Electromagnetically induced transparency over spectral hole-burning temperature in a rare-earth–doped solid

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We have observed electromagnetically induced transparency (EIT) in rare-earth Pr^{3+}-doped Y_2SiO_5 over the spectral hole-burning temperature. The transmission of the probe laser beam is increased by a factor of exp(1.4) at 12 K when a coupling laser of 1.2 kW/cm^2 is applied to the system. The observation of EIT over the spectral hole-burning temperature in a rare-earth–doped solid represents important progress toward high-density echo-based optical memories at higher temperatures. © 1999 Optical Society of America [S0740-3224(99)01605-7]

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1. INTRODUCTION

As information technology develops, not only large-capacity storage but also high-speed information processing is important for mass data communications. Recently, spectral hole-burning materials have attracted much attention because of their potential applications in mass optical data storage, fast optical switches, and computing elements such as a dynamic random access memory modules. For example, the usefulness of the hole-burning materials for high-density storage[1] and high-speed optical switches based on photon echoes[2] have already been demonstrated.

In an inhomogeneously broadened medium having hyperfine states in the ground level, a laser field can deplete atoms from one of the hyperfine states for a while if the population decay time of the hyperfine states is slower than that for the optical transition. This phenomenon is called spectral hole burning because a set of depleted atoms is seen as a spectral hole in the absorption spectrum. Each spectral hole is composed of a different subset of atoms, molecules, or ions.[3] Moreover, the spectral holes for wave multiplexing do not suffer from Bragg-degeneracy–caused cross talk,[4] which limits storage capacity in volume holography. Therefore storage density in volume holography can be significantly increased with spectral multiplexing because the spectral holes act as independent optical channels. Temporal multiplexing has another advantage for high-speed signal processing in photon-echo systems,[1] which is maintaining high-density storage capability. The storage density is determined by the ratio of inhomogeneous to homogeneous widths, which is $\sim 10^6$ per focused laser spot in rare-earth–doped spectral hole-burning solids. This high-density storage capability, however, is available only at near–liquid-helium temperatures because the optical homogeneous width rapidly broadens as temperature rises owing to phonon interactions.

Recently, resonant Raman-pulse–excited spin echoes have been demonstrated to offer a potential for high-speed, high-density optical memories to overcome the temperature restrictions of photon-echo–based memories.[5,6] In the resonant Raman-excited spin-echo memory,[5] it was shown that the spin coherence time T_2 (reciprocal of the spin homogeneous width) replaces the optical T_2 for the length of the write window. Thus, under ideal conditions, the storage density is determined by the ratio of the optical inhomogeneous width to spin (rather than optical) homogeneous width. This distinction is especially important for higher-temperature applications because the spin homogeneous width is less sensitive to temperature. For example, we demonstrated a narrower and temperature-invariant spin homogeneous width in Pr^{3+}-doped Y_2SiO_5 (Pr:YSO) from 4 to 6 K, whereas the optical homogeneous width is exponentially broadened.[5]

For efficient resonant Raman-excited spin echoes, electromagnetically induced transparency[7] (EIT) is an essential condition because the spin coherence (or echo) is optically detected by nondegenerate four-wave mixing. The nondegenerate four-wave-mixing signal is enhanced by EIT.[8] In a three-level system interacting with Raman fields, EIT is caused by destructive quantum interference, so that the optically thick medium can be transparent. Recent demonstrations of EIT[8–10] and resonant Raman-excited spin echoes[5,6] in solids, however, still required near–liquid-helium temperatures.

In this paper we present an experimental observation of EIT in Pr:YSO at temperatures as high as 15 K, well beyond the spectral hole-burning temperature. The difficulty of observation of EIT in solids is due to the broad inhomogeneous width and small oscillator strength ($f \sim 10^{-7}$ for Pr:YSO and Cr^{3+}:Al_2O_3). Therefore a high-power coupling field should be expected.[10] However, with a repump field in a spectral hole-burning medium, inhomogeneous width can be narrowed down to laser jitter, so that the effective number of atoms can be significantly reduced.[8] Here it should be noted that the photon number of a coupling laser must exceed the number of atoms in a probe-laser path to prepare EIT.[11] Following that approach, we successfully observed EIT in our previous experiments by use of low-power lasers through spectral modification.[8,9] As temperature increases, spectral hole burning disappears, so that no spectral modification is possible. Therefore high-power lasers should be expected. In the present paper, however, we demonstrate EIT over spectral hole-burning temperature by using a relatively low-power laser. We have observed that the probe transmission increases by a factor of exp(1.4) at 12 K.

2. CHARACTERISTICS OF Pr:YSO

Our system consists of 0.05 at. % Pr^{3+}-doped Y_2SiO_5 in which Pr^{3+} substitutes for Y^{3+}. For this research the relevant optical transition is $^3H_4 \rightarrow {}^1D_2$, which has a resonance frequency of ~606 nm. The inhomogeneous width of the optical transition is ~4 GHz at near–liquid-helium temperatures. The optical population decay time T_1 is 164 μs at 1.4 K.[12] The optical homogeneous width is linearly broadened to the excitation laser intensity.[12] The extrapolation to zero excitation intensity at 1.4 K yields 2.4 kHz for the optical homogeneous width and increases 1 kHz per every intensity of 4 W/cm^2.[12] Because of the phonon interaction, the optical homogeneous width also broadens as temperature increases. We have observed that the optical homogeneous width broadens ten times in Pr:YSO when temperature increases from 4 to 6 K.[5] The ground ($^3H_4$) and excited ($^1D_2$) state each have three doubly degenerate hyperfine states. The energy splittings between hyperfine states of the ground level ($^3H_4$) are 10.2 MHz($\pm 1/2 \leftrightarrow \pm 3/2$), 17.3 MHz($\pm 3/2 \leftrightarrow \pm 5/2$), and 27.5 MHz($\pm 1/2 \leftrightarrow \pm 5/2$).[12] Owing to slow decay time in the hyperfine states, there is spectral hole burning in the absorption spectrum. The hole decay time varies from ~400 s at 1.6 K to ~50 s at 6 K.[13] The spin inhomogeneous width for the 27.5-MHz transitions is 80 kHz at 1.6 K.[13]

3. EXPERIMENTAL SETUP

Figure 1 shows a schematic of the experimental setup. We use a frequency-stabilized ring dye laser (Coherent 699). The dye laser's frequency jitter is ~2 MHz. For the resonant Raman transition, we excited the $^3H_4(\pm 1/2) \rightarrow {}^1D_2(\pm 3/2)$ transition with a coupling laser and the $^3H_4(\pm 5/2) \rightarrow {}^1D_2(\pm 3/2)$ transition with a probe laser. The coupling and the probe fields are upshifted by 72.5 and 100 MHz from the laser frequency, respectively, so that the difference frequency matches the hyperfine splitting between $^3H_4(\pm 5/2)$ and $^3H_4(\pm 1/2)$. These fields are generated with acousto-optic modulators driven by frequency synthesizers (PTS 160). The probe field is fixed at the resonance, while the coupling field is scanned across its resonance frequency. The two laser beams are circularly polarized with a quarter-wave plate and focused into the sample by a 25-cm focal-length lens. The diameter (1/*e* in intensity) of the coupling laser beam is ~50 μm in the crystal. The coupling laser intensity is varied up to ~1.5 kW/cm^2. To produce laser pulses, we used rf switches driven by pulse generators (Stanford Research DG 535). The pulse width is fixed at 50 μs. The pulse repetition rate is set at 50 Hz to eliminate any Raman coherence accumulation (spin $T_2 \sim 500\,\mu$s).[5] A Boxcar averager (Stanford Research SR 250) averages 30 samples of the probe signals. The angle between the coupling and the probe fields is about 100 mrad. The spectral hole-burning crystal of Pr:YSO is inside a cryostat, and its temperature can be varied. The size of the crystal is 3 mm × 6 mm × 1 mm. Its optical *B* axis is along the 1-mm length, and the laser propagation direction is almost parallel to the optical axis.

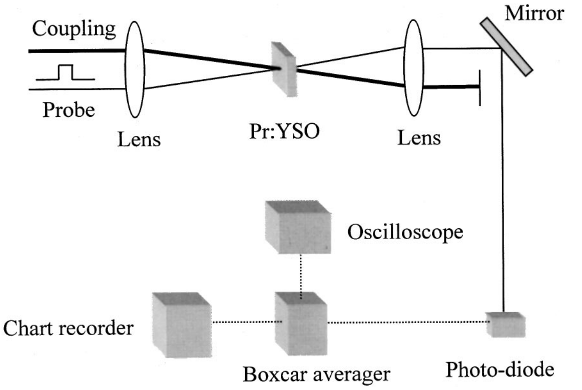

Fig. 1. Schematic of the experimental setup.

4. RESULTS AND DISCUSSION

Figure 2 shows the probe absorption as a function of temperature. For these measurements the coupling laser is blocked, and the probe intensity is adjusted not to saturate (over the temperature of the spectral hole burning). The power of the probe beam is 60 μW. Below ~8 K, the sample is nearly transparent to the probe because of spectral hole burning. The probe transmission rapidly drops down to ~10% at 10 K and then gradually decreases as the temperature increases. We measured 4% probe transmission at 20 K. This high probe absorption continues up to ~25 K and then gradually decreases for the fixed laser frequency. Resonance frequency of the sample, however, depends on temperature, so we need to retune the probe frequency when the temperature changes. As a result, we observed that the probe transmission is less than 4% at temperatures of 25–40 K. Based on the fact that the spin T_1 should not be faster than the optical T_1 below 16 K,[13,14] the hole-burning disappearance in Fig. 2 should be due mainly to optical homogeneous broadening, which should be wider than the splitting (10.2 MHz) of hyperfine states ($\pm 1/2$–$\pm 3/2$).

From the data in Fig. 2, the absorption coefficient α is calculated to be ~30/cm at temperatures of 12–20 K.

Figure 3 shows the probe transmission versus the coupling laser detuning at 12 K. The coupling laser intensity in Fig. 3 is 1.2 kW/cm^2 in the crystal. As we mentioned in the Introduction, the optical homogeneous width broadens as temperature rises. Thus EIT efficiency should be degraded because it is inversely proportional to the homogeneous width. Moreover, over the spectral hole-burning temperature, spectral modification is not possible any longer. Therefore the coupling laser intensity should be increased at least by a factor of $\sim 10^3$ (the ratio of inhomogeneous width to the laser jitter) at beyond the spectral hole-burning temperature to satisfy minimum coupling energy required for EIT. Because of the limitation of our dye-laser power, we solved this problem by reducing the sample length and the laser-beam diameter. As a result, we reduced the laser-beam path length by a factor of $\sim 10^{-1}$ (from 9 to 1 mm) and increased the laser intensity by a factor of $\sim 10^2$ (from 28 to 1200 W/cm^2), compared with those in Fig. 3(b) of Ref. 9. Therefore the minimum energy required for EIT should be satisfied.

At the line center ($\Delta = 0$) of the coupling laser transition in Fig. 3, the probe transmission is increased from 5% to 20%, a factor of exp(1.4). The FWHM of the probe transmission increase is ~2.2 MHz. At this temperature this width is much narrower than the optical homogeneous width, which is deduced to be larger than 10.2 MHz on the basis of the assumption that the spectral hole burning disappears when the optical homogeneous width is larger than the hyperfine splitting. This narrower linewidth in the probe spectrum is taken as an evidence of EIT. In previous research (Ref. 9) more efficient EIT was seen for lower coupling laser intensity because of narrower inhomogeneous width, which was due to spectral modification under the spectral hole-burning temperature and narrower homogeneous width, as we mentioned above.

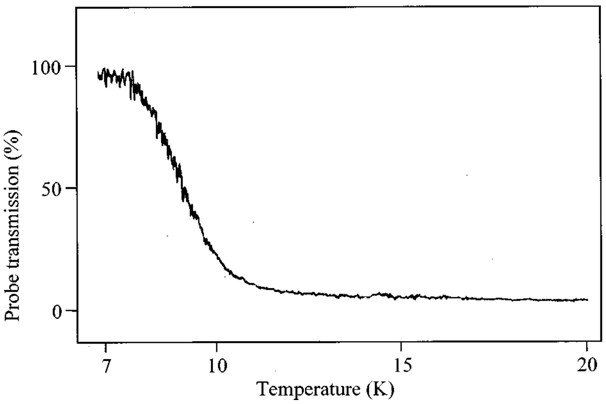

Fig. 2. Probe transmission versus temperature. The probe laser power is 60 μW.

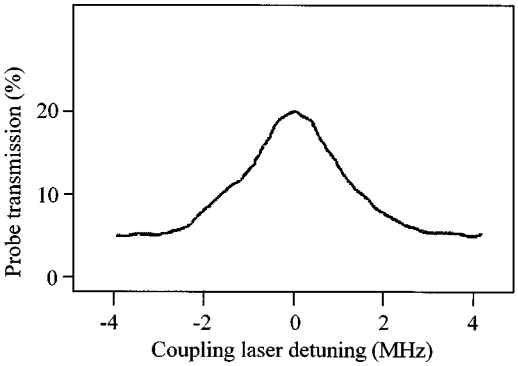

Fig. 3. Probe transmission versus coupling laser detuning at 12 K.

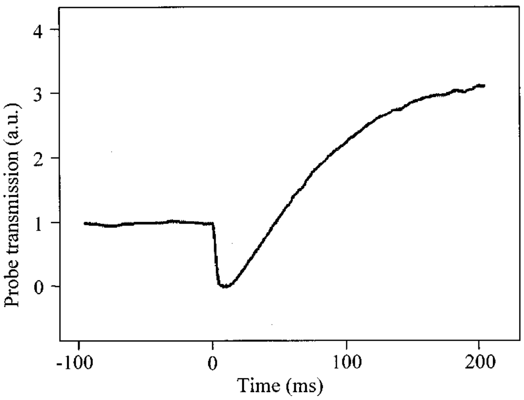

Fig. 4. Probe transmission versus time. At $t = 0$, the coupling laser is off.

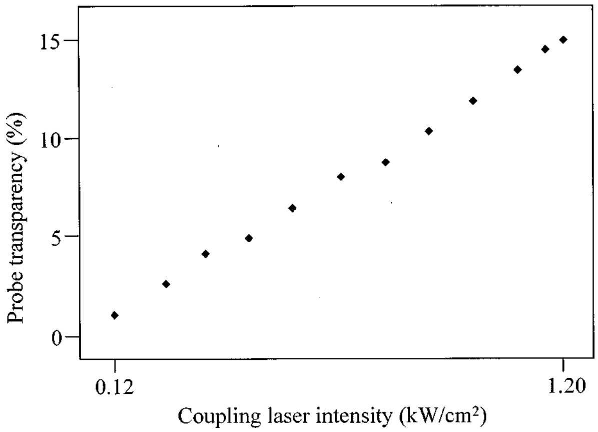

Fig. 5. Probe transparency versus coupling laser intensity.

Figure 4 shows other evidence of EIT. In Fig. 4 we keep the temperature at 10 K, which gives partial spectral hole burning. Initially at $t < 0$, the probe transmission is enhanced, owing to EIT. When the coupling laser beam is switched off at $t = 0$, the probe-beam transmission decreases abruptly and then gradually increases. The transmission decrease at $t = 0$ is due to the loss of EIT; coherently trapped ions begin to absorb the photons. The transmission increase afterward is due to the spectral hole burning. The spectral hole-burning saturation time should depend on the strength of the probe.

Figure 5 shows the probe transparency versus the coupling laser intensity. The temperature is fixed at 12 K. As expected, the probe transparency increases as the coupling laser intensity increases. The probe transparency increase is proportional to the logarithm of the coupling laser intensity. The axis of the coupling laser intensity is

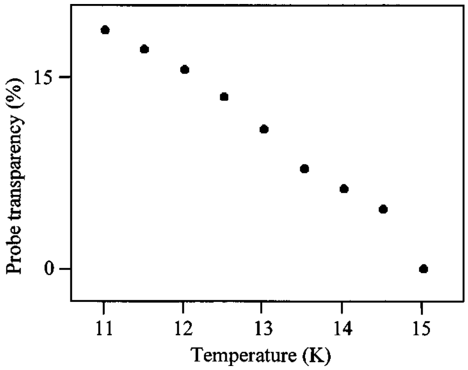

Fig. 6. Probe transparency versus temperature for fixed coupling laser intensity.

a log scale. For the data, the probe transparency is determined by the probe transmission change when the coupling laser is switched on.

In Fig. 6 we measured the probe transparency as a function of temperature with a fixed intensity of the coupling laser. As expected, the probe transparency decreases as the temperature increases. This decrease occurs because the optical homogeneous width is broadened as the temperature increases, so that the EIT efficiency decreases. Over 15 K, we could not detect any EIT effect with a coupling laser intensity of ~1.2 kW/cm^2.

5. CONCLUSION

We experimentally observed EIT in an optically thick, spectral hole-burning solid of Pr:YSO at temperatures higher than needed for spectral hole burning. This demonstration is the first step toward implementation of high-density, high-speed optical memories based on resonant Raman-excited spin echoes. Unlike spectral multiplexing that directly uses burned holes,[3] hole burning is not a necessary condition for storage of Raman-excited spin-echo optical data but is an advantage for the use of optical channels. Unlike photon echoes, Raman-excited spin-echo memory can be achieved at higher temperatures once there is EIT because spin coherence time (the write window) is much less sensitive to temperature than the optical one.[5] Moreover, the spin coherence time can be lengthened by application of an external magnetic field.[15] Therefore the observation of EIT in Pr:YSO over spectral hole-burning temperature opens a door to high-temperature memory applications based on Raman-excited spin echoes.

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