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Preparation of Maximal Atomic Coherence in Space by Fractional Stimulated Raman Adiabatic Passage

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ABSTRACT

We show that in optically dense medium, consisting of three-level Λ-atoms, the effect of fractional stimulated Raman adiabatic passage leads to the maximum coherence on Raman transition to length of the medium considerably exceeding length of the linear resonant absorption. The general case of unequal forces of oscillators on the coupling transitions is analyzed. Results are of interest for a coherent anti-Stokes Raman spectroscopy with the delaying pulses.

1. INTRODUCTION

Preparation of atoms in coherent superposition of quantum states with equal probability amplitudes, which corresponds a maximal coherence, represents great interest as atoms in such state have unusual properties which can be used for different applications [1]. There are some methods of maximal coherence creation [2,3].

The method of induction of maximal coherence (an off-diagonal element of density matrix) on the Raman transition of three-level atom of the lambda-configuration proposed in [4] was named as fractional stimulated Raman adiabatic passage (FStiRAP). The main point is that after the adiabatic interaction with a pair of pulses atoms do not leave the coherent state due to matched termination of pulses. Here we show that this phenomenon takes place in the case of optically dense medium. Under certain conditions the extent of medium in which the maximal coherence is induced exceeds the length of linear absorption of weak radiation on some orders of magnitude: on this extent the value of coherence remains constant, then sharply falls down to zero. The process is robust and stable against pulse transformations in medium depth as well as against variation of time delay between pulses.

2. EQUATIONS

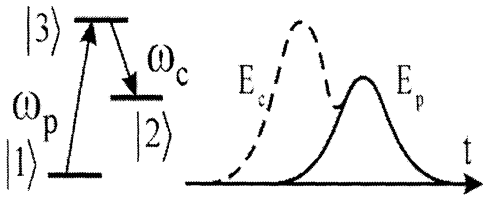

Fig. 1. a) atomic states scheme: 1 – ground state, 2 – metastable state, $\omega_{..}$ – frequencies of resonant fields; b) sequence of coupling E_c and

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$$\frac{\partial}{\partial\tau}\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix}=\frac{i}{2}\begin{pmatrix}i\gamma_1+\delta_1 & 0 & G_1^*\\ 0 & i\gamma_2+\delta_2 & G_2^*\\ G_1 & G_2 & i\gamma_3\end{pmatrix}\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix},\quad \frac{\partial}{\partial\zeta}\begin{pmatrix}G_1\\G_2\end{pmatrix}=2i\begin{pmatrix}K_1a_1^*a_3\\K_2a_2^*a_3\end{pmatrix}. \tag{1}$$

Here $\zeta=z,\tau=t-z/c$ – the time and depth of medium in a frame moving with light velocity in empty space; $a_{1,2,3}$ – the probability amplitudes of atomic states; $\gamma_{1,2,3}$ – longitudinal relaxations of atomic states; $\delta_{1,2}$ – the one-photon detunings of fields from resonant transition frequencies; $2G_{p,c}=E_{p,c}d_{p,c}/\hbar$ – the Rabi frequencies of fields; $E_{p,c}$ – the probe and coupling field strengths; $d_{1,2}$ – the electrical dipole moments of the relevant atomic transitions; $\hbar$ – the Planck's constant; $K_{p,c}=2\pi N\omega_{p,c}\left|d_{1,2}\right|^2/\hbar c$.

Initially all atoms are in ground state $|1\rangle$: $a_{1,2,3}(\tau=-\infty,\varsigma)=1;0;0$. Coupling field E_c enters the medium earlier, than probe E_p (fig. 1b), and pulse durations satisfy $T_c>T_p$. Pulses are assumed short enough that the relaxation of atomic subsystem is negligible. Conditions of one and two-photon resonances are fulfilled: $\delta_{1,2}=0$. In the adiabatic approach $G_1/G_2=-a_2/a_1$ and $|\alpha_3|\ll 1$ and equations (1) lead to photon number conservation law $G_c^2/K_2+G_p^2/K_1=const$ and the field equation [4]

$$\frac{\partial\vec{G}}{\partial\zeta}=-\hat{\mathrm{K}}\frac{1}{\vec{G}^2}\frac{\partial\vec{G}}{\partial\tau},\ \vec{G}=(G_c,G_p). \tag{2}$$

Introducing new variable, mixing angle, which is determined as $tg\theta=G_p/G_c$, we derive

$$\frac{\partial\theta}{\partial\zeta}+\frac{K^2(\theta)}{K_1G_c^2+K_2G_p^2}\frac{\partial\theta}{\partial\tau}=0, \tag{3}$$

where $K(\theta)=\left(K_1G_c^2+K_2G_p^2\right)/\vec{G}^2=K_1\cos^2\theta+K_2\sin^2\theta$. The mixing angle appears constant along characteristic curves

$$\zeta(\tau,\tau_0)=K^{-2}\left(\theta(\tau_0,\zeta=0)\right)\int_{\tau_0}^{\tau}\left(K_1G_c^2+K_2G_p^2\right)d\tau', \tag{4}$$

where τ_0 – the time when the field of given characteristics came into the medium. All physical quantities can be expressed through the mixing angle $\theta(\tau,\zeta)$

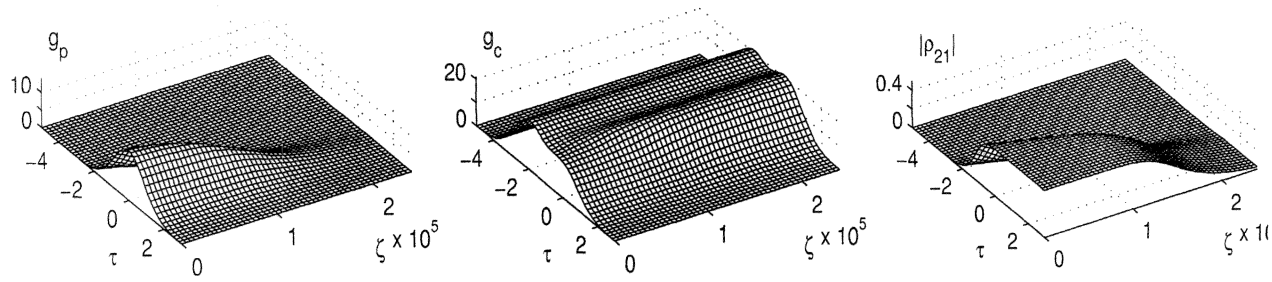
$$\begin{pmatrix}G_p\\G_c\end{pmatrix}=2\sqrt{\frac{\left(K_1G_c^2+K_2G_p^2\right)\big|_{\zeta=0}}{K(\theta)}}\begin{pmatrix}\sin\theta\\\cos\theta\end{pmatrix}\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix}=\begin{pmatrix}\cos\theta\\\sin\theta\\-\left|\partial\vec{G}/\vec{G}^2\partial\tau\right|\end{pmatrix}. \tag{5}$$

3. DISCUSSION

Fractional StiRAP is implemented for the pulses shown on Fig. 1b [3]: the shape of the probe pulse must coincide with trailing edge of coupling pulse. As well as in StiRAP the coupling pulse is switched on earlier, than probe but the pulses switch off simultaneously. Therefore after pulse propagation the system remains in the coherent superposition of states $|1\rangle$ and $|2\rangle$.

Let's consider the case of equal propagation coefficients $K(\theta)\equiv K=K_1=K_2$. Optimal delay of the probe pulse is $\Delta T=2T_p$, where T_p - the half-width of probe pulse at half-height. In this case the numerical solution of equations (1) coincides with the analytic solution (5). When adiabaticity requirements are fulfilled at boundary of medium, the maximal coherence (off-diagonal element of density matrix at the $|1\rangle$-$|2\rangle$ transition) is induced as step function (fig. 2c)

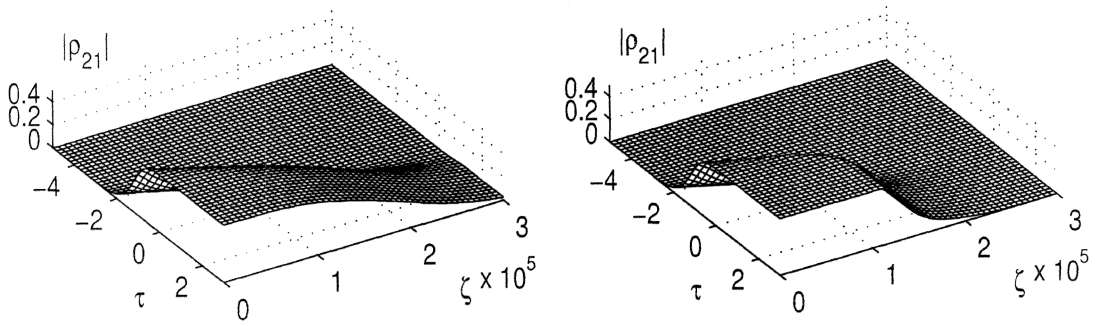
which is maintained in space at propagation of pulses. The length of medium with peak coherence is proportional to $T_p G^2/K$. The lifetime of coherence is determined by its relaxation time.



(a) (b) (c)

Fig. 2. Time-space evolution of Rabi frequencies of a) probe pulse $g_p = G_1 T_p$ $(g_{p\_max} = 15)$, b) coupling pulses $g_c = G_2 T_p$ $(g_{c\_max} = 15\sqrt{2})$ and c) the coherence – off-diagonal element of density matrix at transition $|1\rangle$-$|2\rangle$. ζ is measured in lengths of the linear absorption of probe field, time τ – in terms of T_p.

Figure 3 illustrates spatio-temporal dependence of a density matrix nondiagonal element $|\rho_{21}|$ in both cases of different propagation coefficient $K_1 > K_2$ and $K_1 < K_2$. In the first case the back spatial front of a coherence is more sharply expressed, than in second case.



(a) (b)

Fig. 3. Spatio-temporal evolution of nondiagonal element of density matrix in case of unequal oscillator forces on the coupling transitions. (a) $K_1 = 2K_2$; (b) $2K_1 = K_2$ Remaining parameters as on Fig. 2.

Variation of delay between pulses $\Delta T = 3T_p$ or $\Delta T = T_p$ leads to shape distortion of coherence, to insignificant nonadiabatic oscillations. For the indicated sequence and configuration of pulses the effect is stable against alteration of delay and intensity of fields.

4. CONCLUSION

We have shown that FStiRAP takes place in the case of optically dense medium. Interacting pulses get out of the medium and leave spatial profile of atomic coherence as smooth step function. For adiabatic interaction of atoms with field the analytic solution is obtained, which agrees with direct numerical simulation. Variation of coherence profile with intensity of fields and delays between pulses is investigated.

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