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Storage of images in atomic coherences in a rare-earth-ion-doped solid

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We report on storage of images in atomic coherences driven by electromagnetically induced transparency in a doped solid. We demonstrate image storage times up to the regime of milliseconds (i.e., more than two orders of magnitude larger than in gaseous media). Our data also reveal an improvement in the spatial resolution of the retrieved images by a factor of 40. The long storage times become possible by applying additional radio frequency pulse sequences to drive rephasing of the atomic coherences. Moreover, the perturbing effect of atomic diffusion (which significantly limits image storage times in gases) is absent in the solid. In addition, we monitored pronounced oscillations in the intensity of the retrieved image versus the storage time. These oscillations are due to the beating of dark-state polaritons. All of these results demonstrate the superior properties of coherently driven optical data storage in solids.

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Future applications of optical data processing require novel approaches for efficient storage of optical information in quantized media. Coherent interactions between light and atoms provide powerful tools to achieve this goal. A number of potential concepts have been proposed for coherent memories of increased storage capacity. In particular, quantum information processing highly benefits from the possibilities of coherent interactions. Adiabatic passage processes are a specific class of coherent interactions [1]. Adiabatic passage combines large efficiency with pronounced robustness (e.g., with respect to fluctuations in the experimental parameters). In particular, the technique of electromagnetically induced transparency (EIT) [2] was very successfully applied in recent years to a large variety of applications in the storage, recovery, and processing of light in quantum systems. Among other possibilities, EIT permits the slowing down of a light pulse in a coherently driven atomic medium as well as storage and retrieval of a light pulse [3,4].

The main concept of light storage is as follows: A quantum system of two lower states $|1\rangle$ and $|2\rangle$ and an excited state $|3\rangle$ is driven by two radiation fields [see Fig. 1(a)]. Initially the system is in state $|1\rangle$. The weak data field couples states $|1\rangle$ and $|3\rangle$ at frequency $\omega_d = \omega_{13}$. The strong control field couples $|2\rangle$ and $|3\rangle$ at frequency $\omega_c = \omega_{23}$. When the control field temporally overlaps the data field and both fields are switched off simultaneously and adiabatically the medium is driven to a permanent coherent superposition of states $|1\rangle$ and $|2\rangle$ [see Fig. 1(b)]. Thus, the population is equally and coherently distributed between the two lower states. In this case, the coherence ρ_{12} and the induced dipole moment in the medium become maximal. During the process the data pulse experienced stimulated absorption. Thus, the data pulse is stored in the atomic coherence ρ_{12}. To read out the coherence we apply the control field once more. The control field interacts with the atomic oscillator to produce the beat frequency $\omega_c + \omega_{12} = \omega_d$. Thus, we retrieve the data pulse from the medium. This is the essence of light storage by EIT. The maximum storage time is determined by dephasing and decoherence processes (e.g., collisions, spin exchange, or diffusion).

There are a number of successful experiments on storage and retrieval of one-dimensional optical information, such as light pulses with a uniform spatial profile (i.e., no image information) and variation in the time domain only. The vast majority of these investigations were conducted in the gas phase. We must not fail to mention the recent, striking implementation of light storage in a doped solid with storage times in the regime of seconds [5]. However, future applications require storage of two-dimensional data with large information density (i.e., images). So far, there were only two experiments on storage of images by EIT [6,7]. Both experiments applied rubidium vapor to store an image pattern. The maximum storage time in gaseous media was 30 μs only. Gases suffer strongly from atomic diffusion as the atoms move across the storage volume and wash out the stored image. This perturbing effect sets major restrictions on the maximum storage time as well as the possible spatial resolution. These problems do not occur in a solid. Thus, the application of appropriate solids permits much longer storage times and improved resolution. Moreover, solid media offer high storage densities and scalability.

In the following, we investigate the storage of images in a doped solid, supported by simple techniques to rephase atomic coherences. We apply a cryogenically cooled Pr^{3+}:Y_2SiO_5 crystal (hereafter termed Pr:YSO). Pr:YSO is a promising candidate for quantum information processing [8]. The medium combines advantages of gas phase atoms (spectrally narrow optical transitions and long decoherence times) and solids (large density and scalability). Atomic diffusion does not perturb the medium. Our data demonstrate storage times in the regime of milliseconds with strongly improved spatial resolution compared to gases. In this time regime we can clearly distinguish the image information from the noise background. Moreover, we investigate oscillations in the temporal variation of the image retrieval efficiency. This effect permits additional enhancement of the retrieval efficiency for appropriate storage times.

Figure 1(a) shows the level scheme of Pr^{3+} ions in the doped crystal. The ground state $^3H_4$ and the optically excited state $^1D_2$ exhibit a substructure of doubly degenerated hyperfine

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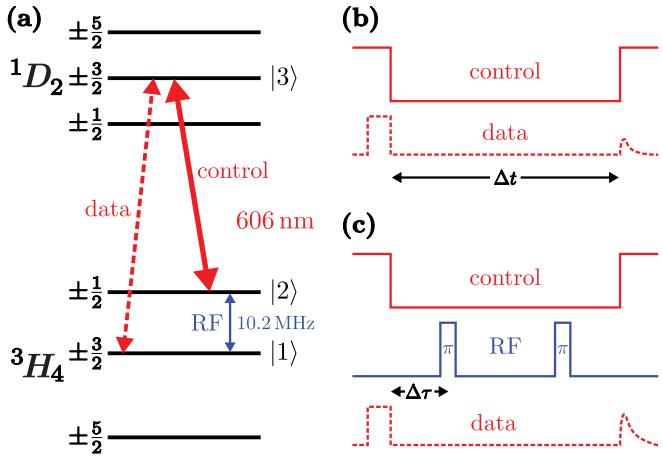

FIG. 1. (Color online) (a) Coupling scheme in Pr:YSO. (b) Pulse sequence for conventional light storage. (c) Pulse sequence including RF rephasing pulses.

states $|\pm\frac{1}{2}\rangle$, $|\pm\frac{3}{2}\rangle$, and $|\pm\frac{5}{2}\rangle$. We relate the specific levels in Pr^{3+} with the labels in our general three-level scheme as follows: ${}^3H_4|\pm\frac{3}{2}\rangle = |1\rangle$, ${}^3H_4|\pm\frac{1}{2}\rangle = |2\rangle$, and ${}^1D_2|\pm\frac{3}{2}\rangle = |3\rangle$. Due to spatial variations of the crystal field in the host lattice, the ${}^3H_4 \leftrightarrow {}^1D_2$ transition is inhomogeneously broadened. To selectively drive single ensembles of Pr^{3+} ions, we apply a preparation process based on spectral hole burning [9].

In the experiment, we cool the Pr:YSO crystal to a temperature of 4 K in a cryostat. The dopant concentration is 0.02%. A single-longitudinal mode dye laser (Coherent 699) provides radiation at 605.98 nm. The radiation is split into a control and a data beam. Both beams pass acousto-optical modulators to modulate intensities and frequencies. The weaker data beam (power $P_d = 400\,\mu$W) passes a binary mask to provide an image in the spatial beam profile. Subsequently, the data beam passes a telescope, which decreases the beam diameter to 200 μm [full width at half maximum (FWHM) of intensity] in the crystal. The stronger control beam (power $P_c = 15$ mW) propagates (almost) anticollinear to the data beam. The diameter of the control beam in the interaction region is 300 μm. Rabi frequencies are defined as $\Omega = \mu E/\hbar$, with the transition moment μ and the electric field of the laser E. The beam parameters correspond to peak Rabi frequencies $\Omega_d = 2\pi \times 80$ kHz and $\Omega_c = 2\pi \times 270$ kHz. Thus, we get $\Omega_d < \Omega_c$. This is the typical condition for EIT.

The pulse sequence for conventional light storage is depicted in Fig. 1(b). The data pulse (with the imprinted image information on it's spatial profile) exhibits a rectangular temporal shape with a duration of $\tau_d = 20\,\mu$s. The data pulse is simultaneously switched off with the control pulse to prepare the atomic coherence. After a time delay Δt, the control pulse is switched on again to read out the coherence. We retrieve the data pulse with the image. The restored image is monitored on a CCD-camera.

Figure 2 shows our first results for the storage of images in Pr:YSO. In this experiment on "conventional" light storage by EIT, we did not apply techniques to overcome dephasing or decoherence. The figure shows the original mask as well as four images, retrieved after different storage times. The

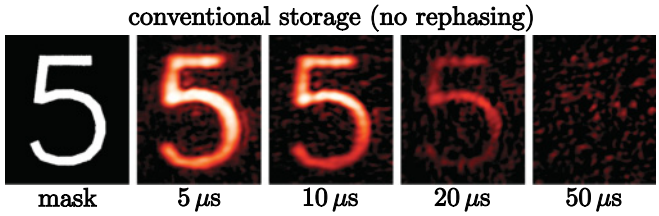

FIG. 2. (Color online) Retrieved images in conventional light storage versus storage time. The width of the stored image is 94 μm.

maximum storage time is 20 μs. The retrieved intensity decreases with the storage time. As already mentioned, light storage is affected by dephasing and decoherence. These processes reduce the atomic coherence in the medium. The decoherence time of state ${}^3H_4$ is rather long (i.e., $T_2 \approx 500\,\mu$s [10]). However, dephasing of different subensembles of Pr^{3+} ions in the medium plays an even more critical role. The dephasing time of the coherence ρ_{12} is approximately 10 μs [11]. After this duration the effective coherence in the medium dropped to $1/e$, though it is preserved in each single hyperfine system. The intensity of the retrieved images in Fig. 2 perfectly mirrors this reduction of the coherence in the medium due to dephasing. After 50 μs the coherences of the different hyperfine systems are fully out of phase. Image information is no longer retrieved. We note that, already, the obtained storage times in this simple setup reach the maximum storage times in gases.

To overcome the perturbing effect of dephasing we apply a sequence of two radio frequency (RF) pulses [see Fig. 1(c)]. The frequency of these pulses matches the energy spacing of states $|1\rangle$ and $|2\rangle$. The pulse area in terms of the Rabi frequency on the magnetic transition between states $|1\rangle$ and $|2\rangle$ is $\mathcal{A} = \int \Omega_{\mathrm{RF}} dt = (2n+1)\pi$, i.e., π pulses. The rephasing pulses act on the medium as follows: If $\Delta\tau$ is the delay between the optical data pulse and the first RF π pulse, the single coherences in all ensembles are rephased again after a time $2 \cdot \Delta\tau$. However, the population in the medium is inverted by this RF π pulse. The medium is no longer in a state of EIT. Retrieval of the data pulse is not possible. Therefore, we apply a second π pulse at time $3 \cdot \Delta\tau$, which rephases the coherence once more and re-establishes the original populations. When we apply the control pulse again at time $4 \cdot \Delta\tau$ we retrieve a strong data pulse from the rephased coherence. We note that this concept is related to the ideas of Longdell *et al.* [5]. In contrast to this previous work, we apply a different optical preparation sequence. Our approach is easy to implement, robust in handling and yields very convincing results in image storage.

The RF pulses are provided by a coil pair close to the crystal (RF power $P_{\mathrm{RF}} = 10$ W). We determined the pulse area of the RF pulses by time-resolved observation of Rabi flopping between states $|1\rangle$ and $|2\rangle$. A π pulse required a quite short RF-pulse duration of 2.8 μs.

Figure 3 shows the results of image storage in atomic coherences in Pr:YSO, assisted by rephasing with RF pulses. In contrast to the results from "conventional" light storage, we now observe storage times of many 100 μs. We note that the intensities of Figs. 2 and 3 are calibrated. The large enhancement in the retrieved intensities becomes apparent

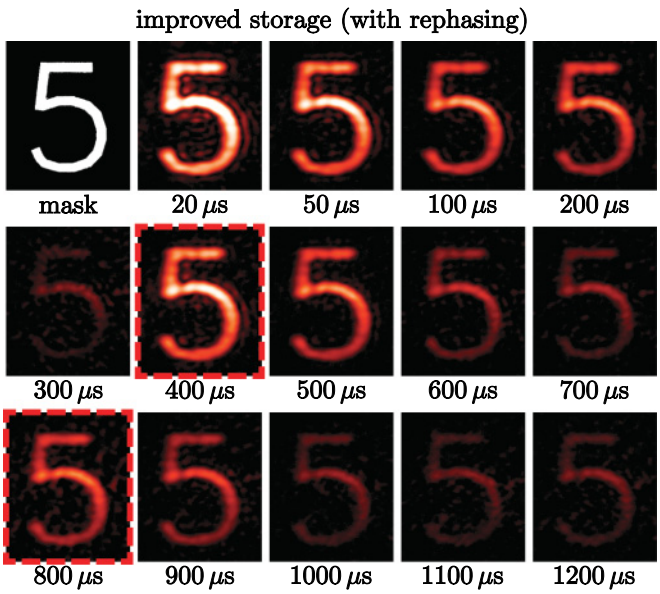

FIG. 3. (Color online) Retrieved images in light storage, assisted by rephasing versus storage time. Dashed frames indicate local maxima in the retrieved intensity (compare also Fig. 4).

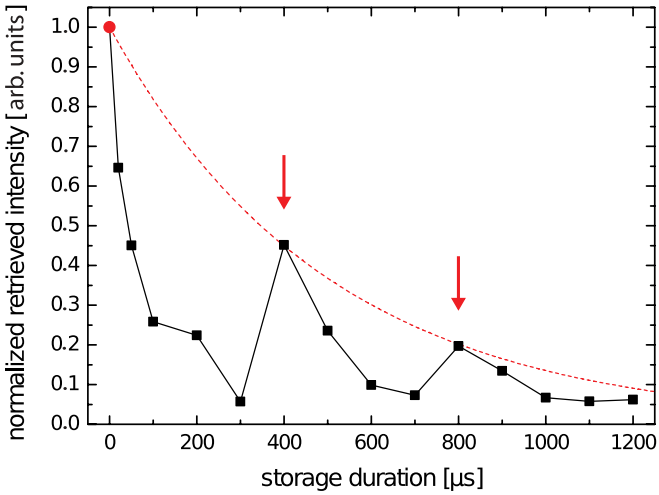

FIG. 4. (Color online) Total intensity of the retrieved images from Fig. 3 versus storage time. Data (black squares) and envelope by exponential decay (dashed line). The arrows indicate local maxima in the retrieved intensity versus storage time (compare also Fig. 3). The intensities are normalized to the extrapolation of the data without rephasing for zero storage time (red dot).

when comparing images at a storage time of 50 μs in Figs. 2 and 3. Even well beyond the ground state decoherence time of 500 μs, we can clearly identify the retrieved image. The storage times of up to a millisecond exceed the maximum storage times in gases by two orders of magnitude.

Figure 3 also reveals an interesting behavior if we analyze the dependence of the retrieved intensity with regard to the storage time. In a simple picture, the retrieved intensity should decrease exponentially with the storage time. However, the retrieved image at a storage time of 400 μs is obviously more intense than the images at shorter storage times of 100–300 μs. The same holds true for the retrieved image at a storage time of 800 μs, which is more intense than the image at shorter storage times of 600–700 μs. In Fig. 4 we plot the total intensity of the retrieved images versus the storage duration. The data show pronounced oscillations below the envelope of the exponential coherence decay. Local maxima show up at storage times of 400 and 800 μs. We identify this as a beating of dark state polaritons (DSP's). DSP's are quasiparticles, which consist of an atomic and a photonic component [12]. During the storage, all information is mapped onto the atomic component (i.e., the coherence between states $|1\rangle$ and $|2\rangle$). In the experiment, the degeneracy of these states is lifted by external magnetic stray fields. This leads to multiple Λ systems with hyperfine ground states $|-\frac{3}{2}\rangle$, $|+\frac{3}{2}\rangle$, $|-\frac{1}{2}\rangle$, and $|+\frac{1}{2}\rangle$. The temporal evolution of the DSP's depends on the energy spacing between the states in which the information is stored [13]. Therefore, we get four different ensembles of DSP's, which oscillate at slightly different frequencies. If the DSP's are transformed back to photons by the light retrieval process each ensemble exhibits a specific phase. In superposition, this results in the pronounced beat signal of Fig. 4, sometimes also referred to as Zeeman oscillations [14]. To the best knowledge of the authors this effect was never observed in a solid before.

Finally, to determine the applicability of image storage in atomic coherences we studied the spatial resolution of the retrieved images. The quality of an image is described by the modulation transfer function (MTF), that is, the retrieved visibility versus the size of the stored structure. To obtain the MTF, we monitor the storage of closely spaced horizontal lines with equal spacing and thickness (see Fig. 5). We performed the measurement for a storage time of 10 μs without rephasing as well as for storage times of 100 μs and 500 μs with rephasing.

Figure 5 shows the visibility versus the line density in the mask. The visibility for up to 60 lines/mm is rather high while it drops for larger line densities. The inset in Fig. 5 shows an original mask at 60 lines/mm, a numerical simulation of the

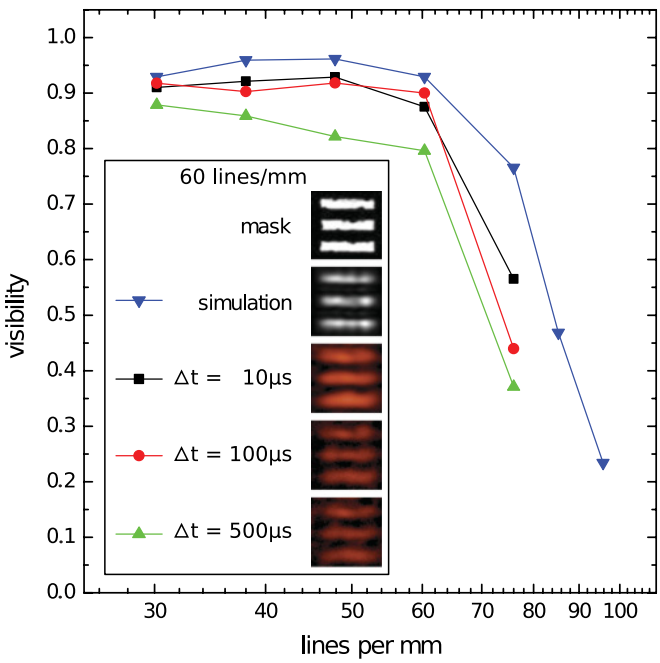

FIG. 5. (Color online) Visibility of the retrieved image.

maximum resolution permitted by the optical setup, as well as three retrieved images at different storage times. Even this small structure, corresponding to line spacings of 8.3 μm, is retrieved with a visibility exceeding 80% for all storage times. At storage times $\Delta t = 10\,\mu$s and $\Delta t = 100\,\mu$s the visibility is still close to 90%. The data are compared to a simulation of the maximal performance of the imaging system—without any effect of light storage. It is apparent from the data that we operate with light storage close to the optimal performance of the imaging system. Compared with experiments in the gas phase [6] we enhance the spatial resolution by a factor of 40, permitting resolution of 60 lines/mm. This is due to the following reason: In gases, the best results were obtained by focusing the image into the medium. This served to store the Fourier transform rather than the real image itself. This setup offers advantages in media suffering from diffusion [7]. However, this setup leads to a loss of information. This is due to the limited area of the control beam in the interaction region. Thus, the control beam does not cover the higher spatial frequency components of the Fourier transform. Therefore, the resolution in the image is reduced. In Pr:YSO diffusion plays no role. Thus, we are not forced to apply Fourier imaging. Instead, we imprint a real image in the crystal. The real image is entirely covered by the control beam. This allows for complete storage of the image information leading to a superior quality of the retrieved image. With regard to other future perspectives, the obtained resolution may also permit storage of many qubits in a single solid device.

In conclusion, we demonstrate and investigate storage of images in atomic coherences driven by EIT in a doped solid. In contrast to gases, such media do not suffer from atomic diffusion. Thus, image storage times of up to 20 μs become possible in the solid medium—even without any additional arrangements. By the application of rephasing techniques the storage times exceeded a millisecond. This exhibits an enhancement by two orders of magnitude compared to the longest image storage times in gases. Moreover, we observed beating of dark-state polaritons in the solid medium. This leads to pronounced oscillations of the retrieval efficiency with the storage time. We also demonstrate enhanced spatial resolution for image storage in atomic coherences. The obtained image resolution is 40 times larger than in gases. The visibility approaches the maximum possible value in our optical setup.

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