Storage and retrieval of light pulses in atomic media with “slow” and “fast” light

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We present experimental evidence that light storage, \textit{i.e.} the controlled release of a light pulse by an atomic sample dependent on the past presence of a writing pulse, is not restricted to small group velocity media but can also occur in a negative group velocity medium. A simple physical picture applicable to both cases and previous light storage experiments is discussed.

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All-optical information processing requires the use of photons as fast and reliable carriers of information. Photons are quantum objects and the search for media where the quantum state of photons can be preserved and processed is of great significance. Recently, broad attention has been focussed on the possibility of “light storage” (LS) which is the preservation of the information carried by a light pulse for controllable later release. Such a possibility was suggested in theory \cite{1} and subsequent experimental results were presented in support of this suggestion in \cite{2}. In all of these experiments, a weak light pulse was “written” into an atomic medium driven by a stronger field and, after a dark interval, retrieved from the medium by turning on the strong (drive) field.

All observations of LS were achieved under conditions of electromagnetically induced transparency (EIT) since, according to \cite{2}, EIT and “slow light” (small group velocity associated with EIT) play a key role. The storage effect is seen as a consequence of the slowing and compression of the light pulse in the atomic medium, the propagation of a mixed light-matter excitation (dark-state polariton), the transformation of the dark-state polariton in the absence of light into a pure atomic spin excitation and finally the release of a light pulse once the drive field is turned on.

The purpose of this letter is to present experimental results and theoretical considerations which broaden the scope of the subject by demonstrating that a LS effect, analogous to that previously reported in \cite{2,3},\cite{4,5}, can take place in media where EIT does not occur and where the probe pulse group velocity is negative (“fast light”) as a result of large anomalous dispersion.

Steep anomalous dispersion exists in driven atomic media in connection with electromagnetically induced absorption (EIA) \cite{6}. EIA occurs when resonant light interacts with a two-level atomic transition in which the Zeeman degeneracy of the excited level is higher than that of the lower level; namely $F_e > F_g > 0$ where $F_e$ and $F_g$ are the total angular momenta of the excited level and ground level, respectively. A resonant increase in the probe absorption occurs under the condition of a Raman resonance with ground state Zeeman sublevels $F$.

In particular, at zero magnetic field the EIA resonance condition is achieved for the two orthogonal polarization components of a single monochromatic optical field. Superluminal pulse propagation in an atomic vapor under the conditions of EIA has been demonstrated in \cite{7}.

The experimental scheme used is very similar to the one presented in Ref. \cite{2}. LS was studied in a 5 cm long vapor cell containing a natural isotopic mixture of rubidium. The cell was placed at the center of a cylindrical $\mu$-metal shield. A solenoid inside the magnetic shield allows tuning of the longitudinal magnetic field $B$. The cell was heated ($\sim70$ °C) to produce almost 100% linear absorption and 50 – 80% absorption at maximum light intensity. Two extended cavity diode lasers were used for the $D_1$ and $D_2$ transitions. Fast switching on and off of the laser light was achieved with an acousto-optic modulator (AOM). After the AOM, a polarizer fixes the polarization of the drive field. A Pockels cell along the light beam was used as an electro-optic modulator (EOM) to generate a probe pulse with orthogonal polarization relative to the drive field. The probe pulse was 5 times weaker than the drive field. Care was taken to use the EOM in the $\lambda/2$ configuration in order to produce in-phase probe pulses relative to the drive field. The light beam was expanded to a 1 cm diameter before the cell. The maximum laser power available at the cell was 0.6 mW and 2 mW for the $D_1$ and $D_2$ lines, respectively. After traversing the atomic vapor, the drive and probe polarization components of the light were separated by a polarizing beam splitter and collected by fast photodiodes. The electronic control and detection response times were shorter than 1 $\mu$s.

Our setup allows the use of linear perpendicular or opposite circular drive and probe field polarization combinations. Qualitatively similar LS effects were observed for both choices. We describe in the following the signals obtained with perpendicular linear drive and probe fields polarizations. LS under conditions of EIT was observed on both the transitions $5S_{1/2} (F = 1) \rightarrow 5P_{3/2}$ ($D_2$ line) and $5S_{1/2} (F = 2) \rightarrow 5P_{1/2} (F' = 1)$ ($D_1$ line) of $^{87}$Rb. We present results obtained for the latter transition which was also used in previous experiments in \cite{2,4,5}.
The width of the EIT resonance, measured at maximum light power by varying the magnetic field, was 65 kHz. Trace a of Fig. 1 obtained with a Gaussian shape probe pulse, reproduces the essential features of the previous LS experiments [2, 3, 4, 5]. Since the inverse of the pulse, reproduces the essential features of the previous

![Image](image-url)

FIG. 1: Observed signals for the probe field intensity transmission. a) Transition: $5S_{1/2} (F = 2) \rightarrow 5P_{1/2} (F' = 1)$ of $^{87}$Rb with Gaussian probe pulse; dashed: Gaussian envelope of transmitted probe pulse without dark interval. b) Same transition; square probe pulse. c) Transition: $5S_{1/2} (F = 2) \rightarrow 5P_{3/2} (F' = 3)$ of $^{87}$Rb; square probe pulse.

cillations are seen on the retrieved pulse envelope for the two types of transitions. The same dependence of the retrieved pulse amplitude on the dark interval duration is observed in the two cases.

To model the observed results, we have solved the Bloch equations for an homogeneous ensemble of atoms with two energy levels with Zeeman degeneracy [11]. The excited state decays spontaneously to the ground state at a rate $\Gamma$ and, in order to mimic time-of-flight relaxation, all states in the system decay at rate $\gamma$ while “fresh atoms” are isotropically injected in the ground levels at the same rate. The atoms interact with an optical field whose polarization is decomposed into two orthogonal (linear or circular) components with arbitrary amplitude and phase. The light propagation in the atomic sample is considered to the lowest order in the sample optical length [11]. Consequently, it is assumed that all atoms in the sample see the same (undepleted) incident field. Under such an assumption, the transmitted field is $\vec{E}_T \simeq \vec{E}_0 + i\alpha\vec{P}$ where $\vec{E}_0$ is the total incident field, $\vec{P} = Tr(\rho \vec{D})$ is the atomic optical polarization per atom, $\vec{D}$ is the electric dipole operator and $\alpha$ is a real constant proportional to the atomic density and the sample length that is adjusted to the observed absorption. The transmitted signal can be computed for either polarization component. The pulse sequence used for the calculation is shown in the upper traces of Fig. 2.

Trace a corresponds to the calculated transmission (at the probe field polarization) for parameters corresponding to the transition $5S_{1/2} (F = 2) \rightarrow 5P_{1/2} (F' = 1)$ of $^{87}$Rb. Trace b was calculated for the transition $5S_{1/2} (F = 2) \rightarrow 5P_{3/2} (F' = 3)$ of $^{87}$Rb. The pulse distortions observed in the experiment are well reproduced and a retrieved pulse is obtained for both transitions after the dark interval. The amplitude of the retrieved pulse depends on the probe pulse amplitude and duration and decays exponentially with a decay time depending on the drive field intensity alone. Similar results to those presented in Fig. 2 are obtained if orthogonal circular polarization are considered for both fields.

The above results can be explained on the basis of a unique physical picture. Consider the basic light-atom interaction process presented in Fig. 3, where an optical field couples the atomic ground-state $C$ (coupled state) to the excited state $e$ while the second ground-state $D$ (dark state) is unaffected by the field. After excitation in state $e$ the atom can decay spontaneously to both lower states. This is an optical pumping process [12]. If the atoms interact with the light for a sufficiently long time and if states $C$ and $D$ are stationary, the atoms will eventually end in state $D$ and the medium will become transparent. During this process, transitions from state $e$ to state $D$ occur spontaneously but may also take place through stimulated Raman emission. The condition for stimulated Raman emission is the existence of nonzero...
coherence between states $C$ and $D$, i.e. $\rho_{DC} \neq 0$ where $\rho_{DC}$ is the element of the density matrix between states $D$ and $C$. Under such a condition the interaction with the applied field results in optical coherence between states $e$ and $D$ ($\rho_{eD} \neq 0$) which in turn radiates a field for this transition which is coherent with the initial field. As a general rule, a light field interacting with a coherently prepared atom in the ground state will induce coherent emission of light in all allowed optical transitions as long as the (ground state) atomic coherence is preserved (Fig. 3).

Direct generalization of the situation represented in Fig. 3a to the more complex case of a two-level system with arbitrary Zeeman degeneracy interacting with an optical field is possible. In general, given the field polarization, after a suitable basis transformation, one can identify several ($C$) states in the ground level, each coupled to a corresponding excited state sublevel, and two, one or zero dark ($D$) states (Fig. 3b). The last case occurs when the Zeeman degeneracy of the excited level is higher than that of the ground level [13, 14]. In all cases the general rule stated above applies.

Two types of systems have commonly been considered for the experimental study of coherent light-atom interaction dynamics. In the first class one has the Hanle type experiments [15, 16, 17, 18, 19] where a single optical field with well defined polarization interacts with two atomic levels with Zeeman sublevels whose energy is tuned with a static magnetic field. If the light polarization is linear it is straightforward that a scheme similar to that of Fig. 3c results by choosing the quantization axis along the direction of the light polarization. Even in the general case of arbitrary elliptical light polarization the scheme of Fig. 3c can be applied after a suitable transformation of the state basis that depends on the incident light polarization [14]. An immediate consequence of this description is that in the presence of ground state coherence the system will respond by the coherent emission of light with a polarization orthogonal to that of the incident field. Such a process was recently discussed in terms of the polarization change that the light experiences while propagating in an atomic medium with light induced anisotropy and an alternative explanation of the LS effect in such terms was proposed [20].

A second class of experiments for which the picture presented in Fig. 3b can be conveniently applied, concerns a system of an excited level and two ground levels with energy separation $\Delta$ driven by two optical fields of frequency $\omega_1$ and $\omega_2$. This system (hereafter designated as the $\Lambda$ system), has been extensively studied theoretically and experimentally in connection with EIT. Since in a $\Lambda$ system each field interacts with a different transition, it is possible after a time dependent unitary transformation to describe the atomic dynamics by a time-independent Hamiltonian and to identify a dark state $D$ and a coupled state $C$ [21]. This “coupled-uncoupled” description exactly corresponds to the situation of Fig. 3a-b. Both levels $C$ and $D$ are linear combinations of the two lower levels that explicitly depend on the amplitudes and phases of the applied fields. Here again, if coherence is present between levels $C$ and $D$, the atomic medium will react to the optical excitation by the coherent emission of fields at frequencies $\omega_1$ and $\omega_2$. These fields are “orthogonal” to the applied fields in the sense that they together only couple to state $D$ (while the incident fields only couple to $C$). As an example we consider the situation corresponding to the retrieval process in the LS experiment reported in [2]. After the dark interval, the drive field ($\omega_1$) alone excites the $\Lambda$ system. Since (previously created) coherence is present between the ground levels (that coincide with $C$ and $D$ in this case), a field
of frequency $\omega_2 = \omega_1 - \Delta$ is emitted by the medium. In the general case, in the presence of coherence between $C$ and $D$, two fields will be emitted with frequencies $\omega_1$ and $\omega_2$ that will interfere with the incident fields.

The previous discussion leads to a very general qualitative understanding of the transient behavior of coherently driven atomic systems. For given excitation conditions, after a long enough time, the system will reach a steady state. If one or more dark states exists the steady state of the system will be the dark state(s) $D$. If no dark state exists the steady state will generally be a statistical mixture (diagonal density matrix) of states $C$. A rapid modification of the excitation conditions, for instance a light polarization change in a Hanle experiment or a change in the amplitude or phase of the fields in a $\Lambda$ scheme, will determine a new set ($C'$, $D'$) of coupled and dark states. The change in the excitation conditions needs to be rapid with respect to the optical pumping time but may otherwise be slow with respect to other characteristic times. Since the previous state of the system is generally a linear combination of the new $C'$, $D'$ states, coherence among the latter states exists and results in the transient emission of an “orthogonal” field. Such emission will last as long as the coherence between $C'$ and $D'$ survives. The decay of the transient emission will be purely exponential with a time constant given by the optical pumping time between states $C'$ and $D'$ if those states are stationary. If they are not stationary (nonzero magnetic field for a Hanle experiment or nonzero Raman detuning in a $\Lambda$ system), the decay will show damped oscillations. If the two different excitation conditions are separated in time by a dark interval then the transient emission of an “orthogonal” field will occur after the dark interval provided that this interval is not long compared to the ground state coherence lifetime. This mechanism applies to the LS experiments previously reported.

The experimental results and the discussion above demonstrate that EIT and propagation in a “slow light” medium is not an essential requirement for the storage and retrieval of a light pulse in an atomic medium. One point in the simple description presented here, which departs from previous theoretical treatments, is the simple consideration of the field propagation in the atomic medium where the spatial variation of the incident field along the sample is essentially neglected. This crude approximation is nevertheless appropriate under conditions where the duration of the probe pulse is comparable or longer than the light propagation time. Such a situation occurred in most LS experiments reported so far (including ours) with the exception of. In the picture presented here, the light retrieval transient appears as a consequence of the irreversible relaxation of the system towards a new steady state. In this context, only exponential decaying pulses can be obtained preventing the retrieval of information about the state of the initial probe pulse other than its presence (one bit information). The storage and recovery of information on the state of the incoming probe pulse are beyond the scope of this simple picture and possibly of most experimental conditions achieved to date.

In conclusion, we have achieved storage and retrieval of light pulses in slow-light and fast-light media and given a unified description of both cases. The results presented in this letter suggest that further theoretical and experimental work is needed for the understanding and practical realization of information preserving storage in an atomic medium. A necessary first step in this direction would be the realization of an atomic medium in which more than one probe pulse (more than one bit of information) can be contained in the atomic sample and propagate without significant distortion.

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