ABSTRACT
We report ultraslow group velocities of light in a solid. Light speeds as slow as 45 m/s were observed, corresponding to a group delay of 66 $\mu$s in a 3-mm thick, optically dense crystal of Pr doped Y$_2$SiO$_5$. Reduction of the group velocity is accomplished by using a sharp spectral feature in absorption and dispersion that is produced by resonance Raman excitation of a ground-state spin coherence. Potential applications of slow and stopped light for the highly efficient storage and recall of optical data are discussed.

Keywords: Raman scattering, spin coherences, group velocity of light, rare-earth doped materials.

1. INTRODUCTION.
Ultraslow light$^{1,2}$ has a number of potential applications ranging from the generation of large time delays for beam steering to the enhancement of the stimulated-Brillouin effect for nonlinear optics$^3$. Producing slow light using Electromagnetically Induced Transparency (EIT)$^4$ has additional advantages. For example, the resultant nonlinearity obtained by this method might be utilized for efficient multi-wave mixing and quantum nondemolition measurements$^5$. Carefully controlled, ultraslow light might even allow a very efficient nonlinear interaction between laser pulses of extremely low (down to a single photon) energy$^6$. These effects can be used to create quantum entanglement between single photons without an ultrahigh finesse cavity and therefore are of great interest for quantum information processing. Slow light is also of interest because it serves as a useful metric to compare the relative merits of dissimilar nonlinear optical interactions. This is especially important for applications that make use of the large optical dispersive properties of EIT for the detection of small phase shifts, such as in very sensitive magnetometers.$^7$

Potential application of ultra slow light to optical storage is based on the recent suggestion$^8$ and experimental demonstration$^9,10$ that the group velocity of light can be slowed to zero, effectively stopping or storing the light. Light stored by this technique can be recalled with near 100% efficiency in principle. This is important for demanding storage applications such as quantum in information storage.

For many potential applications of slow light, a solid-state medium is preferred. For this, spectral hole burning (SHB)$^{11}$ materials are good candidates, since they have already demonstrated utility for ultra-high density optical memories and processors$^{12}$. In particular, it has already been demonstrated that efficient, narrow-linewidth EIT is possible$^{13}$ in a SHB material, namely Pr doped Y$_2$SiO$_5$ (Pr:YSO)$^{13}$.

2. RESULTS
Our crystal of Pr:YSO was supplied by Scientific Materials, Inc. and consists of 0.05 at% Pr with a thickness of 3 mm in the light propagation direction. The experimental setup is shown in Figure 1(b). We used a COHERENT 899-21 dye ring single mode laser pumped by INNOVA 300C argon laser. The dye laser was continuous wave with laser jitter measured to be about 1-2 MHz. All the laser fields shown in Figure 1 were derived from a single mode dye laser output using acousto-optic frequency shifters. This greatly relaxes dye laser frequency stability requirements since the resonant Raman interaction is insensitive to correlated laser jitter. To generate the probe beam absorption spectra, the frequency of the probe beam was scanned around the 10.2 MHz Raman transition frequency with the frequencies of the coupling and the repump beams held fixed. A set of compensating galvos was used to allow changing the frequencies without perturbing the optical alignment. The intersection angle of the coupling and the probe beams was about 4$^\circ$ in the plane of the optical table. The direction of the repump beam was also 4$^\circ$ but out of the plane of the optical table. This geometrical arrangement allowed us to reduce amount of direct and scattered light from the coupling and the repump beams on photodetector. To further increase signal to noise ratio, the probe beam was modulated and transmitted signal was detected by standard phase-locking technique. All laser beams were linearly polarized and focused into the crystal by a
300 mm focal length lens, producing a spot with a diameter about 100 µm. During the experiment, the sample was maintained at a temperature of ~5 K inside the helium flow JANIS cryostat.

The \(^3\text{H}_4 \rightarrow \text{^1D}_2\) optical transition at site 1 is used, which has a central frequency near 606 nm. The relevant energy level diagram is presented in Figure 1(a), where the coupling and the probe fields are denoted by frequencies \(\omega_C\) and \(\omega_P\), respectively, and the sublevels correspond approximately to (Kramers degenerate) nuclear spin states. Due to the long lifetime of the ground state sublevels, more than 100 sec. at 5 °K, these fields soon cause the crystal to become transparent via optical pumping, as illustrated by the solid curve in Figure 2(a), so that cw absorption and EIT are prevented. The width of this transparency or "spectral hole" is determined by the intensities and frequency widths of the coupling and probe fields.

To counteract the spectral hole burning effect and provide a high optical density for EIT, a repump field \(\omega_R\) is also needed, as shown in Figure 1(a). This repump field creates an absorbing "anti-hole" near the center of the hole bleached by the coupling and probe fields, as shown by the dotted curve in Figure 2(a). The width of this anti-hole is determined by laser jitter and its peak absorption is determined by the repump beam intensity. The intensity of the repump field therefore controls the effective probe absorption much the same as varying the atomic density controls the absorption in a vapor. More importantly, the anti-hole width determines the effective inhomogeneous linewidth that must be overcome by the Rabi frequency of the coupling field to establish efficient EIT. Since this anti-hole width is typically on the scale of 1-2 MHz or less, compared to the 4.4 GHz intrinsic inhomogeneous width of the optical transition, efficient EIT can be established at a much lower coupling intensity than would otherwise be predicted. Due to this narrow effective inhomogeneous linewidth, the doped crystal more closely resembles an ultracold vapor than a warm vapor. The absence of atomic motion, and therefore Doppler shifts and diffusion, is also an advantage that the crystal and ultracold vapor share.

A typical anti-hole pattern is shown in Figure 2(b). Note that there are three absorption peaks due to the multiple excited state sublevels. A narrow EIT-like transparency is visible in the central anti-hole. For a sufficiently strong coupling laser, the EIT-induced transparency can approach 100 % as shown in Figure 2(c). An expanded scan of an EIT-induced transparency of about 50 % is shown in Figure 2(d). At this coupling field intensity, the transparency is only slightly power broadened and is comparable to the 60 kHz (FWHM) inhomogeneous linewidth of the ground-state spin transition, as measured by Optically Detected Nuclear Magnetic Resonance (ODNMR)\textsuperscript{15}.

To measure the group velocity of the probe light, the probe is pulsed by chopping the rf power applied to the appropriate acousto optic frequency shifter. To simplify the measurement, the probe is chopped using a periodic square wave. For a periodic modulation, the time delay caused by a slower group velocity produces a phase shift in the

![Figure 1](image-url)
transmitted signal (see Figure 3(a)). This phase shift can be easily detected using a lock-in amplifier, as described in previous slow light experiments in a warm vapor. The results of these light speed measurements are shown in Figure 3(b&c).

Figure 2. (a) Schematic representation of hole burning in the inhomogeneous optical absorption line (solid curve) and an anti-hole created by the repump field (dotted curve). (b) Observed anti-hole absorption. (c) Expanded scan of the central anti-hole showing near 100 % efficient EIT. (d) Expanded scan of an EIT-induced transparency showing a narrow linewidth.  

As shown, group delays greater than 65 µsec are observed, which correspond to light speeds as slow as ~45 m/s for the 3 mm long crystal. The observed group delays are found to be independent of the probe modulation frequency (over the range of 3-6 kHz), as required. The observed dependence of light speed on coupling beam intensity can be explained by noting that at high coupling intensities, power broadening causes an effective light speedup, whereas at low intensities, inefficient EIT causes a speedup. These trends were verified experimentally by measuring the EIT transparency amplitudes and linewidths as a function of coupling intensity, not shown here.

To verify the modulation technique, time delays of individual (square) probe pulses were measured. These are shown in Figure 4(a) for various probe detunings from the center of the EIT-induced transparency. The chosen probe detunings are illustrated graphically in Figure 4(b), by superimposing on a representative EIT lineshape. The first output pulse in each case is due to probe light that propagates undisturbed through the crystal, since the absorption is less than 100 % for the crystal length and repump field intensity used. As expected, the observed group delay is very sensitive to detuning from the EIT transparency. On resonance, a maximum delay of about 65 µsec is measured from center of the input pulse to the center of the delayed pulse. This is nearly identical to the delays measured by the modulation technique (Figure 3), and validates the data.
Figure 3. (a) Schematic representation of a phase shift, $\phi$, in a periodic signal induced by group delay, $\tau_D$. (b) Measured group delay vs. coupling beam intensity. (c) Deduced group velocity of light vs. coupling beam intensity.

Figure 4. (a) Transmitted probe signals showing the dependence of group delay on detuning from the center of EIT-induced transparency. (b) Schematic representation of the detunings used to generate curves in (a), superimposed on representative EIT lineshape.
For applications to optical storage, especially quantum storage, it is important that the “slow light” amplitude be as large as possible, since this is related to fidelity of quantum information storage. Experimentally, we found that this can be accomplished by applying two probe pulses, as shown in Figure 5. The first probe pulse produces only a weak slow light signal, due to absorption. However, because of persistent optical pumping in this crystal, the first pulse also prepares the medium by bleaching out the absorbing atoms. In this case, as shown in Figure 5, the second probe pulse produces a slow-light pulse with an amplitude approaching 50 % of the input intensity, and only a slightly faster group velocity. This “slow light” amplitude is comparable to the best results seen in vapors so far, and can likely be enhanced by better laser frequency stabilization and the use of low-distortion, laser-quality polish on the crystal faces. Here, it should be noted that unlike the previous probe-pulse data, Figure 5 represents a single non-averaged, probe pulse pair that has been selected for a time when the laser jitter is momentarily small (as happens once every 5-7 shots).

![Figure 5. Transmitted probe signal when two probe pulses are applied (solid curve). The dashed curve is the input probe signal. The second “slow light” pulse reaches nearly 50 % of the input probe intensity. These traces represent single-shot data, selected for minimum laser jitter.](image)

In conclusion, we demonstrated an ultraslow group velocity of light of 45 m/s in a rare-earth doped crystal. This first observation of ultraslow light in a solid is a key step toward many potential applications of slow light such as low-intensity nonlinear optics. It is also an enabling step toward the demonstration of stopped light in a solid, which has application to highly efficient optical storage and recall, as required for quantum information.

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### REFERENCES

1. L. V. Hau, S. E. Harris, Z. Dutton, C. Behroozi, Nature, 397 (1999) 594.
2. M. Kash, V. Sautenkov, A. Zibrov, L. Hollberg, G. Welch, M. Lukin, Y. Rostovsev, E. Fry, M. Scully, Phys. Rev. Lett., 82 (1999) 5229.
3. A. Matsko, Y. Rostovsev, H. Cummins, M. Scully, Phys. Rev. Lett. 84 (2000) 5752.
4. S. E. Harris, Physics Today, July 1997, 36; S. E. Harris, L. V. Hau, Phys. Rev. Lett., 82 (1999) 4611; O. Schmidt, R. Wynands, Z. Hussein, D. Meschede, Phys. Rev. A., 53 (1996) R27; M. Xio, Y. Li, S. Jin, J. Gea-Banacloche, Phys. Rev. Lett., 74 (1995) 666; A. Kasapi, M. Jain, G. Y. Yin, S. E. Harris, Phys. Rev. Lett., 74 (1995) 2447; S. E. Harris, J. E. Field, A. Kasapi, Phys. Rev. A, 46 (1992) R29;V. Braginsky, F. Khalili, Quantum Measurement (Cambridge University Press, 1992).
5. M. Lukin, A. Imamoglu, Phys. Rev. Lett. 84 (2000) 1419.
6. M. O. Scully, M. Fleischhauer, Phys. Rev. Lett., 69 (1992) 1360.
7. M. Fleischhauer and M.D. Lukin, Phys. Rev. Lett., 84 (2000) 5094.
8. C. Liu, Z. Dutton, C.H. Behroozi, and L.V. Hau., Nature 409, (2001) 490.
9. D.F. Phillips, A. Fleischhauer, A. Mair, R.L. Walsworth, Phys. Rev. Lett., 86 (2001) 783.
10. R.M. MacFarlane and R.M. Shelby, "Coherent Transients and Holeburning Spectroscopy of Rare Earth Solids" in Spectroscopy of Solids Containing Rare Earth Ions, ed by A.A Kaplyanskii and R.M. MacFarlane, Elsevier Science Publishers 1987, Chpt. 3.
11. H. Lin, T. Wang, and T. W. Mossberg, Opt. Lett. 20 (1995) 1658; X. A. Shen and R. Kachru, Opt. Lett. 20 (1995) 2508; B.S. Ham, M.K. Kim, P. R. Hemmer, and M. S. Shahriar, Opt. Lett., 22, (1997) 1849.
12. R.W. Equall, R.L. Cone, and R.M. Macfarlane, Phys. Rev. B 52 (1995) 3963; K. Holliday, M. Croci, E. Vauthey, and U.P. Wild, Phys. Rev. B 47 (1993) 14741.
13. B. Ham, P. Hemmer, M. Shahriar, Opt. Commun. 144 (1997) 227.
14. L.E. Erickson, Opt. Commun. 21 (1977) 147.