Mechanism for the effect of electric field pulses on the phase memory of the polarization echo

A. I. Validov, B. P. Smolyakov, and S. L. Tsarevskiĭ

V. I. Ul'yanov-Lenin Kazan State University; Kazan Physicotechnical Institute
(Submitted 22 October 1990)
Zh. Eksp. Teor. Fiz. **99**, 1302–1310 (April 1991)

Experimental results are reported on controlling the phase memory of the polarization echo in ferroelectric crystals by applying to the sample, along with the microwave pulses, various combinations of pulses of an electric field of constant amplitude $\Delta\widetilde{E}$ and length Δt. For $LiNbO_3$ crystals, pulses with $\Delta\widetilde{E}\sim 755$ kV/cm and $\Delta t\sim 10^{-7}$ s lead to a complete suppression of the polarization-echo signal in certain cases. In $LiNbO_3$ crystals activated with Ni^{2+} ions, the phase memory is destroyed at $\Delta\widetilde{E}\sim 150$ V/cm and $\Delta t\sim 10^{-7}$ s. This destruction of the phase memory of the polarization echo can be either reversible or irreversible. It stems from dispersion-induced spreading, curvature of the wavefront, and a violation of the phase-matching conditions during phase conjugation of the hypersonic pulse. For crystals doped with Ni^{2+} ions, the phase memory can be controlled efficiently by applying weak pulses with $\Delta\widetilde{E}\sim 1$–10 V/cm ($\Delta t\sim 10^{-7}$–$5\cdot 10^{-7}$ s).

INTRODUCTION

A polarization echo can form in ferroelectric and piezoelectric samples. This echo is a hypersonic response of the substance to the application of two microwave pulses. At the time $t=0$, a traveling hypersonic wave is formed by the first microwave pulse, of frequency ω. This hypersonic wave propagates through the crystal at a velocity s. If a second microwave pulse, of frequency 2ω, is applied to the crystal at the time $t=\tau$, the parametric interaction of the hypersonic wave with the microwave field gives rise to phase conjugation of the hypersonic pulse. At the time $t=2\tau$, the surface of the crystal generates a polarization-echo signal.

The polarization echo in the microwave range has been studied actively[1-3] in a number of piezoelectric and ferroelectric materials. This research has made it possible to distinguish the processes by which hypersound is absorbed from scattering by inhomogeneities and from the diffractive loss stemming from the reconstruction of the wavefront of the oppositely directed wave. It has also been found possible to study the spin-phonon interaction in crystals containing a paramagnetic impurity. Since the amplitude of the polarization echo is proportional to the constants of the nonlinear piezoelectric effect, this phenomenon could in principle be utilized to determine the components of the nonlinear piezoelectric tensor. However, such a study runs into difficulties in the calculation of the actual microwave field in a cavity, with allowance for the distortions of the field which arise when the test sample is inserted into the cavity. Furthermore, the expression for the echo amplitude contains a fairly complex combination of the linear and nonlinear piezoelectric effects. This circumstance poses additional difficulties in attempts to determine the nonlinear constants from polarization-echo experiments. In the present study, we accordingly examine the possibility of determining these constants from the efficiency with which the polarization echo is suppressed by pulses of an electric field of constant amplitude. We also examine the conditions under which it becomes possible to control the phase memory of the polarization echo by applying electric-field pulses of constant amplitude to the sample, both during the application of microwave pulses and in the pauses between these pulses. The results show that either a reversible or an irreversible change in phase memory may occur, depending on the particular experimental conditions.

EXPERIMENTAL PROCEDURE

All the measurements were carried out at liquid-helium temperatures, on two samples: a $LiNbO_3$ sample without a dopant and a $LiNbO_3$ sample doped with Ni^{2+} ions. The samples were rectangular parallelepipeds. The polarization echo was excited in a regime of traveling hypersonic waves by a two-frequency method. The frequencies of the first and second microwave pulses were 9.6 and 19.2 GHz, respectively. The sample was positioned in such a way that its polished end, oriented perpendicular to the z axis, was at a maximum of the electric component of the microwave field of the first cavity, which was tuned to a frequency of 9.6 GHz. The rest of the crystal was in the microwave electric field of the second cavity, which was tuned to 19.2 GHz. The first cavity was used to excite a traveling hypersonic wave in the sample, while the second was used to apply the electric field of the second microwave pulse to the 9.6-GHz hypersound propagating through the crystal. The electric field was applied in the direction perpendicular to the propagation direction of the hypersonic pulse in the sample. Experiments were also carried out in which there was a single-frequency excitation of the polarization echo by microwave pulses with a modulated frequency of 9.6 GHz.

Figure 1 shows experimental results on a $LiNbO_3$ sample both of whose ends perpendicular to the z axis were polished. The sample itself was inserted completely into a resonant cavity. In this case, along with the echo signals on the oscilloscope traces one sees multiple reflections from the plane-parallel ends of the sample of the hypersonic pulses excited by the first and second microwave pulses. Trace *a* corresponds to the excitation of a polarization echo without the application of an electric field pulse. Trace *b* corresponds to suppression of the echo by an electric field pulse.

The traces in Fig. 2 were obtained during two-frequency excitation of the echo. The $LiNbO_3$ sample in this case

 0038-5646/91/040725-06$03.00

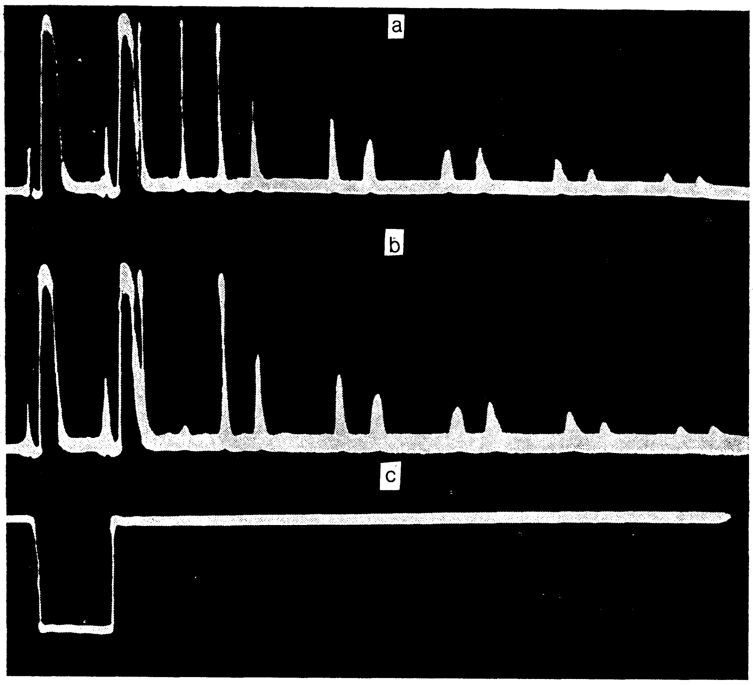

FIG. 1. a—Excitation of the polarization echo and of hypersonic pulses in a plane-parallel $LiNbO_3$ crystal; b—suppression of the echo signal by a pulse of a constant electric field; c—the electric field pulse.

had only one polished end (perpendicular to the z axis). The echo signals on the traces are thus not accompanied by hypersonic pulses. During the recording of the traces, the output signal from the microwave receiver was fed to one differential-amplifier input of the oscilloscope. Pulses of negative polarity were fed to the second input; the length and time of application of these negative pulses corresponded to the electric field pulses applied to the sample. In this case the sample

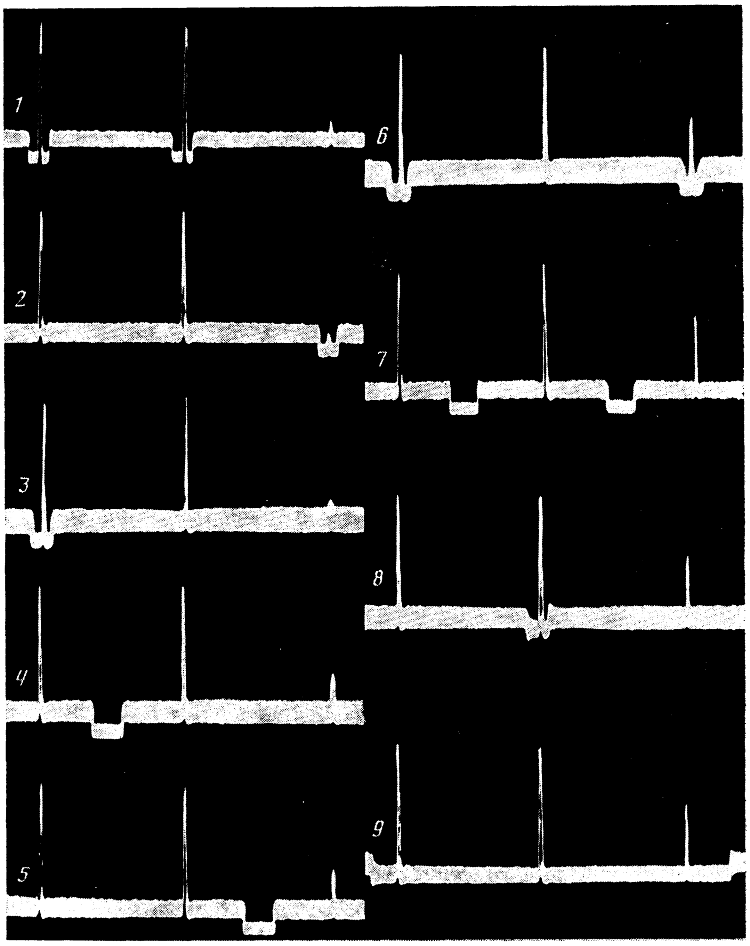

FIG. 2. Effect of electric field pulses of constant amplitude on the polarization echo in $LiNbO_3$. The first two pulses on each of the oscilloscope traces are exciting pulses; the echo signal follows. The negative swings correspond to the electric field pulses of constant amplitude which are applied to the sample.

was positioned between the plates of a structural capacitor, to which electric field pulses were applied both during the microwave pulses and in the pauses between them.

The application of electric field pulses before, during, or after the phase conjugation by the second microwave pulse (traces *1–5* in Fig. 2) resulted in a suppression of the echo signal, because of the asymmetry of the conditions for the propagation of the hypersound in the forward and backward directions. Identical propagation conditions were arranged for the hypersonic pulse before and after its conjugation. Thus a nearly complete restoration of the amplitude of the polarization echo was achieved, by applying additional electric field pulses at the instants at which the hypersound passed through a given region of the crystal, first in the forward direction and then in the backward direction (traces *6* and *7* in Fig. 2). The application of a single electric field pulse at the time of the second microwave pulse (trace *8* in Fig. 2) did not result in any substantial suppression of the echo. Nor was the echo suppressed when an electric field pulse was applied throughout the echo formation process, from the time of the excitation of the echo to the time of its detection (trace *9* in Fig. 2).

INTERPRETATION AND DISCUSSION OF RESULTS

To describe the experimental results we write the free-energy density Ψ of the sample in the form[4]

$$\Psi=\frac{1}{2}C_0U^2-\frac{\varepsilon_0}{8\pi}E^2-\beta_0EU+\frac{1}{6}C_0^{(3)}U^3$$
$$-\varepsilon_0^{\rm nl}E^3-\frac{1}{2}p_0E^2U+\frac{1}{2}\eta EU^2+\frac{1}{2}f_0E^2U^2, \qquad (1)$$

where C_0 and $C_0^{(3)}$ are the linear and nonlinear elastic tensors, respectively, ε_0 and $\varepsilon_0^{\rm non}$ are the linear and nonlinear dielectric tensors, respectively, β_0 and η_0 are the linear and nonlinear piezoelectric tensors, respectively, p_0 is the photoelastic tensor, f_0 is the electrostriction tensor (we are omitting the tensor indices), $U\equiv U_{ij}=1/2(\partial_iU_j+\partial_jU_i)$ is the strain tensor, and $\mathbf{E}=\mathbf{E}_i$ is the electric field (a vector). Using (1), we can derive the coupled equations of the theory of elasticity and electrodynamics. As a zeroth approximation we adopt a wave solution of the linear equations determined by the first three terms in Ψ. These terms characterize the dispersion and the polarization of the wave in the given direction. We then take the nonlinear terms in Ψ into account, with the result that a component $\delta\sigma$ which is nonlinear in U and E appears in the stress tensor:

$$\delta\sigma=C_0^{(3)}U^2+p_0E^2+\eta EU+f_0E^2U. \qquad (2)$$

We consider the propagation of a hypersonic wave of frequency ω through the crystal. The wave is described by the displacement vector U_i under the condition that the following electric fields are present in the crystal: $\tilde{E}_i$, which is a quasiconstant field (these are the constant-field pulses), and E_i^{ω} and $E_i^{2\omega}$, which are the microwave field pulses at the frequencies ω and 2ω; in other words, we have $E_i=\tilde{E}_i(t)+E_i^{\omega}(t)+E_i^{2\omega}(t)$. In addition, the linear piezoelectric effect means that the hypersonic wave with wave vector k is accompanied by an electric wave $E_i^{\omega,\mathbf{k}}$. Assuming the pump wave to be given, and taking (2) into account, we find

$$\partial_{tt}U_i-s'^2\partial_{hk}U_i=\rho^{-1}[\eta_{nijkl}\tilde{E}_n+\eta_{nijkl}E_n^{2\omega}+f_{nmijkl}E_n^{\omega}E_m^{\omega}]\,\partial_{ji}U_k, \qquad (3)$$

where ρ is the density of the crystal, and s' is the velocity of the wave with wave vector $\mathbf{k}$. The tensors $C^{(3)}$, η, and f in (3) have been renormalized with allowance for $E_i^{\omega,\mathbf{k}}$ to p_0 and η_0, as was done in, for example, Ref. 5.

We set

$$U_i=q_i^{(1)}U_1(r,t)e^{i(\omega t-\mathbf{kr})}+q_i^{(2)}U_2(r,t)e^{i(\omega t+\mathbf{kr})}+\text{c.c.},$$
$$E_i^{\omega}=-iq_i^{(3)}\mathscr{E}^{\omega}(t)e^{i\omega t}+\text{c.c.},$$
$$E_i^{2\omega}=-iq_i^{(4)}\mathscr{E}^{2\omega}(t)e^{2i\omega t}+\text{c.c.}\quad |q^{(1)}|=|q^{(2)}|=|q^{(3)}|=|q^{(4)}|=1. \qquad (4)$$

Using the method of slowly varying amplitudes with the given pump wave, we find

$$\partial_zU_1+s^{-1}\partial_tU_1+\Gamma U_1=i\Delta F_1(z,t)+aU_2^*,$$
$$\partial_zU_2-s^{-1}\partial_tU_2-\Gamma U_2=-i\Delta F_2(z,t)-aU_1. \qquad (5)$$

We assume that the wave is propagating along the z axis. Here Γ is the hypersound attenuation coefficient, and $\Delta F_{1(2)}=F_{1(2)}(z,t)-F_1(0,0)$, where

$$F_1(z,t)=\frac{\eta_{nijkl}\tilde{E}_n}{2\rho s^2}k_j^0k_l^0q_i^{(1)}q_k^{(1)}\omega, \qquad (6)$$
$$|\mathbf{k}^0|=1,\quad \mathbf{k}=\mathbf{k}^0k,\quad \omega=ks.$$

We find F_2 from F_1 by replacing $q^{(1)}$ by $q^{(2)}$:

$$a=\left[\frac{\eta_{nijkl}}{2\rho s^2}q_n^{(4)}q_i^{(1)}k_j^0k_l^0q_k^{(2)}\mathscr{E}^{2\omega}\right.$$
$$\left.-i\frac{f_{nmijkl}}{2\rho s^2}q_n^{(3)}q_m^{(3)}q_k^{(2)}q_i^{(1)}k_j^0k_l^0(\mathscr{E}^{\omega})^2\right]\omega, \qquad (7)$$

where s is the sound velocity when the nonlinear $F_1(0,0)$ contributions are taken into account (we are assuming that the hypersonic wave is emitted from the $z=0$ end of the crystal at $t=0$ as a result of the application of the first microwave pulse).

We change variables:

$$U_1=\bar{U}_1(z,t)\exp\left[-\Gamma st+is\int_{t_0}^{t}\Delta F_1(z-st+st',t')\,dt'\right], \qquad (8)$$

$$U_2=\bar{U}_2(z,t)\exp\left[-\Gamma st+is\int_{t_0}^{t}\Delta F_2(z+st-st',t')\,dt'\right]. \qquad (9)$$

A direct substitution of (8) and (9) into (5) easily verifies that the equations for $\bar{U}_1$ and $\bar{U}_2$ become

$$\partial_z\bar{U}_1+s^{-1}\partial_t\bar{U}_1=a\exp\left[-is\int_{t_0}^{t_2}\Delta F(z,t;t')\,dt'\right]\bar{U}_2^*, \qquad (10)$$

$$\partial_z\overline{U}_2 - s^{-1}\partial_t\overline{U}_2 = -a\exp\left[-is\int_{t_0}^{t}\Delta F(z,t;t')\,dt'\right]\overline{U}_1^*,$$

$$\Delta F(z,\ t;\ t') = \Delta F_1(z-st+st',\ t') + \Delta F_2(z+st-st',\ t'). \tag{11}$$

Equations (8)-(11) describe all stages of the evolution of the hypersonic pulses in the polarization echo: (1) In the time interval $0<t<\tau(t_0=0)$, in a pause between microwave pulses, we have $a=0$, $\overline{U}_2=0$, and $\overline{U}_1\neq 0$; and Eqs. (8) and (10) describe a damped wave with an additional phase shift determined by the integral in the argument of the exponential function. (2) In the interval $\tau\leqslant t\leqslant\tau+\Delta t$ (Δt is the length of the second microwave pulse), there is a parametric interaction of the first hypersonic pulse with the electric field of the pump at the second frequency, 2ω. (3) In the interval $\tau+\Delta t<t<2\tau$ ($t_0=\tau+\Delta t$) we have $a=0$, and Eqs. (9) and (11) describe the evolution of the conjugate wave, with damping and with an additional phase shift.

In the absence of external agents, we have $\Delta F_1=\Delta F_2=0$, and Eqs. (10) and (11) become the usual equations of slowly varying amplitudes for three-wave mixing in the approximation of a given pump wave. The coefficients ΔF_1 and ΔF_2 in (5) strongly influence the magnitude of the echo signal. Changes of two types—reversible and irreversible—can occur in the phase memory in this case.

If $\Delta F_1\neq 0$ holds on the interval $0\leqslant t<\tau$, and $\Delta F=0$ holds on the interval $\tau\leqslant t\leqslant\tau+\Delta t$, parametric phase conjugation occurs, but the wave packet representing the hypersonic pulse changes by the time $t=\tau$ as a result of $\Delta F_1\neq 0$, so that by the time $t=2\tau$ a wave packet with a distorted phase profile arrives at the $z=0$ end. In other words, the phase memory is lost. Two reasons for this change could be cited: (1) dispersion-induced spreading of the wave packet [since we have $\Delta F_1\propto\omega$; see (6)] and (2) curvature of the front of the sound wave if the external field $\widetilde{\mathbf{E}}$ is spatially nonuniform.

As can be seen from (8), a total loss of the phase memory of the polarization echo occurs as a result of dispersion-induced spreading of the wave packet of the hypersonic pulse under the influence of the pulse of the constant field, of length Δt, under the condition that the spreading of the packet, δ, is

$$\delta = \frac{\eta_{nijkl}\Delta\widetilde{E}_n k_j^0 k_l^0 q_i^{(1)} q_k^{(1)}\Delta\omega\,\Delta t_1}{2\rho s^2} \sim \pi, \tag{12}$$

where $\Delta\omega$ is the width of the packet.

To estimate the curvature of the wavefront of the acoustic pulse in the presence of a gradient of the electric field $\widetilde{\mathbf{E}}$, we use the geometric-optics method. We assume for simplicity that the crystal is acoustically isotropic. We can then write an equation for an acoustic ray of the hypersonic pulse in the presence of the external field $\widetilde{\mathbf{E}}$. As the refractive index n we must choose

$$n = s/s_E \approx 1-\eta\widetilde{E}/(2\rho s^2), \tag{13}$$

where $s_E=(s^2+\eta\widetilde{E}\rho^{-1})^{1/2}$ is the phase velocity of the hypersonic wave in the external field $\widetilde{\mathbf{E}}$ (we are omitting the tensor indices).

Euler's equations for the acoustic ray are (Ref. 6, for example)

$$\frac{d}{dl}\left(n(\mathbf{r})\frac{dx_i}{dl}\right) = \frac{\partial n(\mathbf{r})}{\partial x_i}, \tag{14}$$

where $x_i=x_i(l)$ are the Cartesian coordinates of point $\mathbf{r}$ on the ray. These coordinates are treated here as a function of the length l measured along the ray. We assume that there is a constant gradient of the electric field, directed perpendicular to the ray. If the ray is directed along the z axis at the $z=0$ end, while the electric field gradient γ is directed along the y axis, we have

$$\widetilde{\mathbf{E}} = \widetilde{\mathbf{E}}_0 + \gamma y, \qquad \left.\frac{dy}{al}\right|_{z=0} = 0. \tag{15}$$

In this case the ray clearly lies in the yz plane. We find the following equation for the component $y(l)$, which characterizes the excursion of the acoustic ray from the z axis:

$$\frac{d^2y}{dl^2}\left[1-\frac{\eta}{2\rho s^2}(E_0+\gamma y)\right] - \frac{\eta\gamma}{2\rho s^2}\left(\frac{dy}{dl}\right)^2 = -\frac{\eta\gamma}{2\rho s^2}. \tag{16}$$

Since l does not appear explicitly in (16), the order of the equation can be lowered, and then a general solution of this equation can be found. Imposing the boundary conditions

$$\left.\frac{dy}{dl}\right|_{z=0} = \left.\frac{dy}{dl}\right|_{l=0} = 0, \quad y|_{z=0}=0,$$

we find the following result for the angle α through which the acoustic ray is deflected from the z axis:

$$\alpha \approx \frac{y}{l} = \frac{l\eta\gamma}{2\rho s^2}. \tag{17}$$

We have assumed $\alpha\ll 1$ in the derivation of (17).

However, the disruption of the phase memory caused by the dispersion-induced spreading and by the deflection of the ray can be repaired if a pulse $\Delta\widetilde{E}_n$ is applied to the crystal after the phase conjugation, in order to cancel the additional phase shift, and if the wave packet is then "gathered up again" and sent back down the curved path, this time in the opposite direction. In this sense, mechanisms of this sort for the disruption of the phase memory can be called "reversible."

If we have $\Delta F\neq 0$ during the time interval $\tau\leqslant t\leqslant\tau+\Delta t$, the pump is phase-modulated, as can be seen from (10) and (11) [a is replaced by

$$a\exp\left[-is\int_{t_0}^{t}\Delta F(z,t;t')\,dt'\right]$$

in (10) and (11) in the process]. This result reduces the efficiency of the parametric phase conjugation, because of the deviation from phase matching (Ref. 7, for example). In certain cases, there is no excitation of the conjugate wave at all (this is an irreversible disruption of the phase memory of the polarization echo). If $\Delta F=\text{const}$ on the interval $\tau\leqslant t\leqslant\tau+\Delta t$, we find from (10) and (11)

$$\partial_{zz}\overline{U}_2 - s^2\partial_{tt}\overline{U}_2 + i\Delta F\partial_z\overline{U}_2 - is^{-1}\Delta F\partial_t\overline{U}_2 + |a|\overline{U}_2 = 0. \tag{18}$$

The general solution of this type of equation, under arbitrary initial conditions, is well known.[8] For the very simple initial condition

$$\bar{U}_2|_{t=\tau}=0,\ s^{-1}\partial_t\bar{U}_2|_{t=\tau}=aA$$

(A is the amplitude of the first pulse) we find

$$\bar{U}_2=-\frac{1}{2}\exp\left(-i\frac{\Delta Fst}{2}\right)aA \times \int_{-s\Delta t}^{s\Delta t} J_0([|a|^2\beta^2-s^2t^2]^{1/2})\exp\left(-i\frac{\Delta F\beta}{2}\right)d\beta, \quad (19)$$

where $J_0(x)$ is the Bessel function of the first kind of index zero. For sufficiently short pulses, under the condition $|a|s\Delta t \ll 1$, we can set $J_0(x) = 1$ in the integrand. As a result, we find the following result for the amplitude of the conjugate wave:

$$I=I_0\frac{\sin\xi}{\xi},\quad \xi=\frac{\eta_{nijkl}\Delta\tilde{E}_n\omega\Delta t}{\rho s^2}k_l{}^0k_j{}^0q_k^{(1)}q_i^{(2)}, \quad (20)$$

where $I_0 = |a|A\Delta t$ is the amplitude of the conjugate wave which has arisen by the end of the pulse, Δt, in the case $\Delta F = 0$.

The reversible and irreversible mechanisms for the disruption of phase memory which were discussed above completely explain the oscilloscope traces in Figs. 1 and 2. We first note that the resolution of the memory, which is associated with the nonuniformity of the field $\tilde{\mathbf{E}}$, is the most sensitive property. Since we have $\varepsilon_0 \gg 1$ for $LiNbO_3$, the nonuniformity of the electric field stemming from edge effects in a cell consisting of a capacitor and a sample is very large. If the electric field $\tilde{\mathbf{E}}$ is applied when the hypersonic pulse is at the boundary of the capacitor, the field $\tilde{\mathbf{E}}$ will vary by a factor of tens in this region. We thus have $\gamma l \sim \Delta\tilde{E}$. Assuming $\gamma l \sim \Delta\tilde{E} = 7.5$ kV/cm, $s = 7.2\cdot 10^5$ cm/s, $\rho = 4.7$ g/cm^3 (Ref. 9), and $\eta_{133} \approx 50$ C/m^2, we find $\alpha \approx 10^{-4}$ from (17). At hypersonic frequencies, a change of this sort in the direction of the wavefront leads to a sharp decrease in the electromagnetic response from the end of the crystal as the hypersonic pulse approaches it (Ref. 10, for example).

Traces *2* and *3* in Fig. 2 confirm the discussion above. If a pulse $\Delta\tilde{\mathbf{E}}$ of the same height and length is applied when the conjugate wave approaches the end, the wave will be sent back in the opposite direction, and the echo signal will be reconstructed (trace *6*). In examining traces *2, 3*, and *6* we should also take the dispersion-induced spreading of the packet into account, but even for very short pulses ($\Delta t \sim 10^{-8}$ s) the spreading of the packet can be ignored since we have $\delta \sim 10^{-3} \ll \pi$, as can be seen from (12) (we are assuming $\Delta\omega \sim 1/\Delta t$).

Traces *4, 5*, and *7* in Fig. 2 can be explained in the same way as traces *2, 3*, and *6*—in terms of the presence of an electric field gradient during the application of a pulse $\Delta\tilde{\mathbf{E}}$ to the crystal. The gradient would arise because of the finite transverse dimensions of the crystal (~ 0.5 cm). In general, an irreversible disruption of the memory associated with a decrease in the phase-conjugation efficiency due to a disruption of the phase matching should have been seen on trace *8*. However, no significant suppression of the echo signal occurred. This result can be explained by calculating ξ from (20). Setting $\Delta\tilde{E}_1 = 7.5$ kV/cm, $\mathbf{k}^0 = (0,0,1)$, $\mathbf{q}^0 = (0,0,1)$, $\Delta t = 3\cdot 10^{-8}$ s, $s = 7.2\cdot 10^5$ cm/s, and $\eta_{133} = 50$ C/m^2 (Ref. 11), we find $\xi = 0.29$ and thus $I = I_0$. In order to observe an irreversible disruption of the echo memory, we would need $\Delta\tilde{E} \approx 10$ kV/cm and some fairly long pulses, with $\Delta t \sim \Delta t_1 \sim 10^{-7} - 10^{-6}$ s.

The suppression and restoration of the polarization-echo signal on traces *1* and *9* in Fig. 2 become understandable as a result of these calculations. A pulse $\Delta\tilde{E}$ applied at the time of the phase conjugation has essentially no effect on the phase conjugation. It affects only the electric field gradient. In other words, the effect is the same as on traces *2, 3*, and *6*. Trace *9* is explained by noting that we have $\Delta F = 0$ in this case, and the nonuniformity of the electric field is the same for the first pulse and for the conjugate hypersonic pulse. There is accordingly no suppression of the echo.

Figure 1 shows traces for undoped $LiNbO_3$. In $LiNbO_3$ crystals doped with Ni^{2+} ions, a polarization echo is observed three orders of magnitude greater than that in undoped crystals.[3] For the case corresponding to traces *2* and *3*, the disruption of the phase memory occurs at $\Delta\tilde{E}_1 = 150$ V/cm (under otherwise equal conditions), so we find the estimate $\eta_{133} = 2500$ C/m^2 in this case.

We note in conclusion that the electric field also affects the first hypersonic pulse, which returns from the opposite end of the crystal after a reflection, but the phase portrait of the returned pulse is strongly masked by edge effects at the opposite ends of the crystal. Consequently, the reconstruction and disruption of the phase memory do not occur as frequently as in the echo signals.

It can be seen from these calculations that the effect of an electric field on the magnitude of the polarization-echo signal could be utilized to determine the constants of the nonlinear piezoelectric effect, η. The most convenient approach here is to use the irreversible disruption of the phase memory of the echo, since in this case the electric-field nonuniformity $\Delta\tilde{\mathbf{E}}$ has no effect, as can be seen from trace *8* in Fig. 2. We might add that, according to (17), if hypersonic pulses of slower transverse waves are excited in $LiNbO_3$ crystals doped with Ni^{2+} ions then one could use some fairly weak pulses of a constant electric field, $\Delta\tilde{E} \sim 1$–10 V/cm, for efficient control of the phase memory. These pulses would have to be applied at the times at which the hypersonic pulse arrives at the end of the crystal. The surface of the crystal should have steep steps in order to increase the electric-field gradient.

We wish to thank B. I. Kochelaev and the participants of his seminar for interest in this study.

[1] B. P. Smolyakov, E. I. Shtyrkov, and B. Z. Malkin, Zh. Eksp. Teor. Fiz. **74**, 1053 (1978) [Sov. Phys. JETP **47**, 553 (1978)].
[2] B. P. Smolyakov and E. P. Khaimovich, Zh. Eksp. Teor. Fiz. **76**, 1303 (1979) [Sov. Phys. JETP **49**, 661 (1979)].
[3] B. P. Smolyakov and V. A. Es'kin, in *Proceedings of the Thirteenth All-Union Conference on Acoustoelectronics and Quantum Acoustics* (Chernovtsy, 1986), Part II, p. 115.
[4] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media*, Nauka, Moscow, 1982, p. 102 (Pergamon, Oxford, 1984).
[5] V. E. Lyamov, *Polarization Effects and Anisotropy of the Interaction of Acoustic Waves in Crystals*, Nauka, Moscow, 1983, p. 85.
[6] V. A. Borovikov and V. E. Kinder, *Geometric Theory of Diffraction*, Svyaz, Moscow, 1978, p. 11.
[7] A. P. Sukhorukov, *Nonlinear Wave Interactions in Optics and Radiophysics*, Nauka, Moscow, 1988, p. 63.
[8] A. V. Tikhonov and A. A. Samarskii, *Equations of Mathematical Phys-*

ics, Nauka, Moscow, 1972, p. 138 (MacMillan, New York, 1963).
[9] A. A. Blistanov, V. S. Bondarenko, and N. V. Perelomova, *Acoustic Crystals*, Nauka, Moscow, 1982, p. 452.
[10] J. W. Tucker and V. W. Rampton, *Microwave Ultrasonics in Solid State Physics*, American Elsevier, New York, 1973 (Russ. Transl. Mir, Moscow, 1975, p. 69).
[11] A. I. Korobov and V. E. Lyamov, Fiz. Tverd. Tela (Leningrad) **17**, 1148 (1975) [Sov. Phys. Solid State **17**, 731 (1975)].

Translated by D. Parsons