Direct observation of focusing of acoustic phonons in ruby crystals

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The technique of optical detection of thermal pulses was used to demonstrate the existence of preferred propagation directions (focusing rays) of transverse acoustic phonons at $\sim 10^{12}$ Hz in ruby.

PACS numbers: 63.20.Dj, 78.20.Nv

The effect of focusing acoustic phonons in crystals[1] consists of a sharp anisotropy of the spatial distribution of the energy flux of the acoustic waves in the lattice. It is due to the elastic anisotropy of the crystals, which causes the group–velocity vector **v**, which determines the propagation of the wave energy,

to deviate from their phase velocity (wave vector q). Phonon focusing was investigated heretofore in experiments with high-frequency acoustic phonons ($\sim 10^{12}$ Hz) generated in the form of thermal pulses and detected bolometrically.[1] The focusing manifested itself in an anomalous ratio of the intensities of the "longitudinal" and "transverse" phonon momenta propagating in the same direction. The present study, by using the technique of optical detection of thermal pulses,[2,3] has shown experimentally that the propagation of (transverse) phonons has a sharp angular anisotropy and there are directions of predominant propagation of phonons in crystals.

The experiments were performed on ruby $Al_2O_3 \cdot Cr^{3+}$. It has been recently shown[4] for the trigonal lattice of corundum Al_2O_3, by a theoretical computer calculation using the known elastic constants, that if the spatial distribution of the wave vectors q of the transverse acoustic waves is isotropic, then the corresponding distribution of the group velocities v has very narrow condensation regions (focusing rays); the direction of these rays in the crystal was calculated.

We used in the experimentals rectangular single-crystal samples of $Al_2O_3 \cdot Cr^{3+}$ with linear dimensions of several dozen mm,[1) (see Fig. 1, which shows a section through the sample). The faces of the sample were oriented along the basal plane perpendicular to the trigonal axis C_3, along the vertical symmetry plane σ_v, and along the plane (C_3, C_2) containing the symmetry axis C_3 and the horizontal axis C_2. The sample was at $T = 2$ K. A thin-film heater "h" was sputtered on one of the faces and was heated at a repetition frequency 100 kHz by current pulses of 200 nsec duration. The thermal phonon pulses that were injected thereby from "h" into the crystal propagated in the crystal ballistically.

The principle of optical detection of thermal pulses was described in[2,3]. The focused Ar-laser light produced inside the crystal a region in which some of the Cr^{3+} ions were transferred into a metastable $E(^2E)$ state. The passage of the thermal pulse through the excited volume induces transitions $\bar{E} \to 2\bar{A}$, and this produces a luminescence pulse in the line $R_2(2\bar{A} \to {}^4A_2)$

$$I_{R_2}(t) \sim n(t) \, \alpha N^{*} \tag{1}$$

Here $n(t)$ and α are the concentration and the absorption cross section of the 19 cm^{-1} (0.87×10^{12} Hz) resonant phonons causing the $\bar{E} \to 2\bar{A}$ transitions, and N^* is the concentration of the Cr^{3+} ions. The light pipe L gathers the luminescence light from the small excited volume "d" located at the intersection of the laser beam and the light-pipe axis. The radiation passes through the light pipe to the slit of a monochromator, which separates the R_2 line, and then to a photomultiplier connected to an electronic recording system. The volume "d" is thus a tuned detector of 29 cm^{-1} phonons, with the luminescent R_2 pulse (1) reflecting the number of phonons $n(t)$ in the detecting volume "d."

Of very great importance for our purposes is the possibility of moving the detector "d" inside the sample; this is easily accomplished by use of a controllable shift of the crystal relative to the immobile system comprising the laser beam and light pipe. This makes it possible to investigate the phonon momenta at different phonon propagation direction 1 (line h—d) in the crystal. Let the position of the phonon propagation vector be characterized by the angle $-\pi/2 < \theta < \pi/2$ with the C_3 axis and by the azimuthal angle in the basal plane.
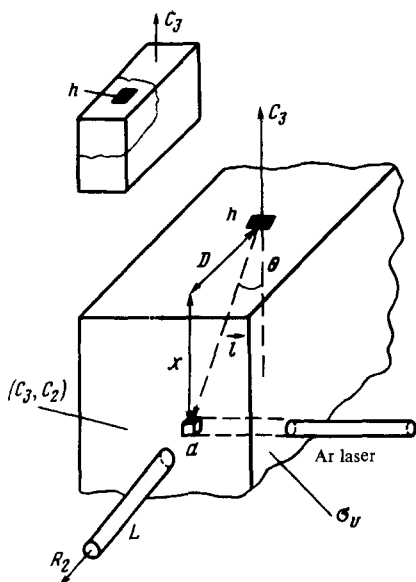
FIG. 1. Experimental setup.

Figure 1 shows an example of the location of the detector "*d*" in a sample
(45×30×10 mm) when the direction of l is varied in the meridional plane which
is the symmetry plane σ_v. In this case the variable angle is $\theta = \cot^{-1}(D/X)$,
where X (variable) and D (7—10 mm) are the two measurable coordinates of
"*d*" (Fig. 1).

Figure 2 shows typical R_2-luminescence pulses $I_{R_2}(t)$ from transverse
phonons, observed in this experimental setup at different angles θ in steps of
$\Delta\theta = 2.5°$. The ballistic phonons propagating along the shortest line $h−d$ have
the shortest time of flight $t = l/v_t$ to the detector (l is the $h−d$ distance and v_t
is the phonon velocity), and produce the steep leading front of the pulse $I_{R_2}(t)$.
Owing to the phonons that reach "*d*" along indirect trajectories (reflection
from the walls or scattering in the volume), the trailing edges of the pulses are
strongly stretched out. It is seen from Fig. 2 that in the angle region near
$\theta_1 = 54°$ the width of the R_2 pulses is greatly decreased and their intensity great-
ly increased. An analogous phenomenon is observed in the propagation of
transverse phonons in the same plane σ_v and in a different angle region, near
$\theta_2 = -38°$.

Measurements made on another sample (12×12×40 mm) have shown that
when the direction of l (of the angle θ) in the meridional plane (C_3, C_2) is
changed, the pulse $I_{R_2}(t)$ from the transverse phonons becomes narrower and
its amplitude increases, but this increase takes place at two other values of
angle, $\theta_1 = 43°$ and $\theta_2 = -45°$. The narrowing and the increase of $I_{R_2}(t)$ at the
indicated angles θ_1 and θ_2 was observed for transverse phonons propagating in
the planes σ_v and (C_3, C_2) also by using several observation setups different
from that of Fig. 1.

The observed narrowing and increase of the amplitude of $I_{R_2}(t)$ point to a
sharp increase in the number of transverse ballistic phonons propagating in the
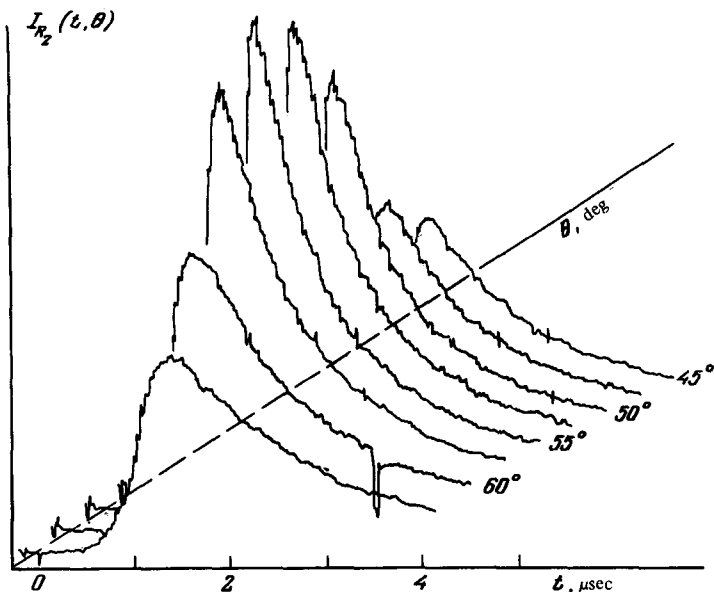
FIG. 2. Pulses of R_2 luminescence due to transverse phonons at different propagation directions in the meridional plane σ_v.

meridional planes σ_v and (C_3, C_2) of the crystal at definite angles θ_1 and θ_2 to the C_3 axis. It is obvious that the effect is connected with the focusing of transverse phonons. The results of the experiment agree well with the computation conclusions[4] that predict the presence of very sharp focusing for transverse phonons propagating in meridional planes—along two directions in each plane.

The observed focusing directions in the planes σ_v ($\theta_1 = 54°$, $\theta_2 = -38°$) and (C_3, C_2) ($\theta_1 = 45°$, $\theta_2 = -45°$) are close to those calculated in[4]. It is interesting that when the direction of l in the basal plane of the crystal is changed, no noticeable focusing was observed at all, likewise in agreement with the theoretical conclusions that take into account the character of the elastic anisotropy of corundum.

In the described experiments, the amplitudes of the R_2 pulses $I_L(t)$ due to longitudinal phonons (which are in general smaller than the R_2 pulses from the transverse phonons $I_T(t)$ [2] because of the difference between the cross sections $\alpha \sim 1/v_L^3$ at $v_L \approx 2v_T$) were very small. In the region of the focusing angles θ_1 and θ_2, the pulse amplitude ratio I_L/I_T decreased appreciably, in full agreement with the fact that according the theory[4] the longitudinal phonons should not undergo noticeable focusing.

It should be noted that the experimental "angular" width of the focusing beams ($\sim 8°$, see Fig. 2) is much larger than the calculated value. [4] The observed width is determined by the angular resolution of the method, which, owing to the relatively large linear dimensions of the heater "h" (~ 1.5 mm) and of the detector "d" is approximately $\Delta\theta = 6°$ at distances $l \approx 10$ mm between h and d.

[1] We used $Al_2O_3 \cdot 0.025\% Cr^{3+}$ single crystals, with a highly homogeneous distribution of Cr, grown by M. I. Musatov by the method of the State Optical Institute.

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