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Efficient electromagnetically induced transparency in a rare-earth doped crystal

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Abstract

We have observed up to 100% transmission of a probe field at line center due to electromagnetically induced transparency (EIT) in an optically dense rare-earth crystal of Pr³⁺ doped Y₂SiO₅ at 5.5 K. We also have examined both laser field intensity and temperature dependence of the EIT. Efficient EIT in this crystal opens potential applications such as efficient high-resolution image processing and signal processing, and optical data storage as well as lasers without population inversion in solids. © 1997 Elsevier Science B.V.

1. Introduction

The interaction of a strong resonant laser field with two levels in a three-level system can modify the absorption and refractive index of a probe field whose transition involves the third level. Particularly, the probe field is not absorbed at line center due to coherence and destructive quantum interference, so that an optically thick medium can become transparent. This is called electromagnetically induced transparency (EIT) [1–5] or sometimes coherent population trapping (CPT) in a Λ -type system. Since the first experimental observation of CPT in atomic sodium [6], EIT and CPT have been studied extensively because of many potential applications, for example frequency up-conversion [7,8], lasers without inversion [9,10], and high-gain phase conjugation [11,12].

Recently, we observed EIT and enhanced four-wave mixing based on EIT in Pr³⁺ doped Y₂SiO₅ (Pr:YSO) for the first time, where we observed a 15% decrease in absorption [13]. In this paper, we demonstrate near 100% transparency of a probe field at line center in an optically thick sample of Pr:YSO with a cw laser. We choose

Pr:YSO, because it has relatively long optical and spin relaxation times and a high oscillator strength. These properties make the observation of EIT possible with a commercially available cw dye laser. Rare-earth doped crystals have properties similar to atomic vapors but with the advantage of no atomic diffusion. This advantage is critical for high resolution applications of EIT such as image processing [14], signal processing [15], and Raman-echo optical data storage [16,17].

2. Characteristics of Pr:YSO

Pr:YSO is known as a good material for optical data-storage because of its big ratio of inhomogeneous to homogeneous widths and long optical pumping lifetime. Fig. 1 shows its energy level diagram. Our system consists of 0.05 at% Pr doped YSO in which Pr³⁺ substitutes Y³⁺. Ideally, the density of Pr-ions in this crystal is calculated straightforwardly from the crystal structure [18], and it is $4.7 \times 10^{18} \text{ cm}^{-3}$. For this work, the relevant optical transition is ³H₄ → ¹D₂ which has a frequency of 605.7 nm at site 1. Each electric singlet is split into three hyperfine states by the low-symmetry crystal field [19]. The splittings of the ground-hyperfine states are 10.2 and 17.3 MHz

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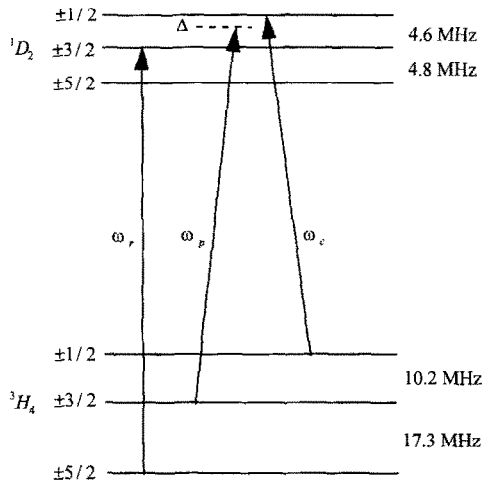


Fig. 1. Energy level diagram of Pr:YSO.

as shown. For the transition of 605.7 nm in 0.02 at% Pr:YSO, the reported optical inhomogeneous width is 4 GHz, and the absorption coefficient is 10 cm^{-1} [20]. The optical population decay time T_1 and transverse decay time T_2 are 164 and 111 μs , respectively [19]. For the spin transition, the T_2 between the hyperfine states has not been directly measured yet, but the T_1 is as long as several minutes. The inhomogeneous widths of these spin transitions are known to be less than 80 kHz. For the 10.2 MHz transition in 0.1 at% Pr:YSO, the measured inhomogeneous linewidth is 30 kHz [19].

In Fig. 1, we call laser fields ω_c , ω_p , and ω_r coupling, probe, and repump field, respectively. The coupling and probe fields produce coherence between ground states $^3\text{H}_4(\pm 3/2 \rightleftharpoons \pm 1/2)$, while the repump field refills the holes burned by the coupling and probe fields. As shown, the coupling field ω_c is on resonance with the transition $^3\text{H}_4(\pm 1/2) \rightarrow ^1\text{D}_2(\pm 1/2)$, while the probe field ω_p is scanned across the resonance frequency of $^3\text{H}_4(\pm 3/2) \rightarrow ^1\text{D}_2(\pm 1/2)$. The repump field ω_r is on resonance with the transition of $^3\text{H}_4(\pm 5/2) \rightarrow ^1\text{D}_2(\pm 3/2)$. Here, it should be noted that Fig. 1 applies to only a small subset of Pr-ions. Because of the large inhomogeneous broadening, each laser field can pump other transitions in the manifold for a subset of Pr-ions having the appropriate transition frequency. However, due to optical pumping, only the subset of Pr-ions shown in Fig. 1 is repumped, and therefore for cw excitation, most of the signal comes from this system. This is easily verified by scanning the repump field frequency across the three excited-hyperfine states, while the probe and coupling fields are held fixed. When the repump field is resonant with one of the excited-hyperfine states, the probe field is absorbed by the medium, otherwise it is transparent due to the persistent spectral hole-burning effects.

3. Experimental

Fig. 2 shows the schematic experimental setup. We use a frequency stabilized Coherent ring dye laser 699 pumped by a Spectra Physics argon-ion laser. The dye laser is continuous wave, and its long term laser jitter is about 1 MHz. We use acousto-optic modulators (AO) driven by frequency synthesizers (PTS 160) to make three different coherent laser fields as shown. The use of AOs makes observing the narrow lineshape of EIT possible because it ensures that laser jitters are correlated, so that the laser frequency differences are stable (typically down to a few Hz). To match Fig. 1, the coupling, probe, and repump field are downshifted 70.5, 60.3, and 47.6 MHz from the laser frequency by AO-C, AO-P, and AO-R, respectively. To escape from any contribution of multi-photon interactions involving the repump field, a separate excited-hyperfine state is chosen for the repump transition as shown in Fig. 1. All three laser fields are circularly polarized with a quarter wave plate and focused into the sample by a 40 cm focal length lens. The measured diameter ($1/e$ in intensity) of the coupling laser beam is about $150 \mu\text{m}$ in the crystal. The coupling laser intensity is varied up to a maximum intensity of 900 W/cm^2 . The angle between the coupling and probe fields is about 25 mrad. The spectral hole-burning crystal of Pr:YSO is inside a cryostat and its temperature can be varied. The

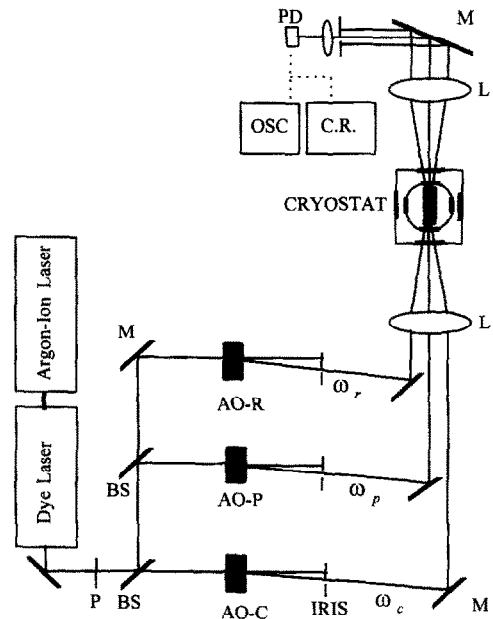


Fig. 2. Schematic diagram of the experimental setup; AO, acousto-optic modulator; BS, beam splitter; C.R., chart recorder; L, lens; M, mirror; OSC, oscilloscope; P, quarter wave plate; PD, photo-diode.

size of the crystal is 3 mm × 6 mm × 9 mm. Its optical *B*-axis is along the 9 mm length, and laser propagation direction is parallel to the crystal *B*-axis.

4. Results and discussion

Fig. 3a–3d show the absorption spectra of the probe field in Pr:YSO at 2 K, when the coupling field intensities are (a) 9, (b) 28, (c) 90, and (d) 280 W/cm². The intensities of the probe and repump fields are held fixed at 9 and 16 W/cm², respectively. The laser frequency is tuned near the center of 4 GHz inhomogeneously broadened absorption profile of Pr:YSO. The full width at half maximum (FWHM) of the absorption spectrum is about 1.2 MHz, which is similar to the estimated laser linewidth based on laser jitter observed with a Fabry-Perot spectrum analyzer. In all cases, the absorption curve disappears when the repump field ω_R is blocked, as expected. Due to EIT, the transmission of the probe field at line center increases from near 0% to (a) 3%, (b) 14%, (c) 36%, and (d) 65%, where the higher transmission corresponds to the higher coupling field intensity. It should be noted that the actual absorption linewidth should be wider than that measured in Fig. 3, because the AO varies the probe beam angle along with its frequency, so that for large detunings, there is laser beam walk-off. Specifically, we find that the beam walk-off becomes important for the probe detunings

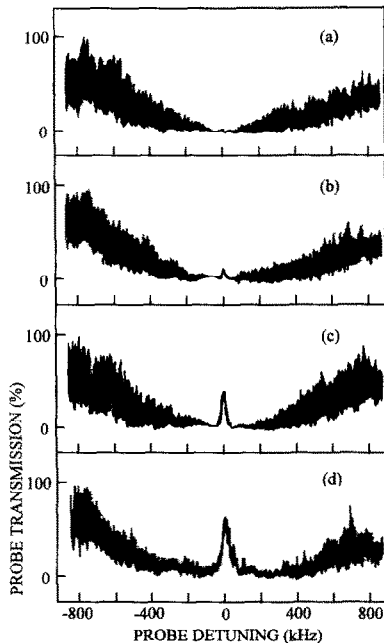


Fig. 3. Transmission versus probe detuning in Pr:YSO at 2 K for a coupling field intensity of (a) 9, (b) 28, (c) 90, and (d) 280 W/cm². The intensities of probe and repump fields are 9 and 16 W/cm², respectively.

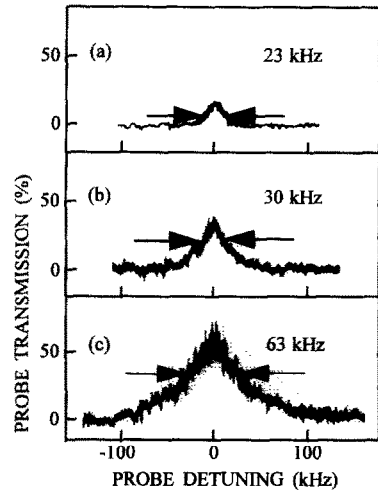


Fig. 4. Expanded scans of EIT at 2 K for (a) Fig. 3b, (b) Fig. 3c, and (c) Fig. 3d.

greater than ± 1 MHz. The noise on wings of the absorption spectra come from the combined effects of laser jitter and the spectral hole burning processes.

To better study the coupling field intensity dependence of EIT, we show expanded scans of the transparency dip in Fig. 4. The measured FWHMs of EIT are (a) 23, (b) 30, and (c) 63 kHz, which correspond to Fig. 3b–3d, respectively. All the EIT linewidths are much narrower than the laser jitter and comparable to the inhomogeneous linewidth of the 10.2 MHz ground state transition which is less than 30 kHz. This insensitivity to correlated laser jitter is the signature of the two-photon transitions responsible for EIT. Here, it is worth noting that additional line narrowing of the EIT is expected under the conditions of this experiment due to the high optical density of the crystal [21].

In Fig. 5, we measure EIT when the coupling field is off resonance. For this, we detune the repump field by (a) 300 and (b) 600 kHz from the resonance frequency, which

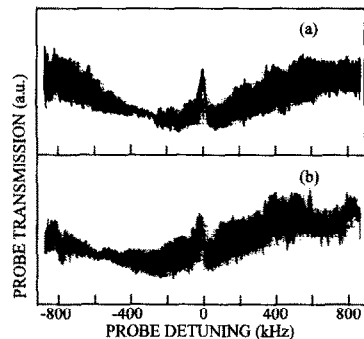


Fig. 5. EIT in Pr:YSO at 2 K with the repump field blue-detuned by (a) 300 and (b) 600 kHz. Increasing Δ corresponds to red detuning (see Fig. 1).

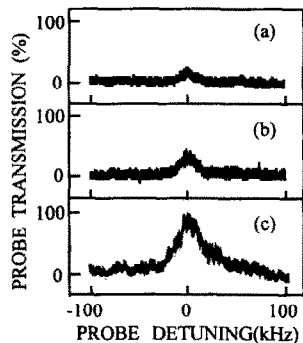


Fig. 6. Transmission versus probe detuning in Pr:YSO at 5.5 K for a coupling field intensity of (a) 90, (b) 280 and (c) 900 W/cm². The intensities of probe and repump fields are 14 and 11 W/cm², respectively.

gives the same effect as opposite detuning of the coupling field. Here, we should note that negative detuning means blue detuning and vice versa by the definition of Δ in Fig. 1. As seen in Fig. 5, the effective absorption line-center is blue-shifted by an amount equal to the repump field detuning, and there is asymmetric EIT on the two-photon resonance, which is in agreement with off resonant CPT measurements made in atomic beams [22]. For this data, the intensity of the coupling field is 90 W/cm².

We also studied EIT in Pr:YSO at higher temperatures. Fig. 6 shows EIT at 5.5 K. In Fig. 6c, we observe near 100% transmission of the probe field at line center when the coupling field intensity is 900 W/cm². The intensities of the probe and repump fields are 14 and 11 W/cm², respectively. The coupling field intensities for Fig. 6a, 6b are the same as for Fig. 3c, 3d, respectively. Comparing Figs. 3 and 6, we find that the EIT induced transmission decreases as temperature increases. This can be explained by noting that as temperature increases the dephasing rate of the spin and optical transitions increase because of phonon interactions [23]. This higher dephasing rate leads to a smaller ground state coherence and a weaker EIT [24]. In Pr:YSO, the optical dephasing rate rapidly increases as temperature increases beyond 4 K [19]. We have observed EIT up to 8 K with the maximum coupling laser intensity of 900 W/cm².

5. Conclusion

In summary, we observed nearly 100% electromagnetically induced transmission of a probe field at line center in an optically dense rare-earth doped crystal of Pr:YSO at 5.5 K. We also studied both coupling field intensity and temperature dependence of EIT. Efficient EIT in a rare-earth doped crystal opens exciting potential applications such as high-resolution nonlinear optical image processing, high efficiency optical signal processing, Raman-echo op-

tical data storage, and LWI at ultra-violet frequencies in solids.

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