Light storage in a doped solid enhanced by feedback-controlled pulse shaping

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We report on experiments dealing with feedback-controlled pulse shaping to optimize the efficiency of light storage by electromagnetically induced transparency (EIT) in a Pr^{3+}:Y_2SiO_5 crystal. A learning loop in combination with an evolutionary algorithm permits the automatic determination of optimal temporal profiles of intensities and frequencies in the driving laser pulses (i.e., the probe and coupling pulses). As a main advantage, the technique finds optimal solutions even in the complicated multilevel excitation scheme of a doped solid, involving large inhomogeneous broadening. The learning loop experimentally determines optimal temporal intensity profiles of the coupling pulses for a given probe pulse. The optimized intensity pulse shapes enhance the light-storage efficiency in the doped solid by a factor of 2. The learning loop also determines a fast and efficient preparation pulse sequence, which serves to optically prepare the crystal prior to light-storage experiments. The optimized preparation sequence is 5 times faster than standard preparation sequences. Moreover, the optimized preparation sequence enhances the optical depth in the medium by a factor of 5. As a consequence, the efficiency of light storage also increases by another factor of 3. Our experimental data clearly demonstrate the considerable potential of feedback-controlled pulse shaping, applied to EIT-driven light storage in solid media.

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I. INTRODUCTION

In recent years, investigations on coherent manipulation of quantum states by light provided powerful concepts in the field of optical (quantum) information storage and processing. In particular, the ideas of electromagnetically induced transparency (EIT) and light storage [1–3] are prominent examples for such versatile coherent interactions. In light storage, a three-level quantum system interacts with two radiation pulses (the coupling and the probe pulse). The probe pulse serves, for example, to represent a data bit. By adiabatic interaction, the probe pulse is stored in an atomic coherence in the medium and can be retrieved afterward. While the majority of experiments on light storage were implemented in the gas phase, the most striking demonstration with longest storage times was realized in a rare-earth-ion-doped inorganic crystal [4]. The latter media combine the advantages of solids (i.e., large density and scalability) with the advantages of free atoms in the gas phase (i.e., narrow linewidths and low decoherence rates). Moreover, the crystals are commercially available and easy to handle.

For a short theoretical introduction of light storage by EIT, we consider a three-level system in Λ-type configuration [1]. The excitation scheme comprises two ground states, $|1\rangle$, $|2\rangle$, and an excited state, $|3\rangle$ (see Fig. 1). A strong coupling pulse (i.e., the "write" coupling pulse) is resonant with the transition $|2\rangle \leftrightarrow |3\rangle$ and a weak probe pulse is resonant with the transition $|1\rangle \leftrightarrow |3\rangle$. The coupling strengths are defined by the Rabi frequencies $\Omega_c = \mu_{23}\mathcal{E}_c/\hbar$ and $\Omega_p = \mu_{13}\mathcal{E}_p/\hbar$. If the condition $\Omega_c \gg \Omega_p$ is maintained ("weak probe limit") and both laser pulses are coincident, the medium is driven to EIT for the probe pulse. If we delay the pulses such that they overlap in the falling edge, the probe pulse is stored in a persistent atomic coherence ρ_{12} between states $|1\rangle$ and $|2\rangle$. To readout the atomic coherence, we apply the coupling pulse again (i.e., we provide a "read" coupling pulse). The coupling pulse beats with the coherence ρ_{12} and generates a signal pulse at the same frequency as the stored probe pulse. We note that the storage efficiency (i.e., the ratio of the stored probe pulse energy to the input probe pulse energy) depends on the intensities and the temporal laser profiles. A theoretical analysis of the storage process [1] predicts the highest efficiency if the ratio of the Rabi frequencies Ω_c/Ω_p (or the ratio of the pulse intensities) remains constant in the falling edge of the pulses. When the ratio equals one, the coherence reaches a maximal value of $\rho_{12} = 1/2$.

To store the probe pulse efficiently in the medium, we must fulfill two conditions: First, the probe pulse must fit *spatially* into the medium. Thus, we require $L_p < L_m$, with the length of the pulse L_p and the length of the medium L_m. The length of the pulse $L_p = v_{gr}T$ is determined by the group velocity v_{gr} in the medium and the pulse duration T. We obtain small pulse length at low group velocities. Theory yields $v_{gr} \sim \Omega_c^{-2}$. Thus, we require small coupling Rabi frequencies to reduce the spatial extension of the probe pulse [5,6].

Second, we require a sufficiently large spectral transparency window to accommodate the probe pulse also *spectrally*. The spectral width Γ of the transparency window in EIT is given by $\Gamma T \gg 1$. Theory shows [7] that the latter two conditions can be expressed in terms of the optical depth z. We get $z \gg \Gamma T \gg \sqrt{z}$. This condition is easily met only for very large values of z. For finite optical depth, the storage efficiency is always limited and depends on the temporal shapes of coupling pulse and probe pulse. Indeed, in most experimental implementations the storage efficiencies were usually rather small.

Gorshkov *et al.* [8,9] applied optimal control theory to iteratively determine the optimal temporal coupling pulse shapes for a specific probe pulse. However, this analytic approach is limited to simple systems without many complicated or unknown perturbing processes. Implementations in realistic systems for applications of high-density optical data storage suffer from additional off-resonant couplings

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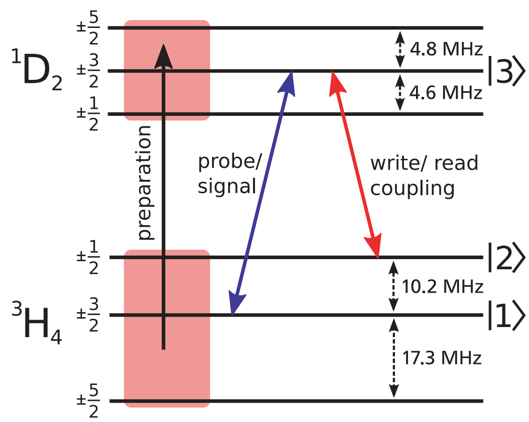

FIG. 1. (Color online) Coupling scheme in Pr:YSO.

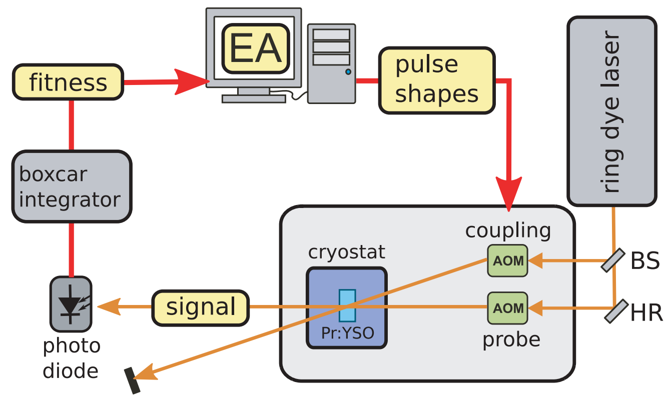

FIG. 2. (Color online) Experimental implementation of the learning loop.

outside the three-level scheme, pulse propagation effects in media of large density (e.g., solids), dephasing and decoherence processes, or even unknown perturbations in complex systems.

As a robust and very universal solution, we experimentally apply feedback-controlled pulse shaping, involving self-learning loops with evolutionary algorithms (EAs). This enables automatic determination of optimal pulse shapes for light storage without any restrictions on the system, the properties of the perturbations, or the temporal shapes of the probe and signal pulses. The concept serves to improve the optical depth, as well as the retrieval efficiency in EIT-driven light storage, in particular in solid media.

EAs imitate the process of natural selection to find optimal solutions in a large parameter space [10,11], for example, the large set of possible temporal profiles of a laser pulse. The aim is to determine optimal temporal laser profiles, that is, variations of intensity or frequency, to optimize a given process. The concept of EAs is as follows. (i) We arbitrarily choose a set of pulse shapes. Each shape is described by a *gene sequence*, that is, a time array of intensities (and/or frequencies). (ii) We apply the pulses to the medium and determine the pulses that yield the best results. (iii) We choose a new set of pulses, including the best previous pulses, modifications of the best pulses (*mutation*, i.e., arbitrary variation of single genes), and combinations of the best pulses (*inheritance*, i.e., mixing of gene sequences). (iv) We repeat steps (ii) and (iii) until the results converge toward an optimal (*fittest*) pulse shape.

In laser-based physics, EAs are well-established tools for optimizing complex temporal shapes of ultrashort laser pulses by feedback-controlled learning loops, for example, to control photochemical reactions [12,13]. In this work, we demonstrate the benefit of the concept also to improve the efficiency of light storage in a solid medium, driven by rather long radiation pulses. The experiments are implemented in a Y_2SiO_5 crystal, doped with praseodymium Pr^{3+} ions (hereafter termed Pr:YSO).

We apply the concept in two directions: First, we optimize the temporal profiles of the coupling laser pulses for storage and retrieval to maximize the storage efficiency for a given probe pulse. Second, we optimize pulse sequences, which serve to prepare the solid medium at a state of optimal absorption. In a subsequent light-storage experiment, the preparation sequence enhances the optical depth and the storage efficiency significantly. Moreover, the optical preparation sequence determined by the learning loop is much faster than conventional preparation sequences, which were used so far for light storage in doped solids.

II. EXPERIMENTAL SETUP

Figure 1 shows the excitation scheme in Pr:YSO. The crystal is cooled in a closed-cycle liquid helium cryostat (Janis, SHI-4-1-331S). We note that the optical transition between states $^3H_4$ and $^1D_2$ at a center wavelength of 605.98 nm exhibits a prominent substructure of hyperfine levels [14], as well as a huge inhomogeneous broadening. Thus, the experiments on light storage in a three-level scheme require optical preparation. We discuss details of the preparation sequence later in this article. We assume now for the discussion of the first experiments that a certain ensemble of praseodymium dopants is prepared in state $|1\rangle$.

To drive the relevant transitions in the experiment (see Fig. 2), we derive laser pulses from a continuous-wave single-longitudinal mode ring dye laser (Sirah Matisse DX) by applying acousto-optical modulators (Brimrose BRI-TEF-80-50-.606). The modulators vary the temporal profiles of intensities and frequencies of all driving laser pulses in the experiment, that is, preparation pulse sequence, probe pulse, and write and read coupling pulses. A learning loop, involving an EA running on a PC, selects temporal variations of pulse intensities and/or frequencies and steers the acousto-optical modulators to generate the corresponding laser pulses. A photodiode monitors the intensity of the retrieved signal pulse in the light storage experiment and provides feedback (i.e., the *fitness*) to the learning loop.

III. ENHANCEMENT OF LIGHT STORAGE BY OPTIMIZED COUPLING PULSE SHAPES

The aim of our first experiment is to enhance the storage efficiency (i.e., the energy of the retrieved signal pulse) by optimizing the temporal intensity profile of the write and read coupling pulses for a given probe pulse (see Fig. 3). The temporal intensity pulse shape of the probe pulse was kept fixed. Also, the frequencies of all laser pulses were kept fixed

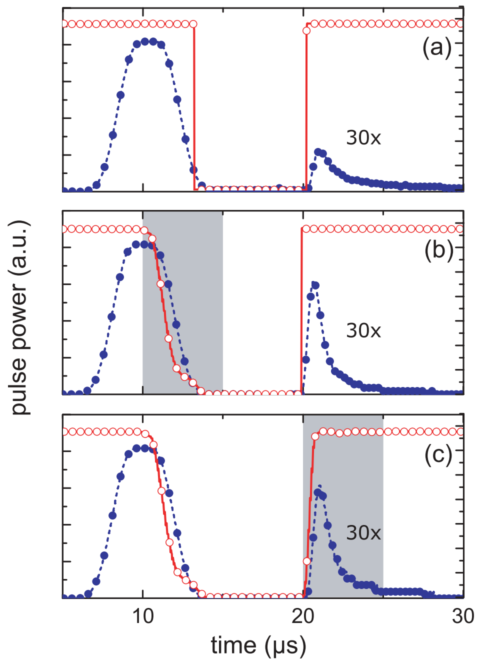

FIG. 3. (Color online) Pulse sequences in light storage (experimental data). "Write" and "read" coupling pulses are depicted by open red circles. Probe and signal pulse are depicted by blue, solid circles. (a) Reference sequence with rectangular coupling pulse shapes. (b) Optimized write coupling pulse. The learning loop was applied to modify the falling edge of the pulse (shaded gray). (c) Optimized read coupling pulse, while the previously optimized write pulse was kept fixed. The learning loop was applied to modify the rising edge of the pulse (shaded gray).

at the relevant transition wavelengths in the selected ensemble of praseodymium dopants.

As a reference, we apply rectangular temporal pulse shapes for the write and read coupling pulses [see Fig. 3(a)]. The probe pulse exhibits an almost Gaussian temporal shape. The probe pulse duration is $\tau_{\mathrm{pr}} = 5\ \mu$s. The intensities of coupling and probe pulse are $I_c = 152$ W/cm^2 and $I_{\mathrm{pr}} = 1$ W/cm^2. This corresponds to peak Rabi frequencies of $\Omega_c \approx 2\pi \times$ 850 kHz and $\Omega_{\mathrm{pr}} \approx 2\pi \times 85$ kHz. To determine the efficiency of the storage process, we monitor the energy of the signal pulse after a fixed storage time of 7 μs. The energy of the signal pulse in this reference experiment corresponds to a storage efficiency of 0.5%. We note that the reference is chosen arbitrarily. Therefore, as well as due to dephasing effects, the absolute storage efficiency is still quite low—which does not matter for the discussed experiment. We let the learning loop optimize now the falling edge of the write coupling pulse for the given probe pulse [see Fig. 3(b)]. The temporal intensity profile is represented in the EA by five nodes connected by a cubic spline. Figure 3(b) shows the optimized write coupling pulse after 30 generations of the EA. At this number of generations, the algorithm converges toward a stable pulse shape. Thus, the EA finds an optimal solution for the write coupling pulse automatically. With the optimized write coupling pulse we obtain an enhancement in the averaged storage efficiency of a factor of 2, compared to the reference coupling pulse. The optimal write coupling pulse resembles the smooth Gaussian edge of the probe pulse, although it does not evolve fully parallel with it. From the simple theory of light storage in a pure three-level system we would expect that the falling edges of write coupling and probe pulse fully coincide. In a first approximation to our experimental data, this is indeed the case. However, the deviation of the write coupling pulse shape from the simple expectation is not just an artifact of experimental perturbations. As a characteristic feature, the evolution of the write coupling pulse is slightly steeper than the edge of the probe pulse in the beginning and flattens out toward the end. We confirmed by simulations that the effect is due to pulse propagation in a multilevel scheme (i.e., beyond the simple approach of three levels only). In particular, deviations from the weak probe limit cause modifications of the optimal coupling pulse in the falling edge. As the ratio Ω_c/Ω_p is only about 10 in our experiment, such deviations play a role. We verified experimentally that the deviations become indeed more pronounced for weak coupling pulses.

In the next step of our experiment, we keep the optimal pulse shape of the write coupling pulse fixed. We let the learning loop now optimize the temporal pulse shape of the read coupling pulse [see Fig. 3(c)]. Though the algorithm changes the rising slope of the read pulse slightly, there is no significant difference with regard to the reference pulse [see Fig. 3(a)]. If we compare with Fig. 3(b), the signal intensity does not increase anymore. We note that the smooth oscillations on the optimized read pulse result from the numerical fit of a cubic spline in the EA. Thus, these oscillations do not contain novel physics. It seems, that the rectangular pulse shape of the read coupling pulse in the reference experiment is already a very good approximation to the optimal solution. On first glance, this seems quite surprising, as the optimal write pulse differed from a rectangular shape.

The explanation is as follows: In contrast to the storage process, the retrieval process does not critically depend on the group velocity in the medium. Therefore, the fast rising edge in the read pulse enables EIT with a good quality for the signal pulse. This minimizes absorption losses of the signal pulse during propagation. The surprising result for the optimized read coupling pulse differs from previous experiment in the gas phase, applying iterative methods and optimal control theory to numerically determine optimal pulse shapes [8]. However, these previous experiments demanded equal pulse shapes for probe and signal pulse as an initial constraint. This leads to symmetric write and read pulses. In our experiment, we did not impose the restriction of equal probe pulse and signal pulse on the learning loop. The fitness of the optimal solution was simply determined by the integrated energy in the signal pulse—no matter what the pulse shape was. Thus, the optimal shapes of write pulse and read pulse are not restricted to symmetric solutions.

IV. ENHANCEMENT OF LIGHT STORAGE BY OPTIMIZED PREPARATION PULSE SEQUENCES

As already briefly mentioned, the optical transition in Pr:YSO (see Fig. 1) exhibits a huge inhomogeneous broadening. This is due to interaction of the praseodymium dopants with the spatially varying electric field of the host lattice. Thus, experiments on coherent interactions in a well-defined three-level scheme require optical preparation of the

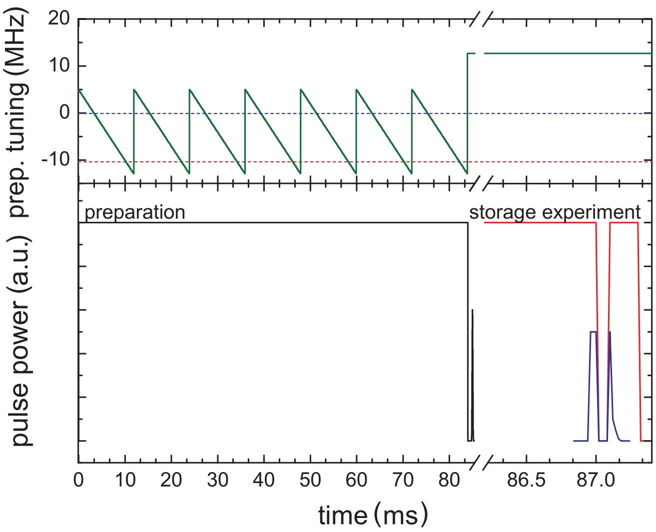

FIG. 4. (Color online) (Top) Temporal frequency variation in the standard preparation pulse sequence (solid green line). The frequency range is defined with regard to the frequency of the probe pulse. The dashed lines [blue (top), red (bottom)] indicate the frequencies of the probe and coupling pulses, respectively. (Bottom) Temporal intensity profile of the preparation pulses (black line) and the temporal positions of the pulses in the subsequent light storage experiment [blue (dark gray), red (light gray) lines]. Please note the different scales of the time axis during the preparation sequence and the light-storage experiment.

inhomogeneously broadened manifold. Preparation of the doped crystal usually relies on long pulse sequences, including pulse trains and/or combinations of frequency chirps, driving optical pumping processes [3,15,16]. Optical preparation is a major issue in all experiments, dealing with coherent interactions in doped solids. As optical preparation is required prior to each cycle of a light storage process, long preparation sequences significantly reduce the duty cycle of data storage in the doped crystal. We consider now a standard pulse sequence for optical preparation of our doped crystal, which we also applied in the light-storage experiments discussed in the previous section (see Fig. 4). The preparation sequence includes an intense preparation pump pulse with a duration of 84 ms and rectangular pulse shape. We chirp the frequency of the preparation pulse seven times in a range of $+5$ to -13 MHz around the center frequency of the probe pulse. Afterward, we prepare a subset of praseodymium ions in state $|1\rangle$ by another short optical pumping process. The frequency of the additional preparation pump pulse is shifted by $+12.7$ MHz with regard to the frequency of the probe pulse. For details on the dynamics of the preparation process in the inhomogeneous manifold, see [3]. Essentially, the preparation sequence generates a broad transmission window in the inhomogeneously broadened spectrum and afterward prepares a certain ensemble of praseodymium ions in a specific hyperfine level of the ground-state $^3H_4$. The preparation sequence requires a total interaction time on the order of 100 ms. This limits the duty cycle for any experiment on optical data storage in Pr:YSO significantly. Moreover, as we select by the preparation process a single ensemble from the huge inhomogeneous manifold, most of the praseodymium ions do not participate in the storage experiment. Thus, the optical depth of the medium and the storage efficiency is rather low. Typically, the optical depth obtained by the preceding standard preparation pulse sequence is below 1.

As the short discussion of the preparation sequence already indicates, the sophisticated preparation process in the inhomogeneously broadened many-level system of a doped solid exhibits quite complicated population dynamics. It would be very difficult (if not fully impossible) to optimize the process analytically, for example, to enhance the optical depth and reduce the preparation time. Feedback-controlled pulse shaping exhibits a much more powerful solution, which permits automatic determination of an optimal solution also in this complex system. We will discuss now the successful experimental application of our learning loop to find an optimized preparation pulse, which enhances the optical depth of the medium, supports light storage efficiently, and reduces the required time for preparation considerably.

When we applied the learning loop to find optimal coupling pulses (as discussed in the previous section) we kept the laser frequencies fixed and varied the temporal intensity profiles. This was a straightforward choice, as EIT requires resonant couplings. In contrast, the preparation pulse sequence relies on optical pumping processes including considerable frequency modulations. Thus, the learning loop must search for an optimal sequence of laser frequencies—rather than intensity modulations. We permit the algorithm to vary the preparation laser frequency during the interaction in a range of ± 40 MHz relative to the probe transition. The EA characterizes the frequency sequence by a cubic spline with 10 nodes. The resulting frequency sequence is repeated three times. We note that one of our aims is to reduce the preparation time. Thus, as an additional and very challenging constraint we forced the feedback-controlled loop to search for a short frequency sequence only. We restrict the EA to a maximum preparation time of 15 ms. This is a factor of 5 less than the standard preparation sequence.

To compare the quality of different preparation frequency sequences, we perform measurements on the efficiency of light storage afterward. In these measurements we apply probe and coupling pulses with fixed rectangular temporal profiles [i.e., similar to the reference experiment in Fig. 3(a)]. The duration of the probe pulse is 20 μs. The duration of the write coupling pulse is 1 ms. We monitor the energy of the signal pulse (i.e., the storage efficiency) as a measure for the quality of a certain preparation frequency sequence. We compare the storage efficiency obtained after the optimized preparation frequency sequence with the storage efficiency obtained after the standard preparation sequence.

Figure 5 shows the experimental result of the optimization process by feedback-controlled pulse shaping. The EA provides an optimal frequency sequence after 70 generations. The frequency sequence consists of an up-chirped feature with pronounced oscillations, which is repeated three times. The major part of the frequency sequence hereby oscillates between a frequency of $\delta\nu = -10$ MHz and $\delta\nu = 15$ MHz relative to the probe frequency. The optimized preparation sequence differs very much from the longer standard preparation sequence (see Fig. 4). The solution determined by the learning loop seems difficult to understand. The lack

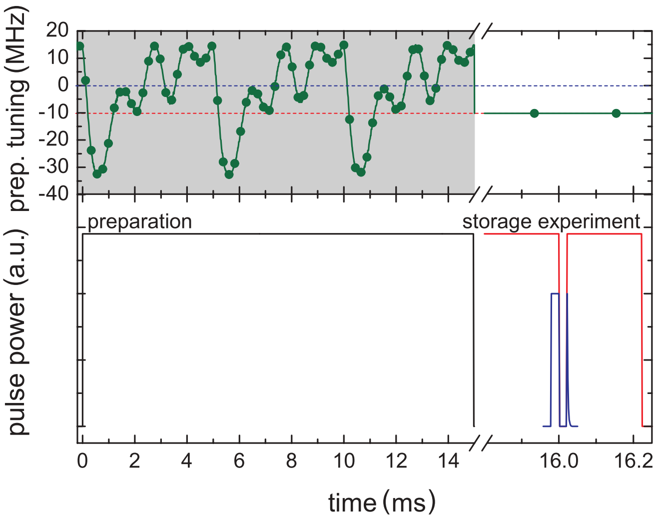

FIG. 5. (Color online) (Top) Temporal frequency variation in the optimized preparation pulse (solid green circles). The frequency range is defined with regard to the frequency of the probe pulse. The gray shading indicates the optimized part of the preparation sequence. The frequencies of the probe and the coupling pulses are indicated by dashed lines [blue (top), red (bottom)]. (Bottom) Temporal pulse profiles of the preparation pulse (black line) and the temporal positions of the pulses in the subsequent light-storage experiment [blue (dark gray), red (light gray) lines]. Please note the different scales of the time axis during the preparation sequence and the light storage experiment.

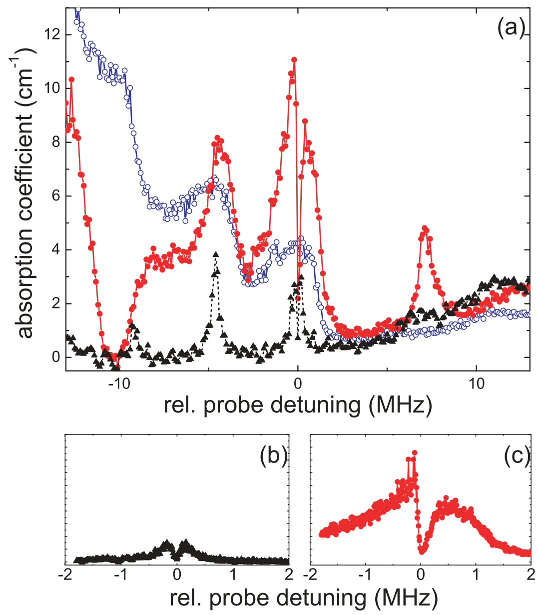

FIG. 6. (Color online) (a) Absorption spectra in Pr:YSO after optical preparation. Open blue circles, spectrum obtained right after the optimized preparation pulse, but before the coupling and probe pulse; solid red circles, spectrum after the optimized preparation pulse, obtained close to the falling edge of the write coupling pulse; solid black triangles, spectrum after the standard preparation sequence, obtained close to the falling edge of the write coupling pulse. (b) Detailed spectrum of the EIT dip close to the probe transition for the standard preparation sequence. (c) Detailed spectrum of the EIT dip close to the probe transition for the optimized preparation sequence.

of physical interpretation is indeed a quite common feature in most experiments on feedback-controlled pulse shaping, typically applied in complicated multilevel systems. We note that a complete understanding requires detailed discussion and simulation of many parallel optical pumping processes in the inhomogeneously broadened six-level scheme. As a main advantage of feedback-controlled pulse shaping, the EA automatically determines the optimal solution—even without any understanding of the relevant physical processes. Nevertheless, we performed simulations on optical pumping processes in the complex system to confirm our understanding of the optimal solution. However, for the sake of readability we will not discuss these details here. Instead, we will briefly analyze absorption spectra to determine the relevant processes during preparation.

To analyze the optimal solution, let us consider experimentally determined absorption spectra after optical preparation. Figure 6 shows absorption spectra in Pr:YSO, with center frequency at the probe transition. Data points in open blue circles indicate the spectrum right after preparation with the optimal frequency sequence, but before the coupling and probe pulse start. The absorption simply decreases with the frequency. This is also obvious from the optimal frequency sequence (see Fig. 5): The frequency variation in Fig. 5 ranges around and especially above the probe frequency. We note that due to the response function of the acousto-optic modulator, the intensity of the preparation pulse slightly varies with frequency. Thus, the intensity of the preparation pulse is somewhat larger for high frequencies (150 W/cm^2). Therefore, optical pumping by the preparation pulse generates a broad spectral region of low absorption in the range above the probe frequency. So far, this does not yet explain the optimal solution at all. As we will see in the following, the EA finds the optimal solution by including the write coupling pulse in the preparation process. In our experiment the write coupling pulse (and later also the short probe pulse) follows the preparation sequence (see Fig. 4).

Let us consider the absorption spectrum after the optimal preparation pulse and after the write coupling pulse, that is, in the falling edge of the write pulse [see solid red circles in Fig. 6(a)]. These data indicate a considerably higher absorption at the probe resonance. Without going into detail here, we attribute this feature to an additional optical pumping process by the coupling pulse—before the coherent interaction with the probe pulse starts. Moreover, two distinct dips show up in the spectrum. The left dip at $\delta\nu = -10.2$ MHz is a spectrally broad feature at the frequency of the coupling pulse. It arises from saturation after optical pumping with the coupling pulse. The right dip at the probe resonance $\delta\nu = 0$ MHz is a strong and spectrally sharp EIT resonance—as required for light storage. A detailed analysis of the complicated spectrum in combination with numerical simulations reveals that the algorithm prepares the medium into one Λ-type system providing the highest absorption at the probe frequency, while it avoids incoherent absorption from other, non-Λ configurations. The absorption spectra in Fig. 6 already permit a conclusion with regard to the efficiency of the

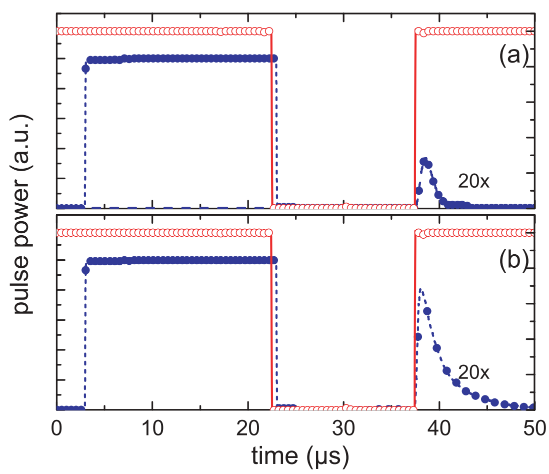

FIG. 7. (Color online) (a) Light-storage sequence following standard preparation (experimental data). (b) Light storage sequence following optimized preparation (experimental data). Write and read coupling pulses are indicated by open red circles. Probe and signal pulse are indicated by solid blue circles.

optimized preparation sequence. For comparison we consider the absorption spectrum, obtained after preparation with the much longer, standard sequence [see solid black triangles in Fig. 6(a)]. The spectrum is monitored in the falling edge of the write coupling pulse. The EIT dip at the probe resonance is now much less pronounced than the EIT dip prepared by the optimal frequency sequence [see graphs (b) and (c) in Fig. 6]. Further, the EIT dip in the optimized spectrum is clearly asymmetric; that is, we prepare an ensemble of ions which is slightly detuned to the coupling resonance. Numerical simulations show that asymmetric EIT resonances provide lower group velocities than symmetric resonances. This is due to the steeper variation of absorption in the asymmetric resonance. Therefore, in addition to the larger optical depth, the optimized frequency sequence also yields a reduced group velocity of the probe pulse—which is a significant advantage for the subsequent storage process.

We consider now the storage efficiency obtained in the solid medium after preparation with the optimized frequency sequence. Figure 7 shows the pulses in a light storage experiment, following (a) the standard preparation sequence and (b) the optimized preparation sequence. The optimized preparation sequence yields a considerably larger signal pulse, which corresponds to an increase in the storage efficiency by a factor of 3.5. The main reason for the significant increase is the gain in optical depth. The optimized sequence yields an optical depth OD ≈ 3, compared to only OD ≈ 0.6 in the standard sequence—though we even restricted the learning loop to short sequences of 15 ms (i.e., a factor of 5 shorter compared to the standard sequence). We note that the maximum optical depth of the doped crystal (without any preparation in the huge inhomogeneous manifold) is OD ≈ 5. However, in this case all ensembles contribute to absorption, but the medium does not provide a proper Λ-type coupling scheme for EIT. The optimized pulse sequence (depending on the exact experimental parameters) enables both EIT and large optical depth, close to the maximum possible value in the crystal.

V. CONCLUSION

We demonstrated the experimental application of feedback-controlled pulse shaping, involving EAs to enhance the storage of light pulses by EIT in a solid medium, that is, a Pr:YSO crystal. The energy of the retrieved signal pulse served as a control parameter for the learning loop. The algorithm automatically included deviations of the real experiment from the simple model of interaction in a pure three-level system. The learning loop determined optimal temporal intensity profiles of the driving coupling laser pulses for a given probe laser pulse. The optimized pulse shapes enhanced the storage efficiency in the medium by a factor of 2 with respect to a reference experiment with rectangular pulse shapes. The optimized temporal profile of the write coupling pulse exhibits deviations from a Gaussian shape, which is due to propagation effects and deviations from the weak probe limit. The optimal temporal profile of the read coupling pulse exhibits a fast rising edge, which differs from simple expectations.

We also applied the learning loop to experimentally determine a fast and efficient pulse sequence, which serves to optically prepare the doped solid, prior to experiments on light storage. This experiment exploits the most significant advantage of feedback-controlled pulse shaping, that is, the capability to automatically determine optimal solutions in complicated multilevel excitation schemes. The aim was to enhance the optical depth and the storage efficiency in the medium, as well as to reduce the preparation time and increase the duty cycle of light storage. The learning loop was applied to determine an optimal sequence of frequencies in the preparation pulse, while keeping the pulse intensity fixed. We compared the optimal sequence to a standard preparation sequence. The EA found a very fast and efficient solution. The optimized solution is a factor of 5 faster than the standard solution. It provides an optical depth, which is enhanced by more than a factor of 5. Moreover, the sequence yielded a slightly asymmetric EIT resonance, which allowed for a further reduction in the group velocity of the probe pulse. This yielded an enhancement of the storage efficiency in the doped medium by a factor of 3.5. In summary, the experimental data clearly demonstrate the potential of feedback-controlled pulse shaping and EAs, applied toward EIT and light storage.

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