Frequency-selective time-domain optical data storage by electromagnetically induced transparency in a rare-earth-doped solid

B. S. Ham and M. S. Shahriar

Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

M. K. Kim

Department of Physics, University of South Florida, Tampa, Florida 33620

P. R. Hemmer

Rome Laboratory, Hanscom Air Force Base, Massachusetts 01731

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We report the experimental observation of optical data storage by frequency-selective stimulated spin echoes based on electromagnetically induced transparency in an inhomogeneously broadened rare-earth-doped solid. We find that the spin dephasing time T_2 is almost constant in the range 2–6 K, whereas the optical T_2 shortens rapidly above 4 K. This experiment demonstrates the potential of spin echoes excited by electromagnetically induced transparency for higher-capacity optical data storage at higher temperature.

Since the proposal[1] and subsequent experimental demonstration of stimulated photon echoes in both vapors[2] and solids[3] there has been increasing interest in their use for high-capacity optical data storage. Much of this interest arises from the large theoretical storage density available in rare-earth-doped solids, given by the ratio of optical inhomogeneous to homogeneous widths, which can be in excess of 10^6. However, for rare-earth-doped solids this storage density is generally available only at temperatures below 4 K and decreases rapidly as temperatures increase owing to the increase of homogeneous width by phonon interactions. In addition, some of the most widely used rare-earth-doped solids require highly frequency-stable lasers to approach theoretical storage densities.[4] To overcome these limitations we proposed[5] a technique to store optical data by use of spin coherences excited by coherent population trapping,[6] which in the present context is equivalent to electromagnetically induced transparency (EIT).[7,8] The advantages are that spin coherences tend to have much longer lifetimes than optical coherences at higher temperatures and that EIT can be made to be insensitive to laser jitter.

In this Letter we experimentally demonstrate frequency-selective time-domain optical data storage in Pr^{3+}:Y_2SiO_5 (Pr:YSO), using spin echoes excited by EIT. We verify the key prediction that the theoretical storage density in this approach does not significantly degrade with increasing crystal temperature up to 6 K. In contrast, at this temperature the theoretical optical storage density determined by the photon echoes is more than an order of magnitude smaller than its value below 4 K (as discussed below). We also verify the predicted insensitivity of theoretical storage density to laser frequency jitter.

The optical technique described in this Letter is analogous to frequency-selective stimulated photon echo memory.[1] In this technique the optical inhomogeneous width is chopped into M accessible channels in the frequency domain, and each channel is used for N-bit data storage in the time domain. Ideally, the Fourier component of each data pulse (and any laser frequency jitter) should be narrower than the assigned channel width. It is easy to show that the maximum storage density, NM, is given by the ratio of optical inhomogeneous to homogeneous widths. The length of the time-domain write window is given by the optical transverse relaxation time T_2. In the present experiment the time-domain portion of the memory utilizes a ground-state spin coherence rather than an optical one. This means that the write window is now given by the spin T_2, which is generally longer than the optical T_2, especially at higher temperatures or if there is appreciable laser jitter. Furthermore, if the inhomogeneous width of the spin transition is equal to or wider than the assigned optical frequency channel, then the theoretical storage density of the new technique is given by the ratio of the optical inhomogeneous width to the spin homogeneous width. This ratio is nearly always larger than the theoretical optical photon echo storage density, especially at high temperatures.

For the detection of frequency-selective stimulated spin echoes excited by EIT we use enhanced nondegenerate four-wave mixing.[8] The advantage of this technique is that it increases echo-detection efficiency.

Figure 1 is an energy-level diagram of 0.05 at. % Pr:YSO in which the optical transition frequency of $^3H_4 \rightarrow {}^1D_2$ is 605.7 nm. The splittings of the ground hyperfine states are 10.2 and 17.3 MHz, as shown.[9] The time-dependent coherence σ_{12} between

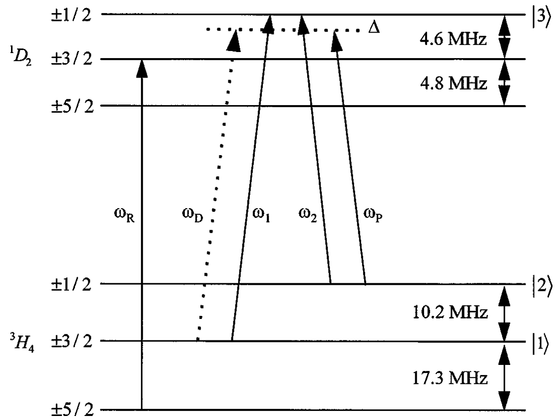

Fig. 1. Energy-level diagram of Pr:YSO.

the ground states $|1\rangle \leftrightarrow |2\rangle$ in Fig. 1 is created by the two resonant optical fields ω_1 and ω_2 according to the following density matrix equation:

$$\begin{aligned} \mathrm{d}\sigma_{12}/\mathrm{d}t = & - iD_{13}E_1\sigma_{32}(t)/\hbar \\ & + iD_{23}E_2\sigma_{13}(t)/\hbar - \gamma_{12}\sigma_{12}(t), \end{aligned} \tag{1}$$

where D_{ij} is a dipole matrix element corresponding to the transition $|i\rangle \rightarrow |j\rangle$ and γ_{12} is the decay rate of σ_{12}. E_1 and E_2 are (slowly varying) pulse amplitudes of the electric fields of the laser beams at ω_1 and ω_2, respectively. As the ground-state coherence term σ_{12} is directly coupled to the optical coherences σ_{13} and σ_{23}, time-dependent phenomena can be predicted by perturbation theory as in two-level systems.[10]

To probe the ground-state coherence, a probe beam ω_P is red detuned by $\Delta = 1.5$ MHz from the frequency of beam ω_2, as shown. A repump beam ω_R is used to provide frequency selectivity in the inhomogeneously broadened optical transition.[11] A stimulated spin echo (rephased coherence σ_{12}) is produced by three resonant Raman pulses, each of which has two frequencies ω_1 and ω_2, and is detected by nondegenerate four-wave mixing using ω_P to generate the signal beam ω_D, which is proportional to the rephased spin coherence.

Figure 2 is a schematic of the experimental setup. A frequency-stabilized cw ring dye laser is pumped by an argon-ion laser. The dye laser has jitter of $\sim$1 MHz. We use acousto-optic modulators driven by frequency synthesizers to make four coherent laser beams, ω_1, ω_2, ω_R, and ω_P, from the dye-laser output as shown. The laser powers of beams ω_R, ω_1, ω_2, and ω_P are $\sim$10, $\sim$30, $\sim$2, and $\sim$10 mW, respectively. The use of acousto-optic modulators makes laser jitter correlated, so laser difference frequencies are stable typically to subkilohertz levels. The angle between beams ω_1 and ω_2 is $\sim$60 mrad. The direction of the probe beam is chosen to satisfy Bragg matching but is not exactly copropagating with either beam ω_1 or ω_2 (inset of Fig. 2). Diffracted beam ω_D, which is generated from the nondegenerate four-wave mixing process, satisfies the phase-matching condition $\mathbf{k}_D = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_P$. All laser beams are forward propagating, circularly polarized with a quarter-wave plate, and focused into the sample (Pr:YSO) by a 40-cm focal-length lens. The measured beam diameters ($1/e$ in intensity) of the beams are $\sim$150 μm in the crystal. The size of the crystal is 3 mm $\times$ 6 mm $\times$ 9 mm with its symmetric optical b axis along the 9-mm direction, and it is mounted inside a cryostat. To pulse the laser beams, rf switches driven by pulse generators are used. The repetition rate of these pulses is 100 Hz. To average the laser jitter noise, 30 diffracted signals are detected by a fast silicon photodiode and averaged by a boxcar averager (SRS 250) with a gate width of 3 μs.

Figure 3 shows the storage of two bits of time-domain optical data by frequency-selective stimulated spin echoes based on EIT. Each input pulse is composed of both resonant Raman beams ω_1 and ω_2. The first two input pulses (d and d′) are data bits. The third and fourth input pulses are write (w) and read (r) pulses, respectively. The pulse width of the repump beam is 1 ms (not shown) and immediately precedes data pulse d. The pulse widths of the data bits (d and d′) are 7 and 2 μs, respectively, separated by 100 μs. The widths of the write and read pulses

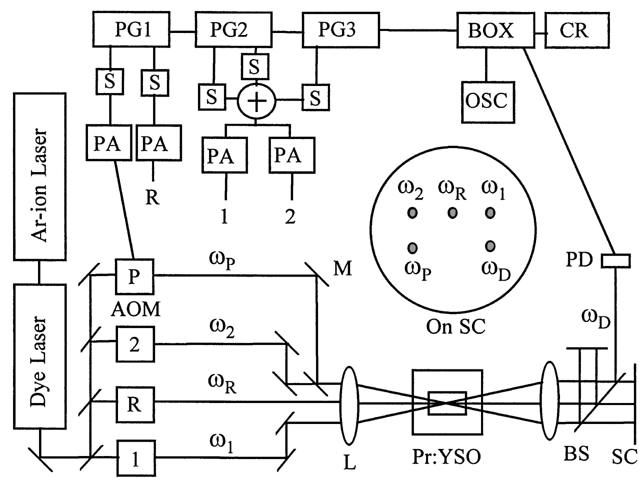

Fig. 2. Schematic of the experimental setup for frequency-selective time-domain stimulated spin echo by EIT: AOM, acousto-optic modulator; BOX, boxcar averager; BS, beam splitter; CR, chart recorder; L, lens; M, mirror; OSC, oscilloscope; PA's, rf power amplifiers; PD, photodiode; PG's, pulse generators; S's, rf switches; SC, screen.

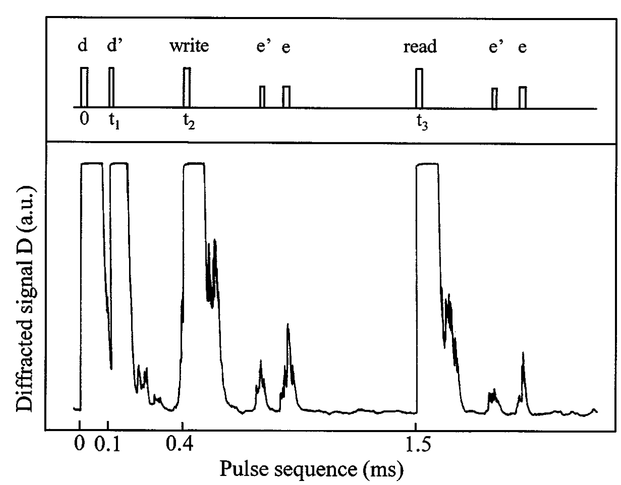

Fig. 3. Two-bit optical data storage by frequency-selective time-domain stimulated spin echo based on EIT at 6 K: d, d′, data; e, e′, echoes.

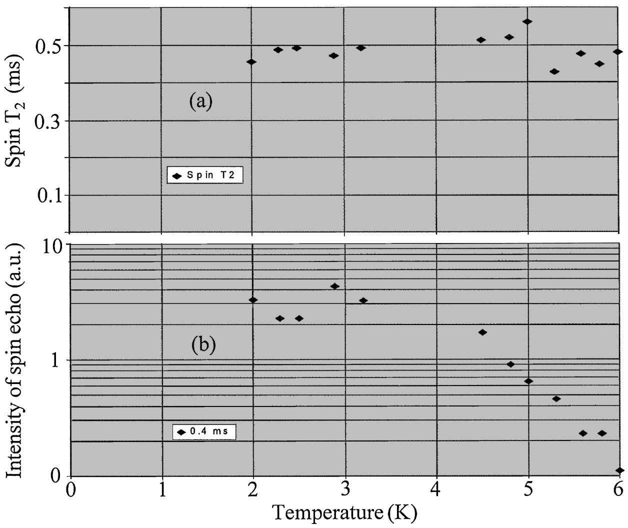

Fig. 4. (a) Spin T_2 versus temperature, (b) inferred optical T_2 versus temperature.

(w and r) are 7 and 5 μs, respectively, separated by 1.1 ms, which is twice the spin T_2. The time delay between data pulse d′ and write pulse w is 300 μs, which is chosen to be longer than the optical T_2 (111 μs) but shorter than the spin T_2. The probe pulse width is 5 μs, and the diffracted signals (30 samples) are averaged by the boxcar averager. When the input pulses are present, the diffracted signals are off scale on the chart recorder. As the figure shows, there are two-pulse echoes just after write pulse w. Echo signal e is bigger than e′ because data pulse d has a wider area than d′. The stimulated echoes are retrieved by read pulse r at $t_3 + t_2$ and $t_3 + t_2 - t_1$. Their intensities are comparable with those of the two-pulse echoes. The theoretical storage time is limited by a spin population decay time T_1, which is ~100 s in this material[9] but is several hours in Eu:YSO.[12] The storage density of the spin transition is determined by the ratio of spin $T_2{}^*$ to T_2. This ratio can be made large by application of a magnetic field to slow down spin T_2 (Ref. 13) or by use of a magnetic-field gradient to create additional inhomogeneous broadening.[14]

Figure 4(a) shows spin T_2 versus temperature. Each spin T_2 is measured from the two-pulse echo intensity (e in Fig. 3) versus write pulse delay t_2 with pulses d′ and r absent. We varied the write pulse delay time from 100 to 900 μs. Fluctuations in Fig. 4 are caused by laser jitter, which affects the observed echo signal intensity. Within the measurement fluctuations, the spin T_2 appears constant up to 6 K. Beyond 6 K the signal was too weak to permit us to measure spin T_2 accurately with our low-sensitivity photodiode, even though we detected echoes as long as there was spectral hole burning (up to ~8 K).

To infer how the optical T_2 depends on temperature, we simply measure the intensity of a two-pulse echo at a fixed write pulse delay t_2 [Fig. 4(b)]. Pulse delay t_2 is kept at 400 μs. The echo intensity should be proportional to the square of the optical T_2 because the efficiency of EIT depends on the product of Ω^2 and the optical T_2, where Ω is the rms Rabi frequency for the transitions at ω_1 and ω_2.[15] As we see from Fig. 4(b), the echo intensity decreases exponentially above 4 K, which implies that the optical T_2 also decreases rapidly as temperature goes up.

In summary, we have observed frequency-selective time-domain optical data storage by using EIT-excited spin echoes in Pr:YSO at 6 K. We showed that the write window is determined by the spin T_2, which is much longer than the optical T_2, especially at higher temperature. We also measured the spin T_2 and found it almost constant in the range 2–6 K. In contrast, at temperatures above 4 K we observed that the optical T_2 decreases rapidly as temperature goes up. Therefore these results demonstrate the potential for higher-capacity optical data storage than by conventional photon echo memories in rare-earth-doped solids at high temperatures.

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