Selective preparation of the maximum coherent superposition state in four-level atoms

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Received March 7, 2011; accepted April 14, 2011; posted online July 29, 2011

We demonstrate that the maximum coherent superposition state can be selectively prepared using a sequence of pulse pairs in lambda-type atomic systems, with the final level as a doublet. In each pair, the Stocks pulse comes before the pump pulse, with their back edges overlapping. Numerical results indicate that by tuning the interval of the adjacent pulse pairs, the selective maximum coherent superposition state preparation between the initial and one of the final levels can be achieved. The phenomenon is caused by the accumulative property of the pulse sequence.

OCIS codes: 270.1670, 270.6620, 320.7110.
doi: 10.3788/COL201109.112701.

The coherent superposition state in atoms or molecules plays a crucial role in quantum physics. It has applications in many areas such as electromagnetically induced transparency[1−5], quantum information[6−8], and control of chemical reaction[9−11]. Many schemes can prepare the coherent superposition state. For instance, the fractional stimulated Raman adiabatic passage(F-STIRAP)[12] and the coherent population trapping[13] can obtain the maximum coherent superposition state of the two lower levels in lambda-type atoms. Our group also proposed several schemes to achieve this goal, such as the methods based on the STIRAP[14,15] and the pulse train method[16].

Currently, many quantum control schemes prefer employing pulse sequence or pulse train. For example, the direct optical excitation, rapid adiabatic passage, and STIRAP can extend to the multi-level case if the pulse train is adopted[17−19]. When the repetition period of the pulse train is smaller than the decay of the upper levels, it will possess the accumulative property of population and coherence[16,20]. This property has already been investigated by many researchers[21−25].

In lambda-type atomic configurations, if the final level is a doublet, and the pulse couples the two levels with the upper level at the same time, preparing the coherent superposition state between the initial and one of the final levels using the methods mentioned above seems difficult. Here, taking advantage of the accumulative property of the pulse train and based on the method of F-STIRAP, we propose that the selective preparation of the maximum coherent superposition state can be obtained using a sequence of pulse pairs. In this proposal, each pair has a similar pulse order with the F-STIRAP scheme. The Stocks pulse comes first and is followed after a certain time delay by the pump pulse. However, the back edges of the two pulses overlap. Numerical calculations show that an appropriate choice in the interval between the neighboring pulse pair can make the initial and one of the final levels go into the maximum coherent superposition state. The number of pulse pairs is not strictly required, but few pulse pairs are preferred to reduce the population loss through the upper level.

Considering the atomic configuration shown in Fig. 1, the final two levels are closely spaced with each other. The Stocks pulse couples the two transitions $|2>\rightarrow|3>$ and $|2>\rightarrow|4>$ simultaneously, and the pump pulse couples levels $|1>$ and $|2>$. The Hamiltonian of the system under the rotating wave approximation can be written as

$$\mathrm{H}=\begin{pmatrix} 0 & \Omega_{\mathrm{p}} & 0 & 0 \\ \Omega_{\mathrm{p}} & \Delta_{\mathrm{p}} & \Omega_{\mathrm{S}} & \Omega_{\mathrm{S}} \\ 0 & \Omega_{\mathrm{S}} & \Delta_{\mathrm{p}}-\Delta_{23} & 0 \\ 0 & \Omega_{S} & 0 & \Delta_{\mathrm{p}}-\Delta_{24} \end{pmatrix}, \quad (1)$$

where $\Delta_{\mathrm{p}}=\omega_{12}-\omega_{\mathrm{p}}$ is the detuning of the pump pulse with the $|1>\rightarrow|2>$ transition, and $\Delta_{23}=\omega_{23}-\omega_{\mathrm{S}}$ and $\Delta_{24}=\omega_{24}-\omega_{\mathrm{S}}$ are the detunings of Stocks pulse with the $|2>\rightarrow|3>$ and $|2>\rightarrow|4>$ transitions, respectively. As we use a sequence of pulse pairs here, the two pulses can be written in the following form: $\Omega_{\mathrm{p,S}}=\sum_{n=0}^{N-1}\Omega_{\mathrm{p,S}}^{0}f_{\mathrm{p,S}}(t-nT_{\mathrm{R}})$, with $\Omega_{\mathrm{p,S}}^{0}$ as the Rabi frequency amplitude, $f_{\mathrm{p,S}}(t-nT_{\mathrm{R}})$ as the envelope, and T_{R} as the interval of the neighboring pulses. Our scheme is based on the F-STIRAP method. Thus, we choose the envelope of the two pulses in the following form[12]:

$$\begin{cases} f_{\mathrm{p}}(t-nT_{\mathrm{R}})=\dfrac{\sqrt{2}}{2}\mathrm{e}^{-(t-\tau-nT_{\mathrm{R}})^2/T^2}, \\ f_{\mathrm{S}}(t-nT_{\mathrm{R}})=\mathrm{e}^{-(t+\tau-nT_{\mathrm{R}})/T^2}+\dfrac{\sqrt{2}}{2}\mathrm{e}^{-(t-\tau-nT_{\mathrm{R}})^2/T^2}, \end{cases} \quad (2)$$

where T is the pulse duration, and τ is the time delay between the Stocks and the pump pulse. The sequence of the pulse pair is given in Fig. 1. The dotted line denotes the Stocks pulse, whereas the solid line denotes the pump pulse.

In the following, we solve the density matrix equations

using the fourth-order Runge-Kutta method. First, we investigate the case when a single pulse pair is used. In the calculation, the parameters are scaled with respect to T, and we set $\Delta_{\rm p}=0$, $\Delta_{23}=0$, $\Delta_{24}=0$, $\Omega_{\rm p}^0=\Omega_{\rm S}^0=20$, and $\tau=0.7$. The population is initially assumed to be in level $|1>$. The parameters are chosen in a way similar to the F-STIRAP scheme. The result is shown in Fig. 2. Only one-third of the population is transferred adiabatically, and the final levels are equally distributed. The reason is that under this condition, the dark state of the system now is

$$\Psi_{\rm D}=\frac{2\Omega_{\rm S}}{\sqrt{4\Omega_{\rm S}^2+2\Omega_{\rm p}^2}}|1>-\frac{\Omega_{\rm p}}{\sqrt{4\Omega_S^2+2\Omega_{\rm p}^2}}(|3>+|4>). \tag{3}$$

When the Stocks and the pump pulse vanish simultaneously from Eq. (3), only one-third of the population can be transferred. Hence, because of the existence of the doublet, the F-STIRAP method is not available any more to prepare the maximum coherent superposition state.

To prepare the maximum coherent superposition state in such atomic configuration, we use a sequence of pulse pairs. Without loss of generality, we change Δ_{23} and Δ_{24} to be 0.1 and 0.5, respectively. We study the population evolution of the four levels under different intervals of the adjacent pulse pair. The results are shown in

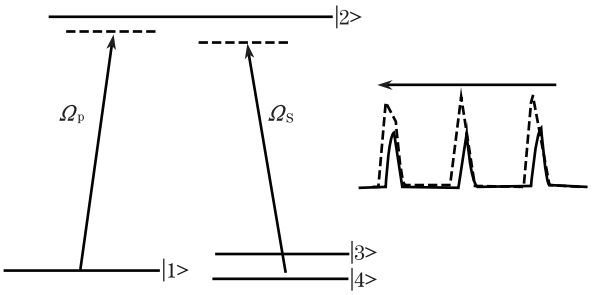

Fig. 1. Schematic atomic configuration and the incident pulse-pair sequence.

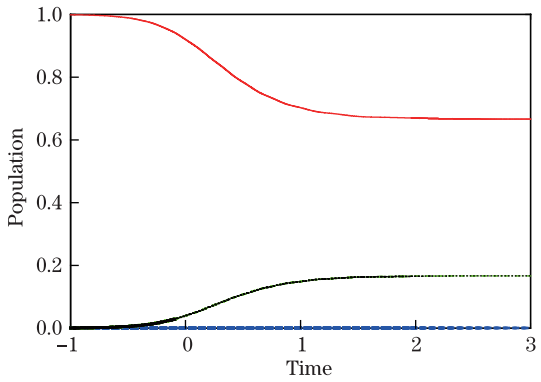

Fig. 2. (Color online) F-STIRAP scheme used in the atomic configuration shown in Fig. 1. The red solid line denotes level $|1>$, the blue dashed line denotes level $|2>$, the green dash dot ted line denotes level $|3>$, and the black dotted line denotes level $|4>$.

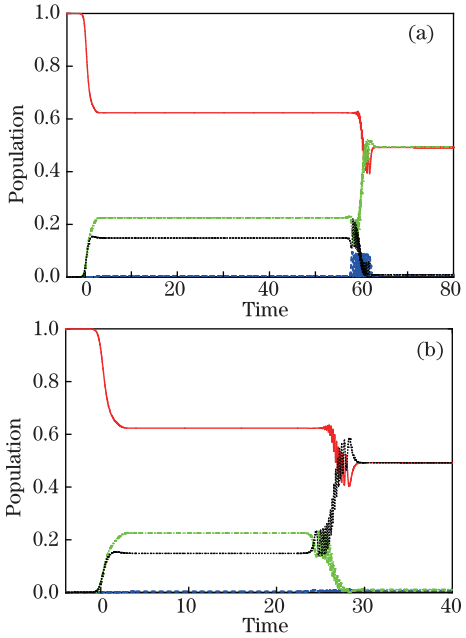

Fig. 3. Population evolution of the four levels at the interval of (a) $T_{\rm R}=59.89$ and (b) $T_{\rm R}=26.39$ when $\Delta_{23}=0.1$, $\Delta_{24}=0.5$.

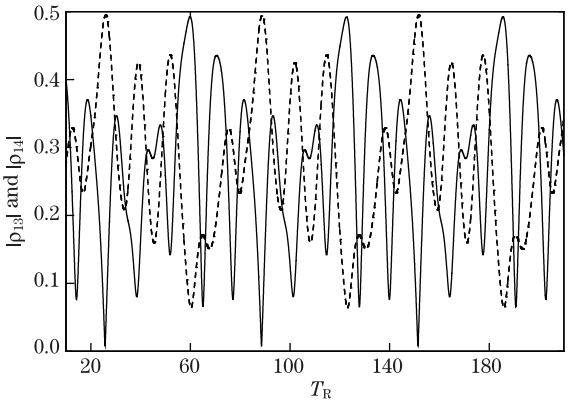

Fig. 4. Amplitudes of $|\rho_{13}|$ and $|\rho_{14}|$ varying with the interval $T_{\rm R}$. The solid line denotes $|\rho_{13}|$, and the dashed line denotes $|\rho_{14}|$.

Fig. 3, where only two pulse pairs are used. In Fig. 3(a), when the interval is $T_{\rm R}=59.89$, the maximum coherent superposition state between levels $|1>$ and $|3>$ can be obtained with the other two levels unpopulated. In Fig. 3(b), when the interval changes to $T_{\rm R}=26.39$, the maximum coherent superposition state of levels $|1>$ and $|4>$ is achieved. Therefore, the maximum coherent superposition state between the initial level and one of the final levels can be prepared by tuning the interval of the neighboring pulse pair. The conclusion is clarified in Fig. 4, where the amplitudes of ρ_{13} and ρ_{14} as a function of the interval are plotted. The figure shows that the periodic structure appears for both of the two coherence terms. The structure is caused by the accumulative property of the pulse train, which is discussed in great detail in our previous work[16]. For example, in the case of $T_{\rm R}=59.89$, the destructive accumulative property drives the population in level $|4>$ to zero. The mechanism of the F-STIRAP then induces the population to be distributed equally in levels $|1>$ and $|3>$.

We must point out that the results shown above are obtained under the condition of two-photon detuning, which means that the strict two-photon resonance condition in STIRAP and F-STIRAP is not required. Further calculations indicate that for these kinds of four-level atoms with arbitrary detunings of $\Delta_{\rm p}$, Δ_{23}, and Δ_{24}, the selective maximum coherent superposition state is always available by merely adjusting the pulse interval. Using more pulse pairs obtains the same results, but note that using only several pulse pairs is always better. The reason is that the population in the upper level must be avoided, and using only several pulse pairs can attain the interaction in such an ultrashort time that the spontaneous decay can be ignored. Moreover, we should keep in mind that the pulse duration should be chosen to satisfy the condition that the interval between the adjacent pulse pair should be smaller than the decay of the upper level.

Finally, we demonstrate the feasibility of our proposal in experiment. First, the atoms should have the same configuration as required and long coherence time of the lower levels. Thus, gas-phase atoms, especially cold atoms, are preferable in carrying out the experiment. The configuration in our scheme is a tripod, which is common in many atoms as long as the selection rule is satisfied ($\Delta m = 0, \pm 1$). Hence, the frequently used cold ^{87}Rb atom is suitable. As regards to the pulse train sequence, the single pulse pair with back edges overlapping has been considered to be produced easily using two laser sources[12]. As only two pulse pairs are required in our proposal, a beam splitter can be employed to split simply the single pulse pair, and the delay between them can be tuned with a delay line. If more pulse pairs are required, two laser sources that generate pulses repeatedly are preferred, with their repetition period adjusted the same.

In conclusion, we investigate the selective preparation of maximum coherent superposition state in lambda-type atoms with the final level as a doublet. This state is implemented using a sequence of pulse pairs based on the F-STIRAP scheme. The selectivity is realized by tuning the interval of the adjacent pulses. The accumulative property of the pulse train is the key to this phenomenon.

This work was supported by the National Natural Science Foundation of China (Nos. 10874194 and 60978013). and the Shanghai Commission of Science and Technology (No. 10530704800)

References

1. M. Lu, F. Jose, and J. D. Weinstein, Phys. Rev. A **82,** 061802 (2010).
2. B. Wu, J. F. Hulbert, E. J. Lunt, K. Hurd, A. R. Hawkins, and H. Schmidt, Nat. Photon. **4,** 776 (2010).
3. T. Kampschulte, W. Alt, S. Brakhane, M. Eckstein, R. Reimann, A. Widera, and D. Meschede, Phys. Rev. Lett. **105,** 153603 (2010).
4. X. Yan, L. Wang, B. Yin, and J. Song, Chin. Opt. Lett. **8,** 795 (2010).
5. Y. Qi, H. Gao, and S. Zhang, Chin. Opt. Lett. **8,** 1 (2010).
6. Z. S. Yuan, X. H. Bao, C. Y. Lu, J. Zhang, C. Z. Peng, and J. W. Pan, Phys. Rep. **497,** 1 (2010).
7. C. Chudzicki and F. W. Strauch, Phys. Rev. Lett. **105,** 260501 (2010).
8. G. Toth, W. Wieczorek, D. Gross, R. Krischek, C. Schwemmer, and H. Weinfurter, Phys. Rev. Lett. **105,** 250403 (2010).
9. Z. Li, C, Xie, B. Jiang, D. Xie, L. Liu, Z. Sun, D. H. Zhang, and H. Guo, J. Chem. Phys. **134,** 134303 (2011).
10. R. S. Zhu and M. C. Lin, J. Chem. Phys. **134,** 054307 (2011).
11. I. B. Malham, N. Jarrige, J. Martin, N. Rakotomalala, L. Talon, and D. Salin, J. Chem. Phys. **133,** 244505 (2010).
12. N. V. Vitanov, K. A. Suominen, and B. W. Shore, J. Phys. B **32,** 4535 (1999).
13. V. G. Arkhipkin and I. V. Timofeev, Phys. Rev. A **64,** 053811 (2001).
14. Y. P. Niu, S. Q. Gong, R. X. Li, and S. Q. Jin, Phys. Rev. A **70,** 023805 (2004).
15. L. Deng, Y. P. Niu, Y. Xiang, S. Q. Jin, and S. Q. Gong, J. Phys. B **43,** 035401 (2010).
16. L. Deng, Y. P. Niu, L. L. Jin, and S. Q. Gong, J. Phys. B **43,** 205502 (2010).
17. L. E. E. de Araujo, Phys. Rev. A **77,** 033419 (2008).
18. E. A. Shapiro, V. Milner, and M. Shapiro, Phys. Rev. A **79,** 023422 (2009).
19. E. A. Shapiro, A. Pe'er, J. Ye, and M. Shapiro, Phys. Rev. Lett. **101,** 023601 (2008).
20. D. Felinto, C. A. C. Bosco, L. H. Acioli, and S. S. Vianna, Phys. Rev. A **64,** 063413 (2001).
21. D. Felinto, C. A. C. Bosco, L. H. Acioli, and S. S. Vianna, Opt. Commun. **215,** 69 (2003).
22. D. Felinto, L. H. Acioli, and S. S. Vianna, Phys. Rev. A **70,** 043403 (2004).
23. A. A. Soares and L. E. E. de Araujo, Phys. Rev. A **76,** 043818 (2007).
24. W. F. Yang, S. Q. Gong, R. X. Li, and Z. Z. Xu, Phys. Rev. A **74,** 013407 (2006).
25. A. A. Soares and L. E. E. de Araujo, Phys. Rev. A **80,** 013832 (2009).