Transporting and Time Reversing Light via Atomic Coherence

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We study basic issues central to the storage of quantum information in a coherently prepared atomic medium such as the role of adiabaticity. We also propose and demonstrate transporting, multiplexing, and time reversing of stored light.

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Recent theoretical [1,2] studies have discussed the use of coherently driven media to store the *quantum* state of an optical pulse by simply switching off the driving field. This information can then be retrieved by switching back on the driving field. The restored optical pulse has the same frequency, polarization, and direction of propagation as the initial one. Experiments [3,4] support the theoretical predictions. The switching is adiabatic in [1,4], while in Refs. [3,5] it has been noted that the adiabaticity condition can be relaxed.

In this Letter we explore, clarify, and extend the quantum information storage technique for arbitrary time scale and various configurations of writing and reading fields. Our calculations and experiments support the conclusion that even instantaneous switching of the writing and reading fields allows one to store a light pulse in a coherently driven medium. Furthermore, we suggest several ways to significantly expand the capabilities of the quantum information storage technique. In particular, we demonstrate the possibility of transporting the state of light between different spatial and temporal points. We show how to transfer the state of light with one frequency and wave vector to another frequency and wave vector (multiplexing). We also demonstrate possibilities for time reversal (phase conjugation) of the restored pulse.

The question has been raised [6] as to the connection between the recent work in Refs. [1,3,4] and early Raman photon echo studies [7–10], as well as recent four-wave mixing experiments [11–15]. The usual photon echo experiments do not involve "photons," in that they involve only intense *classical* fields rather than single-photon *quantum* fields. However, experiments involving electromagnetically induced transparency (EIT) are capable of demonstrating nonlinear optical effects at the few-photon level [13,16–18]. Unlike photon echo experiments wherein the time delay is associated with the spin restoration in an inhomogeneously broadened medium, our experiments involve no time delay between reading and restored pulses. The present Doppler-free configuration of fields allows us to reproduce the signal pulse at any moment of time within the spin-coherence lifetime. Finally, unlike other resonant four-wave mixing experiments, we spatially and temporally separate the writing fields (which create the coherence grating in the atomic medium) from the reading field.

We now turn to the issue of adiabaticity. To describe the propagation of the light pulses through the atomic vapor we use Maxwell-Bloch equations in the slowly varying amplitude and phase approximation. We treat a homogeneously broadened gas of Λ-type atoms (levels $|a_1\rangle$, $|b\rangle$, and $|c\rangle$ as in Fig. 1). The results for adiabatic and instantaneous switching times are shown in Fig. 2.

We first consider the case of slow switching times T for the writing and reading pulses, i.e., T is much longer than $\sqrt{\kappa L}\,\gamma/|\Omega|^2$ [14,16] and $1/\gamma$ [1], where κ^{-1} is the Beer's law absorption length, L is the length of the medium, Ω is the initial Rabi frequency of the writing pulse $\mathcal{E}_1$, and γ is the decay rate of both allowed atomic transitions.

The signal pulse $E_1^{\rm in}$, denoted as "in" in Fig. 2, enters the medium which has interacted with the field $\mathcal{E}_1$ for a long time so that all atomic population is optically pumped into the state $|c\rangle$. When the entire signal pulse enters into the medium we switch off the writing field, and this leads

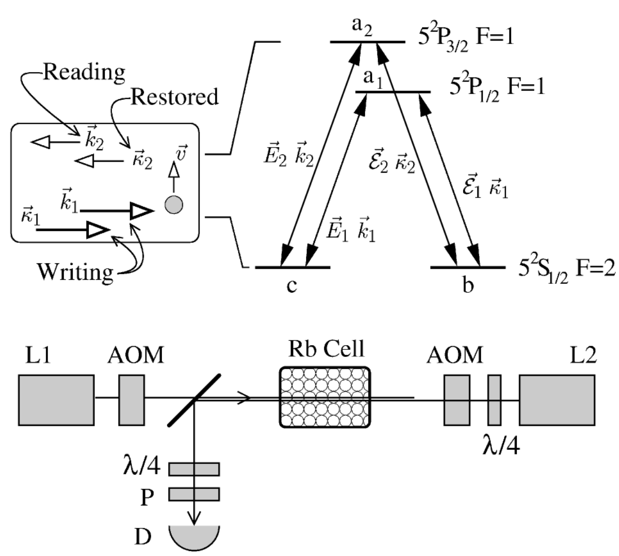

FIG. 1. Energy level scheme and experimental setup.

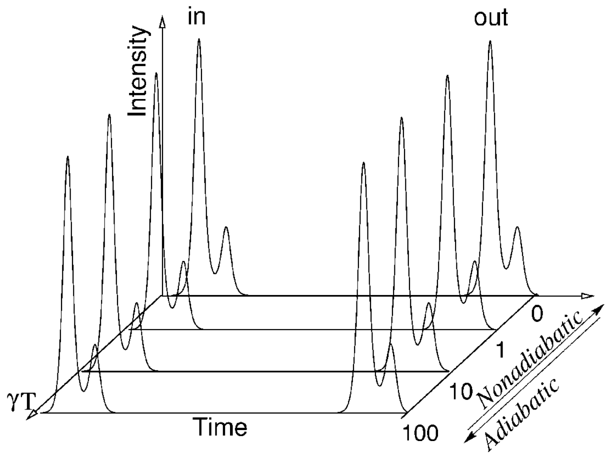

FIG. 2. "Storage of light": intensity of the signal field vs time for different switching times T of the writing/reading fields.

to the absorption of the signal. The energy associated with the signal pulse leaves the medium with the writing field.

After some delay, we launch the reading pulse (switch on $\mathcal{E}_1$) probing the $|b\rangle \rightarrow |a_1\rangle$ transition and look for the pulse emitted on the frequency of the $|c\rangle \rightarrow |a_1\rangle$ transition E_1^{out}, denoted as "out" in Fig. 2. The shape of this retrieved pulse coincides with the shape of the signal pulse. Our exact numerical simulations support the approximate analytical calculations presented in [1].

Let us consider next the short switching times $T \rightarrow 0$, much less than $\sqrt{\kappa L}\,\gamma/|\Omega|^2$ and $1/\gamma$, such that there is no adiabatic following of atomic coherence to the driving field. Even in this case the shape of the retrieved pulse is nearly the same as the shape of the signal pulse (Fig. 2). This would support the conclusion [3] that nonadiabatic writing and reading processes lead to the same results as the adiabatic ones.

In the case of adiabatic passage, complete pulse restoration appears for strong writing and reading fields, such that the so-called "dark polariton" transforms to the signal field almost completely [1]. The abrupt switching of the writing field leads to the absorption of the "free field" part of the dark polariton. Only the "bound part," i.e., the low frequency atomic coherence, survives. The ratio between the "free" and "bound" parts of the polariton is equal to the ratio of the group velocity of the signal pulse [19] and speed of light in vacuum c. The smaller the initial group velocity of the signal pulse the better the writing-reading quality.

As a result of our study of the adiabatic and nonadiabatic information storage techniques we conclude that for *any* switching time almost perfect information storage is possible if (i) the group velocity of the signal pulse is much less than c and (ii) the bandwidth of the signal pulse is much less then the width of the two-photon resonance, i.e., the signal pulse enters the medium without reflection and absorption.

The slowly varying amplitude approximation of the Maxwell-Bloch equations contains resonant terms which depend only on one- and two-photon detunings of the fields from the relevant atomic transitions, but not the actual optical frequencies. As a result, the reading pulse may be applied to either one-photon transition. The scattering of the reading pulse by the atomic coherence excited by the writing pulses is independent of the frequency of the writing pulse. For example, we can write the information with $\mathcal{E}_1$ and E_1 pulses and read it with an $\mathcal{E}_2$ pulse applied to a different transition (see an example in Fig. 1). This phenomenon could be used as an effective multichannel optical switch, or image storage system.

This technique also enables us to time reverse the incident signal pulse. There are two ways to do this. For the same writing procedure as above, we send the reading pulse in the opposite direction from the signal and writing pulses. But we can apply the reading pulse to either transition $|c\rangle \rightarrow |a_1\rangle$ or $|b\rangle \rightarrow |a_1\rangle$. In the first case, the retrieved pulse leaves the medium reversed in time, i.e., the head follows the tail. The result of numerical simulations here looks the same as the result shown in Fig. 2. In the second case, the restored field appears on the $|b\rangle \rightarrow |a_1\rangle$ transition; its shape is time reversed compared to the initial signal pulse. Moreover, the retrieved pulse is the phase conjugate of the signal pulse.

Concerning the case of phase conjugation or "time reversal," we note that the atomic coherence $\hat{\sigma}_{bc}$ is governed by $-\hat{\mathcal{E}}_1^*/E_1$ (we assume here $\hat{\mathcal{E}}_1 \ll E_1$) which yields

$$\left(\frac{\partial}{\partial t} + c\,\frac{\partial}{\partial z}\right)\hat{E}_2 = -\eta\hat{E}_2 + \mu\hat{\sigma}_{bc}(\hat{\mathcal{E}}_1^*, E_1)\mathcal{E}_2 \,. \quad (1)$$

Equation (1) shows that we can reproduce the time reversed operator field $\hat{\mathcal{E}}_1^*$ by taking the writing field E_1 and the reading field $\mathcal{E}_2$ in the classical limit (coherent states). This allows us to generate time reversed $\hat{\mathcal{E}}_1$ quantum pulses, and to do so on demand.

Generally speaking, the direction of the restored light is determined by a phase matching condition between the fields. Two writing fields E_1 and $\mathcal{E}_1$ induce a coherence with wave vector $\vec{k}_{bc} = \vec{k}_1 - \vec{\kappa}_1$, producing a spatial grating. After some time delay, the reading pulse $\mathcal{E}_2$ interacts with this grating and generates pulse E_2, which propagates in the direction determined by the phase matching condition $\vec{k}_2 = \vec{\kappa}_2 + \vec{k}_1 - \vec{\kappa}_1$. This phase matching condition is similar to that in photon echo and four-wave mixing.

We next turn to the issue of transfer of quantum information between two points in space; this is similar in spirit to cw photon echoes [20]. Let us consider an idealized physical picture of a beam of atoms moving in the $+\vec{x}$ direction. The atoms first cross the light beam consisting of the writing field $\mathcal{E}_1$ and the signal field E_1, and then cross the reading field $\mathcal{E}_2$. All light beams propagate in the $+\vec{z}$ direction, and the writing and reading fields are separated by a distance x_0. As a result of the interaction with the writing fields, the atoms acquire long-lived ground state coherence that can be read in different space locations by the reading field.

In reality atomic cells often contain a buffer gas. In this case, after the light beams are switched off the atoms freely diffuse in space and the spatial distribution of the atomic coherence $\hat{\sigma}_{bc}(\vec{r}, t)$ changes according to Ref. [21]

$$D\vec{\nabla}^2\hat{\sigma}_{bc} = K\hat{\sigma}_{bc} + \left(\frac{\partial}{\partial t} + (\vec{v}\vec{\nabla})\right)\hat{\sigma}_{bc}, \qquad (2)$$

where D is the diffusion coefficient, K is a quantity related to the coherence decay due, and $\vec{v}$ is the velocity of the convective flow of the gas. We demonstrate such a "diffusive" transport experimentally.

Hence, the atomic coherence provides a potentially new tool for the storage and transfer of quantum information. It may be used to multiplex information. It also allows us to effectively time reverse light. All this can be done for very weak light fields. In the following we report experimental results in support of the theoretical predictions.

In our experiment we use one pair of pulses having the same spatial and temporal shapes (called "writing" fields) to prepare a grating in one component of the ground state hyperfine manifold of ^{87}Rb and another pulse (the "reading" pulse) is used to retrieve information concerning the original writing fields.

The experimental setup is shown in Fig. 1 and is similar to one of the recent experiments on "stopped" light [4] and to our recent experiments on nonlinear magneto-optic spectroscopy [22]. We perform the experiment in a 7.5-cm-long cylindrical glass cell containing atomic ^{87}Rb vapor at 77 °C, which corresponds to an atomic density $N \sim 6 \times 10^{11}$ cm^{-3}. The cell also contains 3 Torr of Ne buffer gas and is placed into a three-layer magnetic shield. The cell is made from Pyrex glass and sealed by optical quality windows with low birefringence. A solenoid mounted inside the magnetic shield allows us to control a static magnetic field along the propagation axis of the light pulses. We use two low-power cw extended-cavity diode lasers which are switched on and off with acousto-optic modulators. The writing laser pulse has a 1.5 ms duration, whereas the reading pulse has a duration of about 10–50 μs. Rise and fall times of the pulse edges are less than $T = 2$ μs. The beams are collimated and parallel to each other within $\sim 10^{-4}$ rad. The cw power of the reading and writing lasers is 1.3 and 0.62 mW, respectively. The beam size inside the cell is 1.5 mm. Under these conditions the cell transmission is only 5–10%. The adiabaticity condition is not fulfilled here because $\sqrt{\kappa L}\,\gamma/|\Omega|^2 \simeq 3$ μs $> T$.

The writing laser pulse is linearly polarized and tuned to the $5\,^2S_{1/2}F = 2 \rightarrow 5\,^2P_{1/2}F = 1$ transition of ^{87}Rb (the D_1 line). This laser generates long-lived Zeeman coherence in the $5\,^2S_{1/2}F = 2$ level. After some time delay following the writing pulse, we read the information stored in the coherence by applying a right circularly polarized reading pulse to the $5\,^2S_{1/2}F = 2 \rightarrow 5\,^2P_{3/2}F = 1$ transition (the D_2 line). The transmitted reading light is blocked by means of a $\lambda/4$ wave plate and polarizer, which transmits only left circularly polarized light. This is shown in Fig. 1.

It is best to consider the linearly polarized writing laser field as two opposite circularly polarized components (control and signal pulses in the language of Ref. [4]) which create a coherent superposition of the Zeeman sublevels of the ground state of the transition. This superposition is referred to as the dark state of the atomic medium [23]. The coherence allows propagation of the laser pulse through the cell without complete absorption, which is a manifestation of EIT [24]. To study this effect we apply a static magnetic field parallel to the propagation axis of the lasers which produces an antisymmetric shift aB of Zeeman sublevels of the ground state (where B is the magnetic field and $a = 2\pi \times 0.7$ MHz/G is the magneto-optic constant for ^{87}Rb). This shift leads to an increase of the absorption and loss of the "restored" pulse because the two-photon resonance condition is violated. The corresponding EIT transmission peak has an FWHM of 2 mG.

The reading laser scatters on the spin coherence, producing a restored pulse with left circular polarization. Figure 3 shows restored pulses with different delay times between writing and reading pulses. Negative time delay means that the writing and reading pulses are overlapped in time, and the restored pulse has the largest possible amplitude at this point. The conversion efficiency of the reading pulse to the retrieved pulse is several percent. We emphasize that the restored pulses have different frequency from and propagate opposite to the writing pulse and that the shape of the recovered pulse depends on the power of the reading pulse.

The Doppler broadening of rubidium vapor at room temperature (540 MHz) exceeds the hyperfine splitting of the upper $5\,^2P_{3/2}$ state so the reading light interacts with all three hyperfine components ($F' = 1, 2, 3$) of this state.

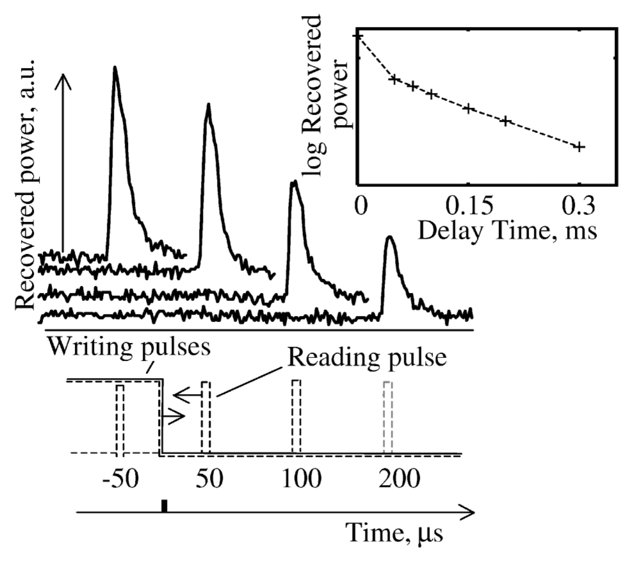

FIG. 3. Experimentally detected restored light pulses at different delay times: −50, 50, 100, and 200 μs. Inset: relative amplitude of the restored pulse vs delay time. An exponential degradation of the amplitude due to the relaxation of the coherence between Zeeman levels ($F = 2$, $5\,^2S_{1/2}$) is clearly seen.

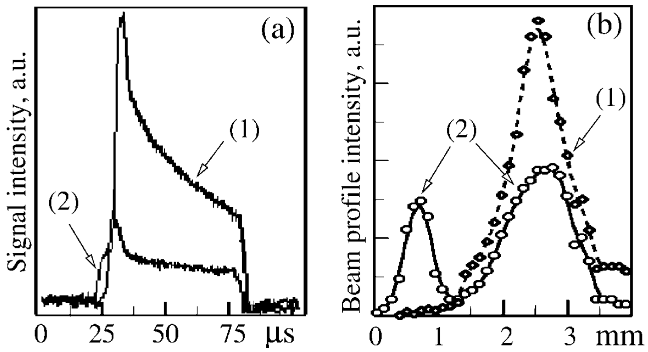

FIG. 4. (a) Restored pulse for spatially overlapped [curve (1)] and separated [curve (2)] writing and reading beams. Zero count on the time scale corresponds to the switch-off time of the writing pulses. (b) Intensity profiles of the spatially overlapped (dashed line) and separated (solid line) writing and reading laser beams. The writing beam waist is broader than the reading one.

This aspect is important for understanding the efficiency of recovered light generation achieved in our experiment. In other words, although the coherent grating leads to recovered light from the $F' = 1$ state, much of this light is then absorbed by the $F' = 2, 3$ states.

The amplitude of the restored pulse decreases with increasing time delay between writing and reading pulses due to the decay of coherence. The dependence of the relative amplitude of the signal is practically insensitive to the amplitude of either writing or reading pulses and is purely determined by the medium properties such as the coherence decay rate and atomic motion. We were able to observe the signal delayed up to 1.5 ms (see Fig. 3, inset).

To demonstrate the information transport discussed above, we have spatially separated the writing and reading beams. After the writing pulse is applied, atoms diffuse into other regions of the cell. As the beams are separated, the recovered pulse amplitude decreases. Nevertheless, in our experiment we have observed atomic coherence transfer for up to 6 mm separation for beams of 1.5 mm in diameter. An example of the effect is shown in Fig. 4. This proves the possibility of the coherent information transport.

In conclusion, we have found conditions for quantum information storage of optical pulses in coherently driven media with nonadiabatic switching of the fields. Furthermore, we suggest several ways to expand the capabilities of the quantum information "storage" technique and have performed experiments in support of our theoretical results.

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