Observation of a long-lived multiple optical echo

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A long-lived multiple optical echo has been observed in a $LaF_3:Pr^{3+}$ crystal (the $^3H_4$–$3P_0$ transition). An agreement of the temporal shape of the signals representing the long-lived multiple optical echo and the temporal shape of the code pulse has been observed and studied for the first time under conditions of multiple readout.

A long-lived multiple optical echo was proposed, and the conditions for its formation were analyzed theoretically, in Ref. 1. Specific calculations were carried out in Ref. 2 for the intensity of these echo signals in the case of inorganic crystals containing impurity ions. In the present letter we report the first experimental observation of this echo effect, in a $LaF_3:Pr^{3+}$ crystal, on the energy transition $^3H_4$–$^3P_0$ (at a wavelength $\lambda = 4777$ Å) at a temperature $T = 2.2$ K. Figure 1 shows the order in which the echo signals are excited and the times at which they are generated. The echo signals are emitted by the medium after a time interval τ (equal to the delay of the second pulse with respect to the first) after each readout pulse (with index $n \geqslant 3$) along the direction of the wave vector $\mathbf{K} = -\mathbf{K}_1 + \mathbf{K}_2 + \mathbf{K}_n$, where $\mathbf{K}_1$, $\mathbf{K}_2$, and $\mathbf{K}_n$ are the wave vectors of the first, second, and readout pulses, respectively. Convenient for a reliable spatial

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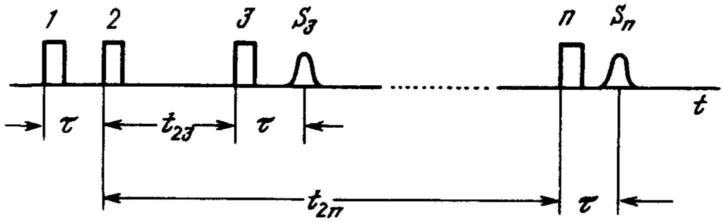

FIG. 1. Multipulse excitation of long-lived multiple optical echo signals. The numbers specify the order of the excitation pulse, n; S_n, represents the echo signal.

selection of the echo signals is the inversion regime,[3] in which, with $\mathbf{K}_2 = -\mathbf{K}_n$, we have $\mathbf{K} = -\mathbf{K}_1$. In our experiments we studied only the signals of the inverted long-lived multiple optical echo.

In the simplest case, with a single intermediate-relaxation mechanism,[1] the intensity of these echo signals is proportional to both a relaxation factor and a product of factors κ_i:

$$I \sim \exp(-2kt_{2n}) \prod_{i=3}^{n-1} \kappa_i \,. \qquad (1)$$

Each determines the signal loss during the application of the preceding readout pulses and depends on the relaxation constants of the system and the areas (Θ_i) under the readout pulses.[1] If Θ_i are identical, and if the intervals between readout pulses are also identical, the intensity of this echo signal falls off in a geometric progression. In the case of a splitting of the ground and excited states into three sublevels, as in the LaF_3: Pr^{3+} crystal, the dependence of the signal intensity on t_{2n} and n is more complicated[2] and contains several terms of the type in (1). Again in this case, however, most of the relaxation processes occur at time scales in the millisecond range, so after a long time only one of the relaxation mechanisms is important, and we can use expression (1). Noting that the area under the pulses experimentally is $\Theta_i \approx 10^{-2}$, we conclude that the factors κ_i are equal to unity within 10^{-5} and that the decay of the signal is determined primarily by relaxation processes, rather than by a loss of information during the readout by one of the pulses.

The experimental apparatus is similar to that described in Ref. 4. Readout pulses were applied to the sample at a repetition frequency $\nu = 12.5$ Hz. In order to demonstrate the possibility of recording pulses of complex shape by means of the long-lived multiple optical echo—such a possibility exists in the case of the stimulated optical echo[5]—we use a coded pulse as the second readout pulse. This code pulse was produced with the help of an auxiliary mirror and beam splitters.[3] The oscilloscope trace in Fig. 2a shows the shape of the code pulse. At the right in this figure is the first writing pulse, while the code pulse is at the left. The peak power levels of the first and readout pulses were 10 kW, while the power of the code pulse was an order of magnitude lower, so that we could work in a linear excitation regime.[6] At these power levels, the echo signals are so intense that they can be seen visually even after the seventh

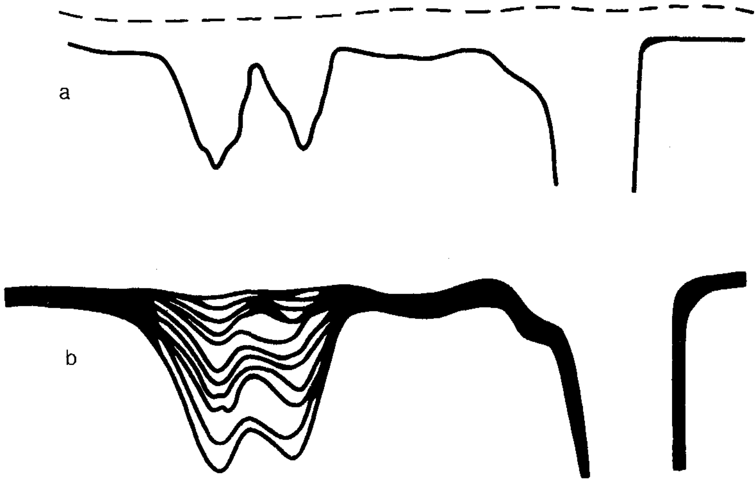

FIG. 2. Experimental oscilloscope traces. a: First and second writing pulses. The second pulse, which is the code pulse, is double humped. The time intervals between markers are 10 ns. b: Readout pulses and long-lived multiple optical echo signals. Successive pulses have been brought into coincidence along the time scale.

pulse. The oscilloscope trace in Fig. 2b illustrates the existence of the echo effect and the temporal decay of the intensity. It also demonstrates the agreement between the temporal shape of the echo signals and the temporal shape of the code pulse. Shown at the right on the oscilloscope trace is the readout pulse, while the echo signals are shown at the left. The trace was found by photographing a train of the first ~ 10 pulses on the screen of the oscilloscope, with the sweep being triggered by each readout pulse.

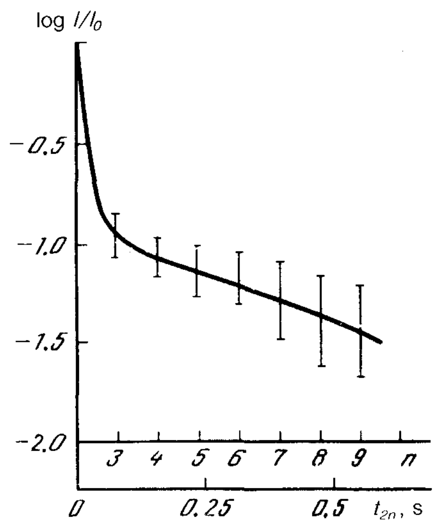

FIG. 3. Logarithm of the intensity of the long-lived multiple optical echo signal versus the number of the readout pulse. The pulse repetition frequency is 12.5 Hz.

For this reason, all of the echo signals in the figure are superimposed. This superposition permits a detailed comparison of the shape of the pulses and a measurement of the relaxation rate. This agreement of the temporal shapes is seen most clearly under conditions such that the time between the maxima of the subpulses making up the code pulse is no less than 15 ns. The double-humped structure of the echo signal is observed up to $n \sim 38$. The echo signal itself can be detected up to $n \sim 60$.

Figure 3 shows the intensity of the echo signal versus the delay time t_{2n} (or versus n) in semilogarithmic scale. The experimental points were found through an analysis and averaging of the data from ten traces. At $n > 9$ the measurement error is large because the signal is small; we are not reproducing those data here. The value I_0, with respect to which all the intensities are measured, is the intensity of the signal, of the stimulated optical echo with $t_{23} = 6$ ns. The relaxation rate found from the data in Fig. 3 is $k = 0.5 \pm 0.2\ \mathrm{s}^{-1}$. This value is approximately the same as the value found by the hole-burning method for the rate (k_{23}) of the relaxation between the hyperfine sublevels of the ground state.[7] The relaxation rate k_{12} is an order of magnitude smaller,[7] since the lifetime of the long-lived multiple optical echo can be tens of seconds. In order to observe such relaxation times, however, we would need apparatus more sensitive than that used in the present experiments.

In summary, these experiments have yielded the first observation of a long-lived multiple optical echo, and they have also revealed that the shape of the signal is the same as that of the code pulse under multiple-readout conditions. The double-humped temporal shape of the code pulse is obviously the simplest case of data coding. The incorporation of an electromically controlled coding unit in an optical arrangement would make it possible to achieve optical data storage in entire words.

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