the light propagation direction. Acoustic waves are excited parametrically by a longitudinal pump[9] at the frequency of the fundamental contour-shear mode, $\omega/2\pi = 0.5$ MHz. The amplitude of the magnetic oscillations accompanying the acoustic deformation is monitored with a remote pickup coil and a tuned receiver. A parametric method is used, in order to eliminate stray pickup by the receiver at the frequency ω_1 from the excitation circuits. The light intensity is modulated with a photomultiplier or visualized with an image converter. The changes which occur in the constant component of the intensity of the transmitted light and in the variable components at the frequencies ω_1 and $2\omega_1$ upon the excitation of sound in the sample are measured. Figures 1b, 1c, and 1d show the observed contributions to the intensity, which are characteristic for a modulation of the birefringence, plotted as a function of the angle (α) between the polarization vector of the incident light and the twofold axis ($\mathbf{x}$)||$\mathbf{H}$) (the voltage components at the photomultiplier output are plotted along the ordinate). Figure 2 shows the variable component of the intensity at the frequency ω_1

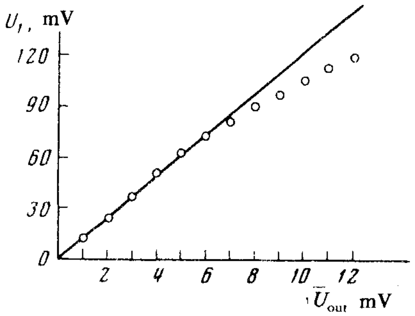

FIG. 2. Dependence of the ω_1 component of the intensity of the transmitted light on the oscillation amplitude ($\alpha = \pi/8$).

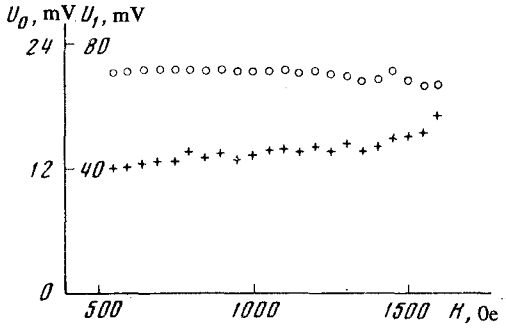

FIG. 3. Field dependence of two components of the intensity of the transmitted light. 0—Constant component; +—variable component at the frequency ω_1.

(for $\alpha = \pi/8$) of the signal induced by the magnetic oscillations in the pickup coil. The effect tends toward saturation at $U_{\text{out}} > 6\text{mV}$. From the ratio of the signals at $2\omega_1$, at $\alpha = 0$ and ω_1 at $\alpha = \pi/8$, we can determine the amplitude of the angular deviation of the antiferromagnetic vector, $\phi = U_{2\omega_1}/U_{\omega_1}$ (the level $U_{\text{out}} = 12$ mV corresponds to the angle $\phi = 0.32$ rad): Since the acoustic strain amplitude was not monitored directly during the resonance measurements, the results shown in Fig. 3 for the field dependence of the constant and variable acoustic contributions to the light intensity were obtained at a constant amplitude of the magnetization oscillation. The angular deviations of the antiferromagnetic vector in the contour-shear oscillations are related to the fundamental component of the shear strain, u_{xy} (Ref. 10), by

$$\phi = \zeta \frac{c_{14}}{B_{14}} \frac{1-\kappa}{1-\zeta} u_{xy}, \qquad (3)$$

where

$$\zeta = \frac{H_E}{M_0} \frac{(2B_{14})^2}{C_{44}\,(\omega_{s0}/\gamma)^2}, \quad \kappa = \frac{C_{44}}{C_{14}} \frac{B_{11} - B_{12}}{2B_{14}},$$

and $\hat{c}$ is the elastic modulus tensor.

According to (3), the amplitude of the magnetic oscillations is held constant upon an increase in the magnetic field H from 0.5 to 1.5 kOe by an increase in the strain amplitude by a factor of more than two. The experimental results in Fig. 3 show that the contribution of the acoustic modulation to the constant component of the intensity changes by no more than 25% in this case, while at the modulation frequency this contribution does not exceed the 10% accuracy of the measuring receiver. These results show that the magnetic mechanism for the acousto-optic modulation is playing the major role. This magnetophotoelastic effect substantially simplifies the problem of visualizing the acoustic fields of acoustic waves which are magnetoelastically coupled in a linear manner (in comparison with the case of waves for which there is no linear coupling). A narrow light beam 0.2 mm in diameter has been used to measure the strain distribution in the fundamental contour-shear mode. The observed distribution agrees with theoretical distributions and indirect experimental data.[10]

We wish to thank A. S. Borovik-Romanov, M. A. Savchenko, N. M. Kreĭnes, and V. S. Lutovinov for a discussion of these results; we also thank V. A. Murashov and A. A. Evdokimova for furnishing the hematite single crystals.

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Translated by Dave Parsons
Edited by S. J. Amoretty