Reversal of residual damping of longitudinal hypersound in dielectric crystals

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The reversal of residual damping of longitudinal hypersound following coherent (with conservation of frequency) scattering of a narrow hypersonic beam in dielectric crystals is observed and studied. The effect consists in periodic restoration of the state of a hypersonic beam which had experienced a finite number of reflections from the boundary surfaces of the crystal. The conditions for reversal (stability conditions) of a hypersonic beam which moves along a two-fold crystallographic axis or one of higher order are found by taking the anisotropy into account. A method is developed and employed for measuring the residual damping coefficient α_0 in quartz, sapphire, and lithium niobate. The effect is realized in a planar-spherical geometry of the reflecting surfaces of the crystal and with 3 and 9.4 GHz longitudinal hypersonic beams. The lowest residual damping is observed for longitudinal hypersound propagating along a threefold axis in lithium niobate. For the latter, the ratio k'/k'' (k' and k'' are the real and imaginary components of the hypersonic wave vector) reaches 2×10^7 at a frequency of 3 GHz and at the temperature of liquid helium. The effective mean free path of the hypersonic phonon in this case $l_{ph}=\alpha_0^{-1}$ is almost three orders of magnitude greater than the size of the sample. The experimental data may be regarded as a direct proof of the coherence of the scattering of hypersound in dielectric crystals in helium temperatures.

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1. INTRODUCTION. STATEMENT OF THE PROBLEM

Along with the damping of hypersonic waves at low temperatures, we must also consider, in the study of the various processes in solids, those which take place with the participation of longwave acoustic phonons. Numerous theoretical and experimental investigations have been devoted to this problem of hypersonic damping, the first of which was the well known work of Landau and Rumer.[1] Recently, interest in this problem has been greatly stimulated since it has become clear that the propagation of hypersound in dielectric crystals at low temperatures can be used successfully for the construction of high-capacity memory devices for microwave signals.

The fundamental qualitative features of the damping of hypersound at low temperatures, which are possessed by practically all dielectric crystals studied up to the present, are as follows. At temperatures of the order of 0.1Θ, where Θ is the Debye temperature, there the damping coefficient has a strong temperature dependence, $\alpha\propto T^{4-7}$, and a linear frequency dependence. Such a sharp decrease in the damping with decrease in temperature is observed down to $T\approx0.01\Theta$, the damping coefficient decreasing by an order of magnitude. However, upon further decrease in the temperature the falloff in the damping is greatly diminished and the curve of the temperature dependence of α reaches a plateau. The temperature-independent hypersound damping α_0 in the region of the plateau is usually known as residual damping.[2]

Up to the present time, the principal effort has been directed toward the clarification of the mechanism of temperature-dependent damping in the region $0.01\Theta<T<0.1\Theta$. In this region of temperatures $\omega\tau\gg1$, where ω is the frequency of the hypersound and τ is the lifetime of the thermal phonons that predominate at the given temperature, while the absorption can be described as the scattering of the phonon flux, which is the hypersonic wave, by thermal phonons.[1] Under the conditions $\omega\tau\gg1$, $\hbar\omega<kT$, it is principally transverse hypersonic waves that are scattered. The conditions of conservation of energy and momentum forbid the scattering of longitudinal waves in a three-phonon process; however, if we take into account the lifetime of the scattered thermal phonon and the uncertainty of its energy connected with this, then the forbiddenness is progressively lifted with the increase in the uncertainty, and damping of the longitudinal wave sets in (the Simons mechanism[3]). As has been shown in a number of experimental researches,[4-6] the Simons mechanism predominates at temperatures of the order of 0.1Θ, when the uncertainty in the energy of the thermal phonon is rather large. Calculations on the basis of this mechanism allow us to obtain for the frequency and temperature dependences of the hypersound damping α comparatively simple expressions corresponding to the experimental data of Ref. 7.

The situation is different for the residual damping α_0 of longitudinal hypersound, the nature of which is still not entirely clear, in spite of the fact that a great deal of data has been accumulated on measurements of this damping in a large group of crystals at various hypersonic frequencies. The values of α_0 given in the different researches have such a wide scatter that it is not possible to establish with any reliability, definite regularities in the dependence of the damping on the frequency of the hypersound and on such characteristics of the material as the Debye temperature, the symmetry of the crystal lattice, and others. Data on the residual damping indicate only that the damping, even in perfect crystals, is comparatively large. On the basis of results of numerous measurements (these results are given in Ref. 8), we can conclude that in the

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frequency range 3–10 GHz, that quantity that is the reciprocal of the damping amounts to several centimeters, i.e., it is of the order of the size of the sample used for the measurement of the hypersound absorption.

It should be noted that the notion that the hypersonic-wave or long-wave phonon is propagated over comparatively small distances is widely used in the analysis of the different processes associated with the damping of the long-wave phonons. As an example, we can cite researches on the phonon "bottleneck" in the spin-lattice relaxation of impurity paramagnetic centers in dielectric crystals, where it is usually assumed that the lifetime of the resonant phonon is determined by its propagation to the boundary of the sample.[9]

Considering the damping of longitudinal hypersound from the viewpoint of time coherence of the scattering processes, we can note that the scattering from the thermal phonons in the range $0.01\Theta < T < 0.1\Theta$ is not a coherent process. At the same time, at $T < 0.01\Theta$, where the temperature dependence of the damping vanishes, the role of incoherent scattering is greatly reduced. The independence of α of the temperature is indicative of this. The same conclusion can be reached if we extrapolate the temperature dependence of the hypersonic damping, obtained on the basis of the Simons mechanism, to the range $T < 0.01\Theta$. The values of the damping coefficient turn out to be two or three orders smaller than those observed experimentally. We can therefore assume that the residual damping is connected with the elastic scattering of the hypersound by volume and surface defects of the crystal. Such an assumption was proposed earlier[2]; however, the existing experimental data were patently insufficient to verify it. The fact is that these measurements were carried out in a relatively narrow temperature range and the absence of a temperature dependence of α_0 in it did not make it possible to exclude the possibility of attributing α_0, for example, to relaxation absorption by defects with several stable states,[2] or to the incoherent phonon "bottleneck" effect observed in Ref. 10. Moreover, scattering from defects with dimensions much less than the hypersonic wavelength would lead to the strong frequency dependence ω^4, but the measured dependence of α_0 on the frequency turned out to be significantly weaker: ω^γ with $\gamma < 3$ (Ref. 8). The assumption that the residual damping is connected with elastic scattering by defects did not really contain a constructive element; it only indicated a possible difference between the residual damping mechanism and the temperature-dependent scattering of hypersound by thermal phonons. As a consequence, the problem of the damping of hypersound at low temperatures in the range $T < 0.01\Theta$ remained open.

The goal of the present work was to proceed further and answer the following question: if the residual damping represents elastic scattering, would it be impossible to reverse this damping? In other words, would it be possible to return the scattered hypersonic beam, at least partially, to the state given in its excitation? This consideration is based on the well known physical analogy between the mechanics of material particles and geometric acoustics, described by the Hamilton-Jacobi equation. Therefore, reversibility of the trajectory of the hypersonic beam in the crystal should correspond to the reversibility of the trajectory of the particle.

In the research, we discovered and investigated the effect of reversal of the residual damping of longitudinal hypersound in crystals. Reversal takes place if the thin beam of hypersound, propagating in the direction of a symmetry axis of second or higher order, is reflected in turn from a surface whose shape satisfies certain conditions. The reversal conditions were found with account taken of anisotropy. A method of measurement of the residual damping under the reversal conditions was developed, allowing us to determine small absolute values of the damping coefficient of longitudinal hypersound, and the measurement of α_0 was made at frequencies of 3 and 9.4 GHz in crystals of quartz, sapphire, and lithium niobate. The measurements showed that the residual damping in these crystals under reversal conditions decreases by about an order of magnitude. It was established by the same direct method, first, that the fundamental contribution to this absorption is made by the coherent scattering of the hypersound from inhomogeneities that are appreciably larger than the wavelength and, second, that the dielectric crystals studied possess extraordinarily high transparency for longitudinal hypersound at $T < 0.01\Theta$. The free path length of the corresponding long-wave phonon exceeds here the dimensions of the sample by two or three orders of magnitude.

2. REVERSAL CONDITIONS

In order to make clear the possibility of reversal of the residual damping associated with elastic scattering, we consider the properties of a longitudinal hypersonic wave propagating in a crystal between two reflecting surfaces. Let the distance between these surfaces in the direction of propagation be L, the radii of the curvature of the surfaces be R_1 and R_2, the diameter of the region occupied by the wave in the transverse direction be d, and the wavelength be λ, all satisfying the inequalities

$$L,\ R_1,\ R_2 \gg d \gg \lambda. \tag{1}$$

These are precisely the conditions realized in the measurement of hypersonic damping. As the direction of propagation of the wave, we choose the crystallographic twofold symmetry axis. We direct one of the coordinate axes x_1 along it and the other two axes x_2 and x_3 we locate in the transverse plane.

Keeping (1) in mind, we describe the hypersonic wave in the geometric acoustics approximation in the form of a narrow beam of rays, the state of each of which at the reflecting surface is determined by the four parameters $\{\xi_i\}$, $i = 1, 2, 3, 4$, $\xi_1 = x_2$; $\xi_2 = n_2$; $\xi_3 = x_3$; $\xi_4 = n_3$, where x_2 and x_3 are the coordinates of the point of intersection of the ray with the reflecting surface, and n_2 and n_3 are the projections of the wave normal vector $\mathbf{n}$ at this point, $n_2, n_3 \ll 1$. We denote the initial state of the ray by $\{\xi_i^{(0)}\}$, and its state after n-fold passage through the crystal by $\{\xi_i^{(n)}\}$. The problem is to find the conditions under which, after a finite number of passages through the crystal, all the rays in the beam acquire the same state they possessed upon excitation at the reflecting surface.

In the approximation of geometric acoustics, the change in the state of the ray is described by the canonical equations, in which the role of the Hamiltonian is played by the frequency of the hypersound ω as a function of the wave vector **k**, which satisfies the dispersion equation for elastic waves in a crystal.[11] The resultant function ψ—the analog of the eikonal in geometric acoustics—can be written, in our case of a homogeneous anisotropic medium, in the form

$$\psi=\omega l/s(\mathbf{n}), \tag{2}$$

as is easy to show; here l is the length of the path traversed by the ray in the crystal, s is the modulus of the ray velocity vector, $\mathbf{s}=\partial v/\partial \mathbf{n}$, and v is the phase velocity. From symmetry considerations, we have for the phase velocity of a narrow beam

$$v=v_0(1+\varepsilon n_2^2+\delta n_3^2+\gamma n_2 n_3), \tag{3}$$

where v_0 is the phase velocity along the crystallographic axis. The coefficients ε, δ, γ, as well as v_0, are found by the solving of the Christoffel equation. They are expressed in terms of the elastic modulus of the crystal. The coordinates of the axes x_2 and x_3 in the transverse plane of the beam are so directed that $\gamma = 0$. We write out the expression for ψ as a function of the transverse coordinates of the point of intersection of the ray with the reflecting surface before and after passage through the crystal. With account of symmetry and with accuracy up to terms of second order, ψ has the form

$$\psi=K+a(x_2^2+x_2'^2)+b(x_3^2+x_3'^2)+cx_2x_2'+dx_3x_3', \tag{4}$$

where K is a constant; the coefficients a, b, c, d depend on the radii of curvature of the reflecting surfaces and on the elastic moduli of the crystal; x_2 and x_3 are the initial coordinates of the ray; x_2' and x_3' are the coordinates after passage of the ray through the crystal. In addition, we have

$$n_2=-\frac{\partial\psi}{\partial x_2},\quad n_3=-\frac{\partial\psi}{\partial x_3},\quad n_2'=\frac{\partial\psi}{\partial x_2'},\quad n_3'=\frac{\partial\psi}{\partial x_3'}. \tag{5}$$

Substituting (4) in (5), we obtain a set of linear equations connecting the primed and unprimed variables, which we write down in the form

$$\xi'=A\xi, \tag{6}$$

where ξ is the group of four parameters $\{\xi_i\}$ characterizing the state of the ray, and A is a matrix of fourth rank:

$$A=\begin{pmatrix} A_1 & 0 \\ 0 & A_2\end{pmatrix},\quad A_1=\begin{pmatrix} 2a/c & 1/c \\ -c+4a^2/c & 2a/c\end{pmatrix},$$
$$A_2=\begin{pmatrix} 2b/d & 1/d \\ -d+4b^2/d & 2b/d\end{pmatrix}. \tag{7}$$

If the propagation of the ray is not accompanied by irreversible absorption in the volume of the crystal or on its surface, the state of each ray $\{\xi_i\}$ after n passages will be connected with the original state by the matrix A^n, and the reversal condition is that there exists a finite n, which is the same for all rays of the beam, and is not too large and under real conditions ($n \leq 10$), for which $A^n = E$, where E is the unit matrix. On the basis of the Cayley-Hamilton theorem we can conclude that for this it is necessary that the roots of the characteristic equation of the matrix A be different and equal in modulus to unity. Since the transformation of the parameters ξ_i is canonical, the matrices A, A_1, and A_2 are equal to unity. Therefore, the reversal conditions can be written in the form

$$|\mathrm{Tr}\,A_1|,\quad |\mathrm{Tr}\,A_2|<2. \tag{8}$$

We now find the number n at which $A^n = E$. On the basis of (8), we represent the trace of the matrix A_1 in the form $\mathrm{Tr}\,A_1 = 2\cos\varphi$. We then have for the p-th power of the matrix A_1

$$A_1^p=S_{p-1}(z)A_1-S_{p-2}(z)E, \tag{9}$$

where $z = \cos 2\varphi$, $S_{p-1}(z)$ and $S_{p-2}(z)$ are Chebyshev polynomials of the second kind,

$$S_p(z)=\sin(p+1)\varphi[\sin\varphi]^{-1}.$$

From (9) we find that p at which $A_1^p = E$ is the smallest integer of the form

$$p=2\pi q/\arccos\varphi, \tag{10}$$

where q is a positive integer. Similarly, we can find the number m at which $A_2^m = E$. It then follows that the desired n is equal to the least common multiple of p and m.

The reversal conditions in the case of propagation of the beam along a twofold symmetry axis include as special cases the propagation of longitudinal hypersound along the three-, four-, and sixfold symmetry axes. For narrow beams under these conditions, there is axial symmetry in the elastic properties in the transverse plane, by virtue of which $A_1 = A_2 = A_a$ and the reversal condition reduces to $|\mathrm{Tr}\,A_a| < 2$.

Upon satisfaction of the reversal conditions the hypersonic rays propagate in a region bounded by a caustic surface and execute stable periodic motion here in the transverse plane, under which conditions, the picture of the elastic field specified in the excitation is repeated after a finite number of passages. The periodic motion of the beam of rays can be stable also in the presence of inhomogeneities which produce elastic scattering at small angles. If the characteristic dimensions of the inhomogeneities are sufficiently large and satisfy the conditions of applicability of geometric acoustics (1), their effect can be taken into account by the dividing the path traversed by the ray into a series of uniform intervals, for each of which we can determine a generating function ψ_i of the form (4) and a corresponding matrix A_i. The matrix A, which corresponds to passage of the ray through the crystal, will obviously be equal to the product of the matrices A_i. Since each A_i is a unimodular matrix, A will also be unimodular and the reversal condition will take the same form as (8). Upon its satisfaction, we can realize the reversal effect in which the hypersonic wave scattered by the inhomogeneities will periodically return to the original state.

3. FEATURES OF THE EXPERIMENTAL METHOD

Experiments on the reversal of the residual damping of longitudinal hypersound in dielectric crystals were carried out by measurement of the temperature dependence of the damping coefficient in the temperature region 2–60 K at frequencies of 3 and 9.4 GHz. Samples were used which had been prepared from high-quality crystals of quartz, sapphire and lithium niobate. All the samples were rods of circular cross section, of diameter 4 mm and length from 3.4 to 60 mm. The geometric axis of the rod was oriented to within 0.5°, along a given crystallographic direction. In the quartz and sapphire samples, it was directed along the threefold crystallographic axis, along the normal to the plane of symmetry, and along the longitudinal normal direction in the symmetry plane and making an angle of about 57° with the threefold axis. The quartz rods were cut from native quartz of the type "Ekstra," of weight about 2 kg, the sapphire rods from boules measuring about 100 mm, produced by the GOI (State Optical Institute) Method. Single-domain boules of length 80 mm were used for preparation of the lithium-niobate samples.

To satisfy the reversal conditions, one of the ends of the rod was made plane, with its normal along the axis, and the other spherical, with the center of curvature located on this same axis. In the case of the planar-spherical geometry of the reflecting surfaces, when the geometric axis of the rod is directed along the crystallographic twofold symmetry axis, we have

$$a=\frac{k}{2L}\left(\nu-\frac{1}{2}+\frac{\varepsilon}{1+2\varepsilon}\right),\quad b=\frac{k}{2L}\left(\nu-\frac{1}{2}+\frac{\gamma}{1+2\gamma}\right),$$
$$c=\frac{k}{2L}\left(1-\frac{2\varepsilon}{1+2\varepsilon}\right),\quad d=\frac{k}{2L}\left(1-\frac{2\delta}{1+2\delta}\right), \tag{11}$$

where $k=\omega/v_0$, $\nu=L/R$, R being the radius of curvature of the spherical surface. From (8) and (11), we find the reversal condition

$$\nu<\min\{(1+2\varepsilon)^{-1},\ (1+2\delta)^{-1}\}. \tag{12}$$

If the direction of the geometry axis of the rod coincides with an axis of symmetry of third order, $a=b$, $c=d$, $\varepsilon=\delta$ and the condition for reversal takes the form $\nu<(1+2\varepsilon)^{-1}$.

For the measurement of the hypersound absorption, we used a pulse method in which we recorded the amplitude distribution of pulse echoes that arise as the result of successive reflections of the hypersonic wave from the ends of the sound conductor. The hypersonic pulse was supplied to the crystal by means of piezoelectric transduction of the microwave electromagnetic field in the interior of a resonator in which one of the ends of the rod was placed. In crystals of lithium niobate, thanks to the piezoeffect, the excitation of the hypersound was effected directly at the end surface. In the case of quartz and sapphire, a textured film of zinc oxide, applied by vacuum vaporization on the end face of the rod, was used for this purpose.

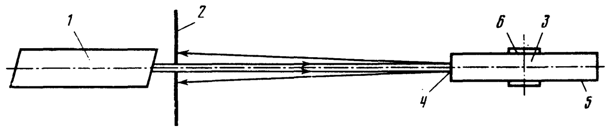

FIG. 1. Setup for monitoring of the mutual position of the mirrors: 1—helium-neon laser, 2—screen with aperture for exit of laser radiation, 3—sample, 4—spherical end of sample, 5—plane end, 6—sample container.

In the preparation of the samples, it was necessary to guarantee the symmetric location of the spherical mirror relative to the axis of the rod along which the crystallographic symmetry axis and the normal to the plane mirror were directed. For this purpose, we used the simple scheme pictured in Fig. 1 to monitor the mutual position of the reflecting surfaces in the process of their preparation. The monitoring procedure was as follows. A narrow light beam from the He–Ne laser 1, passing through the aperture in the screen 2, falls on the spherical surface; it is partially reflected and passes into the interior of the rod and is reflected from the plane end. Then it returns to the spherical end, leaving a mark here in the form of a clear luminous spot, which must coincide with the point of incidence of the light beam on the spherical surface through adjustment of the sound duct in the holder 6. Upon coincidence the beam propagates along a straight line drawn perpendicular to the plane end from the center of curvature of the surface of the spherical end. From the deviation of the coincidence point from the center of the spherical end, one can determine the angle between the indicated straight line and the axis of the sound duct with an accuracy of the order of 10′ at a distance 1.5 m between the spherical end of the rod and the screen. The spherical and plane surfaces in the prepared samples were finished to a very high degree of accuracy,[1)] while the required distance between the surfaces was accurate to within 20–30′. Since the scatter of the data on the residual damping of the hypersound in different samples of the same material was not large, it could be assumed that the indicated accuracy was adequate.

In measurements of the residual resistance under conditions of reversal, it was necessary to reduce to a minimum the effect of external sources of inelastic scattering of the hypersound, since at the small value of this damping they could significantly affect the results of the measurements. From this viewpoint, the end surfaces of the samples were subjected to careful cleaning, as is usually employed in vacuum evaporation of films, and the resonator, along with the sample, was enclosed in a copper vessel which protected the sample from contact with the liquid helium.

All the measurements of hypersound damping were carried out in a linear regime at a hypersound intensity of 1 mW/cm², prior to the onset of the nonlinear effects associated, in particular, with focusing of the hypersonic beam.

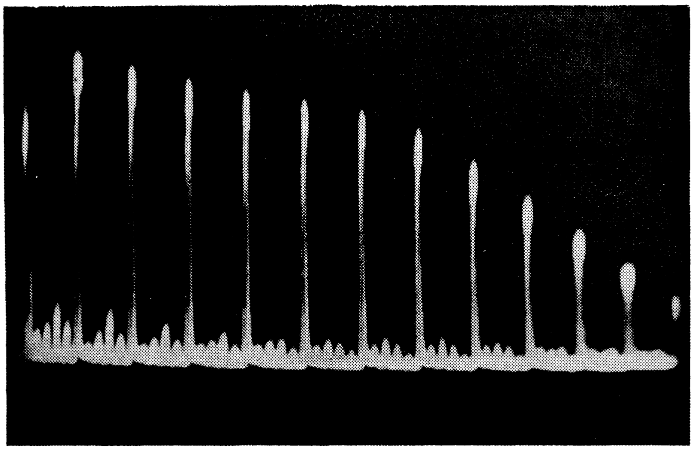

FIG. 2. Oscillogram of echoes of longitudinal hypersound in a sapphire crystal in the case of planar-spherical geometry of the reflecting surfaces. Every fifth echo is separated in amplitude.

4. RESULTS OF MEASUREMENTS

The effect of reversal of the residual damping of hypersound in the case of planar-spherical geometry of the mirrors is revealed already by the very character of the change in the amplitude of the echoes in the time sequence (Fig. 2). Since the transformation of the hypersound into an electromagnetic field is very sensitive to the phase distribution on the elastic strains on the surface of the mirror, only those echoes whose equal phase surface is close to the geometric profile of the mirror will be accompanied by small losses. As a result, maximum-amplitude signals in the time sequence will be those corresponding to periodic restoration of the elastic-field picture specified by the profile of the mirror. These pulses, in correspondence with the reversal conditions, follow within different intervals whose length of which, as follows from (10) and (11), depends for the given crystal on the ratio L/R. In particular, in the propagation of hypersound along a threefold symmetry axis, this time interval for the planar-spherical geometry of the reflectors, is equal to $2nL/v_0$, where n is the smallest integer of the form

$$n=\frac{\pi q}{\arcsin[\nu(1+2\varepsilon)]^{1/2}}. \qquad (13)$$

Here q is a positive integer.

This character of the time sequence of echoes is observed under conditions of reversal in all the crystals that we studied, and is more pronounced at 9.4 GHz than at 3 GHz. This circumstance is explained by the fact that at the higher frequency, because of the phase sensitivity of the piezotransduction, a more exacting selection of the echoes takes place: echoes are given off that satisfy with high accuracy the condition (13), while intermediate signals, which correspond to hypersound rays incident on the surface of the mirror at an angle to the normal, lead to out-of-phase excitation of the transducer, as a result of which they are absorbed.

If the reversal effect were to be reduced only to the restoration of the state of the hypersonic wave scattered by the spherically reflecting surface, then the residual damping in samples with planar-spherical geometry would be close in value to the damping in the same samples with plane-parallel ends. However, it was found that under the reversal conditions, the residual damping measured by the decay of the echo signals of maximum amplitude, decreases significantly. This fact was consistently observed in all the studied samples with planar-spherical geometry of the reflector. In order to establish this fact, measurements were first carried out on samples with plane parallel (with accuracy to within about 1″) ends, when the reversal conditions are certainly known not to be unsatisfied, after which one of the reflecting surfaces was made over into a spherical one.

It is seen from the data shown in Figs. 3–6 that the residual damping is considerably reduced in the case

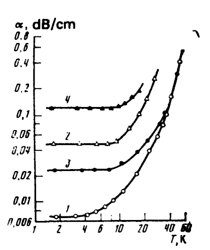

FIG. 3. Temperature dependence of the damping of longitudinal hypersound in lithium niobate along a threefold axis at a frequency of 3 GHz–(1) and (3), 9.4 GHz–(2) and (4); 1 and 2–with reversal (R = 44.8 mm, L = 442 mm, ε = -0.2), 3 and 4–without reversal.

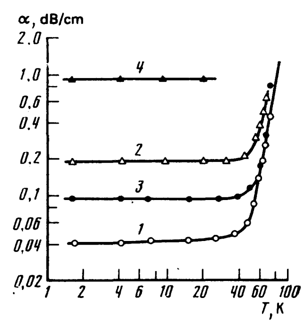

FIG. 4. Temperature dependence of the damping of longitudinal hypersound in sapphire along a threefold axis at a frequency of 3 GHz—(1) and (3), 9.4 GHz—(2) and (3); 1 and and 2—with reversal (R = 44.8 mm, L = 22.5 mm, ε = -0.016, 2 and 4—without reversal.

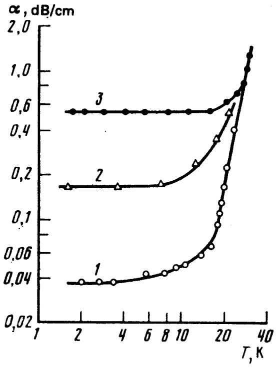

FIG. 5. Temperature dependence of the damping of longitudinal hypersound in quartz along threefold axis at a frequency of 3 GHz (1) and (3) and 4 GHz–(2); 1 and 2—with reversal (R = 119 mm, L = 40 mm, ε = 0.26), 3—without reversal.

of reversal. The damping decreases by an order of magnitude in quartz and by a factor of 3–5 in sapphire and lithium niobate. The smallest absolute magnitude of the residual damping of longitudinal hypersound was observed in crystals of lithium niobate in the propagation of the hypersonic beam along an axis of symmetry of third order. At a frequency of 3 GHz, the residual damping coefficient (in intensity) amounted to 1.6×10^{-3} cm^{-1}. Echoes were observed here that underwent approximately 2000 reflections and the length traversed in the crystal amounted to almost 10^4 cm. Similar results were obtained in the propagation of longitudinal hypersound along the normal to the plane of symmetry of the lithium niobate crystal, and also along the direction of longitudinal normal, which lies in the symmetry plane of the crystal.

Measurements under reversal conditions show that the residual damping of longitudinal hypersound in the dielectric crystals studied is extraordinarily small. Thus, the characteristic ratio k'/k'', where k' and k'' are the real and imaginary components, respectively, of the hypersonic wave vector, amounts to 2×10^7 in lithium niobate at a frequency of 3 GHz. Because of this, the effective free path length of the corresponding hypersonic phonon, $l_{ph} = \alpha_0^{-1}$, exceeds the dimensions of the crystal under these conditions by three orders of magnitude.

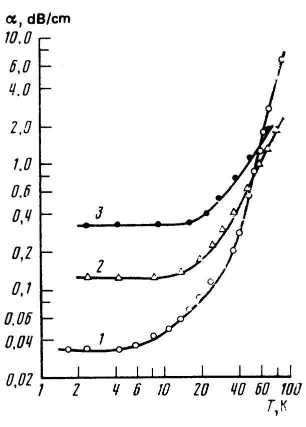

FIG. 6. Temperature dependence of the damping of longitudinal hypersound at a frequency of 3 GHz in lithium niobate along the normal to the plane of symmetry (1) and along the longitudinal normal, lying in the plane of symmetry of the crystal; 1—with reversal (R = 44.8 mm, L = 16 mm ε = 0.06, δ = -0.15); 2—with reversal (R = 44.8 mm, L = 3.4 mm), 3—without reversal.

The frequency dependence of the residual damping under reversal conditions is ω^γ with $1.3 < \gamma < 1.7$, as is seen from the data shown in Figs. 3–6. Since $\gamma < 4$, it can be concluded that the contribution to the scattering from small inhomogeneities of size $r \ll \lambda$ is not large. At the same time, the independence of α_0 of temperature and the comparatively weak frequency dependence allow us to conclude that it is associated with the irreversible coherent scattering from inhomogeneities that do not satisfy the approximation of geometric acoustics.

The data obtained earlier on the residual damping of the hypersound in samples with plane-parallel reflectors can be explained from the viewpoint of stability and reversal of the hypersonic beam. It is easy to show that in the propagation of a hypersonic wave between plane parallel reflectors we have $|\mathrm{Tr}\, A_1| = |\mathrm{Tr}\, A_2| = 2$, and the motion of the beam does not possess the required stability relative to exact parallelism of the reflectors, as well as relative to the volume inhomogeneity described by the matrix A_i for which $|\mathrm{Tr}\, A_i| > 2$. Here the state of the beam is not restored after a finite number of reflections; on the contrary it deviates more and more from the initial state with each passage through the crystal. This leads to a decrease in the effective transduction of the hypersonic echo, and it is perceived in the measurements as damping of the hypersound. It can therefore be assumed that, under conditions of very small damping of the longitudinal hypersound in dielectric crystals, the data obtained previously on samples with plane-parallel geometry of the reflecting surfaces serve as a measure of the instability of the hypersonic beam in the crystal. Their large scatter in magnitude is obviously connected with this.

It should be noted that the observed reversal effect is not restricted to longitudinal hypersonic waves in dielectric crystals; it can also be realized for other quasiparticles, for example, conduction electrons in metals under conditions in which their motion can be considered in the geometric approximation of narrow beams experiencing mirror reflection from the boundary surfaces.

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1)Both acoustical mirrors—the spherical and the plane—had the same quality of surface (polished to the 14th class of accuracy), departure of the plane and spherical ends from planarity and sphericity was monitored by test glasses and were within the limits of tolerance of the first class of accuracy.[12]

[1]L. D. Landau, Sobranie trudov (Collected Works) vol. 2, Moscow Nauka (1969), p. 227.

[2]P. G. Klemens, in Physical Acoustics (ed. W. Mason) Vol. 3B (Russian translation Moscow, Mir, 1968, p. 244).
[3]S. Simons, Proc. Phys. Soc. (London) **82**, 401 (1963).
[4]M. Pomerantz. Phys. Rev. **139A**, 501 (1965).
[5]E. M. Ganapol'skiĭ and A. N. Chernets, Zh. Eksp. Teor. Fiz. **51**, 383 (1966) [Sov. Phys. JETP **24** 255 (1967)].
[6]R. Nava, I. Arzt, I. Ciccarello and K. Dransfeld, Phys. Rev. **134A**, 581 (1964).
[7]J. W. Tucker and V. W. Rampton, Microwave Ultrasonics in Solid State Physics, North Holland, Amsterdam, 1972, (Russian translation Moscow, Mir, 1975, p. 120).
[8]S. N. Ivanov, I. M. Kotelyanskiĭ, V. V. Medved', and E. N. Khazanov, Zh. Eksp. Teor. Fiz. **70**, 281 (1976) [Sov. Phys. JETP **43**, 146 (1976)].
[9]C. Jeffries, Dynamic Nuclear Orientation, Interscience, 1963. (Russian translation, Mir, 1965, p. 68).
[10]J. DeKlerk, D. I. Bolef, and P. G. Klemens, Phys. Rev. Lett. **10**, 127 (1963).
[11]L. D. Landau and E. M. Lifshitz, Teoriya uprugosti (Theory of Elasticity) Moscow, Nauka, 1965, p. 138. (English translation, Pergamon, Oxford, 1970).
[12]A. L. Ardamatskiĭ, Almaznaya obrabotka opticheskikh detaleĭ (Diamond Machining of Optical Details) Leningrad, Mashonostroenie 1978, p. 34.

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