

Reversed light echo in a ruby

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The reversed light echo produced as a result of a two-pulse, laser resonance excitation of a ruby crystal under conditions when the first pulse is a traveling wave and the second one is a standing wave was investigated. The transverse, irreversible relaxation time was determined from the intensity decay curve of this signal.

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The light (photon) echo is a promising method of optical spectroscopy¹, which makes it possible to obtain information on relaxation time, correlation time of random processes and hyperfine and superhyperfine structure of lines that are masked by inhomogeneous broadening. It also shows promise in dynamic holography when the object and reference pulses are separated in time.² The echo signal in this case has a wavefront which is a complex conjugate of the front of the first pulse. In this regard, the reversed light echo is of great interest. In this paper we report its first observation and investigation. The reversal of the wave of the first pulse was accomplished by means of a standing wave supplied to the resonance medium in the form of a pulse after a time interval (τ) that was shorter than the transverse, irreversible relaxation time (T_2). Since the reversed echo propagates in the opposite direction to that of the first pulse, the "signal-to-noise" ratio can be increased considerably after its detection, because the photomultiplier is free from exposure to the radiation of the excitation pulses.

A ruby single crystal with a 0.05 wt. % Cr^{3+} ion concentration was used as the

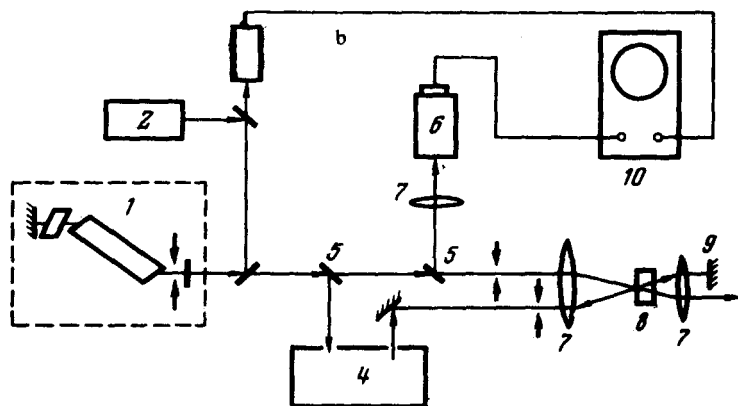
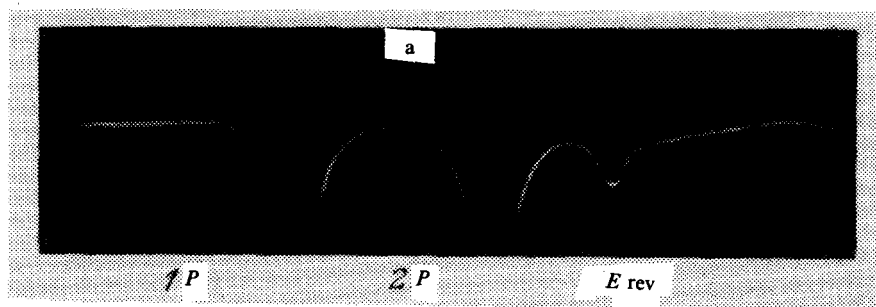


FIG. 1. a, Oscillogram of reversed light echo signal in a ruby (${}^4A_2\text{-}{}^2E(\bar{E})$); $\tau = 24$ nsec; $H_0 = 180$ G; b, block diagram of the experimental setup used for investigation of the reversed light echo: 1, low temperature ruby laser; 2 He-Ne laser for alignment; 3 and 6, high-speed ELU-E photodetectors; 4 optical delay line; 5, beamsplitter plate; 7, focusing lenses; 8, test specimen in a helium cryostat; 9, mirror; 10, I2-7 time interval meter.

resonance medium. Excitation of a (0.1-cm-thick) crystal held at a temperature of 1.7-2.2 K and the generation of an echo signal were done at the $4A_2\text{-}{}^2E(\bar{E})$ energy transition.

An oscillogram of the reversed light echo signal and the block diagram of the experimental setup used to investigate this signal are shown in Fig. 1. The excitation was done (at a wavelength $\lambda = 6935$ Å) by means of the radiation of a ruby laser whose active element was held at liquid nitrogen temperature. The first pulse (a convergent laser beam) was directed along the crystal axis. The angle between the action axis of the standing wave and the optical axis was varied from 0 to 6° (the constraint was due to the location of the windows of the optical cryostat). The reversed light echo signal was a diverging light beam that propagated in the opposite direction to k_1 . The apparatus made it possible to apply a constant magnetic field up to 1500 G along the optical axis of the crystal, which greatly increased the intensity of the echo signal. The optical signals were received by a ELU-FT high-speed photodetector with a resolution of better than 2.7 nsec, whose output signal was directed to a I2-7 time-interval gauge.

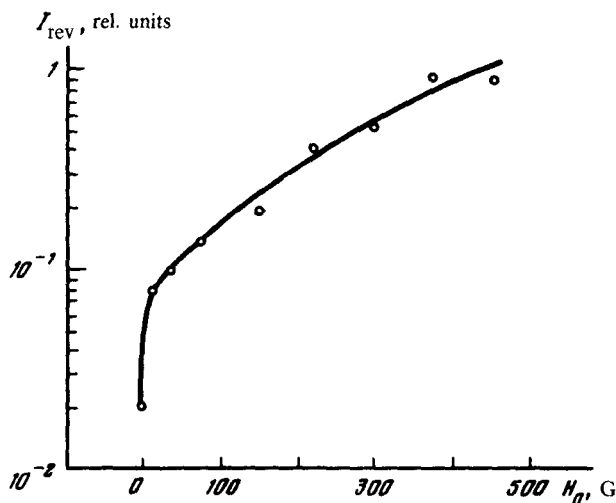


FIG. 2. Dependence of the intensity of the reversed light echo on the constant magnetic field in a ruby (4A_2 - ${}^2E(\bar{E})$).

The length of the excitation pulses was 10 nsec, and the interval between the pulses was varied from 20 to 120 nsec.

The theory of excitation of a light echo by standing and traveling waves has been discussed elsewhere.³⁻⁵

A calculation shows that the intensity of optical coherent responses at the time 2τ is proportional to the following coefficient:

$$A = \exp\left(-4 \frac{\tau}{T_2}\right) \Phi \sum_i^N \sum_{j \neq i}^N \exp\{i(\mathbf{k} + \mathbf{k}_1)(\mathbf{r}_i - \mathbf{r}_j)\} \times \sin^2\{\theta_2 \cos \mathbf{k}_2 \mathbf{r}_i\} \sin^2\{\theta_2 \cos \mathbf{k}_2 \mathbf{r}_j\}, \quad (1)$$

where \mathbf{k}_1 is a wave vector of the first pulse, \mathbf{k}_2 is a wave vector of one of the two traveling waves (forming the standing wave) whose propagation direction is close to the direction \mathbf{k}_1 , \mathbf{k} is the wave vector of the response, \mathbf{r}_l is the radius vector of the location of the l th particle, N is the number of active particles, θ_2 is the "area" of the second pulse (for a square pulse: $\theta_\xi = \hbar^{-1} p \epsilon_0^{(\xi)} \Delta t_\xi$; p is the modulus of the electric dipole moment of the resonance transition, $\epsilon_0^{(\xi)}$ and Δt_ξ is the amplitude of the electric-field intensity and length of the ξ th pulse, respectively), Φ is the form factor of the responses for a partial excitation of an inhomogeneously broadened line by a narrow pulse spectrum [the form factor, from which the factor $\sin^2(\theta_2 \sin \mathbf{k}_2 \mathbf{r})$ has been removed, is found in Ref. 6; the "area" of the first pulse is included in the form factor]. Using the expansion $\sin(\theta_2 \cos \mathbf{k}_2 \mathbf{r}) = 2 \sum_{n=0}^{\infty} (-1)^n J_{2n+1}(\theta_2) \cos[(n+1)\mathbf{k}_2 \mathbf{r}]$ (where J_k is a first-order Bessel function) we can easily obtain

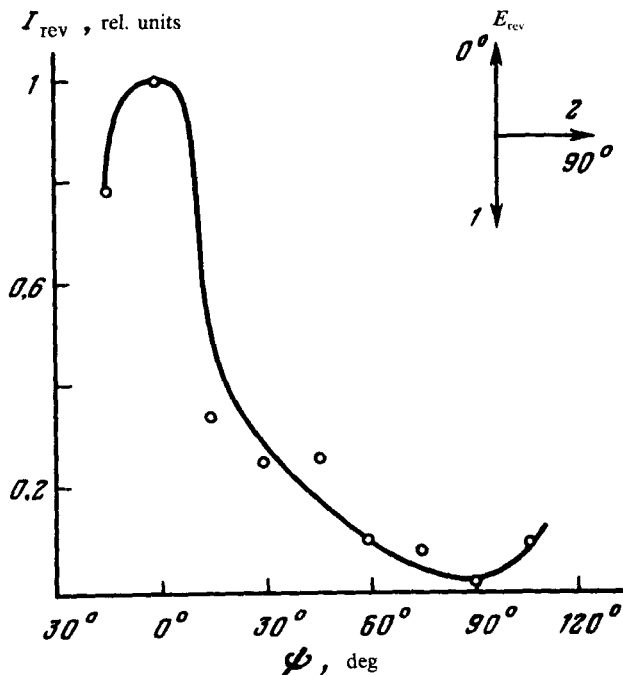


FIG. 3. Dependence of the intensity of the reversed light echo on the polarization angle of this signal.

$$A = 4 \exp(-4\tau/T_2) \Phi \sum_{i \neq j}^N \sum_{i \neq j}^N \{ \exp[i(\mathbf{k} + \mathbf{k}_1)(\mathbf{r}_i - \mathbf{r}_j)] \sum_{n=0}^{\infty} J_{2n+1}^2(\theta_2) + \exp[i(\mathbf{k}_{\parallel} + \mathbf{k}_1 - 2\mathbf{k}_2)(\mathbf{r}_i - \mathbf{r}_j)] \sum_{k=0}^{\infty} J_k(\theta_2) J_{k+1}(\theta_2) \}, \quad (2)$$

where the first term inside the braces corresponds to inversion of the light echo in the direction $\mathbf{k} = -\mathbf{k}_1$ and the second term corresponds to an ordinary primary echo⁷ in the direction $\mathbf{k}_{\text{prim}} = 2\mathbf{k}_2 - \mathbf{k}_1$. Both coherent response were observed simultaneously in the experiment. At angles $\widehat{\mathbf{k}_1 \mathbf{k}_2} > 3^\circ$ the signal of the ordinary, primary echo was normal^{7,6} and the reversed echo signal remained almost the same. Such spatial behavior of both coherent signals can easily be explained by examining the extremum of the factors) derived from Eq. (2) as a result of double summation over the locations of the active particles (the corresponding factor of the reversed echo does not depend on \mathbf{k}_2).

We investigated the dependence of the intensity of the reversed echo signal on the interval τ between the pulses and determined the time T_2 from the decay curve. In a 170-G magnetic field the relaxation time is $T_2 = 43 \pm 5$ nsec.

We investigated the effect of the constant magnetic field on the reversed echo intensity (Fig. 2). It was found that as the field increased to 400 G the intensity of this response increased by two orders of magnitude, whereas in a field $H_0 > 400$ G the

reversed echo signal remained the same. An increase in the intensity with increasing field is attributable primarily to removal of the degeneracy of the working levels⁸ and also to suppression of the relaxation due to interaction of the Cr^{3+} ions with the Al nuclei.⁷

We also investigated the dependence of the reversed light echo on the polarization angle of this signal for a certain relative orientation of the polarization vectors of the excitation pulses. This dependence is consistent with the behavior of similar dependences of high-energy $1/2-1/2$ transitions. The observed coherent response is of interest not only from a spectroscopic point of view but also from the technical, since: 1) this signal has a wavefront that is reversed in time; 2) the reversal of the wave propagation direction for $\mathbf{k}_1/\mathbf{k}_2$ (optimum condition: $\mathbf{k}_1 \perp \mathbf{k}_2$) can be accomplished in any volume of the test sample (in this respect, the effect resembles the well-known Thomson-Quate effect⁹ in acoustoelectronics).

We observed in this experiment a correlation between the echo signal and the first pulse when this pulse had a low intensity and the standing wave had a high intensity.

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