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Efficient selective excitation in optically thick extensive media by adiabatic population transfer

V. G. Arkhipkin[a], D. V. Manushkin[b], V. P. Timofeev[b], I. V. Timofeev[c]

[a]L.V.Kirensky Institute of physics, Krasnoyarsks 660036 Russia

[b]Krasnoyarsk state technical university 660074 Russia

[c]Krasnoyarsk state university 660041 Russia

ABSTRACT

In this work the feature of spatio-temporal evolution of two partially overlapped short pulses of counterintuitive sequence in a medium of three-level absorbing atoms in conditions of adiabatic transfer of population are investigated. The analytic solution is constructed. It is shown, that selective excitation of two-photon resonant state with a near-unity probability is conserved on the length of medium, which is considerably greater than the absorbtion length of a weak probe pulse in the absence of a coupling pulse at the adjacent transition.

Keywords: adiabatic population transfer, electromagnetically induced transparency, counterintuitive pulse sequence.

1. INTRODUCTION

The resonant interaction of two laser pulses with three-level atoms of Λ-configuration has attracted a great interest in recent years. Some aspects of laser pulses propagation in conditions of electromagnetically induced transparency were investigated, for example, in [1-6]. As a rule, the situations are considered, when both pulses have an identical form, and their duration is more than the relaxation time of an intermediate resonant state (matched pulses [1]; dressed field pulses [2,3]) or the duration of a coupling radiation considerably exceeds the duration of probe (adiabatons [5,6]).

The temporal evolution of adiabatic population transfer (APT) [7-11] is well investigated. As far as we know neither the problem of space evolution of interacting pulses in an optically dense medium, nor the features of space dynamics of population of final state excited in the course of APT are investigated. Here we shall investigate the propagation of two identical partially overlapping short laser pulses of counterintuitive sequence [10] in an absorbing three-level medium in conditions of APT.

The effect of APT is observed for the pulses, which envelopes vary slowly enough and satisfy the criterion of adiabaticity [10]:

$$\sqrt{|G_1|^2 + |G_2|^2}T >> 1, \tag{1}$$

where $G_{1,2} = d_{10,12}E_{1,2}(t)/2\hbar$; T - the Raby frequency and the duration of interacting pulses, consequently.

This adiabaticity condition can be achieved for strong enough pulses even if the pulse duration is short [3,10]. Further we shall consider just such a situation.

The theoretical model consists of a system of coupled Schrödinger equations and reduced wave equations, describing simultaneously temporal and space evolution of atomic subsystem and of radiation. In adiabatic approximation (1) the analytic solution is constructed and the three-dimensional vector model of adiabatic following is suggested. It is shown, that the probe pulse can propagate over a distance considerably exceeding the length of linear absorption, but finally it is completely transferred into the coupling pulse. Although we demonstrate that APT leads to practically complete population inversion at the dipole-forbidden transition over characteristic propagation length that considerably exceeds the linear absorbtion length of the probe pulse.

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2. BASIC EQUATIONS AND SOLUTION

Let's consider a propagation of two partially overlapping pulses in a medium of three-level atoms shown in Fig.1. The intermediate condition $|1\rangle$ is one-photon resonant to each field interacting only with "its own" transition. Further we shall name the pulse with frequency ω_1 as probe, and another - coupling. The pulses travel in accordance with specific temporal sequence (counterintuitive sequence): the interaction with coupling pulse $G_2(t)$ is switched on and off earlier than the interaction with probe pulse $G_1(t)$ (Fig.1). The amplitude of the latter may be comparable with the amplitude of coupling field.

The system of equations for probability amplitudes $a_{0,1,2}$ and Raby frequencies in a moving coordinate system with local time $\tau = t - z/c$ has the form:

$$\frac{\partial a_0}{\partial \tau} = iG_1^* a_1, \quad \frac{\partial a_2}{\partial \tau} = iG_2^* a_1, \quad \frac{\partial a_1}{\partial \tau} = -iG_1 a_0 - iG_2 a_2, \tag{2}$$

$$\frac{\partial G_1}{\partial z} = -iK_1 a_1 a_0^*, \quad \frac{\partial G_2}{\partial z} = -iK_2 a_1 a_2^*. \tag{3}$$

Here $K_{1,2}$ - the propagation constants. We assume that coupling pulse is applied to a medium with all atoms initially in the ground state: $a_0(-\infty, z) = 1, a_{1,2}(-\infty, z) = 0$. The boundary condition on the fields at $z = 0$ is $E_1(t) = E_1^0 \exp(-\tau^2/2T^2)$, $E_2(t) = E_2^0 \exp(-(\tau - \tau_0)^2/2T^2)$, where τ_0 - the delay time between pulses, T - the pulse duration.

In adiabatic approximation the solution of the system (2) has the form:

$$a_0 \simeq \frac{G_2}{G} = \cos\theta, \quad a_2 \simeq -\frac{G_1}{G} = -\sin\theta, \quad a_1 \simeq \frac{1}{G_1}\frac{\partial (G_2/G)}{\partial \tau} \simeq -\frac{1}{G_2}\frac{\partial (G_1/G)}{\partial \tau}, \tag{4}$$

where $G = \sqrt{G_1^2 + G_2^2}$, and θ - some angle, which sense will be clear below.

It follows from (4), that in the tail of the coupling pulse $|a_0|^2 \simeq 0$, and $|a_2|^2 \simeq 1$, in other words, the population of the ground state $|0\rangle$ is transferred into state $|2\rangle$. In this process angle θ varies from zero up to $\pi/2$. Actually the value of this angle also depends on a coordinate, as will be shown below. Therefore the above-stated is correct only up to defined values of z. The expression for a_1 can be reduced in a form:

$$a_1 = (G_2\dot{G}_1 - G_1\dot{G}_2)/G^3. \tag{5}$$

It is easy to show, that in approximation (1) $|a_1| << 1$, i.e. the population of an intermediate condition $|1\rangle$ is negligible during all time of interaction with pulses. The last physically means, that the resonant absorption of pulses is low – electromagnetically induced transparency. Therefore pulses can propagate over the distance essentially exceeding the length of linear absorption of a single weak probe radiation.

Substituting the solution (4) in the field equations (3), we obtain a system of the connected nonlinear equations:

$$\frac{\partial G_1}{\partial z} = -(K_1/G)\frac{\partial (G_1/G)}{\partial \tau}, \qquad \frac{\partial G_2}{\partial z} = -(K_2/G)\frac{\partial (G_2/G)}{\partial \tau}. \tag{6}$$

One can show from (6), that the value $K_2 G_1^2(\tau, z) + K_1 G_2^2(\tau, z)$ does not depend on coordinate z and is equal to $\tilde{G}^2(\tau) = K_2 G_1^2(\tau, z = 0) + K_1 G_2^2(\tau, z = 0)$. It reflects the fact, that the pulses propagate concordantly.

Let's mark, that an integral $\int_{-\infty}^{\infty} d\tau [K_2 G_1^2(\tau, z) + K_1 G_2^2(\tau, z)] = const$.

If $K_1 = K_2 = K$, the equations simplify and can be solved analytically, for example, by characteristic method. The exact solutions are:

$$G_1 = G(0,\tau)\frac{G_1(0,p)}{G(0,p)}, \qquad G_2 = G(0,\tau)\frac{G_2(0,p)}{G(0,p)}. \tag{7}$$

Here $p = Z^{-1}(Z(\tau) - z)$, $Z(\tau) = K^{-1}\int_{-\infty}^{\tau} d\tau' G^2(0, \tau')$, $Z^{-1}(z)$ - inverse function of $Z(\tau)$.

In Fig.2 the normalized Raby frequensies $g_{1,2} = G_{1,2}T$ versus time and depth of penetration of radiation in a medium calculated from formula (7) are shown. They demonstrate, that in a resonant medium the probe pulse can propagate over a distance, which is several orders greater than the length of linear absorption of weak probe pulse. However the energy of the leading edge of the probe pulse is partially absorbed, and the energy of the coupling pulse is amplified. The absorbed energy is used in adiabatic transfer of the atomic system to an excited state and in amplification of the coupling pulse. Eventually the probe pulse is completely transferred in coupling pulse.

In Fig.3 the populations $\rho_{0,2} = |a_{0,2}|^2$ versus time and length of medium are shown. APT thus makes it possible to achieve practically 100% inversion on dipole-forbidden transition in extensive media. The obtained analytic results coincide with the results of the numeric analysis of system of equations (2) and (3) [12].

3. GEOMETRIC INTERPRETATION OF APT

These results can be interpreted in terms of a three-dimensional vector model, using the vectors $\vec{a} = (a_0, a_1, a_2)$ and $\vec{G} = (G_2, 0, -G_1)$ as a variables (Fig.4). In the given terms the system (2) may be rewritten as:

$$\dot{\vec{a}} = \vec{G} \times \vec{a}, \tag{8}$$

where the sign $(\times)$ means a vector product. The solution of equation (8) is vector $\vec{a} = (G_2/G, 0, -G_1/G)$, which lies in the plane $(\vec{i}, \vec{k})$, also including vector $\vec{G}$ under angle θ to axis $\vec{i}$ ($\cos\theta = G_2/G$, see (4)). The components of vector $\vec{a}$ practically coincide with the adiabatic solution (4), as far as $|a_1| << 1$ and this value may be neglected. Therefore vector $\vec{a}$, corresponding to adiabatic solution (4), is practically parallel to vector $\vec{G}$ and adiabatically follows it and precesses around it with frequency $G = \sqrt{G_1^2 + G_2^2}$. During interaction $\vec{G}$ turns to 90^o and aligns along axis $\vec{k}$. The latter means the transfer of population from ground state $|0\rangle$ into final state $|2\rangle$. So, there is an analogy with the case of adiabatic following at interaction of light pulse with two-level atom (see, for example, [13]). With account of propagation the angle θ is a function of time and coordinates. Therefore the presented process has place only at lengths, where maximum amplitudes of Raby frequensies do not differ too much. When the amplitude of probe pulse becomes much less than the amplitude of coupling pulse, APT disappears.

4. CONCLUSION

In the given work the effect of APT is investigated with account of propagation of interacting counterintuitive pulses in an optically thick three-level medium with Λ-configuration of atomic levels. It is shown, that the effect of APT leads to practically complete inversion at dipole-forbidden transition in extensive medium. This phenomenon can be used to conversion of frequency of picosecond and femtosecond lasers in anti-Stokes radiation with a tunable wavelength. Apparently, it may be also used for observation of cooperative anti-Stokes scattering of light.

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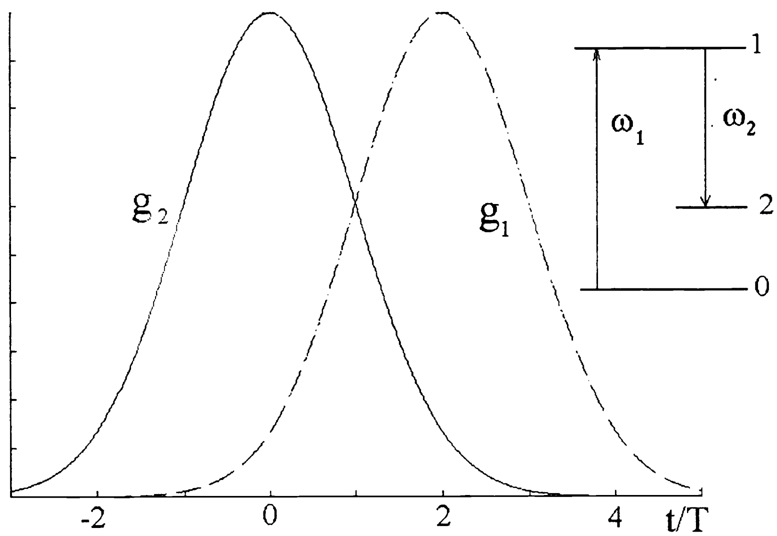

Fig.1. A configuration of energy levels in atom and Raby frequencies at an input of a medium. $\omega_{1,2}$ — carrier frequencies of probe $g_1(t)$ and coupling $g_2(t)$ pulses, consequently.

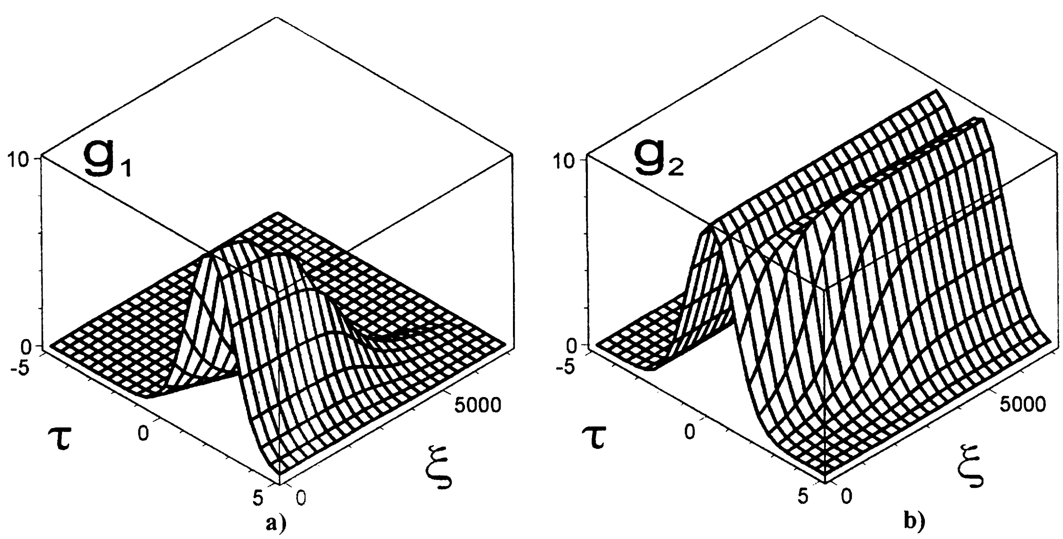

Fig.2. The normalized Raby frequencies $g_1 = G_1 T$ (a) and $g_2 = G_2 T$ (b) versus time and length of a medium. The parameters are as follows: $\tau_0/T = 2$, $G_1^0 T = 10$, $G_2^0 T = 10$ ($G_{1,2}^0$ — value of Raby frequency $G_{1,2}$ in a maximum); $\Gamma_{10} T = 0.1$, $\Gamma_{12} T = 0.1$, $K_1 = K_2$.The time τ is measured in terms of pulse duration T, and length of a medium ξ — in terms of the length of linear absorption of a probe radiation with frequency ω_1

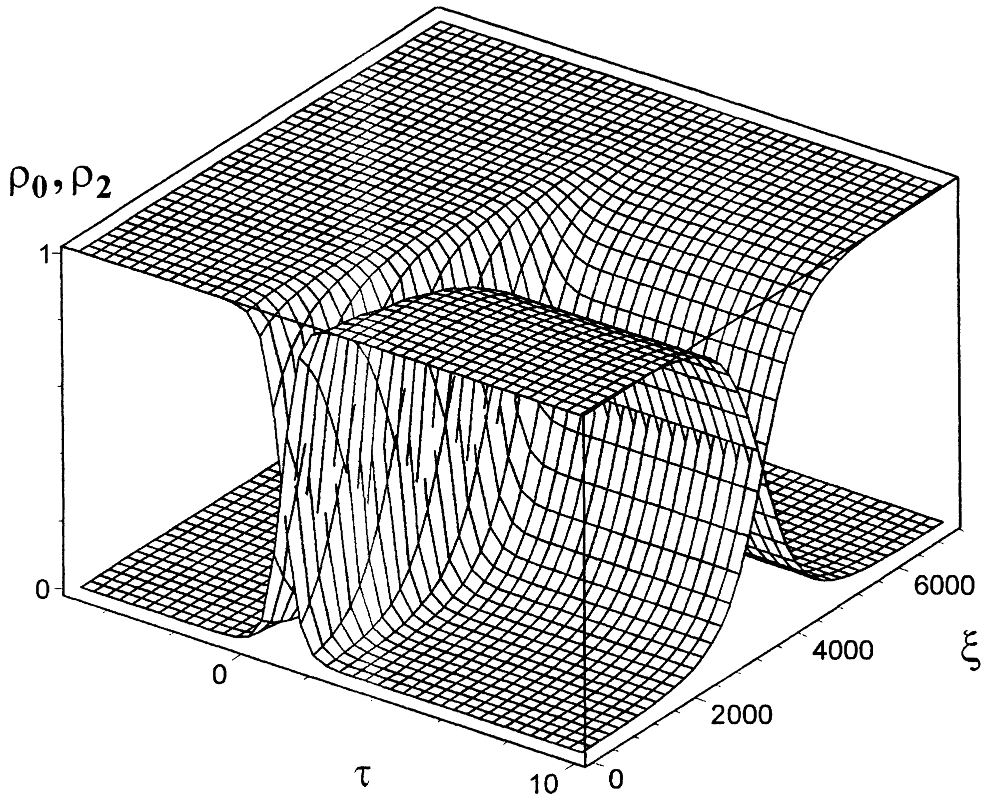

Fig.3. The level populations $\rho_{0,2} = |a_{0,2}|^2$ versus time and length of a medium. The parameters are the same as in Fig.2.

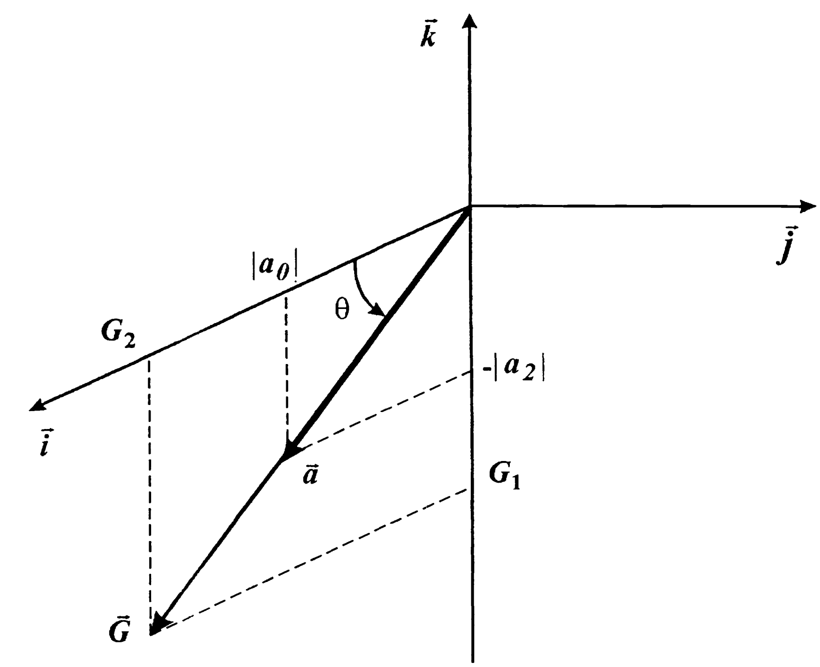

Fig.4. The vector model of adiabatic interaction of two short pulses with three-level Λ -system.