Acoustic self-induced transparency in $LiNbO_3 : Fe^{2+}$

V. V. Samartsev, B. P. Smolyakov, and R. Z. Sharipov

Kazan' Physico-technical Institute, USSR Academy of Sciences
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Deformation of an acoustic pulse of duration shorter than the irreversible relaxation times was observed in a resonant medium, namely single-crystal $LiNbO_3:Fe^{2+}$. An analysis of the singularities and conditions of the evolution of the deformation shows that this deformation is due to acoustic self-induced transparency.

Self-induced transparency[1] is an effect in which total or partial "bleaching" of the resonant medium sets in (the absorption coefficient decreases abruptly), starting with a certain threshold power of the optical or acoustic pulse, the duration of which is shorter than all the irreversible relaxation times.

This effect is accompanied by deformation of the pulse contour and by a decrease of its propagation velocity. In acoustics, the theory of such processes was developed in[2], but experimentally only one observation of acoustic self-induced transparency (ASIT) was observed in experiment by now, namely in single crystal $MgO : Fe^{2+}$, Ni^{2+}.[3]

We report here experimental observation of ASIT in the ferroelectric $LiNbO_3$ activated by Fe^{2+} ions. From the physical point of view, the deformation of the pulse is due to reradiation of the absorbed energy from the medium into the pulse passing through it. In practice, this problem calls for the solution of a combined system of differential equations of elasticity theory and the equations for the components of the effective spin.[2]

To observe ASIT it is necessary to satisfy the following conditions: 1) the presence of acoustic resonance between the frequency ν of the acoustic pulse and the transition frequency ν_0 between any two energy levels; 2) the pulse duration Δt must be shorter than all the irreversible relaxation times; 3) the pulse power should exceed the power of the π pulse in the medium.[1]

Let us discuss the satisfaction of these conditions in our experiment. We investigated acoustic resonant

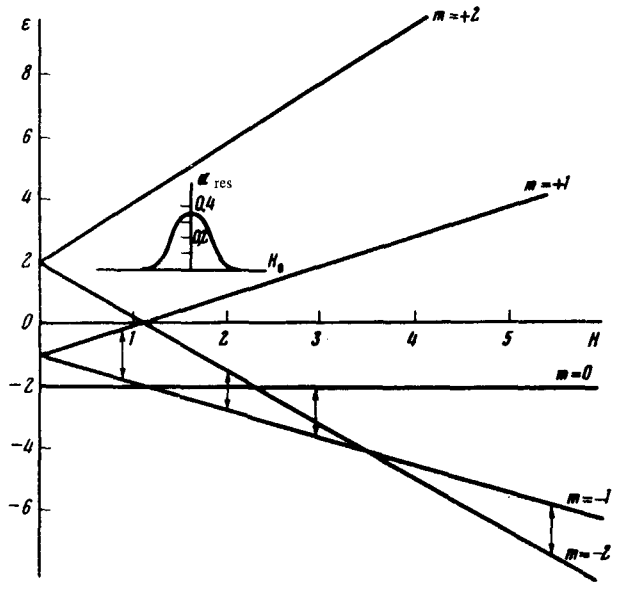

FIG. 1. System of energy levels of the Fe^{2+} ion in $LiNbO_3$. One of the characteristic curves of the resonant acoustic absorption. Each scale division for the energy ϵ, the magnetic field H_0, and the resonant absorption coefficient α_{res} equals 0.21 cm^{-1}, 1000 G, and 0.1 cm^{-1}, respectively.

absorption in a single-domain lithium-niobate sample. Figure 1 shows the system of energy levels of the Fe^{2+} ion in $LiNbO_3$ for the case of parallel orientation of the constant magnetic field H_0 and the polar axis of the crystal. The vertical arrows show the possible energy transitions under the influence of an acoustic perturbation at the frequency $\nu \approx 10$ GHz. The figure shows also one of the characteristic curves of electron acoustic resonance, observed in the experiment (it corresponds to a magnetic field $H_0 = 2050$ G and a transition between energy levels with magnetic quantum numbers $m = -2$ and -1).

The pulse duration was 40 nsec and was shorter than the irreversible relaxation times (which exceed 10^{-7} sec according to[4,5]).

The pulse power, with allowance for the nonresonant losses, corresponded to a parameter $\theta \approx 1.27\pi$. We recall that in the theory of pulsed resonant passage[1,2] the acoustic-pulse parameter is $\theta_{\gamma\delta} = \hbar^{-1} G_{\gamma\delta\alpha\beta} \times \int_{-\infty}^{\infty} \epsilon_{\alpha\beta}(z, t)\, dt$, where $\epsilon_{\alpha\beta}$ are the components of the strain tensor of the medium at the point z (the cases $\mathbf{k} \parallel \mathbf{z} \parallel \mathbf{C}$ are investigated) at the instant of time t; $\mathbf{k}$ is the wave vector of the pulse; $\mathbf{C}$ is a unit vector along the polar axis of the crystal; $G_{\gamma\delta\alpha\beta}$ are the components of the spin-phonon interaction tensor.

We observed experimentally the ASIT effect in all the transitions where electronic acoustic resonance took place. The experiment was performed in the following manner:

Hypersonic pulses of 40 nsec duration were excited at ~10 GHz and 4.2 °K in a single-domain $LiNbO_3 : Fe^{2+}$ crystal. To this end, the investigated ferroelectric sample was placed in a broadband waveguide-coaxial junction coupled to a magnetron generator of short microwave pulses. The excited hypersound pulses circulated in the sample. Out of the sequence of the echo pulses we selected one, on which the concrete measurements were made. In our experiments, the select pulse traversed in the sample a path equal to 2.4 cm and was registered with a broadband traveling-wave-tube receiver and a high-speed oscilloscope. The sensitivity of the receiver was of the order of 10^{-12} W and its bandwidth was 50 MHz. The oscillograms shown in Fig. 2 illustrate the change in the acoustic-pulse contour as the external magnetic field H_0 approaches the resonant value. It is seen here that the pulse is delayed in the resonant medium and that its "center of gravity"[6] shifts backwards.

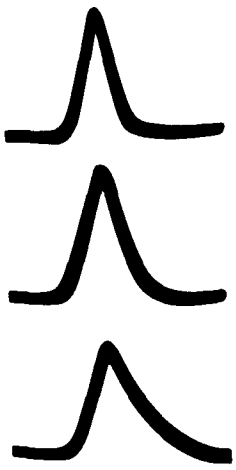

FIG. 2. Deformation of pulse contour in the sample as the conditions for the transition to resonance are approached (in downward direction).

We observed a delay of 5–6 nsec, in agreement with the value obtained from the known expression of the ASIT theory,[1,2] namely $1/V = 1/V_0 + (\alpha_{res}/2)\Delta l$, where V is the pulse propagation velocity in the resonant medium, V_0 is the pulse propagation velocity under nonresonant conditions, and α_{res} is the coefficient of resonant absorption of the hypersound pulse.

In the experiment, the deformation and delay of the pulse were also accompanied by an appreciable bleaching of the resonant medium, by ~30% in comparison with the resonant-absorption coefficient of the hypersound pulses that did not satisfy the ASIT observation condition (Δl longer than the irreversible relaxation times).

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