waves, the right-hand sides of (2.7) and (2.9) vanish and this is used below. Actually, however, the monochromatic field is unstable, and harmonics with other values of **k** appear (see below), while (2.7) and (2.9) contain field amplitudes

$$\mathbf{E}(\mathbf{r},t)=\int\frac{\mathbf{k}}{k}E_{\mathbf{k},\omega}\exp(-i\omega t+i\mathbf{k}\mathbf{r})\,d\mathbf{k}\,d\omega,$$

that are sums (integrals) over all the harmonics.

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Polarization echo and induction signals excited by pulses of various durations

V. P. Smolyakov and E. P. Khaĭmovich

Physicotechnical Institute, Kazan' Branch, USSR Academy of Sciences

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The polarization echo and phonon induction excited by one long pulse as well as by a combination of a long and short pulse have been observed and investigated. The results were interpreted by using a spectral resolution of the applied pulses. It is shown that in the case of the single-pulse excitation the front edges play the role of two exciting pulses. All the remaining observed signals are generated by all possible combinations of the edges of the long pulse with the short one.

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1. INTRODUCTION

The observation of spin echo, photo echo, and other similar phenomena is usually carried out under conditions when the applied pulses are short. Yet it has been observed that the use of long pulses can alter radically the character of the phenomenon. Thus, when induction is excited by one long pulse, edge echo was produced.[1] A number of anomalous singularities were observed in the study of induction and photon echo excited by two pulses, one of which was long.[2] For example, the relaxation time of locked echo was determined by the time of longitudinal relaxation T_1, and the relaxation time of notched echo was due to transverse relaxation. "Single-pulse" echo was also observed in ferromagnets.[3] Attention was called to the role played by the slope of the front of the applied pulse. What remains unclear, first, was whether the single-pulsed echo is identical with the edge echo or whether it was due to a frequency echo-formation mechanism, and second, what the locked and edge echo have in common and why distorted waveforms of the induction and echo signals are obtained.

To reveal the singularities due to long pulses, it is convenient to use the polarization-echo effect, in which the signals have high intensity. We have observed and investigated polarization echo and phonon induction at a frequency ~10^{10} Hz at $T=4.2$ K, excited both by a single long pulse and by a sequence in which at least one pulse was long. It was possible to observe in this way the aforementioned singularities, which were previously observed in experiments on spin and photon echo. To interpret all the results we used a spectral resolution of the applied pulses. It turned out that in a case of single-

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pulse excitation the fronts play the role of two excited pulses.

Locked echo is formed by one narrow pulse and by the edges of the long pulse, and is in essence the ordinary stimulated echo. All the other signals are generated in all possible combinations of the edges of the long pulse with the short one. In addition, the spectral analysis made it possible to explain the compression we observed in the signals of the polarization echo excited by two frequency modulated microwave pulses.

2. EXPERIMENT AND BASIC RESULTS.

The experiments on polarization echo were carried out at helium temperatures on samples of KH_2PO_4, $LiNbO_3$, and $LiTaO_3$, whose surface irregularities exceeded considerably the length of the hydrosonic wave. In contrast to the ordinary procedure of exciting electron spin echo signals by two or three short pulses, we used long pulses for combinations of short and long pulses. A pulse of duration Δ will be regarded as broad if the condition $v\Delta > l$ is satisfied, where v is the hypersound velocity in the sample and l is the length of the investigated crystal. The duration of the short pulse was fixed at $\sim 4 \times 10^{-8}$ sec, and the duration of the long pulse could range from 10^{-7} to 10^{-4} sec. The powers of the short and long pulses could be independently regulated and varied in a wide range. The investigated samples were placed in a microwave broadband measuring cell. The echo signals were also registered with a broadband traveling-wave-tube receiving unit with sensitivity 10^{-12} W.

The measurements yielded the following results. When one long pulse was applied to samples of single-domain ferroelectric crystals, a phonon induction signal was observed (Fig. 1). The induction intensity was maximal immediately behind the trailing edge of the exciting pulse and decreased exponentially with time. For each sample we chose a pulse duration that yielded the maximum induction signal.

It appears that the phonon induction signal characterizes irreversible hypersound damping averaged over all the crystallographic directions. At the instant when the electric component of a microwave pulse acts, phonons are generated on the surface of the crystal and propagate in a variety of directions (the crystal is not treated) and traverse different paths prior to emerging to the surface. In the case of a short exciting pulse $v\Delta < l$ each phonon emerges to the surface at a different instant of time, and the resultant signal turns out to be zero. For a long pulse, the entire sample is sounded, and the surface of the crystal generates an exponentially decreasing signal. A characteristic feature is that the phonon induction signals are observed only if the crystals are not treated beforehand. In the case of treated crystals, the ordinary sequence of damped echo pulses is observed.

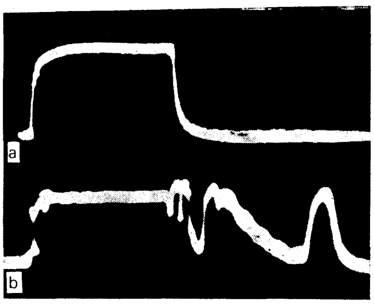

FIG. 1. a) Waveform of exciting microwave pulse. b) Oscillogram of polarization echo in a single-domain $LiNbO_3$ crystal. The echo appears at a time 2Δ after the leading front of the pulse. The dip ahead of the induction signal is due to overloading of the receiving unit.

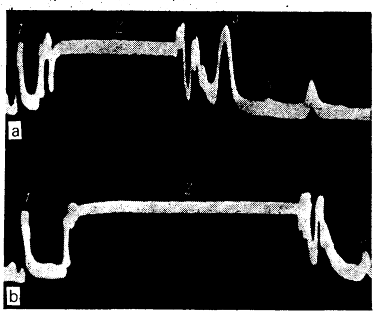

FIG. 2. Oscillograms of echo signals for two different values of the duration of the long pulse and of the intervals between the pulses: a) 1 and 2—short and long exciting microwave pulses, 3—stimulated-echo signal produced by the fronts of the long pulse, 4—secondary echo signal excited by the trailing edge of pulse 2 and by the echo signal 3, 5—echo signal formed by the two fronts of the long pulse, b) 1 and 2—short and long exciting microwave pulses, 3—stimulated echo signal.

Besides the induction signal, an echo pulse is observed at a distance equal to double the pulse duration (see Fig. 1). The intensity of the signal decreased exponentially with increasing Δ. In addition, the echo intensity depended on the rise time of the applied pulse.

It should be noted that the same value of the time constant of the decrease of the relaxation curve is obtained in the usual two-pulse procedure of exciting echo signals. Experiments were also performed on the excita-

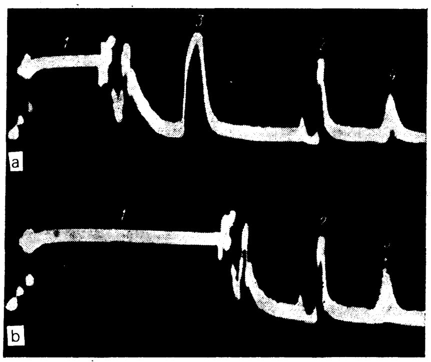

FIG. 3. Oscillograms of echo signals for 2 different values of the durations and intervals between the pulses: a) 1 and 2—long and short exciting microwave pulses, 3—signal echo excited by the fronts of the pulse 1, 4—stimulated echo excited by the fronts of pulse 1 and by the short pulse 2; b) 1 and 2—long and short exciting microwave pulses, 3—secondary echo produced by the trailing edge of pulse 1 and by pulse 2.

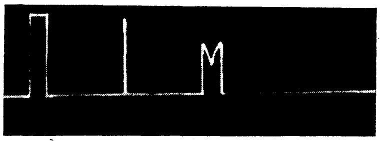

FIG. 4. Distortion of the echo signal waveform in the case of pulses of different duration.

tion of echo signals by a combination of a short and a long pulses, and vice versa. The results of the experiments are shown in Figs. 2–4 and indicate that the obtained echo signals are all possible combinations of the short exciting pulse and the two edges of the long pulse. We note among them signals similar to capture and notched echo. The relaxation times obtained with such a procedure correspond to the characteristic times T_1 and T_2 in the usual three-pulse and two-pulse excitations. To ascertain whether these results are possessed only by polarization echo, we performed experiments with analogous excitation of electron spin echo in crystals of irradiated quartz with F centers. The results were the same.

Experimental studies were made also of the shape of the polarization echo excited by two microwave pulses with a linear frequency modulation whose rate of change could be independently regulated for each pulse. At a modulation rate twice as fast in the second pulse as in the first, the echo signal duration was compressed compared with the durations of the exciting pulse.

3. DISCUSSION OF RESULTS.

Observation of the polarization echo signals produced by one broad pulse, similar to spin and photon echo, indicates that we are dealing with a common property inherent in all echo-type phenomena and determined by the spectral characteristics of the microwave exciting pulses. The validity of this premise will be demonstrated with polarization echo as an example, using spectral analysis methods.

To describe the formation of polarization-echo signals one uses mainly two models: the model of anharmonic oscillators[4-8] and a model based on the fact that when the sound interacts with the electric field of the second pulse an acoustic wave appears and propagates in the opposite direction.[9] The first model is convenient for the interpretation of experiments on powders, whereas the second is more frequently used to describe echo formation processes in single crystals. However, the second model is of little use for a number of experimental results in crystals, for example the onset of stimulated echo,[10] the anomalous dependence of the intensity of the echo signals on the separation between the exciting pulses,[11] as well as the appearance of multiple echo signals.[12] To interpret the results we therefore use the anharmonic oscillator model.

In this model, the coherent response of the system following a two-pulse action is proportional, according to Ref. 8, to

$$V(t)\propto\int_{-\infty}^{\infty} G_1^*(\omega_1)G_2^2(\omega_2)e^{i\omega(t-2\tau)}d\omega, \qquad (1)$$

where $G_1(\omega)$ and $G_2(\omega)$ are the spectral densities of the first and second pulses, and τ is the time between the first and second pulses. Assume that two ideal rectangular microwave pulses of duration Δ are applied to the system. The spectral density of the first pulse can be represented as a sum of the spectral densities of two fronts $S(\omega)$ shifted in phase by $\omega\Delta$:

$$G_1(\omega)=S_1(\omega)+S_2(\omega)e^{-i\omega\Delta}=S_1(0)\frac{\sin(\omega\Delta/2)}{\omega\Delta/2},$$

where $S_1(0)$ is the area of the pulse. The spectral density of the second pulse is described by a similar expression but shifted in phase by $\omega\tau$. If one pulse is applied to the system, formula (1) is likewise valid, but in place of $G_1(\omega)$ and $G_2(\omega)$ we must substitute the spectral densities of the leading and trailing edges $S_1(\omega_1)$ and $S_2(\omega_2)$. In this case the time τ between the applied pulses is replaced by the time Δ between the two fronts. It follows therefore that the echo signal appears at a time 2Δ after the leading front.

We proceed now to the case of a realistic rectangular pulse with front rise times τ_1 and τ_2 to the maximum value E_1, and compare it with ordinary two-pulse excitation of echo signals. If the pulses are short, then they can be regarded with a high degree of accuracy as triangular. The shape of the echo signals is determined in this case by the expression

$$E_1E_2^2\int_{-\infty}^{\infty}\frac{\sin^6(\omega\tau_1/2)}{\tau_1^3\omega^6}\exp\{i\omega(t-2\tau_1)\}d\omega. \qquad (2)$$

As $\omega\tau_1\to 0$ expression (2) goes over into $P_1P_2^2$, where $P_1=E_1\tau_1/2$, $P_2=E_2\tau_1/2$ are the areas of the pulses. In the general case expression (2) is not equal to zero in the interval $|t-2\tau_1|\leq 3\tau_1$.

The spectral density of a front of duration of τ_1

$$S_1(\omega)=E_1\left[\frac{1}{i\omega}-\frac{1-\cos\omega\tau_1-i\sin\omega\tau_1}{\tau_1\omega^2}\right]. \qquad (3)$$

The spectral density (3) contains terms $\sin^2(\omega\tau_1/2)/\tau_1\omega^2$ that lead to an ordinary echo signal described by expression (2), as well as terms that lead to a different signal. As $\tau_1\to 0$ the spectral-density component that leads to the signal described by expression (2) decreases like τ_1, whereas the remaining part $S_1(\omega)$ decreases like τ_1^2. Therefore observation of the echo signal formed by two fronts calls for the optimal choice of the front rise time or for an increase in the power of the applied pulses.

We can consider similarly the formation of signals of the capture and matched type. The former is ordinary stimulated echo formed by the short pulse and two fronts of the broad pulse, while the second is excited by the trailing edge of the broad pulse, which is applied first and is followed by the short pulse.

The echo signals observed by us were not distorted. The analogous signals for spin or photon echo were frequently distorted, for example, a two-hump echo appeared, etc. These distortions can be explained by taking into account the dependence of the echo signal on the relative detunings $\Delta\omega$ and on the intensity of the applied microwave field ω_1(Ref. 13). We wish to point out that there is another cause of distortion of the echo signal, connected with the excitation of the echo signals by the fronts of the applied pulses. Thus, when series of two pulses of durations 10^{-6} sec and 4×10^{-8} sec and in the opposite sequence were applied, we observed the distorted signals shown in Fig. 4. The intensity of the former case is higher, because the power of the short pulse was larger, and the intensity of the echo signal is proportional according to (1) to $E_1E_2^2$.

The considered spectral approach enables us to explain the singularities of formation of echo signals by two microwave pulses with linear frequency modulation $\omega(t)=\omega_0+\beta t$, $\omega_0+\beta' t$, where β and β' are the modulation rates of the first and second pulses. The spectral density of the linearly modulated microwave pulse can be represented in the form[14]

$$G_1(\omega)=\frac{E_1T_c}{2^{3/2}\sqrt{m}}\exp\left[-\frac{i(\omega-\omega_0)^2}{2\beta}\right]\{C(u_1)+C(u_2)+i[S(u_1)+S(u_2)]\},$$

where T_c is the pulse duration, $m=\beta T_c^2/2\pi$, $C(u)$ and $S(u)$ are Fresnel integrals. At large values of m and $\omega=\omega_0$ we get $C(u_2)\approx S(u_2)\approx 0.5$. Substituting these values for the first and second pulses in (2), we find that the spectral density of the echo signal is proportional to

$$\exp\left[-\frac{i(\omega-\omega_0)^2}{2}\left(\frac{1}{\beta}-\frac{2}{\beta'}\right)\right].$$

The spectrum is nearly rectangular, and at $\beta'=2\beta$ the phase is constant, corresponding for the time picture to a compression of the echo signal in the absence of frequency modulation.

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Field-ion-microscopy study of collective field-emission evaporation of tungsten atoms

I. M. Mikhaĭlovskiĭ, Zh. I. Dranova, V. A. Ksenofontov, and V. B. Kul'ko

Khar'kov Physicotechnical Institute, Ukrainian Academy of Sciences

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Field ion microscopy is used to investigate the kinetics of evaporation of tungsten in an electric field at temperatures 21–180 K in the evaporation-rate interval 10^{-4}–10^{-7} Å/sec. Below 110 K, the average rate of desorption of atoms from the (110) face increases by more than two orders of magnitude when the dimensions of the atomic complexes decreases. It is observed that at 110 K the collective desorption changes into separate-atom desorption. The collective desorption is attributed to a shift of the effective electron surface because of the increase of the electron density with decreasing dimensions of the atomic complexes.

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Field-ion-microscopy study of the kinetics of low-temperature evaporation of metals in electric fields 10^8–10^9 V/cm (Ref. 1) yields data on the electron structure of metals,[2] on the dynamics of surface atoms,[3] and on the effect of various physical processes in strong electric fields on the formation of the ion field-emission image.[1,4] It is known that in the course of field evaporation of atoms from close-packed faces the rate of evaporation increases sharply after the atomic complex reaches a certain critical size.[5,6] To determine the mechanism of this phenomenon, we have investigated in the present paper the singularities of the field evaporation kinetics of tungsten from the {110} face, in a wide evaporation-rate interval (10^{-4}–10^{7} Å/sec), using ion field emission microscopy.

EXPERIMENTAL PROCEDURE AND RESULTS

The samples were subjected to an electric field produced by a 5–30 kV dc source and a series-connected generator of pulses of duration 2×10^{-7} – 2×10^{-5} sec and amplitude 0–10 kV. When the acceleration is by a dc