Preparing of coherent superposition state in serial multi-Λ-type system by stimulated Raman adiabatic passage

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A scheme for creating an arbitrary coherent superposition of two atomic states in serial multi-Λ-type system is proposed. This technique with the application of a control field is based on the existence of two degenerate dark states and their interaction. The mixing of the dark states can be controlled by changing the relative delay time of the control pulse. One can get any desired superposition by changing the delay time of the control pulse.

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In recent years, the technique called stimulated Raman adiabatic passage (STIRAP) process has been intensively studied experimentally, analytically and numerically[1−10]. In the straightforward population transfer, the STIRAP has been applied to manipulate and create coherent state superposition. The original STIRAP process has thus been utilized to create coherent superposition in three- and four-level systems[1−5], and to prepare N-component maximally coherent superposition state[6]. In most cases, the existence of a dark state is the basis of the adiabatic transfer, which utilizes the eigenstate corresponding to zero eigenenergy. If the system is prepared in this state at the initial time, it will remain there during the time of evolution as long as adiabatic process is maintained. If the adiabatic state is arranged to go over into the desired state at the final time, this process provides a smooth and efficient population transfer between the states. And the extension of STIRAP has been developed quickly. For instance, tripod-STIRAP[2,4], fractional-STIRAP[7,8], and other variations of STIRAP[9,10].

In the present work, a scheme to create coherent superposition state of two states in serial multi-Λ-type system[11] is proposed. Serial multi-Λ-type System has been studied previously in population transfer[3], molecular vibrational ladder climbing[11,12], and creating coherent superposition state[13]. Creating coherent superposition state can be carried out via fractional-STIRAP in serial multi-Λ-type system. But all the intermediate pulses must vanish simultaneously in fractional-STIRAP, which is very difficult to realize experimentally. But by using another control laser[2], we can also create coherent superposition state. The advantage of this method is that we do not need to control the laser pulses vanishing simultaneously, instead, we only need to control the delay time of control pulse which is much easier to realize experimentally. This method has been used to create superposition state in three-level Λ-type system[2]. In this letter, we extend the method to serial multi-Λ-type system, and our goal is to create superposition state of initial state and final state of Λ-type system. The results show that the final superposition state can be controlled by adjusting the time of the pulses (the relative delay of the control pulse).

Firstly, we consider the five-level Λ-type system shown in Fig. 1. The atoms are assumed to be initially in state $|1\rangle$. The time-dependent Schrödinger equation for this system can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}C(t) = -iW(t)C(t), \qquad (1)$$

where $C(t)$ is a column vector, whose components are the probability amplitudes $C_n(t)$, and the evolution matrix $W(t)$ has the form

$$W(t) = \frac{1}{2}\begin{pmatrix} 0 & P_1(t) & 0 & 0 & 0 & 0 \\ P_1(t) & 0 & S_1(t) & 0 & 0 & 0 \\ 0 & S_1(t) & 0 & P_2(t) & 0 & 0 \\ 0 & 0 & P_2(t) & 0 & S_2(t) & Q(t) \\ 0 & 0 & 0 & S_2(t) & 0 & 0 \\ 0 & 0 & 0 & Q(t) & 0 & 0 \end{pmatrix}, \qquad (2)$$

where $P_1(t)$, $P_2(t)$, $S_1(t)$, $S_2(t)$, and $Q(t)$ are the time-dependent Rabi-frequencies of the pump, Stokes and control pulses, respectively. We assume $P_1(t)$, $P_2(t)$, $S_1(t)$, $S_2(t)$, and $Q(t)$ to be real without loss of generality. Then the eigenvalue of this system is

$$\lambda = 0, \pm\Omega_1(t), \pm\Omega_2(t), \qquad (3)$$

where

$$\Omega_1(t) = \sqrt{P_1(t)^2 + S_1(t)^2}, \qquad (4)$$

$$\Omega_2(t) = \sqrt{P_2(t)^2 + S_2(t)^2 + Q(t)^2}. \qquad (5)$$

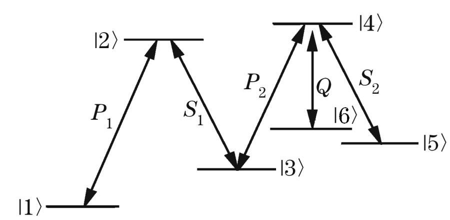

Fig. 1. Five-level Λ-type system. P_1 and P_2: pump pulses; S_1 and S_2: Stokes pulses; Q: the control pulse.

The analysis of the system is simplified by introducing a set of adiabatic states $\Phi_k(t)$. There exist two degenerate dark states with null eigenvalue and no component of atomic states ψ_2 and ψ_4. And the two corresponding degenerate dark states are

$$|\Phi_1\rangle = \sin\varphi\cos\theta|1\rangle - \sin\varphi\sin\theta|3\rangle + \cos\varphi|5\rangle, \quad (6)$$

$$|\Phi_2\rangle = \cos\varphi\cos\theta\sin\alpha|1\rangle - \cos\varphi\sin\theta\sin\alpha|3\rangle - \sin\varphi\sin\alpha|5\rangle + \cos\alpha|6\rangle, \quad (7)$$

where

$$\tan\theta = \frac{P_2(t)}{S_2(t)}, \quad \tan\varphi = \frac{P_1(t)\sqrt{P_2^2(t)+S_2^2(t)}}{P_1(t)S_2(t)}, \quad (8)$$

$$\tan\alpha = \frac{Q(t)\sqrt{P_1^2(t)+S_1^2(t)}}{\sqrt{P_1(t)^2P_2(t)^2+S_1(t)^2S_2(t)^2+P_1(t)^2S_2(t)^2}}. \quad (9)$$

Because the proposed technique is based on the existence of two degenerate dark states and their interaction, we do not write remaining eigenvectors Φ_3, Φ_4, Φ_5, and Φ_6. And in the adiabatic limit, the nonadiabatic coupling of dressed states $\Phi_1(t)$ or $\Phi_2(t)$ to the other dressed states can be neglected, only the transition between the degenerate dressed states $\Phi_1(t)$ and $\Phi_2(t)$ is important. The two degenerate adiabatic states Φ_1(t) and Φ_2(t) do not contain states ψ_2 and ψ_4.

The desired pulse sequence to create an arbitrary superposition of ψ_1 and ψ_5 will be designed so that the two degenerate dark states correspond, for $t \to \pm\infty$, to bare atomic states:

$$\text{Initial stage}: \psi_1 \to \Phi_1, \quad (10)$$

$$\text{Interaction stage}: \Psi(t) \to \cos\Theta_\infty\Phi_1 + \sin\Theta_\infty\Phi_2, \quad (11)$$

$$\text{Final stage}: \Phi_1 \to \psi_1, \quad \Phi_2 \to \psi_5, \quad (12)$$

The result of the sequence state :

$$\Psi(t\to\infty) = \cos\Theta_\infty\psi_1 + \sin\Theta_\infty\psi_5, \quad (13)$$

where Θ_∞ is the asymptotic mixing angle, and this angle determines the asymptotic superposition coefficients. From Ref. [2] we know

$$\Theta_\infty = \int_{-\infty}^{t} \mathrm{d}\tau_{\mathrm{Q}}\dot{\vartheta}(\tau_{\mathrm{Q}})\sin\varphi(\tau_{\mathrm{Q}}), \quad (14)$$

where τ_{Q} is the delay time of the control pulses relative to the pump and Stokes pulses.

Initially the system will evolve from ψ_1 to Φ_1, and because of the coupling of Φ_1 and Φ_2, it will finally end up with superposition state of ψ_1 and ψ_5. For example, to generate equal superposition state, first to evolve ψ_1 into Φ_1, we should have $\theta = 0$ and $\varphi = \pi/2$, which means that $S_1(t)$ precedes $P_1(t)$, and $S_2(t)$ precedes $P_2(t)$ based on Eq. (8); at the end of interaction, to get superposition state of ψ_1 and ψ_5, the mixing angles should be $\theta = 0$, $\varphi = \pi/2$, and $\alpha = \pi/2$, which means that $P_2(t)$ vanishes earlier than $S_2(t)$, $P_1(t)$ vanishes earlier than $S_1(t)$, and $S_2(t)$ vanishes earlier than Q based on Eqs. (8) and (9). We illustrate the procedure in Fig. 2. Figure 2(a) shows the pulses and Fig.2 (b) shows the resulting populations. We can see that the initial bared atomic state ψ_1 is turned into an equal superposition state of ψ_1 and ψ_5.

We can also generate any desired superposition by varying the delay time of the control pulse. From Eq. (14), we can get any desired superposition by altering the mixing angle Θ_∞ which is governed by the relative delay time of the control pulse. So by varying the delay τ_{Q} among the control pulse and the pump and Stokes pulses, we can

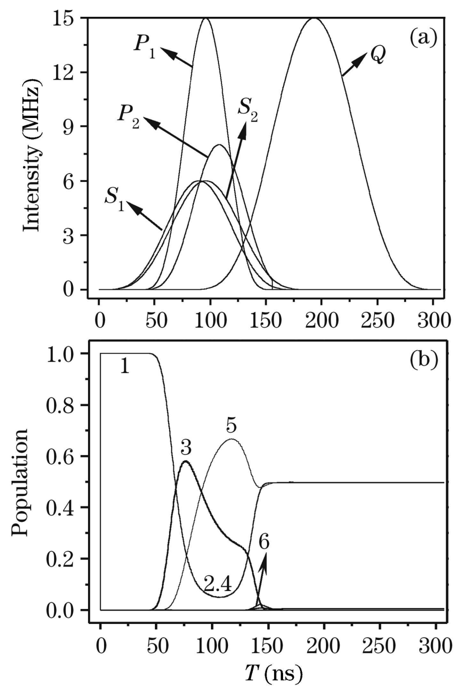

Fig. 2. (a) Example of pulses for coherence generation. $A_{P_1} = 15$, $A_{P_2} = 8$, $A_{S_1} = A_{S_2} = 6$, $A_Q = 15$, $T_{P_1} = 120$, $T_{P_2} = 1.2T_{P_1}$, $T_{S_1} = 1.5T_{P_1}$, $T_{S_2} = 1.6T_{P_1}$, and $T_Q = 1.9T_{P_1}$, $\tau_{\mathrm{Q}} = 0.66T_{P_1}$, $\tau_{P_1} = \tau_{P_2} = 0.3T_{P_1}$; (b) time evolution of populations as produced by these pulses. The populations of excited stated states 2 and 4 remain zero. A_i $(i = P_1, P_2, S_1, S_2, Q)$ are the Rabi-frequencies of the pulses, and T_i $(i = P_1, P_2, S_1, S_2, Q)$ are the widths of the pulses.

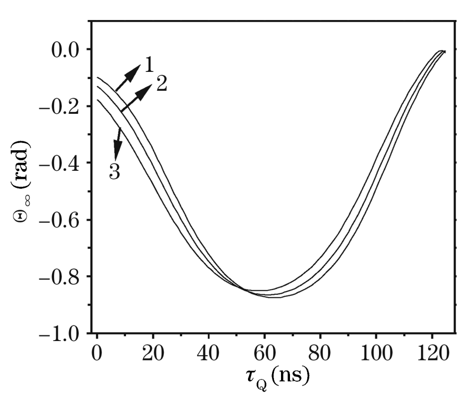

Fig. 3. Asympotic mixing angle Θ_∞ as a function of delay time τ_{Q} of the control pulse. Curve 1, 2 and 3 show $A_Q = 18$, 15, and 13, respectively.

produce a range of superposition. Figure 3 shows the mixing angle Θ_∞ as a function of the delay time τ_Q. It can be seen that the mixing angle Θ_∞ ranges from -0.1 to -0.9 as the delay time τ_Q changes, and Θ_∞ is not very sensitive to variations of the control-pulse amplitude. Then it is possible to choose the delay time to produce any desired superposition.

This method can be extended to the seven serial multi-Λ-type system, in which the control pulse $Q(t)$ couples the intermediate state ψ_6 to a eighth state ψ_8. The system has two dark states:

$$\Phi_1 = \sin\alpha\sin\beta\cos\gamma\,|1\rangle - \sin\alpha\sin\beta\sin\gamma\,|3\rangle + \sin\alpha\cos\beta\,|5\rangle - \cos\alpha\,|7\rangle\,, \tag{15}$$

$$\Phi_2 = \cos\alpha\sin\beta\cos\gamma\sin\theta\,|1\rangle - \cos\alpha\sin\beta\sin\gamma\sin\theta\,|3\rangle + \cos\alpha\cos\beta\sin\theta\,|5\rangle + \sin\alpha\sin\theta\,|7\rangle - \cos\theta\,|8\rangle\,, \tag{16}$$

$$\tan\alpha = \frac{S_3\sqrt{S_1^2S_2^2+P_1^2P_2^2+P_1^2S_2^2}}{P_1P_2P_3},$$

$$\tan\beta = \frac{S_2\sqrt{S_1^2+P_1^2}}{P_1P_2}, \quad \tan\gamma = \frac{P_1}{S_1}, \tag{17}$$

$$\tan\theta = \frac{Q\sqrt{S_1^2S_2^2+P_1^2P_2^2+P_1^2S_2^2}}{\sqrt{S_1^2S_2^2S_3^2+P_1^2P_2^2S_3^2+P_1^2S_2^2S_3^2+P_1^2P_2^2P_3^2}}. \tag{18}$$

In order to get the equal superposition state of ψ_1 and ψ_7, we must achieve $\alpha = \pi/2$, $\beta = \pi/2$, and $\gamma = 0$ initially, $\alpha = \pi/2$, $\beta = \pi/2$, $\gamma = 0$ and $\theta = \pi/2$ at the end of interaction, which requires that the Stokes pulses arrive earlier but vanish later than the corresponding pump pulses, and the control pulse arrives and vanishes last.

So for any serial multi-Λ-type system, we can create any superposition state of ψ_1 and ψ_n if the control pulse $Q(t)$ couples the intermediate state ψ_{n-1} to state ψ_{n+1}. All the Stokes pulses arrive earlier but vanish later than the corresponding pump pulses, and the control pulse arrives and vanishes last.

In conclusion, we have analytically and numerically explored creating superposition states of ψ_1 and ψ_n in serial multi-Λ-type system. By using a controlled field, we have two degenerate dark states. Through the interaction of these two states and the proper design of laser pulse sequence, we can create arbitrary superposition state by only controlling the pulse delay time. This is much easier to realize experimentally than fractional-STIRAP.

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