Information erasing in the phenomenon of long-lived photon echo

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The possibility of erasing information in an arbitrary cell of an optical memory device based on the phenomenon of long-lived photon echo is theoretically considered. Optimal conditions for a maximal number of write–erase cycles in a given cell are obtained, and an experimental setup for observing this effect is proposed.

The phenomenon of long-lived photon echo (LPE) has recently attracted much attention.[1–8] This interest stems from the possible application of this phenomenon in high-capacity optical memory devices[9,10] (OMD's). The LPE phenomenon allows us to realize practically all functions of on-line nonarchival OMD's: high-capacity, high-speed read–write functions, etc. Moreover, it allows us to write images,[4] to obtain phase conjugation at readout,[5] and to write and read composite pulse envelopes.[6,7,10]

At present many problems crucial to the construction of an operating device have been solved. The possibility of multiple information readout without refresh has been shown theoretically[11] and experimentally.[7,12] Resonant media with storage times of the order of tens of hours and more have been investigated.[6,7] The Eu^{3+} impurity ions in different host crystals are used as resonant media in such experiments. These investigations give more hope of creating OMD's based on the LPE phenomenon. Nevertheless, up to now it has not been clear whether it is possible to erase information selectively in an arbitrary memory cell. The only method of erasing information considered to date is to heat the sample to temperatures above that of liquid helium. But it is clear that this will erase the entire volume of a resonant medium. It was pointed out for the first time in Ref. 13 that it is in principle possible to erase information with random access by using LPE signal suppression.

In this Letter the effect of LPE signal suppression is shown in more detail, and a simple technique for random access information erasing is shown. First, several leading considerations are cited. The effect of accumulated photon echo has been investigated.[14,15] The essence of this effect is the writing of information in a resonant multilevel medium as a frequency modulation of population by a continuous sequence of weak pulse pairs that appear successively, separated arbitrarily in time. Obviously, all pairs of pulses must be identical to each other up to the phase difference between pulse carriers. In this case the population modulation in the ground state will increase slowly after each pair of pulses, and the LPE signal intensity will also increase up to an experimentally observable level.

The question arises as to whether the echo will be accumulated in all cases. Is it possible that the echo signal will be suppressed rather than gained by the next pair of pulses? It can easily be shown that the depth of frequency modulation of the population will decrease after the influence of the next pair of pulses if the phase difference between carriers of these pulses is opposite to the phase difference of the previous pair of pulses. In this case the contribution to the frequency modulation of the ground state by this pair will be opposite in phase to the frequency modulation created by the previous pairs. As a result, the frequency modulation of the population will decrease or even disappear completely and the echo signal from the medium will be suppressed.

In the case of the usual LPE (in contrast to the accumulated photon echo), more-powerful pulses are used so that a single pair of pulses can create the population modulation deeply enough to permit observation of the LPE signal. It is clear that the information written by some pair of strong pulses can also be suppressed by an additional pair of pulses irradiating the same region of the resonant media. To show this, the simplest model of a resonant multilevel medium in which the LPE effect exists is used. This is a host crystal with organic impurity molecules having a long-lived triplet state.[3] The scheme of energy levels is shown in Fig. 1, in which $|1\rangle$ and $|2\rangle$ are the resonant levels of energy transition and $|3\rangle$ is a long-lived triplet state. The spin sublevels of $|3\rangle$ will be neglected.

For calculational convenience the method of solving the density-matrix equation that is given in Ref. 3 and

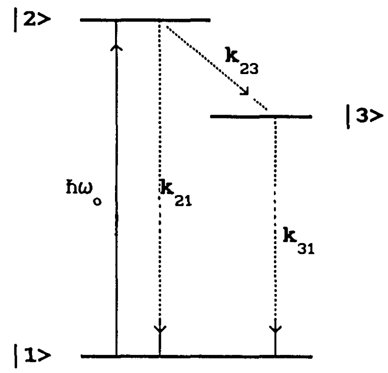

Fig. 1. Scheme of energy levels used in the calculations.

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applied in Ref. 11 is used to analyze the effect of multiple information readout. The method consists of transforming from the density-matrix equation to the Liouville equation, the solution of which allows us to express the excitation by short pulses as well as relaxation processes simply as the action of a linear operator on a column vector consisting of density-matrix elements that we are interested in. For brevity the notation and the approximations, and the Liouville operators, of Ref. 3 are used. This allows us to write out the final formulas immediately.

In our problem we can operate with a column vector consisting of only five elements, $\rho = \{\rho_{11}, \rho_{12}, \rho_{21}, \rho_{22}, \rho_{33}\}$. Let us consider a resonant system in thermodynamic equilibrium with a host crystal before excitation by an optical field, such that the single nonzero density-matrix element is $\rho_{11} = 1$. (We assume that the time separation τ_w between the writing pulses is short relative to the longitudinal relaxation time T_1 and comparable with or shorter than the transverse relaxation time T_2; see Fig. 2.) In this case the diagonal elements of the density matrix at the moment immediately after the influence of pair of pulses 1 and 2 are of the form

$$\rho_{11} = {}^1\!/_2[(1 + \cos\varphi_1 \cos\varphi_2) - \sin\varphi_1 \sin\varphi_2 \times \exp(-\tau/T_2)\cos(\Delta\mathbf{k}_w\mathbf{r} + \Delta\phi_w + \Delta\Omega\tau_w)], \quad (1)$$

$$\rho_{22} = {}^1\!/_2[(1 + \cos\varphi_1 \cos\varphi_2) + \sin\varphi_1 \sin\varphi_2 \times \exp(-\tau/T_2)\cos(\Delta\mathbf{k}_w\mathbf{r} + \Delta\phi_w + \Delta\Omega\tau_w)], \quad (2)$$

where φ_1 and φ_2 are the areas[16] of the first and second pulses, respectively, $\Delta\Omega$ is the frequency deviation from the center of the inhomogeneous line, $\mathbf{k}_1$ and $\mathbf{k}_2$ are the wave vectors, ϕ_1 and ϕ_2 are the phases of the two pulses, $\Delta\mathbf{k}_w = \mathbf{k}_1 - \mathbf{k}_2$, and $\Delta\phi_w = \phi_1 - \phi_2$, in which the subscript w denotes the relevance of corresponding values to the pair of writing pulses.

The forms of the nondiagonal elements of the density matrix are not essential because they are equal to zero after a time interval $t_w \gg T_2$ after the second pulse. Moreover, we consider time intervals $t_w \gg T_1$ because we are interested in information storage for times longer than the time of pure optical relaxation. In this case the matrix element $\rho_{22} = 0$ as well. For the ground state we have

$$\begin{aligned}\rho_{11}' &= \rho_{11} + [1 - \beta\exp(-k_{31}t_w)]\rho_{22} \\ &= 1 - \frac{\beta}{2}\exp(-k_{31}t_w)(1 - \cos\varphi_1\cos\varphi_2) \\ &\quad - \frac{\beta}{2}\exp(-k_{31}t_w)\sin\varphi_1\sin\varphi_2\exp(-\tau/T_2) \\ &\quad \times \cos(\Delta\mathbf{k}_w\mathbf{r} + \Delta\phi_w + \Delta\Omega\tau_w), \quad (3)\end{aligned}$$

where $\beta = k_{23}/(k_{31} + k_{23} - k_{31})$, and the decay rate constants k_{ij} are shown in Fig. 1.

One can see from Eq. (3) that the population of the ground state is frequency and spatially modulated. This grating is stored during a period $t_w \sim k_{31}^{-1}$ and leads to generation of an echo signal[3] after illumination of the medium by a third (readout) pulse [Fig. 2(a)]. As mentioned above, the grating can be suppressed by heating the sample to temperatures higher than that of liquid helium. Heating leads to a sharp increase in the decay rate constant k_{31} and hence to the return of the resonant system from the triplet state to the ground state, yielding $\rho_{11} = 1$. However, in this case the information will be lost in the entire crystal.

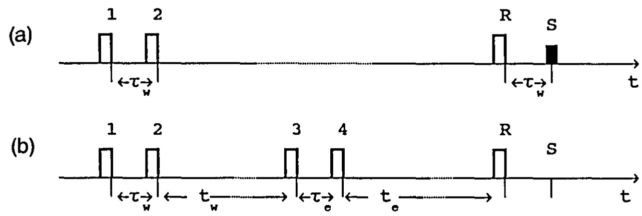

Fig. 2. Sequence of pulses (a) at information writing and readout and (b) at information erasing. 1 and 2 are the writing pulses, 3 and 4 are the erasing pulses, R is the readout pulse, and S is the echo signal.

The other method of echo-signal suppession proposed here is to write new information with a phase of frequency-modulated population opposite to that of the existing information, thus superimposing two frequency population modulations that have opposite phases such that the full modulation disappears. Suppose that the radiation of a new pair of pulses identical to the first one [Fig. 2(b)] but with a phase difference $\Delta\phi_e = \Delta\phi_w + \pi$ impinges upon the same spatial memory cell. It can easily be shown that, under the approximations used above, the influence of this pair and the optical relaxation during the time $t_e > T_1$ after the pulses mathematically are equivalent to the factorization of density-matrix element ρ_{11} with respect to the value χ, which is

$$\begin{aligned}\chi &= 1 - \frac{\beta}{2}\exp(-k_{31}t_e)(1 - \cos\varphi_3\cos\varphi_4) \\ &\quad - \frac{\beta}{2}\exp(-k_{31}t_e)\sin\varphi_3\sin\varphi_4\exp(-\tau/T_2) \\ &\quad \times \cos(\Delta\mathbf{k}_e\mathbf{r} + \Delta\phi_e + \Delta\Omega\tau_e), \quad (4)\end{aligned}$$

where φ_3 and φ_4 are the areas of the erasing pulses, t_e is the time interval after the erasing pair, and the subscript e relates to the parameters of the erasing pair. The second nonzero matrix element ρ_{33} has no influence on the echo signal and is not written here. Thus, after irradiating the sample by an erasing pair of pulses, the matrix element ρ_{11} takes the form

$$\begin{aligned}\rho_{11}'' &= 1 - \frac{\beta}{2}\exp(-k_{31}t_w)(1 - \cos\varphi_1\cos\varphi_2) \\ &\quad - \frac{\beta}{2}\exp(-k_{31}t_e)(1 - \cos\varphi_3\cos\varphi_4) \\ &\quad - \frac{\beta}{2}\exp(-k_{31}t_w - \tau/T_2)\sin\varphi_1\sin\varphi_2 \\ &\quad \times \cos(\Delta\mathbf{k}_w\mathbf{r} + \Delta\phi_w + \Delta\Omega\tau_w) + \frac{\beta}{2}\exp(-k_{31}t_e \\ &\quad - \tau/T_2)\sin\varphi_3\sin\varphi_4\cos(\Delta\mathbf{k}_e\mathbf{r} + \Delta\phi_e + \Delta\Omega\tau_e). \quad (5)\end{aligned}$$

In obtaining Eq. (5) the terms of the order β^2 are neglected since $\beta \ll 1$, which is relevant to a majority of organic molecules.

The echo signal after irradiation by the readout pulse (denoted by R in Fig. 2) is defined by terms proportional to $\cos(\Delta\mathbf{k}_w\mathbf{r} + \Delta\phi_w + \Delta\Omega\tau_w)$ and $\cos(\Delta\mathbf{k}_e\mathbf{r} + \Delta\phi_e + \Delta\Omega\tau_e)$. The conditions of erasing are identical to the conditions of writing, namely, $\varphi_1 = \varphi_3$, $\varphi_2 = \varphi_4$, $\Delta\mathbf{k}_w = \Delta\mathbf{k}_e$, and $\tau_w = \tau_e$, but the phase differences between the carriers for writing and erasing pulses differ by π: $\Delta\phi_e = \Delta\phi_w + \pi$. We take the relaxation factors $\exp(-k_{31}t_w)$ and $\exp(-k_{31}t_e)$ to be equal to unity because of the condition $t_{w,e} \ll k_{31}^{-1}$. In this case the terms in Eq. (5) with frequency modulation are canceled. The remaining terms do not depend on frequency and have no influence on the echo signal. Thus, by irradiating the given memory cell by a pair of pulses identical to the writing pair but with a phase difference of π, one can suppress the LPE signal totally.

Strictly speaking, the procedure described is not literally erasing because recurrence to the initial state of the cell with $\rho_{11} = 1$, which was the case before any irradiation, does not occur. After the erasing procedure the probability of finding the system in the ground state does not equal unity but differs from it by $\mathbb{C} \cong -\beta/2(2 - \cos\varphi_1 \cos\varphi_2 - \cos\varphi_3 \cos\varphi_4)$ owing to the triplet-state bottleneck effect. Hole burning in the inhomogeneous line occurs with a width equal to the spectral width of the laser light. Hence, the second pair of pulses paints over the information in the memory cell rather than erasing it. Therefore, for large relaxation times k_{31}^{-1} it is possible to write and erase information in a particular memory-cell-limited number of times. The number of cycles depends on the relation between k_{21} and k_{23} and on the areas of the writing and erasing pulses.

As an example, consider the case in which the areas of all pulses are equal to each other. In this case $\mathbb{C} \cong \beta \sin^2\varphi_1$. If $\beta \sim 0.1$ (Ref. 9) and $\varphi \sim 0.1$, then the number of write–erase cycles is of the order of 10^3. By choosing the most suitable resonance molecules and optimizing the pulse parameters, we can increase the number of write–erase cycles up to 10^5 or more. Hence, the described erasing process can be used well in OMD's. Thus information erasing in OMD's based on the effect of LPE can be done by simply introducing some kind of additional device for monitoring the phase delay in the optical path of one of the pulses in the pair.

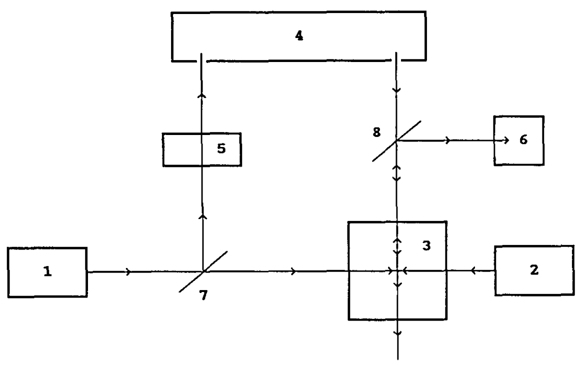

Fig. 3. Proposed experimental setup for observation of LPE and information erasing from a given memory cell. 1, The writing laser; 2, the erasing laser; 3, the resonant medium; 4, the optical delay line; 5, the electro-optical crystal; 6, the photodetector; 7, 8, the beam splitters.

For experimental observation of the erase process the setup shown in Fig. 3 can be used. In this scheme 1 is a writing laser. The pulse produced by this laser is split off by beam splitter 7, producing two pulses propagating along two different optical paths. One of the pulses irradiates the resonance medium directly after transmission through beam splitter 7, whereas the second pulse irradiates the sample after transmission through the electro-optic crystal 5 and optical delay line 4. Electro-optical crystal 5 with transparent electrodes permits monitoring of the phase of this delayed pulse. For simplicity, the deflectors and focusing elements are not shown.

During the writing of information the voltage on the electrodes of crystal 5 is absent. This corresponds to a definite phase difference between the pulses. If one needs to erase the information in a given memory cell one must apply the fixed voltage on crystal 5, which gives an additional phase difference of π between the pulses. Then the influence of the second pair of pulses on resonance medium 3 erases the information written by the first pair. The erasing of, e.g., written images and pulses of complex form can be done in the same way. In these cases the erasing pair of pulses must also be equal to the writing pair, with the exception of the phase shift π between carriers.

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