Stopped Light with Storage Times Greater than One Second Using Electromagnetically Induced Transparency in a Solid

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We report on the demonstration of light storage for times greater than a second in praseodymium doped Y_2SiO_5 using electromagnetically induced transparency. The long storage times were enabled by the long coherence times possible for the hyperfine transitions in this material. The use of a solid-state system also enabled operation with the probe and coupling beam counterpropagating, allowing easy separation of the two beams. The efficiency of the storage was low because of the low optical thickness of the sample; as is discussed, this deficiency should be easy to rectify.

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Some of the most significant advances in quantum information processing have been made using quantum optics-based techniques. For example, working practical quantum cryptosystems already exist, and there have been demonstrations of linear optics quantum computing [1], quantum teleportation, quantum nondemolition measurements [2], and quantum feedback and control [3]. To proceed further, it is necessary to have devices such as single photon sources, quantum memories, and quantum repeaters, where quantum information is exchanged in a controlled fashion between light fields and material systems. It has been proposed that both the required control and strong coupling can be readily achieved using an ensemble approach, where the light field interacts with a large number of identical atoms. Such ensemble based approaches now exist for single photon sources [4], ''cat'' state sources [5], quantum memories [6–8], and quantum repeaters [4]. Experiments have demonstrated heralded single photon sources [9,10] and the mapping of quantum information on a light field onto spin states of an atomic ensemble [11]. Experiments using electromagnetic induced transparency have demonstrated the storage and recall of optical pulses [12,13].

The quantum systems used for these ensemble based demonstrations have almost exclusively been atomic vapors. An issue with these demonstrations is that even for laser cooled ensembles, the atomic motion impacts the devices' performance. Ensembles of solid-state optical centers provide an alternative to atomic systems where the relative motion is zero. In this Letter we investigate the use of a solid-state system for ensemble based quantum optics and highlight its usefulness by stopping a light pulse using electromagnetically induced transparency (EIT). Unlike an earlier experiment [14], the current demonstration highlights for the first time two advantages of using optically active solid-state centers: a 1000-fold increase in storage time and the ability to operate with a less restrictive beam geometry.

When storing light using EIT, characteristics of the field are recorded as a spin wave in the ensemble. The storage time is determined by the coherence times of the hyperfine transitions. In principle, coherence times for hyperfine transitions in atomic systems can be very long and many minutes have been measured in ion traps [15]. However, these long coherence times in large ensembles suitable for EIT have not been achieved. Transit time broadening in vapor cells and magnetic inhomogeneity in trapped systems mean that the longest that light has been stored in atomic systems is a few milliseconds. In contrast, in earlier work we have demonstrated techniques to obtain hyperfine coherence times of tens of seconds in $Pr:Y_2SiO_5$ [16,17]. Here we show it is possible to utilize these long coherence times to stop light for similar lengths of time.

EIT is sensitive to atomic movement, with the spin wave being scrambled once the atoms have moved significantly compared to the wave vector mismatch between the probe and the coupling beams. To minimize this wave vector mismatch, experiments in atomic systems typically operate with the beams copropagating. Because the probe and coupling beams are close in frequency, in this configuration, the wave vector mismatch is typically less than $1\ \mathrm{cm}^{-1}$. A consequence of this copropagating operation is that it is difficult to separate the probe and the coupling beam. In a solid-state system, where the optical centers are locked in a crystal lattice, copropagating operation is not required; in the present work the probe and the coupling beams are counterpropagating. With counterpropagating beams it is easier to separate the probe and coupling beam while maintaining optimum overlap.

The experimental setup is shown in Fig. 1. Because of the narrow 2500 Hz optical homogeneous linewidth of the $^3H_4 \rightarrow {}^1D_2$ transition in $Pr^3 + :Y_2SiO_5$, a highly frequency stabilized dye laser was required for the experiment not to be limited by laser jitter. The laser used was a modified Coherent 699 dye laser with a linewidth 200 Hz over 1 s time scales. The laser output was split into two beams, one

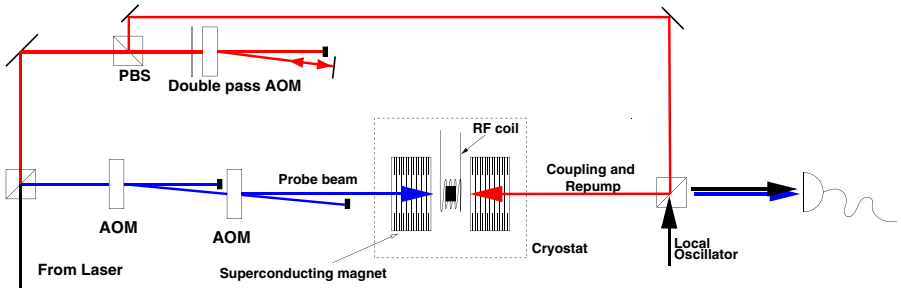

FIG. 1 (color online). The experimental setup. A beam picked of the laser was put in the remaining port of the rightmost beam splitter and is not shown. This enabled heterodyne detection of the probe beam that was transmitted through the sample.

of which was frequency shifted and gated by two acousto-optic modulators (AOMs) and used as the probe beam. The other beam was frequency shifted and gated using a double pass AOM setup. This beam was used for the coupling and repumping fields. This coupling-repump beam was aligned on a beam splitter to go through the sample counterpropagating with the probe. The spare port of this rightmost beamsplitter was used to combine a local oscillator beam with the transmitted probe beam, enabling the heterodyne detection of the signal.

The sample used was the same as that used in Ref. [17] and consisted of 0.05% praseodymium doped in Y_2SiO_5. It was 4 mm thick along the direction of light propagation. The sample was mounted in a bath liquid helium cryostat. Three orthogonal superconducting magnets were used to apply a dc magnetic field to the sample and a six turn rf coil was used to apply a rf field.

The dominant dephasing mechanism for the hyperfine states of the Pr^{3+} ions is random Zeeman shifting due to fluctuating magnetic fields from the yttrium nuclei. Dramatic increases in coherence times can be achieved by operating at a magnetic field where the transition frequency is insensitive to magnetic field changes to first order [16]. The magnetic field required is 78 mT in an orientation described in Ref. [16]. Once the magnetic field is obtained, the remaining fluctuations have reasonably long correlation times. This situation enables the effective use of dynamic decoherence control (DDC) techniques [18], and coherence times in excess of half a minute have been demonstrated [17].

An energy level diagram showing the transitions driven during the experiments is shown in Fig. 2. While the optical inhomogeneous linewidths is a few GHz. The narrow homogeneous linewidth (of order 1 kHz) and long hyperfine population lifetimes (of order 1 min) enabled the experiment to be carried out on an ensemble with a much smaller range of optical frequencies. At the beginning of each shot a sequence of the five optical frequencies (labeled "R" in Fig. 2) was applied repeatedly. The repump frequencies were applied sequentially rather that all at once to avoid the possibility of dark states and nonlinear mixing of the different frequencies in the AOM. The gap in time between the repumping and each experimental shot was long enough to ensure that ions had no remaining optical coherence. This repumping procedure prepared an ensemble of ions in the desired hyperfine state and gives a narrow adsorption with an inhomogeneous width of 100 kHz when measured by sweeping a week probe in frequency (line given by dots in Fig. 3). When the coupling beam was applied, a narrow transparency was obtained in the absorption of the weak probe (solid trace in Fig. 3).

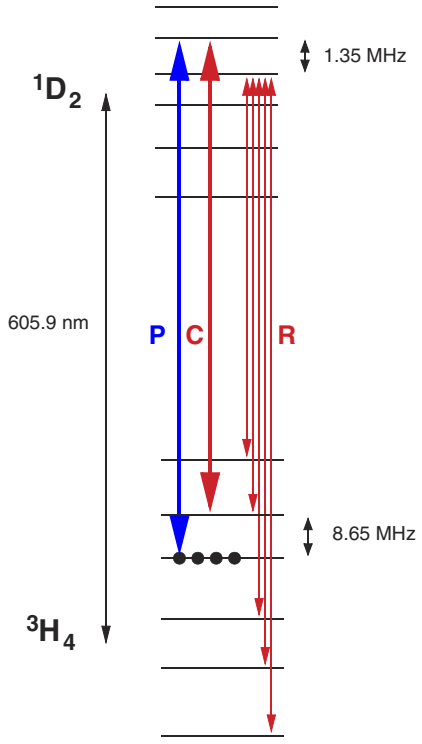

FIG. 2 (color online). Energy level diagram showing transitions driven as part of the experiment. The experiment was carried out on the zero phonon line of the $^3H_4 \rightarrow {}^1D_2$ optical transition. The hyperfine levels are shown, and these are due to the 5/2 spin of the praseodymium nuclei. In the presence of a magnetic field these are linear combinations of the zero field states. The probe, coupling, and repump beams are labeled P, C, and R, respectively.

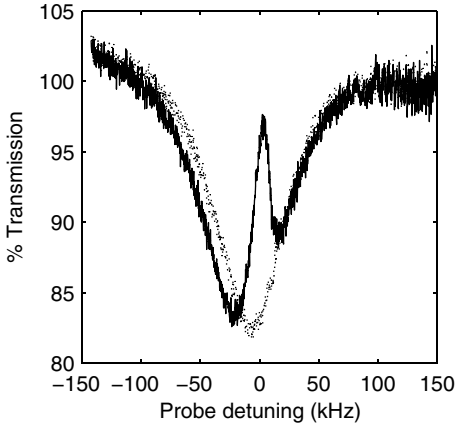

FIG. 3. Transmission of a weak probe, 10 μW, as its frequency is swept through resonance with the prepared ensemble. The solid line was taken with a 1 mW coupling beam on and the dotted line with the coupling off.

The repumping beams were applied after each shot and the 300 kHz span shown was swept in 4 ms. The transmitted probe beam was detected as a heterodyne beat signal, and the bandwidth of the rf detector was comparable to 300 kHz; the extra noise at each end of the spectrum came from dividing out this frequency response. For coupling intensities above 1 mW the EIT was observed to depend linearly on the amplitude of the coupling beam. The limiting EIT width at low intensity was 10 kHz, corresponding to the hyperfine inhomogeneous linewidth. Below 1 mW the EIT transmission decreased with decreasing coupling intensity.

It can be seen from Fig. 3 that the peak absorption of our ensemble is only about 15% and, as is discussed below, this limits the efficiency of the storing process.

The time sequence for the light storage demonstration is shown on the left of Fig. 4. A 20 μs long probe pulse was applied, and then the 10 mW coupling beam was turned off to transfer the optical coherence onto the spin transition. As in the previous solid-state stopped light [14] experiment, rf rephasing pulses were used to rephase the inhomogeneous broadening in the spin transition. Although one rf rephasing pulse is enough to rephase the spin wave, it also flips the spin-wave's direction. Therefore when not using copropagating beams, as is the case here, it is necessary to use an even number of rephasing pulses.

The size of the pulse of light recalled as a function of delay can be shown with and without dynamic DDC, and the results are shown in Fig. 4. The decay constants for the stored signal output were 0.35 s without DDC and 2.3 s with DDC. These decay rates were comparable to measurements of T_2 made using the same method as Fraval *et al.* [16]. The difference between the present measurements of T_2 and those obtained by Fraval *et al.* [16] is attributed to not having tuned the magnetic field as carefully as was achieved by Fraval *et al.*

Shown in the inset of Fig. 4 is the intensity of the output pulse as the intensity of the input probe pulse is varied. From the graph it can be seen that the storage process is linear at low powers and starts to saturate at higher powers once the input pulse becomes a significant fraction of a $\pi/2$ pulse. This demonstration of linearity is important. Previous solid-state experiments [14] have been restricted by laser frequency jitter to using probe pulses with areas greater than π. At such high powers effects such as self-induced transparency [19] cannot be ignored.

While the effect was linear and scaled to low powers, the efficiency was low, of the order of 1%. This in part can be improved with better timing and shaping of the probe and coupling waveforms. However, the main reason for the low

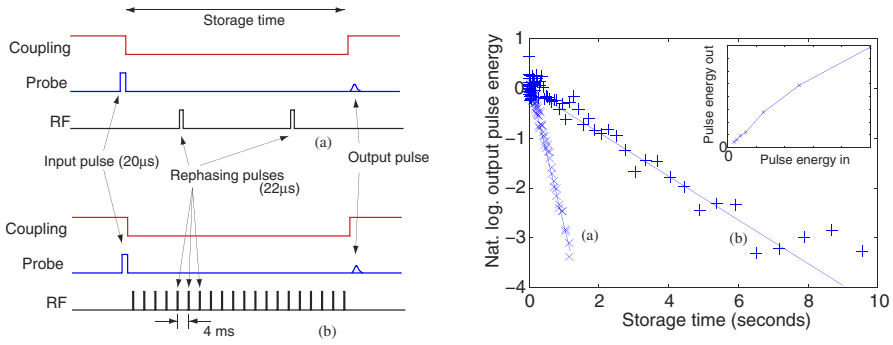

FIG. 4 (color online). On the left is the time sequence used in the stopped light experiments (a) with simple rephasing of the inhomogeneous broadening of the spin transitions and (b) with "bang-bang" dynamic decoherence control. In (a) two rephasing pulses are used, placed 1/4 and 3/4 of the way through the storage time. In (b) N rephasing pulses were used (N even). The first rephasing pulse was applied 2 ms after the light was stored, the pulses were separated by 4 ms, and the last pulse was applied 2 ms before the light was recalled. The rephasing pulses lasted 22 μs. On the right is the size of the recalled pulse as a function of time. The faster decay was acquired using simple rephasing of the ground state spin coherence (a). The slower decay was acquired using bang-bang [22] decoherence control (b). The inset shows the energy of the recalled pulse as a function of the energy of the input pulse, the probe pulse length was 20 μs, and the delay held constant at 100 ms.

efficiency is the low optical absorption at the probe frequency and the accompanying modest group delay.

The sample used for this experiment was only 4 mm thick, longer samples as well as multipass cells and cavities are simple means to increase the optical absorption. Preliminary measurements on samples with a range of praseodymium concentrations [20] suggest that at least twofold or threefold increases in the optical thickness can be achieved by increasing the concentration without significantly increasing the inhomogeneous broadening of the hyperfine transition.

As it is a goal of this line of research to store and retrieve quantum mechanical states, it is worthwhile to consider the effect that rephasing pulses would have on few photon states stored in the hyperfine coherences. It has been asserted in a theoretical investigation of quantum information storage in the solid state [21] that one would not be able to apply the rf π pulses with sufficient accuracy. This is not the view of the authors of this Letter. In Ref. [21] it was assumed that the π pulse would have to be applied with an accuracy close to 1 part in N (where N is the number of atoms) in order that the few photon pulse not be swamped by light caused by inaccuracies of the π pulse. However this light will be emitted randomly rather than in the very precise spatiotemporal mode of the output pulse. This should enable the output pulse to be easily separated from the background with very high efficiency.

In conclusion, we have demonstrated stopped light in $Pr:Y_2SiO_5$ for time scales of several seconds, which is 3 orders of magnitude longer than any obtained previously. Based on previous measurements of T_2 it should be possible to extend this storage time by at least one more order of magnitude.

For the first time stopped light has been demonstrated in a solid with the coupling and probe beams counterpropagating. This configuration is desirable as it allows easy separation of the two beams. However, it is practical only if the atoms movement during the storage time is small compared to the optical wavelength. Even for ultracold systems this places significant limits on storage time. In a solid where the atoms are locked into position, this is not a problem.

The efficiency of the storage process required for a quantum memory should be obtainable by increasing the density of the dopant ions and by increasing the interaction length.

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