Investigation of acoustic activity in crystals by the method of Bragg reflection of light

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It is proposed to investigate the acoustic activity of crystals by using the method of Bragg scattering of light by elastic waves. The feasibility of the method is demonstrated by using as an example quartz crystals in which the acoustic activity was measured at elastic-wave frequency 1.55 GHz.

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The phenomenon of acoustic activity is related to the spatial dispersion of the elastic moduli[1–4]

$$c_{ijkl}(\omega, \mathbf{q}) = c_{ijkl}(\omega) + i\gamma_{ijklm}(\omega)\, q_m + \dots . \tag{1}$$

Here c_{ijkl} is the elastic modulus, γ_{ijklm} is the acoustic gyrotropy tensor, and ω and $\mathbf{q}$ are the frequency and wave vector of the elastic waves.

When account is taken of the spatial dispersion for transverse elastic waves propagating along the z axis, which is degenerate in the absence of gyrotropy, the following expressions are obtained for the velocity of the elastic waves and for the corresponding displacements:

$$v^{\pm} \cong v(1 \pm \frac{1}{2}\gamma_{543}\, {}^{q_z}/_{c_{44}}), \tag{2}$$
$$u_x^{\pm} = \pm i u_y,$$

where $v = \sqrt{c_{44}/\rho}$ is the velocity of the elastic waves in the absence of gyrotropy and ρ is the crystal density.

Thus, acoustic gyrotropy lifts the degeneracy for the transverse elastic waves propagating along the z axis: the normal modes are now, as follows from (2), elastic waves with left-hand and right-hand circular polarization and with different propagation velocities.

The splitting (2) of the acoustic spectral branches with which the phenomenon of acoustic phenomena is connected can be investigated with the aid of neutrons[5] or with the aid of Mandel'shtein-Brillouin scattering of light.[6] The acoustic activity is measured directly in ultrasonic (hypersonic) experiments, and such measurements have been performed so far in only two studies[7,8] on quartz crystals. In the ultrasonic experiments, a transverse elastic wave with linear polarization is introduced into the crystal with the aid of an external piezoelectric converter. This wave breaks up in the crystal, in accordance with (2), into two circularly polarized components propagating with different velocities. When these components are added together in an exit piezoelectric converter, a linearly polarized wave is again obtained, but its polarization is rotated relative to the initial one through an angle ϕ, equal to

$$\phi = \frac{1}{2}(q^- - q^+)z = \frac{1}{2}\,\omega\left(\frac{1}{v^-} - \frac{1}{v^+}\right)z ,$$

where z is the path traversed by the elastic wave in the crystal.

Substituting (2), we obtain

$$\phi = az = \frac{\gamma\omega^2}{2\rho v^4}\, z . \tag{3}$$

Here $\gamma \equiv \gamma_{543}$, and α is the specific rotation ability.

Measurements of the angle of rotation of the plane of polarization (3) in ordinary ultrasonic experiments[7,8] is a rather complicated problem. These measurements call for a variation of either the frequency of the elastic waves or the length of the samples, or else of the orientation of the receiving converter. In addition, experiments of this kind yield results that are averaged over the entire length of the crystal.

We propose to investigate the acoustic activity by using the method of Bragg scattering of light by elastic waves. This method is superior to ordinary ultrasonic methods because of its simplicity and the possibility of investigating the effects of acoustic gyrotropy at arbitrary points of the sample.

The acoustic activity was investigated with quartz crystals. Linearly polarized transverse elastic waves of frequency 1.55 GHz were excited with the aid of a piezoelectric converter of x-cut lithium niobate, and propagated along the z axis of the quartz. The accuracy with which this axis was oriented was about 2′ (we note immediately that at this orientation accuracy and at the high frequency employed by us the contribution of the linear acoustic birefringence, due to deflection of the wave vector of the elastic waves away from the z axis, is small enough[7]). The samples were parallelepipeds with dimensions 5×6×40 mm and with the long side along the z axis. We measured in the experiment the intensity of the Bragg scattering of light of wavelength 6328 Å as a function of the distance z from the piezoconverter (see Fig. 1). The light was incident and scattered in the xz plane.

It can be shown that the intensity of light scattered by elastic waves is proportional to

$$I \sim p_{44}^2 \sin^2\left(\frac{\pi}{2} + \alpha z\right), \tag{4}$$

where p_{44} is the photoelastic constant.

In the derivation of (4) we have neglected the Bragg angle θ, which is quite small at the employed frequencies and, in addition, we have chosen the origin such that at $z = 0$ the intensity of the scattered light was maximal.

It follows from (4) that when the sample is moved along the propagation

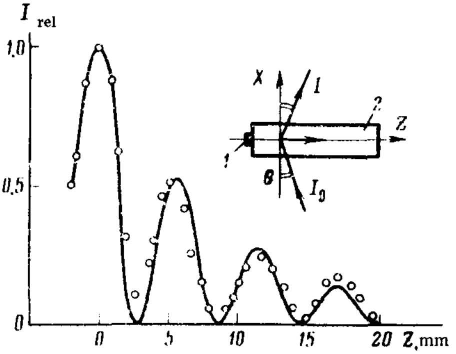

FIG. 1. Dependence of the relative intensity of the light scattered by elastic waves on the distance z, and the experimental setup: 1—piezoelectric converter, 2—crystal. Elastic-wave frequency 1.55 GHz. Solid curve—calculation by formula (5). The value $z = 0$ corresponds to the second maximum of the intensity as counted from the start of the crystal.

direction of the elastic waves, i.e., when z is varied, the intensity of the scattered light should oscillate with a period $z_0 = \pi/\alpha$, the value of which is determined by the specific rotation ability of the crystal α.

The results of the experiments are shown in Fig. 1, which shows the dependence of the relative intensity of the scattered light on the distance z traversed by the elastic wave in the crystal. It is seen from Fig. 1 that the dependence of the signal on z has indeed an oscillatory character.

If we take into account the damping Γ of the elastic waves, then the relative intensity of the scattered light as a function of z should be given by

$$I_{rel} = \sin^2\left(\frac{\pi}{2} + \alpha z\right) e^{-\Gamma z} . \tag{5}$$

Using the value $\Gamma = 1.1\ \text{cm}^{-1}$, we find that the best agreement between experiment and calculation by formula (5) takes place at $\alpha = 312$ deg/cm or $\alpha = 130$ deg/cm GHz^2. This yields $\gamma = \gamma_{543} = 1.47 \times 10^4$ dyn/cm.

The errors in the determination of these quantities, which are due to the experimental errors, do not exceed 10%.

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