Storage and retrieval of ultraslow optical solitons in coherent atomic system

Zhengyang Bai (白正阳), Chao Hang (杭 超), and Guoxiang Huang (黄国翔)*

State Key Laboratory of Precision Spectroscopy and Department of Physics, East China Normal University, Shanghai 200062, China

**Corresponding author: gxhuang@phy.ecnu.edu.cn*

Received October 18, 2012; accepted December 7, 2012; posted online January 6, 2013

We investigate the propagation of intense probe pulses in a lifetime broadened Λ-type three-level atomic system with a configuration of electromagnetically induced transparency. We find that ultraslow optical solitons formed by a balance between dispersion and nonlinearity can be stored and retrieved in the system by switching off and on a control field. Such pulses are robust during storage and retrieval, and hence may have potential applications in optical and quantum information processing.

OCIS codes: 190.5530, 270.1670, 270.5530.

doi: 10.3788/COL201311.012701.

In recent years, much attention has been paid to the study on electromagnetically induced transparency (EIT). Due to the quantum interference effect induced by a control laser field, the absorption of a probe laser field propagating in an EIT medium can be largely eliminated. Additionally, a drastic change of dispersion of the system occurs, leading to a significant reduction of group velocity of the probe field[1]. In 2000 Fleischhauer and Lukin[2] introduced the idea of a dark state polariton, which is a combination of atomic coherence and probe field. The dark state polariton prominently shows atomic character when control field is switched off and the optical character when the control field is switched on. Consequently, storage and retrieval of *weak* probe pulses are possible, which have been verified by many experiments[3−5]. Generalizations to nonadiabatic switching off and on control field[6] and including detunings of probe and control fields[7] have also been considered.

However, up to now most of previous works on optical storage based on EIT are carried out in linear regime, where probe pulse is much weaker than control field. It is known that linear probe pulses suffer a spreading and attenuation due to the existence of dispersion, which may result in a serious distortion for retrieved pulses[4,5]. For applications of quantum information such as quantum memory, it is necessary to realize robust storage and retrieval of light pulses.

In this work, we study the propagation of an intense probe pulse in a lifetime broadened three-level atomic system with a configuration of EIT. We demonstrate that the ultraslow optical soliton formed by a balance between dispersion and nonlinearity can be stored and retrieved in the system by switching off and on a control field. Because the probe pulse before and after the storage is shape-preserved and hence very robust, the result obtained may have promising applications in optical and quantum information processing. Our study is related to Refs. [8–10]. In Ref. [8], the storage and retrieval of a probe pulse at moderate intensity are studied, but no ultraslow optical soliton is taken into account. In Refs. [9,10], ultraslow optical solitons are found, but no storage and retrieval of them are investigated.

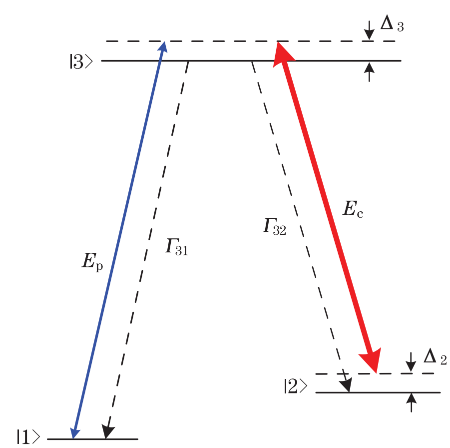

Fig. 1. (Color online) Energy-level diagram and excitation scheme of the three-level Λ system. A weak, pulsed probe field (strong, continuous control field) E_p (E_c) couples to the atomic states $|1\rangle$ ($|2\rangle$) and $|3\rangle$. Γ_{ij} denotes incoherent decay rate from state $|j\rangle$ to state $|i\rangle$. Δ_2 and Δ_3 are two- and one-photon detunings, respectively.

The system under study is a resonant, life-broadened three-state Λ-type atomic system with one upper state $|3\rangle$ and two lower states $|1\rangle$ and $|2\rangle$, as showed in Fig. 1. A pulsed probe field (with pulse width τ) of the center frequency $\omega_p/(2\pi)$ couples to the transition $|1\rangle \to |3\rangle$ and a control field of the frequency $\omega_c/(2\pi)$ couples to the transition $|2\rangle \to |3\rangle$, respectively. The electric field of the system can be written as $\mathbf{E} = \sum_{l=\mathrm{p,c}} \mathbf{e}_l \mathcal{E}_l e^{\mathrm{i}(k_l z-\omega_l t)}$+c.c., where $\mathbf{e}_l(\mathcal{E}_l)$ is the unit polarization vector (envelope) of lth component and $k_l = \omega_l/c$ is the corresponding wavevector. For simplicity, we have assumed that both fields propagate along z-axis. The half Rabi frequencies of the probe and control fields are respectively defined as $\Omega_p = (\mathbf{e}_p \cdot \mathbf{p}_{13})\mathcal{E}_p/(2\hbar)$ and $\Omega_c = (\mathbf{e}_c \cdot \mathbf{p}_{23})\mathcal{E}_c/(2\hbar)$, where $\mathbf{p}_{ij}$ is the electric-dipole matrix element associated with the transition from $|i\rangle$ to $|j\rangle$. In interaction picture and under rotating-wave and slowly-varying envelope approximations, equations of motion for atoms and the electric field read

$$\mathrm{i}\frac{\partial}{\partial t}\rho_{11} - \mathrm{i}\Gamma_{12}\rho_{22} - \mathrm{i}\Gamma_{13}\rho_{33} + \Omega_{\mathrm{p}}^{*}\rho_{31} - \Omega_{\mathrm{p}}\rho_{31}^{*} = 0, \quad (1a)$$

$$\mathrm{i}\frac{\partial}{\partial t}\rho_{22} + \mathrm{i}\Gamma_{12}\rho_{22} - \mathrm{i}\Gamma_{23}\rho_{33} + \Omega_{\mathrm{c}}^{*}\rho_{32} - \Omega_{\mathrm{c}}\rho_{32}^{*} = 0, \quad (1b)$$

$$\mathrm{i}\frac{\partial}{\partial t}\rho_{33} + \mathrm{i}(\Gamma_{13} + \Gamma_{23})\rho_{33} - \Omega_{\mathrm{p}}^{*}\rho_{31} + \Omega_{\mathrm{p}}\rho_{31}^{*} - \Omega_{\mathrm{c}}^{*}\rho_{32} + \Omega_{\mathrm{c}}\rho_{32}^{*} = 0, \quad (1c)$$

$$\left(\mathrm{i}\frac{\partial}{\partial t} + d_{21}\right)\rho_{21} - \Omega_{\mathrm{p}}\rho_{32}^{*} + \Omega_{\mathrm{c}}^{*}\rho_{31} = 0, \quad (1d)$$

$$\left(\mathrm{i}\frac{\partial}{\partial t} + d_{31}\right)\rho_{31} - \Omega_{\mathrm{p}}(\rho_{33} - \rho_{11}) + \Omega_{\mathrm{c}}\rho_{21} = 0, \quad (1e)$$

$$\left(\mathrm{i}\frac{\partial}{\partial t} + d_{32}\right)\rho_{32} - \Omega_{\mathrm{c}}(\rho_{33} - \rho_{22}) + \Omega_{\mathrm{p}}\rho_{21}^{*} = 0, \quad (1f)$$

$$\mathrm{i}\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\Omega_{\mathrm{p,c}} + \kappa_{\mathrm{p,c}}\rho_{31,32} = 0, \quad (1g)$$

where ρ_{ij} $(i, j = 1,\ 2,\ 3)$ are density matrix elements and $d_{21} = \Delta_2 + \mathrm{i}\gamma_{21}$, $d_{31} = \Delta_3 + \mathrm{i}\gamma_{31}$, and $d_{32} = (\Delta_3 - \Delta_2) + \mathrm{i}\gamma_{32}$. Here $\Delta_3 = \omega_{\mathrm{p}} - (\omega_3 - \omega_1)$ and $\Delta_2 = \omega_{\mathrm{p}} - \omega_{\mathrm{c}} - (\omega_2 - \omega_1)$ are the one- and two-photon detunings. $\gamma_{ij} = (\Gamma_i + \Gamma_j)/2 + \gamma_{ij}^{\mathrm{col}}$ with $\Gamma_j = \sum_{i<j}\Gamma_{ij}$. Γ_{ij} denotes the spontaneous emission decay rate from $|j\rangle$ to $|i\rangle$ and $\gamma_{ij}^{\mathrm{col}}$ denotes the dephasing rate reflecting the loss of phase coherence between $|i\rangle$ and $|j\rangle$ without changing of population, as might occur due to elastic collisions. The coupling constants $\kappa_{\mathrm{p,c}} = \mathcal{N}_{\mathrm{a}}\omega_{\mathrm{p,c}}|\mathbf{p}_{13,23}|^2/(2\varepsilon_0 c\hbar)$ with $\mathcal{N}_{\mathrm{a}}$ being the atomic concentration. Our calculations will include the dynamics of the control field, which becomes especially important when the intensity of the probe pulse is not weak, as shown in Ref. [11].

From the results shown in Refs. [10,12], from the Maxwell-Bloch (MB) Eq. (1) one can derive a nonlinear Schrödinger (NLS) equation for Ω_{p} if Ω_{c} is strong and constant. In this case, one can obtain analytical solutions of ultraslow optical solitons valid for ant time t. However, in order to store and retrieve an intense probe pulse one must manipulate Ω_{c}, i.e. Ω_{c} must be time-dependent. In this situation, an analytical solution of the problem is not available, and hence we resort to a numerical approach.

As is known[1], it is possible to store and retrieve a linear probe pulse by switching off and on the control field. When the control field is switched off, the group velocity of the probe pulse reduces to zero. The probe pulse is absorbed by atoms and gets stored inside the medium in the form of atomic coherence. When the control field is switched on, one can retrieve the stored probe pulse. The storage time depends mainly on the life-time of the atomic coherence. The switching off and on the control field can be modeled by the combination of two tangent functions with the form

$$\Omega_{\mathrm{c}}(t,0) = \frac{\Omega_{\mathrm{c0}}}{2}\left[2 - \tanh\frac{(t/\tau - T_{\mathrm{off}})}{\sigma} + \tanh\frac{(t/\tau - T_{\mathrm{on}})}{\sigma}\right], \quad (2)$$

where T_{off} and T_{on} represent the times of switching off and on the control field, respectively.

In this work, we use the time-dependent Ω_{c} given by Eq. (2) to explore the storage and retrieval of *non-linear* probe pules by numerically simulating the MB Eq. (1). Shown in panels (a)–(c) of Fig. 2 is the result of the storage and retrieval of a dimensionless nonlinear probe pulse $|\Omega_{\mathrm{p}}\tau|$ with different intensities as functions of z and t. The time evolution of $|\Omega_{\mathrm{c}}\tau|$ is also given. In the simulation, we take practical parameters related to cold ^{87}Rb atoms as $\gamma_3\tau = 1.76$, $\gamma_2\tau = 1.0 \times 10^{-4}$, $\Delta_2\tau = 0.2$, $\Delta_3\tau = 1.15 \times 10^2$, $\Omega_{\mathrm{c0}}\tau = 40.0$, $\Omega_{\mathrm{p0}}\tau = 2.8$, and $\kappa\tau = 1.0 \times 10^3$ cm^{-1}, with $\tau = 1.0 \times 10^{-7}$ s. For the $\Omega_{\mathrm{c}}(0,t)$, we assume $T_{\mathrm{off}}/\tau = 12.0$ and $T_{\mathrm{on}}/\tau = 24.0$. The waveshape of the input probe pulse is taken as a hyperbolic secant one, i.e. $\Omega_{\mathrm{p}}(0,t) = \Omega_{\mathrm{p0}}\,\mathrm{sech}(t/\tau)$. Lines from 1 to 5 in panels (a) and (b) are respectively for $z = 0$, 7.5, 15, 22.5, and 30 cm; lines from 1 to 6 in panel (c) are respectively for $z = 9$, 13.5, 18, 22.5, 27, and 30 cm.

From the figure, we obtain the following conclusions. (i) For weak probe pulse (Fig. 2(a)) where $\Omega_{\mathrm{p}}(0,t) = 2.8\,\mathrm{sech}(t/\tau)$, the medium is dispersion-dominant. The retrieved probe pulse suffers a significant distortion. (ii) For intermediate probe pulse (Fig. 2(b)) where $\Omega_{\mathrm{p}}(0,t) = 20.0\,\mathrm{sech}(t/\tau)$, the retrieved probe pulse has nearly the same shape with the one before the storage. The physical reason of the shape-preservation of the probe pulse before and after the storage is due to a balance between dispersion and nonlinearity of the system. In this case, the probe pulse forms a ultraslow optical soliton which is rather stable during propagation. The storage time of the soliton shown is about 1.2 μs. (iii) For strong probe pulse (Fig. 2(c)) where $\Omega_{\mathrm{p}}(0,t) = 28.0\,\mathrm{sech}(t/\tau)$, the medium is nonlinearity-dominant. In this situation, the amplitude (width) of

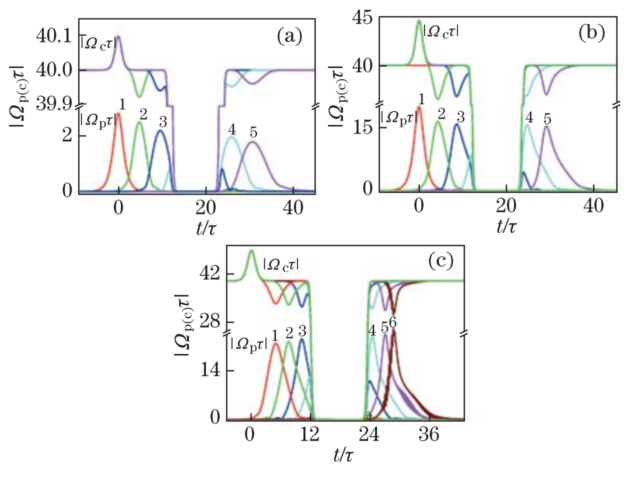

Fig. 2. (Color online) Storage and retrieval of dimensionless probe pulse $|\Omega_{\mathrm{p}}\tau|$ with different intensities as functions of z and t. The time evolution of $|\Omega_{\mathrm{c}}\tau|$ is also shown. (a) $\Omega_{\mathrm{p}}(0,t) = 2.8\,\mathrm{sech}(t/\tau)$ (weak probe field); (b) $\Omega_{\mathrm{p}}(0,t) = 20.0\,\mathrm{sech}(t/\tau)$ (intermediate probe field); (c) $\Omega_{\mathrm{p}}(0,t) = 28.0\,\mathrm{sech}(t/\tau)$ (strong probe field). Lines from 1 to 5 in panels (a) and (b) correspond to $z = 0$, 7.5, 15, 22.5, and 30 cm, respectively. Lines from 1 to 6 in panel (c) correspond to $z = 9$, 13.5, 18, 22.5, 27, and 30 cm, respectively. The parameters are given in the text.

the retrieved pulse is much larger (narrower) than that of the one before storage, and hence the retrieved pulse displays also a significant distortion.

Figures 3(a)–(c) show the evolution of the atomic coherence ρ_{12}. The initial probe pulses used in each panels are the same as those used in Fig. 2. Since the probe pulse is stored in the form of atomic coherence when the control field is switched off and retained until the control field is switched on again, the atomic coherence can be treated as an intermediary for storage and retrieval of the probe pulse. From this figure, we see that the shape of ρ_{12} is similar with that of the probe pulse in each panels when the control field is switched on, and retains a constant value when the control field is switched off.

Now we give a simple explanation on the above numerical results analytically. When the control field is switched on, Eq. (1) can be reduced to the NLS equation:[12]

$$\mathrm{i}\frac{\partial F}{\partial z} - \frac{K_2}{2}\frac{\partial^2 F}{\partial t^2} - W|F|^2 F = 0, \qquad (3)$$

where F is the envelope function of the probe pulse, i.e. $\Omega_\mathrm{p} = F e^{\mathrm{i}[K(\omega)z-\omega t]}$, with the linear dispersion relation $K(\omega) = \omega/c + \kappa(\omega+d_{21})/[|\Omega_\mathrm{c}|^2 - (\omega+d_{21})(\omega+d_{31})]$. Here $K_2 = [\partial^2 K(\omega)/\partial\omega^2]|_{\omega=0}$ is the dispersion coefficient and W is the nonlinearity coefficient with its explicit expression given in Ref. [12]. For the EIT system the imaginary part of the coefficients is much less than their real part, and hence the Eq. (3) admits a single soliton solution. When the control field is switched off, the probe pulse is nearly zero. Therefore, the solution can be approximated as

$$\Omega_\mathrm{p} = \begin{cases} \dfrac{A_0}{\tau}\sqrt{\dfrac{\widetilde{K}_2}{\widetilde{W}}}\mathrm{sech}\left[\dfrac{1}{\tau}\left(t - \dfrac{z}{V_\mathrm{g}}\right)\right]\mathrm{e}^{\mathrm{i}[\widetilde{K}_0 - \widetilde{K}_2/(2\tau^2)]z}, \\ \text{for} \quad t < T_\mathrm{off} \\ 0, \quad \text{for} \quad T_\mathrm{off} \leqslant t \leqslant T_\mathrm{on} \\ \dfrac{B_0}{\tau}\sqrt{\dfrac{\widetilde{K}_2}{\widetilde{W}}}\mathrm{sech}\left[\dfrac{1}{\tau}\left(t - \dfrac{z}{V_\mathrm{g}}\right)\right]\mathrm{e}^{\mathrm{i}[\widetilde{K}_0 - \widetilde{K}_2/(2\tau^2)]z}, \\ \text{for} \quad t > T_\mathrm{on} \end{cases} \qquad (4)$$

where $V_\mathrm{g} \equiv 1/\widetilde{K}_1$ is the group velocity of the probe pulse, which is about $6.5 \times 10^{-6}\,c$. Thus the optical solitons before the storage and the retrieval are ultraslowly propagating ones. In Eq. (4), the tilde denotes the real part of the corresponding quantity, $K_1 \equiv [\partial K(\omega)/\partial\omega]|_{\omega=0}$, $K_0 \equiv K(\omega)|_{\omega=0}$, A_0 and B_0 are constants depending on initial condition.

In conclusion, we have investigated the propagation of intense probe pulses in a lifetime broadened Λ-type three-level atomic system with a configuration of EIT. We have found that ultraslow optical solitons formed by the balance between dispersion and nonlinearity can be stored and retrieved in the system by switching off and on a control field. Because their robust character, the storage and retrieval of the ultraslow optical solitons may have potential applications in optical and quantum information processing.

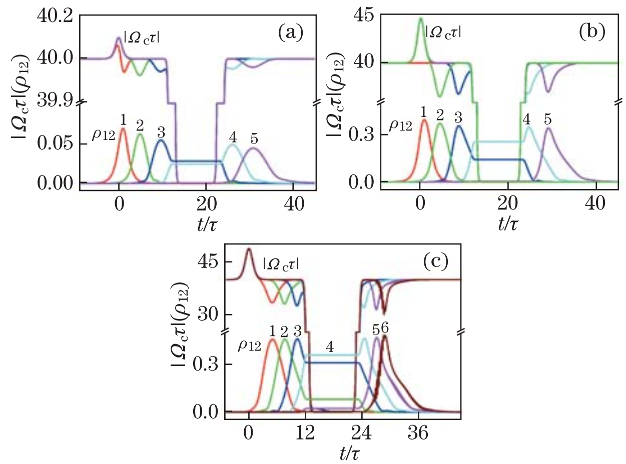

Fig. 3. (Color online) Atomic coherence ρ_{12} as functions of distance z and time t. Initial probe pulses used in each panels are the same as those used in Fig. 2. Lines from 1 to 5 in panels (a) and (b) are respectively for z = 0, 7.5, 15, 22.5, and 30 cm. Lines from 1 to 6 in panel (c) are respectively for z = 9, 13.5, 18, 22.5, 27, and 30 cm. The parameters are given in the text.

This work was supported by NSF-China under Nos. 11174080 and 11105052, and by the Open Fund from the State Key Laboratory of Precision Spectroscopy, East China Normal University.

References

1. M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. **77,** 633 (2005).
2. M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84,** 5094 (2000).
3. L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, Nature **397,** 594 (1999).
4. C. Liu, Z. Dutton, C. Behroozi, and L. Hau, Nature **409,** 490 (2001).
5. I. Novikova, R. L. Walsworth, and Y. Xiao, Laser Photon. Rev. **6,** 333 (2012).
6. A. B. Matsko, Y. V. Rostovtsev, O. Kocharovskaya, A. S. Zibrov, and M. O. Scully, Phys. Rev. A **64,** 043809 (2001).
7. C. Mewes and M. Fleischhauer, Phys. Rev. A **66,** 033820 (2002).
8. T. N. Dey and G. S. Agarwal, Phys. Rev. A **67,** 033813 (2003).
9. Y. Wu and L. Deng, Phys. Rev. Lett. **93,** 143904 (2004).
10. G. Huang, L. Deng, and M. G. Payne, Phys. Rev. E **72,** 016617 (2005).
11. H.-j. Li, C. Hang, and G. Huang, J. Opt. Soc. Am. B **26,** 2028 (2009).
12. B. Luo, C. Hang, H. Li, and G. Huang, Chin. Phys. B **19,** 054214 (2010).