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Electromagnetically Induced Transparency; Writing, Storing, and Reading Short Optical Pulses

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Abstract—The spatiotemporal propagation dynamics of a weak probe pulse in an optically dense medium of three-level atoms is studied in the adiabatic approximation under conditions of electromagnetically induced transparency. The atomic coherence induced at the dipole-forbidden transitions is found to be spatially localized. This effect is used for the analysis of the reversible writing (reading) of short optical pulses. The method of pulse time reversal is suggested. © *2002 MAIK "Nauka/Interperiodica".*

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1. The phenomenon of electromagnetically induced transparency (EIT) is caused by quantum interference. It renders an absorbing medium transparent to the probe resonance radiation in the presence of a control coherent field interacting with the adjacent transition. This effect was predicted and experimentally implemented back in the late 1960s and early 1970s (nonlinear interference effect; see, e.g., [1, 2]). At present, the EIT effect is being extensively studied and widely developed, e.g., in the context of lasing without inversion [3], nonlinear optics, including the interacting radiations with energy corresponding to several photons ("one photon for one atom") [4, 5], subfemtosecond pulse generation [6], atomic coherence control [3, 7], etc.

EIT gives rise to unusual propagation laws for resonant pulses in a medium: matched pulses [8, 9], field-dressed pulses [10], and adiabatons [11] propagating without absorption and changing their shape at a distance exceeding linear absorption length by several orders of magnitude (see also [12–15]). EIT also leads to a giant (by 10^7 times or more) decrease in the group velocity of an optical pulse ("slow light"). In recent experiments, ultraslow propagation was observed in the Bose–Einstein condensate of sodium atoms (~17 m/s [16] and ~1 m/s [17]), in ruby vapor (~90 m/s [18] and ~8 m/s [19]), and in a Pr:Y_2SiO_5 crystal (~45 m/s [20]).

Moreover, the optical pulse can be "stopped" [21] (dynamic EIT); the possibility of obtaining negative group velocity has also been the subject of discussion [22]. At low velocities (tens of m/s and lower), the probe pulse is spatially compressed and localized in a medium. Based on this fact, the authors of [23] suggested and experimentally demonstrated a method of writing, storing, and reconstructing (reading) optical pulses in ruby vapor in the situation where the pulse switching-on and switching-off times are much longer than the lifetime of the intermediate state. In [24], this idea was implemented in the Bose–Einstein condensate of sodium atoms.

In this work, the possibility of writing, storing, and reading light is considered for the case where the pulse duration is shorter than all relaxation times in a medium (short pulses). It is not assumed from the outset that the signal pulse is spatially localized. We consider the case where the propagation of a weak probe (signal) pulse with frequency ω_p in a three-level optically dense medium occurs in the presence of a strong control (write) pulse with frequency ω_c resonant with the frequency of an adjacent $|2\rangle$–$|1\rangle$ transition (Fig. 1). The lower state $|0\rangle$ is the atomic ground state and state $|2\rangle$ is metastable. The pulses are assumed to be plane waves $E_{p,c} = 1/2E_{p,c}\exp[-i(\omega_{p,c}t - k_{p,c}z)]$ + c.c. propagating in one direction along the z axis ($k_{p,c}$ are the moduli of wavevectors of the probe and control pulse, respectively). The intensity of the probe pulse is much lower than the intensity of the control pulse and has virtually no effect on the population of levels with which the pulse interacts. At the medium input, the pulses may have various shapes, but their duration satisfies the condition $T_c > T_p$, where T_c and T_p are the durations of the control and probe pulse, respectively.

In this work, the spatiotemporal evolution of the probe pulse and atomic (Raman) coherence induced at the $|0\rangle$–$|2\rangle$ transition in an optically dense medium under EIT conditions is analyzed. The spatial localization of atomic coherence is demonstrated and, on this basis, the possibility of writing, storing, and reading optical pulses through their transformation into atomic coherence and vice versa is considered.

2. We first consider the spatiotemporal evolution of atomic coherence under EIT conditions. The interaction of optical fields with a three-level quantum system is described by the standard system of Maxwell–Bloch equations, which is solved self-consistently. To the first order in probe field G_p, it has the following form in the coordinate system with local time $\tau = t - z/c$:

$$\frac{\partial\rho_{10}}{\partial\tau} = i(G_p\rho_0 + G_c\rho_{20}),$$
$$\frac{\partial\rho_{20}}{\partial\tau} = iG_c^*\rho_{10}, \quad \frac{\partial G_p}{\partial z} = iK_p\rho_{10}. \tag{1}$$

Here, ρ_{ij} and d_{ij} are nondiagonal elements of the density matrix and the dipole transition moment, respectively; $2G_p = d_{10}E_p(t)\hbar$ and $2G_c = d_{12}E_c(t)\hbar$ are the Rabi frequencies; $K_p = (\pi\omega_p N|d_{10}|^2/c\hbar)$ is the propagation constant; and N is the atomic concentration.

The system of Eqs. (1) is written on the assumption that the pulse carrier frequencies are resonant with the corresponding atomic transitions. At the instant the fields are switched on, all atoms are in the ground state $|0\rangle$ ($\rho_0 = 1$ and $\rho_{1,2} = 0$, where $\rho_{0,1,2}$ are the populations of corresponding levels), and the pulse durations satisfy the following conditions: $T_p \ll \Gamma_{10}^{-1}$, $T_c \ll \Gamma_{20}^{-1}$, $\Gamma_{10} \gg \Gamma_{20}$ (Γ_{10} and Γ_{20} are, respectively, the halfwidths of the $|1\rangle$–$|0\rangle$ and $|2\rangle$–$|0\rangle$ transitions), $T_c > T_p$, and the adiabaticity condition $G_c^0 T_p \gg 1$ (see, e.g., [25]).

We will assume hereafter that the Rabi frequency G_c of the control pulse is a given time-dependent function and that it does not depend explicitly on the coordinate z. Numerical calculations will be carried out with the Gaussian input ($z = 0$) pulses $G_p(t) = G_p^0\exp(-\ln 2t^2/2T_p^2)$ and $G_c(t) = G_c^0\exp(-\ln 2t^2/2T_c^2)$ ($G_p^0 \ll G_c^0$).

In the adiabatic approximation (with allowance for the leading nonadiabatic correction to ρ_{10}), the solutions for ρ_{10} and ρ_{20} in Eqs. (1) can be represented in the form

$$\rho_{20} = -\frac{G_p(\tau, z)}{G_c(\tau)}, \quad \rho_{10} = -\frac{i}{G_c^*(\tau)}\frac{\partial\rho_{20}}{\partial\tau}. \tag{2}$$

By differentiating ρ_{20} with respect to z and using the third equation in (1), one can obtain the equation for the spatial evolution of the nondiagonal density matrix elements ρ_{20}:

$$\frac{\partial\rho_{20}}{\partial\tau} + \frac{G_c^2(\tau)}{K_p}\frac{\partial\rho_{20}}{\partial z} = 0. \tag{3}$$

When deriving Eq. (3), it was assumed that G_c is a real quantity and that it does not depend explicitly on z. The parameter G_c^2/K_p has the meaning of the coherence (ρ_{20}) propagation velocity in a medium. The boundary condition is written as $\rho_{20}^0 = \rho_{20}(\tau, z = 0) = -G_p(\tau, z = 0)/G_c(\tau)$.

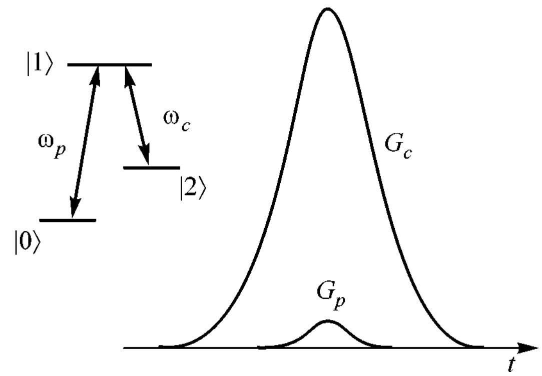

Fig. 1. Scheme of atomic levels and the configuration of interacting optical pulses at the medium input $z = 0$.

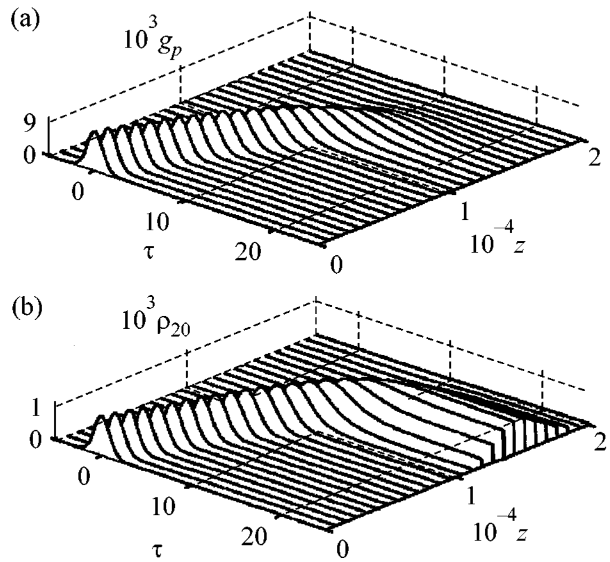

Fig. 2. Time dependences of (a) atomic coherence ρ_{20} and (b) normalized Rabi frequency $g_p = G_pT_p$ of the probe field at different points of the medium. $G_c^0 T_p = 10$ and $T_c/T_p = 10$. Time is measured in units of probe pulse duration and length is in units of linear absorption length.

Equation (3) can be solved, e.g., by the method of characteristics. The solution has the form

$$\rho_{20}(\tau, z) = \rho_{20}^0(Z^{-1}(Z(\tau) - z)), \tag{4}$$

where $Z(\tau) = K_p^{-1}\int_{-\infty}^{\tau} G_c^2(\tau')d\tau'$ and Z^{-1} is the inverse of the function $Z(\tau)$.

The spatiotemporal evolution of atomic coherence ρ_{20} and probe pulse $g_p = G_pT_p$ is illustrated in Fig. 2. One can see that, as the pulse propagates through the medium, it decelerates and its energy gradually decreases because of the energy transfer to the control

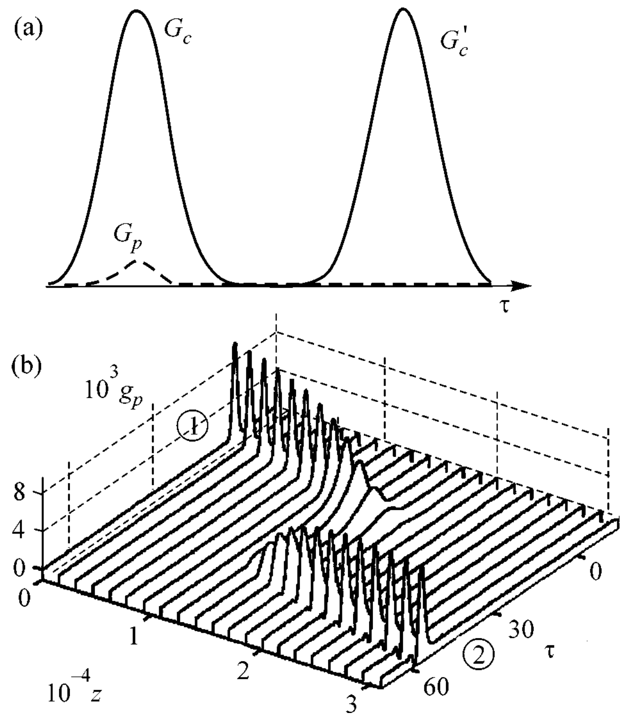

Fig. 3. (a) Signal (G_p), write (G_c), and read (G'_c) pulses at the medium input $z = 0$. (b) Writing (circled figure 1) of the signal pulse G_p and (circled figure 2) its reading by the pulse G'_c. Conditions as in Fig. 2.

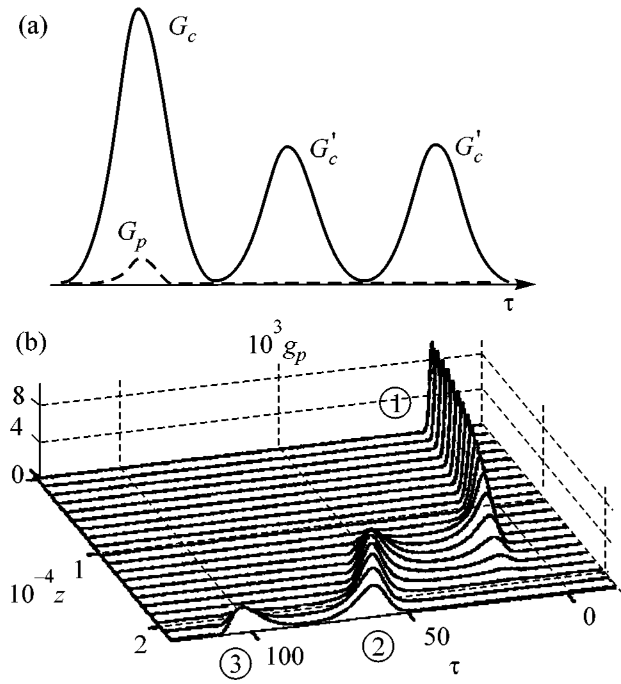

Fig. 4. Double readout of a written pulse. (a) Signal (G_p), write (G_c), and read (G'_c) pulses at the medium input $z = 0$. (b) Time dependences of the signal pulse G_p in the course of (circled figure 1) writing and (circled figures 2 and 3) reading at different points of the medium. Condition are as in Fig. 2.

pulse. The coherence described by the nondiagonal element ρ_{20} of the density matrix is spatially localized and its spatial profile is similar to the shape of the input signal pulse. This can also be considered as a pulse-induced phase grating in the medium. A comparison of the numerical results for ρ_{20} with the data obtained using Eq. (4) shows that the agreement is good.

The results obtained have a certain relevance to the predictions of [21] but present the problem in a different aspect. The difference is that, first, we consider short pulses with duration shorter than the medium relaxation time. Second, what is more important, the boundary conditions are specified. With such an approach, it is not assumed from the outset that the probe pulse is spatially localized in the medium, as was done in [21], where the spatial distribution of the probe pulse in a medium was specified at zero time. By contrast, we specify the pulse time distribution at the boundary $z = 0$, i.e., solve the boundary-value problem. In our opinion, this formulation of the problem is more natural and allows one to trace the pulse deceleration and the spatial localization of atomic coherence.

3. The spatial distribution of atomic coherence in a medium contains information on the probe pulse. This can be used for writing and storing the probe optical pulse in a medium followed by its reading. The term "writing" implies the conversion of a probe (signal) pulse into the atomic coherence ρ_{20}, whose lifetime is determined by its relaxation time and can be as long as several milliseconds or longer. If a "read" optical pulse is fed into the medium with a time delay relative to the control pulse, the output pulse will arise as a result of read pulse scattering by the atomic coherence; i.e., the atomic coherence converts back into light (reading process).

The properties of the reconstructed pulse depend on the read pulse. In the case when the read pulse is identical with the control (write) pulse and propagates in the same direction, the reconstructed (red) pulse will be the exact copy of the signal pulse, as illustrated in Fig. 3. During the atomic coherence lifetime, reading can be performed repeatedly (see Fig. 4). The curves in Fig. 4 were calculated numerically using Eqs. (1), where G_p and G_c imply the red (reconstructed) and read pulses, respectively. The initial and boundary conditions were taken in the form $G_p = 0$, $G_p = G_p = G_p(\tau)$ at the boundary $z = 0$, and $\rho_{20} = \rho_{20}(z)$ at the instant of time τ_0 corresponding to the onset of reading.

For the close transition frequencies ω_{10} and ω_{12}, the written pulse can be reconstructed by sending the read pulse in the direction opposite to the initial writing direction. The reading process is described by the equations of type (1), in which G_p and G_c should be regarded as the reconstructed and read pulses, respectively, and τ

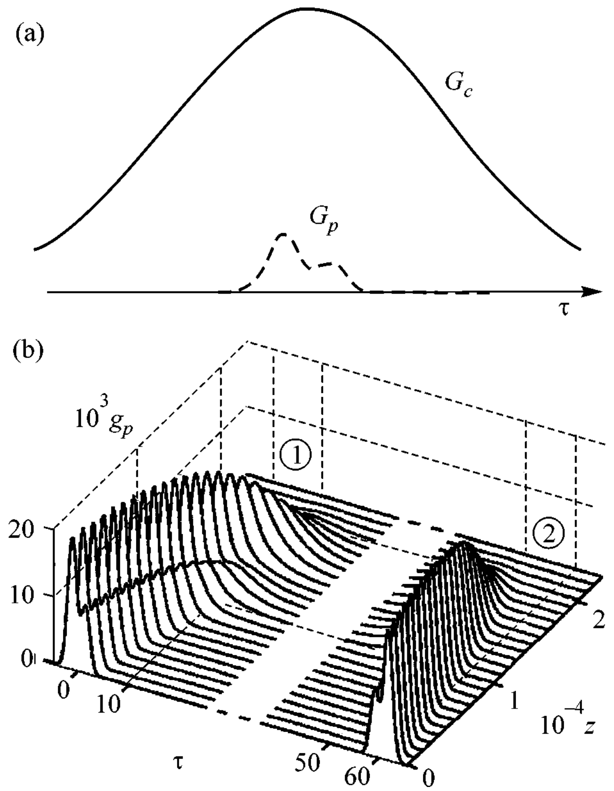

Fig. 5. Time-reversal reading. The read and write pulses propagate in opposite directions. (a) Signal (G_p) and write (G_c) pulses at the medium input $z = 0$. (b) Time dependence of the signal pulse at different points of the medium in the course of writing (circled figure 1), and the same for the pulse reconstruction (circled figure 2).

and z should be replaced by $\tau' = t - z'/c$ and $z' = L - z$, respectively, where L is the medium length. The boundary conditions for fields are specified at the output plane $z = L$ of the medium: the red field is zero, and the write field reflected from a mirror can be taken as a read field. The initial condition for ρ_{20} is specified by the spatial distribution $\rho_{20}(\tau, z)$ induced in the course of reading. It should be written in the τ' and z' coordinates. The result of reading is demonstrated in Fig. 5. It is worth noting that the reconstructed pulse is time-inverted; i.e., its leading and trailing edges are reversed, as is seen in the figure. The time reversal is caused by the fact that the information about the pulse leading edge is carried by the leading (spatial) front of atomic coherence, which penetrates into the medium deeper than the trailing front that carries information on the trailing (temporal) edge of the probe pulse (see Fig. 2b). Evidently, the pulse portion scattered at the tail of atomic coherence will escape the medium earlier than the portion scattered at the leading part, because the propagation velocity of the reconstructed pulse is lower than that of the read pulse. Similar results are obtained for the case $T_c/T_p < 10$, with the only difference that the coherence ρ_{20} is localized in a larger part of the medium.

Since the read pulse scattering by atomic coherence is independent of the pulse frequency, one can use read pulses with the carrier frequency ω_1 differing from the frequency of the control (write) field. In this case, the frequency of the reconstructed pulse will be shifted to $\omega_s = \omega_p - \omega_c + \omega_1$.

4. In this work, the spatiotemporal evolution of a weak probe pulse with a duration shorter than all the relaxation times in a medium has been studied under conditions of electromagnetically induced transparency. The atomic (Raman) coherence was shown to be spatially localized in a medium. Its spatial profile contains information on the signal pulse. These facts were used to demonstrate the possibility of writing and reading short optical pulses. The results obtained are complementary to the results in [21] and extend the range of their applicability. Various variants of read signal pulse were considered. It was shown that the pulses can be time-reversed. Interestingly, the pulses with steep edges, including rectangular ones, can be used as write and read pulses. Similar effects also arise in the case when the signal Rabi frequency is comparable with the control Rabi frequency, as well as if the counterintuitive pulse sequence is used (the control pulse is switched on and off before the signal pulse, and the pulses partially overlap). These results will be reported in a separate publication.

The results obtained may be of interest for the quantum processing of optical signals and images.

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REFERENCES

1. S. G. Rautian, G. I. Smirnov, and A. M. Shalagin, *Nonlinear Resonances in Atomic and Molecular Spectra* (Nauka, Novosibirsk, 1979).
2. A. K. Popov, *Introduction to the Nonlinear Spectroscopy* (Nauka, Novosibirsk, 1983); Izv. Akad. Nauk, Ser. Fiz. **60**, 99 (1996).
3. S. E. Harris, Phys. Today **50** (7), 36 (1997).
4. S. E. Harris and Y. Yamamoto, Phys. Rev. Lett. **81**, 3611 (1998).
5. S. E. Harris and V. H. Lene, Phys. Rev. Lett. **82**, 4611 (1999).
6. F. L. Kien, N. H. Shon, and K. Hakuta, Phys. Rev. A **64**, 051803(R) (2001).
7. E. Arimondo, in *Progress in Optics*, Ed. by E. Wolf (Elsevier, Amsterdam, 1996), Vol. 35, p. 257.
8. S. E. Harris, Phys. Rev. Lett. **72**, 52 (1994).
9. G. Vemuri, K. V. Vasavada, G. S. Agarwal, *et al.*, Phys. Rev. A **54**, 3394 (1996).
10. J. H. Eberly, M. L. Pons, and H. R. Hag, Phys. Rev. Lett. **72**, 56 (1994).

11. R. Grobe, F. T. Hioe, and J. H. Eberly, Phys. Rev. Lett. **73**, 3183 (1994); Phys. Rev. A **54**, 794 (1996).
12. V. G. Arkhipkin, D. V. Manushkin, and V. P. Timofeev, Kvantovaya Élektron. (Moscow) **25**, 1084 (1998).
13. V. G. Arkhipkin and I. V. Timofeev, Kvantovaya Élektron. (Moscow) **30**, 180 (2000); V. G. Arkhipkin, I. V. Timofeev, and E. A. Sizykh, in *Proceedings of the International Conference "Mathematical Models and Methods for Their Study," Krasnoyarsk, 2001*, Vol. 1, p. 36.
14. G. G. Grigoryan and Y. T. Pashayan, Phys. Rev. A **64**, 013816 (2001).
15. V. G. Arkhipkin and I. V. Timofeev, Phys. Rev. A **64**, 053811 (2001).
16. L. V. Hau, S. E. Harris, Z. Dutton, *et al.*, Nature (London) **397**, 594 (1999).
17. S. Inouye, R. F. Low, T. Gupta, *et al.*, cond-mat/0006455.
18. M. M. Kash, V. A. Sautenkov, A. S. Sibrov, *et al.*, Phys. Rev. Lett. **82**, 5229 (1999).
19. D. Budker, D. F. Kimball, S. M. Rochester, *et al.*, Phys. Rev. Lett. **83**, 1767 (1999).
20. A. V. Turukhin, M. S. Sudarshanam, M. S. Shariar, *et al.*, Phys. Rev. Lett. **88**, 023602 (2002).
21. M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84**, 5094 (2000).
22. O. Kocharovskaya, Yu. Rostovtsev, and M. Scully, Phys. Rev. Lett. **86**, 628 (2001).
23. D. F. Phillips, A. Fleischhauer, A. Mair, *et al.*, Phys. Rev. Lett. **86**, 783 (2001).
24. Ch. Liu, Z. Dutton, C. H. Behroozi, *et al.*, Nature (London) **409**, 490 (2001).
25. R. N. Shakhmuratov, J. Odeurs, R. Coussement, *et al.*, Phys. Rev. Lett. **87**, 153 601 (2001).

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