# Temporal shape manipulation of intense light pulses by coherent population trapping

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We describe how to control the temporal shape of adiabaton using peculiarities of propagation dynamics under coherent population trapping. Temporal compression is demonstrated as a special case of pulse shaping. The general case of unequal oscillator strengths of two optical transitions in an atom is considered.

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## I. INTRODUCTION

Electromagnetically induced transparency (EIT) and coherent population trapping (CPT) can facilitate coherent control of light under propagation through a medium [1,2]. In addition to their fundamental interest, investigations of these processes are stimulated by practical possibilities, such as manipulating a group velocity of light and light storage in atomic medium [3,4], enhanced nonlinear optical processes [5], quantum memory [4], and so on.

The CPT is a quantum interference effect and takes place under resonance interaction of two laser fields (probe and coupling) with three-level atomic systems. The essence of this effect is that under certain conditions atoms are trapped into the coherent superposition of two lower states $|1\rangle$ and $|2\rangle$, which is called the CPT state [6,7]. Under the CPT condition the medium becomes coherent and possesses unusual properties, many of which contradict with the intuitive views. The CPT leads to the maximal coherence at the Raman transition and the medium becomes transparent for the probe and coupling pulses [5,8]. This phenomenon allows recording, storing, and reading of information about strong optical pulses [9,10], controling the degree of excitation of spatially localized regions inside an absorbing three-level medium [11] and generating matched pulses [12,13], dressed-field pulses [14], and adiabatons [15]. Experimental observation of adiabatons was reported in [16].

Recently it was shown how EIT can be used for coherent control of the weak pulse shape [17]. The idea is following. Under EIT the weak probe pulse propagates with a slow group velocity depending on an intensity of the coupling field. If the intensity of the coupling field depends on time, different points of the probe pulse experience different values of intensity of coupling field and travel with different propagation velocities, giving rise to temporal reshaping of the probe. A proper choice of the temporal shape of the coupling pulse allows control and manipulation of the probe pulse envelope. In the same way authors of [18] suggested manipulating the retrieval of stored weak light pulses. In this paper we generalize this method for controling the temporal shape of the intense probe pulse using the peculiarities of the CPT propagation dynamics. Temporal compression of adiabatons is demonstrated as a special case of pulse tailoring. Also the general case of unequal oscillator strengths of two optical transitions in an atom is considered.

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## II. PRINCIPAL EQUATIONS

We consider the interaction of two copropagating pulses with three-level atoms as shown in Fig. 1. Pulses propagate along an axis $z$ in one direction. The propagation direction is $z$. A probe pulse [with the slowly varying envelope $E_1(t)$ and frequency $\omega_1$] is tuned on resonance with $|3\rangle$-$|1\rangle$ transition, and the coupling pulse $[E_2(t),\omega_2]$ is tuned so that exact two-photon resonance between states $|1\rangle$-$|2\rangle$ is achieved. The coupling pulse is switched on earlier and switched off later than probe. For the sake of simplicity and in order to obtain analytical results, we restrict our model to the interaction time much shorter than any relaxation times of medium and ignore inhomogeneous broadening.

The joint time-space evolution of atoms and pulses is described by the Schrödinger equation for atomic amplitudes $a_{1,2,3}$ and reduced wave equations for Rabi frequencies which should be solved self-consistently. For the case when the fields are in resonance with their respective transitions, Maxwell-Schrödinger equations are

$$\frac{\partial}{\partial\tau}\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix}=i\begin{pmatrix}0&0&G_1^*\\0&0&G_2^*\\G_1&G_2&0\end{pmatrix}\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix},\tag{1}$$

$$\frac{\partial}{\partial\zeta}\begin{pmatrix}G_1\\G_2\end{pmatrix}=i\begin{pmatrix}K_1a_1^*a_3\\K_2a_2^*a_3\end{pmatrix}.\tag{2}$$

Here $\zeta=z$, $\tau=t-z/c$—space and time coordinates in a frame moving with light velocity $c$ in empty space; $2G_{1,2}=E_{1,2}d_{1,2}/\hbar$—the Rabi frequencies of fields; $E_{1,2}$—the probe

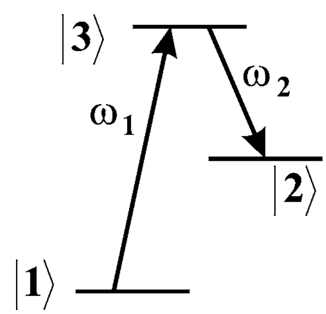


FIG. 1. The three-level system coupled by two resonant pulses with Rabi frequencies $G_1$ and $G_2$. $\omega_1$ and $\omega_2$ are the frequencies of the probe and control pulses. The transition $|1\rangle$-$|2\rangle$ is dipole forbidden.

 

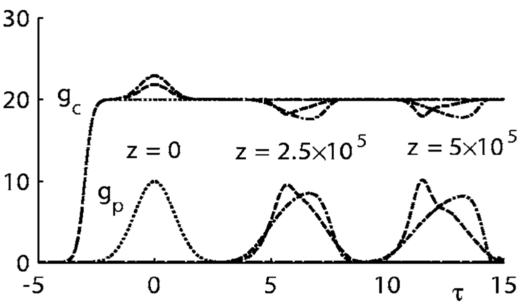


FIG. 2. Propagation of the adiabatons ($g_p = G_1 T_1, g_c = G_2 T_1$) for different propagation distances within the medium in the case $K_1 \neq K_2$: $K_2/K_1 = 1.25$—dash-dot line, $K_2/K_1 = 0.75$—dashed line.

and coupling field strengths; $d_{13,23}$—the electrical dipole moments of the relevant atomic transitions; $K_{1,2} = 2\pi N \omega_{1,2} |d_{13,23}|^2 / \hbar c$—the field-atomic coupling constants; $N$—the atomic concentration. Initially all atoms are in the ground state $|1\rangle$: $a_{1,2,3}(\tau = -\infty, \zeta) = (1;0;0)$. Further we shall consider the values $G_{1,2}$ to be real due to the proper choice of the phases of the basis wave function.

The solution of Eqs. (1) and (2) gives the complete evolution of the atom-field system. The analytical solution of the equation system (1,2) is possible only in adiabatic approximation [8,15]. In this case $|a_3| \ll 1$ and $G_1/G_2 = -a_2/a_1$. The condition $|a_3| \ll 1$ means, that the population of intermediate state $|3\rangle$ is close to zero in the interaction of pulses with atoms. The population is trapped in a coherent superposition of states $|1\rangle$ and $|2\rangle$—the effect of CPT. Under CPT pulses do not interact with medium [2,7]. It means that pulses can propagate practically without absorption.

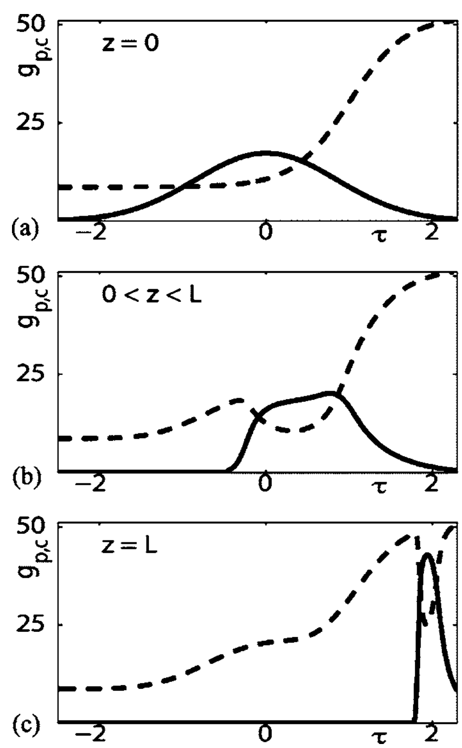


FIG. 3. The compression of the probe pulse in the case $K_1 = K_2$. Temporal profiles of the normalized Rabi frequencies of the probe $g_p = G_1 T_1$ and control (dashed line) $g_c = G_2 T_1$ pulses at different propagation distances within the medium. (a) At the input of medium $z=0$; (b) at some distance within the medium; (c) at the output of medium $z=L$.

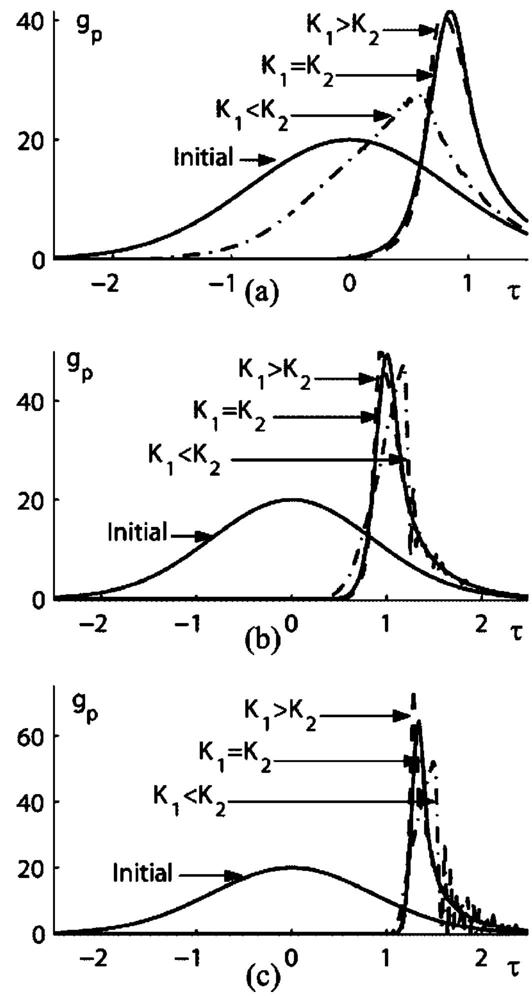


FIG. 4. The time evolution (numerical solution) of the Rabi frequency of probe pulse $g_p$ at the different depths in the medium: (a) $z_1 = L/9$; (b) $z_2 = L/2$; (c) $z_3 = L$. The solid line, $K_1 = K_2$; dashed line, $K_1 = 4K_2$; dashed-dot line, $4K_1 = K_2$.

In the adiabatic approximation the solution of Eqs. (1) and (2) can be presented as [8]

$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} \cos\theta \\ \sin\theta \\ -\dfrac{\partial\theta/\partial\tau}{\sqrt{G_2^2 + G_1^2}} \end{pmatrix}, \tag{3}$$

$$\begin{pmatrix} G_1 \\ G_2 \end{pmatrix} = 2\sqrt{\frac{(K_1 G_2^2 + K_2 G_1^2)|_{\zeta=0}}{K(\theta)}} \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix}. \tag{4}$$

Here $K(\theta) = K_1 \cos^2[\theta(\tau,z)] + K_2 \sin^2[\theta(\tau,z)]$; $\theta$ is the mixing angle ($\tan\theta = G_1/G_2$), which can be expressed through the border conditions

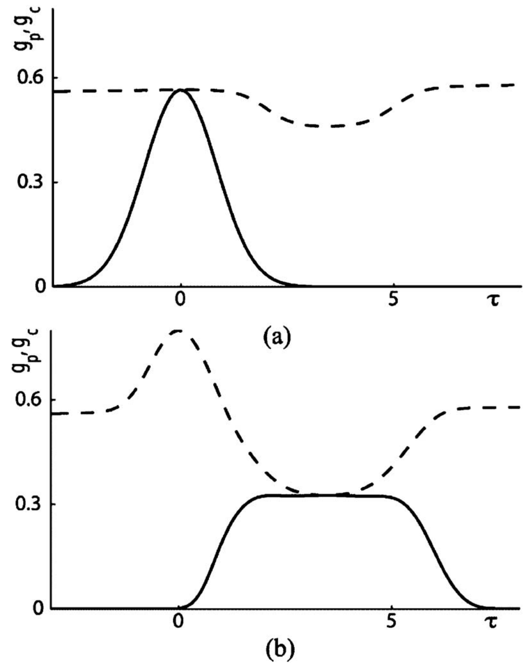


FIG. 5. Flat-top pulse (the case $K_1=K_2$): Time evolution of normalized Rabi frequencies of probe $g_p$ (continuous curve) and coupling $g_c$ (dashed-line curve) pulses at medium input (a) and at medium output (b). Rabi frequencies are normalized to a maximal value of $[G_2^2(\tau)+G_1^2(\tau)]^{1/2}$.

$$\theta(\tau,\zeta)=\theta(\tau_0,0)=\arctan[G_1(\tau_0,0)/G_2(\tau_0,0)],$$

at the time moment $\tau_0$ satisfying characteristic equation

$$\zeta(\tau,\tau_0)=K^{-2}[\theta(\tau_0,\zeta=0)]\int_{\tau_0}^{\tau}(K_1G_2^2+K_2G_1^2)d\tau'.$$

The solution (3), (4) can be applied only within the area of adiabaticity which is limited by the relation [15]

$$\left|G_2\frac{\partial G_1}{\partial\tau}-G_1\frac{\partial G_2}{\partial\tau}\right|\ll(G_2^2+G_1^2)^{3/2}. \qquad (5)$$

In contrast to the usual steady state solution which does not depend on initial conditions, the space-time evolution of the probe and coupling pulses under CPT conditions depends on the pulse forms at the input of medium. In our paper [8] the case of Gaussian pulses was analyzed, assuming that $T_1<T_2$ ($T_{1,2}$ is the probe and coupling pulse duration). The Rabi frequencies of both pulses are comparable.

In a case of equal coupling constants ($K_1=K_2$), when $T_1\ll T_2$ and the amplitude of the coupling pulse is constant, the probe and coupling pulses have complementary envelopes and propagate without shape variation and with equal group velocity. Such pulses are called adiabatons [15].

Under unequal coupling constants $K_{1,2}$ (unequal oscillator strengths of two optical transitions in the atom) the adiabatons are not shape preserving but undergo a front sharpening (Fig. 2): under $K_1<K_2$ a back edge becomes steeper (dash-dot line), and under $K_1>K_2$ a leading edge becomes steeper (dashed line).

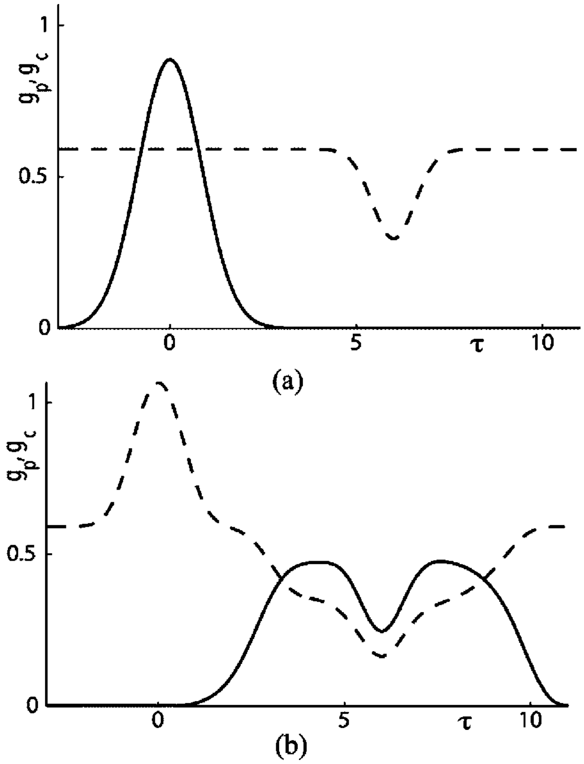


FIG. 6. Two-peaked pulse (the case $K_1=K_2$): time evolution of normalized Rabi frequencies of probe $g_p$ (continuous curve) and coupling $g_c$ (dashed-line curve) pulses at medium input (a) and at medium output (b).

### III. TEMPORAL SHAPE CONTROL OF THE PROBE PULSE BY CPT: COMPRESSION OF PULSES

Since under CPT the space-time evolution of the probe pulse depends on the temporal shape of the coupling pulse, we can manipulate the shape of the probe pulse by proper choice of the coupling pulse envelope at the entry of medium. In this regard CPT can be viewed as a way of the coherent control of temporal pulse shaping. In particular, it is possible to choose such coupling pulse shape, that the trailing edge of the probe pulse travels faster than the leading one. This results in the compression of a probe pulse. Figure 3 demonstrates an example of the temporal compression of probe pulse using coupling pulse with the envelope shown in Fig. 3(a) (dashed line). The parameters of numerical simulation are close to experimental values reported in [16] for lead vapour medium. In our case $T_1=1$ ns, $G_1^{max}=2/3$ cm$^{-1}$, oscillator strength of probe transition 0.2, medium length 10 cm. A time evolution of pulses is much similar to adiabatons propagation [15]. Pulse propagation in this case can be treated as adiabatonic pair extended to time shape variation (quasiadiabatons) since both pulse envelopes vary coherently and travel with equal velocity. As in [17] the compression can be connected with the manipulation of propagation velocities. Exactly, the leading edge of probe pulse is slowed down more strongly than the trailing one. As a result the probe pulse is compressed in time under propagation through the medium and its amplitude increases. A factor of compression is limited by the adiabaticity condition (5) and its magnitude can amount to several times.

Note that the compression effect is independent on the detailed temporal structure of the coupling pulse. The compression takes place also under a linear growth of amplitude of the coupling pulse.

The pulse compression takes place also in the case of unequal coupling constants $K_{1,2}$, which are defined by the oscillator strengths of transitions (Fig. 4). The optimal compression takes place for the common case of strong probe transition ($K_1 > K_2$). The numerical simulation shows that at certain length of medium the distortion (a temporal oscillation) of pulse shape takes place, especially at the case of different coupling constants ($K_1 \neq K_2$). This distortion is an evidence that adiabaticity conditions break down.

Pulse compression is a particular case of temporal shaping. In the general case, the proper choice of the temporal shape of the coupling pulse allows us to obtain probe pulse with different temporal shapes at output. For example, we can obtain a flat-top pulse (Fig. 5) or two-peaked pulse (Fig. 6) like in [17]. In contrast to [17] in our case the coupling pulse shows strong reshaping at propagation [see dashed line at Figs. 5(a), 5(b), 6(a), and 6(b)]. The same effects take place in the case of unequal coupling constants. For the results presented we have checked that under adiabatic conditions the numerical solution of the Maxwell-Schrödinger equations and obtained analytical expression provide exactly the same results.

In conclusion, we have shown that temporal pulse compression can be achieved using CPT schemes. In the same way it is possible to manipulate retrieval of stored strong light pulses [19]. These processes present both fundamental interest and applications in nonlinear optics, because the compressed pulse as a light source can increase the efficiency of nonlinear processes. Let us notice that practical realization of this phenomenon benefits from use of photonic crystal waveguides, which provide high field intensity at great length.

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