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Physical and geometrical optics of phonons

D.J. Dieleman, A.F. Koenderink, M.G.A. van Veghel, M.A. de Vries, A.F.M. Arts*, H.W. de Wijn

Faculty of Physics and Astronomy, Debye Research Institute, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

Abstract

Several experiments are presented to study the physical and geometrical optics of narrow diffraction-limited monochromatic phonon beams in the frequency range 1–6 GHz. The experiments include diffraction by fixed and sideward moving gratings, and the realization of a phonon lens. © 1999 Elsevier Science B.V. All rights reserved.

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By the use of a recently developed technique generating narrow Fresnel-diffracted monochromatic phonon beams [1] it is feasible to perform experiments on the physical and geometrical optics of phonons in the frequency range 1–6 GHz. The phonons, of longitudinal polarization, are generated by periodic heating of a thin (400–900 nm) Au film deposited on the (0 0 1) surface of a single crystal of lead molybdate ($PbMoO_4$). This heating, in turn, is achieved by interference of two tunable cw single-frequency dye lasers, operating at slightly different frequencies and focused on the Au film to a spot 40 μm in diameter. The generated acoustic beam, having a frequency equal to the difference frequency of the lasers, is detected via Brillouin scattering, which enables in situ measurement of the beam intensity as well as the phase velocity. Below, we consider experiments featuring a static phonon grating, a sideward moving phonon grating, and a phonon lens.

The direction of propagation of the acoustic beam in the crystal can be swept by allowing a mutual angle α between the two dye-laser beams striking the transducer. This causes the temperature modulation to travel along the transducer surface, and accordingly the wave vector of the strain wave possesses a component parallel to the surface. At the transducer-crystal interface the transverse wave vector is conserved, and as a result the strain wave injected into the crystal propagates at an angle with the normal to the surface, i.e., the *c*-axis. Due to the elastic anisotropy of $PbMoO_4$, however, the energy of the acoustic beam propagates in a direction different from the wave vector associated with the phase velocity. This effect, known as phonon focusing, or rather defocusing in the case of $PbMoO_4$, is directly observed by Brillouin detection. Fig. 1 shows transverse intensity profiles of the acoustic beam at a series of fixed distances from the transducer. The phonon frequency is $\omega/2\pi = 3.1$ GHz.

* Corresponding author. Fax: + 31-30-2532403; e-mail: arts@phys.uu.nl.

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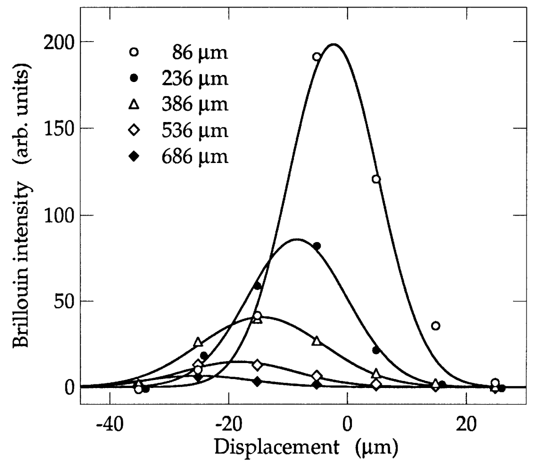

Fig. 1. Lateral intensity profiles of the acoustic beam as a function of the distance from the transducer. The lateral displacement, taken in absolute value, adds to a rotation over $\theta = 13.2°$ to find θ_{group}.

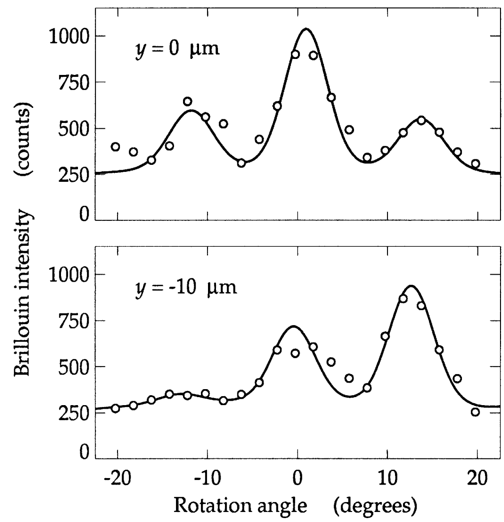

Fig. 2. Lateral Brillouin intensity profiles, obtained by rotating the crystal at a fixed distance of 188 μm from the transducer. An additional shift (lower graph) cause imbalance between the first-order maxima.

The observed shifts, linearly increasing with the distance, are additional to a rotation of the crystal over an angle $\theta = 13.2°$ from the c-axis, so that we find $\theta_{group} = 15.7°$ for the angle of the group velocity. This result is in conformity with the value calculated from the elastic constants at the given θ_{phase} for the phase velocity. In the experiment the angle α was set to 5.7°, corresponding to $\theta_{phase} \approx \arcsin[2(kv/\omega)\sin\frac{1}{2}\alpha] = 11.7°$. Here, $k = (2\pi/580)\,nm^{-1}$ is the optical wave vector, and $v = 3.63$ km/s the phonon velocity. We note that in the experiment the crystal was rotated slightly further out than θ_{phase} to compromise between satisfying the Brillouin condition on the one hand and alignment along the group velocity on the other. The strong decrease in the Brillouin intensity at larger distances is caused by phonon damping, while the increase in the width is essentially determined by Fraunhofer diffraction [1].

A transducer in the form of a microscopic Au grating rather than a uniform film leads to the phonon equivalent of optical Fraunhofer diffraction by multiple slits. A high-quality grating was fabricated by photo-etching of a homogeneous gold layer (600 nm), leaving an array of parallel strips 3.0 μm in width with a grating constant of 8.0 μm. At a phonon frequency of 2.2 GHz, standard diffraction theory then predicts first-order interference maxima occurring at an angle $\theta \approx 12°$ from the c-axis. This is confirmed by the top graph of Fig. 2, which shows a typical angular scan of the Brillouin intensity at a depth of 188 μm below the transducer. Here, the rotation angle is defined as before. Again, phonon defocusing makes the group velocity deviate to a larger angle in comparison with the phase velocity. Phonon defocusing appears to strongly affect the observed diffraction patterns. To show this more clearly, scans were taken in which the spot of the phonon generation, i.e., the focus of the dye lasers, was laterally shifted by -10 μm with respect to the Brillouin scattering plane (lower graph of Fig. 2). In this geometry, the orientation of the Brillouin plane is maintained, but the detection volume views the generation spot under an angle closer to the group velocity for one first-order diffraction maximum, and under a less favorable angle for the other maximum. Indeed, the diffraction pattern has turned asymmetric. The solid lines in Fig. 2 represent a detailed calculation of the diffraction profile in the Fraunhofer approximation, including the effects of elastic anisotropy and a Gaussian intensity distribution of the strain source over the grating.

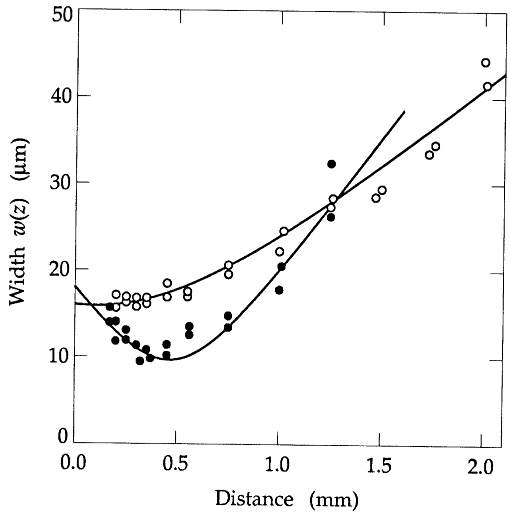

Fig. 3. Half the 1/e width of the intensity of the acoustic beam versus the distance from the transducer for overlapping laser foci (open circles) and for laser foci separated by 1.2 mm (filled circles).

In the third experiment, we simulated a lens for phonons by introducing a radially symmetric phase shift in the periodic heating profile at the transducer. This may be realized by shifting the focal waists of the collinearly aligned dye laser beams along the optical axis, with respect to each other and with respect to the transducer surface. Via the thermomodulation mechanism, the ensuing phase distribution over the heated area is passed on to the generated strain profile. From the geometry and the Gaussian profiles of the dye-laser beams one may calculate the radii of curvature R_1 and R_2 of the optical wavefronts at the transducer [2], and subsequently derive the acoustic focal length f through

$$\frac{1}{f}=\frac{1}{q}\left(\frac{k_2}{R_2}-\frac{k_1}{R_1}\right), \quad (1)$$

with q the phonon wave vector, and $k_{1,2}$ the optical wave vectors. To study the divergence of the phonon beam propagating in the crystal, the width of the beam was measured as a function of the distance from the transducer. To minimize phonon damping, the experiment was conducted at 2.1 K. Results for half the 1/e width of the beam are presented in Fig. 3 for a phonon frequency of 5.5 GHz. The open data points apply to the case in which the both focal waists are positioned at the transducer. The illuminated spot then has its minimum diameter, and the injected strain has a uniform phase, i.e., no lens is expected. Good agreement is obtained (open circles) with the result of Fresnel diffraction theory [3] including phonon focusing effects for a circular aperture (solid line). The filled data points have been taken with a waist separation of 1.2 mm. An initial narrowing of the acoustic beam is observed. The corresponding line is calculated on the basis of the theory of optical diffraction with account of the curved optical wavefronts and phonon focusing. The effective focal distance of the acoustic lens amounts to 0.65 mm in this configuration.

In conclusion, several experiments have been presented exploiting the analogy between physical optics and the diffraction of coherent longitudinal phonon beams. Diffraction theory incorporating crystalline elastic anisotropy excellently accounts for the observed phenomena.

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