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Citation: Applied Physics Letters **95**, 221103 (2009); doi: 10.1063/1.3269997
View online: http://dx.doi.org/10.1063/1.3269997
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/95/22?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **95**, 221103 (2009)

Realization of a single and closed Λ-system in a room-temperature three-level coherently prepared resonant medium with narrow D_1 hyperfine splittings

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(Received 9 July 2009; accepted 9 November 2009; published online 1 December 2009)

A single, closed three-state Λ-system in room-temperature rubidium is investigated experimentally using a copropagating beam parallel-polarization configuration under *weakly driven* electromagnetically induced transparency (EIT) condition. Compare with the widely used orthogonal-polarization beam EIT configuration where multiple nonclosed Λ-schemes coexist, the parallel-polarizations configuration can completely eliminate the leakage light from the control field. Our state preparation and laser polarization lead to a single and closed Λ-scheme that eliminates the detrimental absorption due to nearby states in atomic species with hyperfine separations smaller than Doppler-broadened line widths, a case where the conventional EIT configuration fails completely. © *2009 American Institute of Physics*. [doi:10.1063/1.3269997]

Electromagnetically induced transparency (EIT) (Ref. 1) is a technique that has been widely used to reduce or suppress absorption of a probe field tuned to a strong one-photon transition. In room-temperature gaseous phase *weakly driven*[2] three-state Λ-type media, EIT is observable *only* in a copropagation beam geometry because of the dominant Doppler effect.[3–7] All weakly driven EIT demonstrations using Zeeman sublevels reported in the literature to date employ such an excitation configuration together with an orthogonal polarization beam geometry (i.e., $\sigma_{\rm probe}^{(\mp)}-\sigma_{\rm control}^{(\pm)}$) [Fig. 1(b)]. This beam geometry, however, has two drawbacks under weak driving conditions that are essential in all slow light and storage of light operations. First, the birefringence of the medium under the excitation of the control field rotates the polarization of the control field slightly. This results in a small fraction of the control laser, which is still significant compared with the very weak probe light, exiting the probe light port and giving a substantially elevated background that often has large fluctuation and noise. Second, at room-temperature such an orthogonal polarization beam geometry (i.e., $\sigma_{\rm probe}^{(\mp)}-\sigma_{\rm control}^{(\pm)}$) leads to multiple Λ excitation channels with various detunings even with state preparation, causing significant near-by state absorption to the probe light.[3–7] This is particularly the case for alkali elements with the lowest *P* hyperfine splittings being significantly less than the average Doppler broadened line widths [see Fig. 1(b)]. For instance, the D_1 manifolds of ^{23}Na and ^{85}Rb have only 192 and 364 MHz hyperfine splittings, respectively,[8] whereas their room-temperature Doppler broadened linewidths are 300–600 MHz. The situation with D_2 line is much worse because of the closely packed hyperfine levels and multiple allowed Λ transitions. Narrow hyperfine splittings is one of the main reasons why these elements are not used for weakly driven EIT applications such as light storage.[5,6]

In this letter, we demonstrate a scheme that can eliminate these problems. Our work is based on two principles [Fig. 1(a)] (1) proper state-preparation and (2) parallel laser polarizations with small angle crossing beam geometry. It is the combination of these two key elements that yields a unique single and closed Λ atomic medium where a clear EIT signal can be observed with atomic species of very narrow hyperfine splittings at elevated temperature, a situation where the popular orthogonal-polarization beam configuration fails completely. We note that the technique of state preparation and parallel-beam geometry have been employed previously in many studies.[9–18] However, none of these studies has used the state preparation as reported here.[19]

We use a room-temperature atomic vapor of ^{85}Rb to demonstrate the single, closed three-state Λ-type weakly driven EIT effect because of its closely spaced hyperfine states in D_1 line transitions. We first prepare the medium using two combined optical pumping processes. In the first

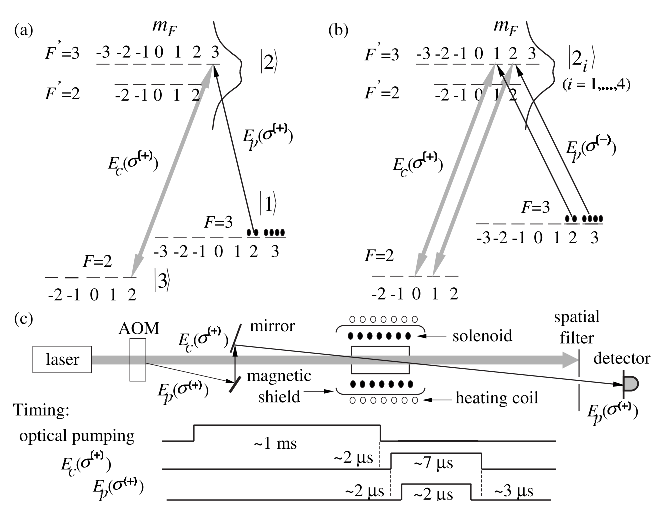

FIG. 1. (a) A single, closed Λ channel enabled by the $\sigma_{\rm probe}^{(+)}-\sigma_{\rm control}^{(+)}$ scheme studied in this work and (b) widely used $\sigma_{\rm probe}^{(-)}-\sigma_{\rm control}^{(+)}$ scheme where multiple unclosed on-resonance ($F'=3$) and off-resonance ($F'=2$) Λ channels coexist because of strongly overlap of Doppler broadened lines. (c) Experiment setup and timing scheme (also see Ref. 3).

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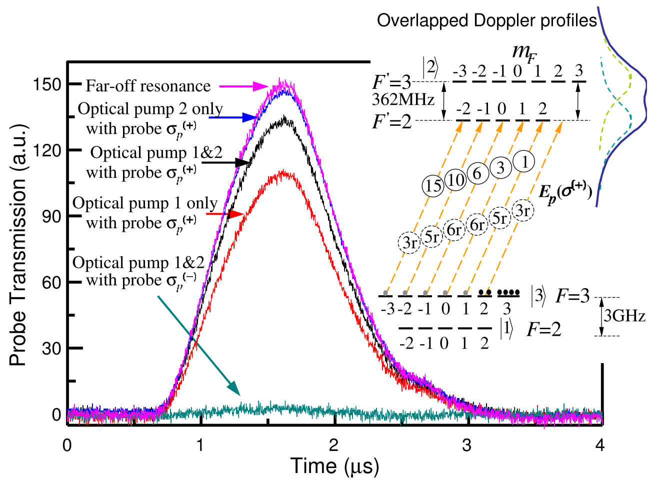

FIG. 2. (Color online) Population probing. Inset: transitions used to analyze residual population after optical pumping. Numbers in solid circles are relative transition strengths (Ref. 21). Dashed circles describe off-resonance contributions which are given by relative transition strengths multiplied by a parameter r $(0<r<1)$, which can be precisely calculated from quantum mechanics (Ref. 21), to account the reduction of transition strength due to hyperfine separation or detuning.

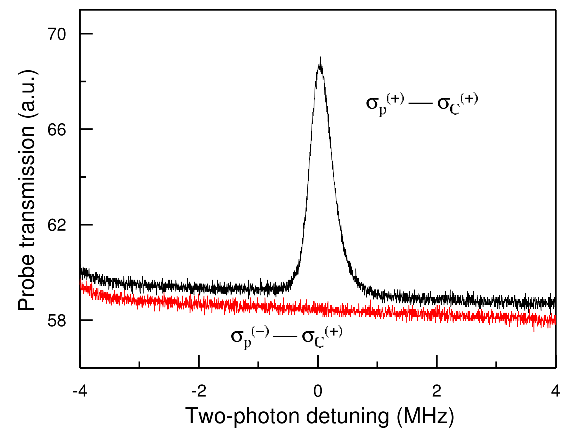

FIG. 3. (Color online) EIT probe transmission as a function of two-photon detuning. Upper trace: $\sigma^{(+)}_{\rm probe}-\sigma^{(+)}_{\rm control}$ scheme [Fig. 1(a)]. Lower trace: $\sigma^{(-)}_{\rm probe}-\sigma^{(+)}_{\rm control}$ scheme [Fig. 1(b)]. $T\approx 60$ °C, $2|\Omega_p|=2\pi\times 7.6$ MHz, $2|\Omega_C|=2\pi\times 39$ MHz. Traces are intensionally shifted to show clarity.

optical pumping process a $\sigma^{(+)}$ laser field (E_{P1}, $\lambda=795$ nm) drives the $5S_{1/2},F=2\rightarrow 5P_{1/2},F'=3$ transition. All magnetic substates in the $5S_{1/2},F=2$ manifold are emptied because of angular momentum selection rule. In the second optical pumping process a separate $\sigma^{(+)}$ laser field (E_{P2}, $\lambda=795$ nm) drives $5S_{1/2},F=3\rightarrow 5P_{1/2},F'=2$ transition. This process empties all $m_F=-3,\ldots,+1$ magnetic substates because of the selection rule. From angular momentum consideration $m_F=+2,+3$ substates should not be affected by the $\sigma^{(+)}$ light. However, because of the nearby hyperfine manifold $5P_{1/2},F'=3$ (i.e., its $m_{F'}=+3$ substate), there is a weak pumping-out rate (because of the hyperfine separation) for the $m_F=+2$ sub state. Consequently, we have an atomic medium with population only in $m_F=2$ (small) and $m_F=3$ (large) magnetic sublevels of the $5S_{1/2},F=3$ manifold. The latter state, however, does *not* contribute to our EIT measurement precisely because of selection rule.

The first key experimental step is to make sure that only $m_F=+2,+3$ substates of $5S_{1/2},F=3$ manifold are populated. Using a $\sigma_p^{(+)}$ probe field that couples $5S_{1/2},F=2\rightarrow 5P_{1/2},F'=3$ transition, we find *no* noticeable absorption, therefore $5S_{1/2},F=2$ manifold is emptied. We now concentrate on detecting possible population in the $m_F=-3,\ldots,+1$ magnetic substates of the $5S_{1/2},F=3$ manifold. This is done by probing the $5S_{1/2},F=3$ manifold using different polarization combinations (Fig. 2). We first probe the $5S_{1/2},F=3$ manifold using a $\sigma_p^{(+)}$ light coupling $5S_{1/2},F=3\rightarrow 5P_{1/2},F'=3$ with very large detuning. This gives probe field reference (top trace, no absorption). We then tuned the $\sigma_p^{(+)}$ probe field on $5S_{1/2},F=3\rightarrow 5P_{1/2},F'=3$ resonance and probe the manifold with only the first optical pumping process carried out (see description above). Since the first optical pumping process empties the $5S_{1/2},F=2$ manifold, therefore all population is transferred to the $5S_{1/2},F=3$ manifold, resulting in increased absorption (fourth trace from the top).[20] We then probe the manifold with only the second optical pumping process carried out (second trace from the top). This curve shows that the second optical pumping process is very efficient. Next, we probe the manifold with both optical pumping processes carried out together. This is the state preparation we use for our EIT experiment. The drop of the transmission peak indicates the population in the $m_F=+2$ substate of the $5S_{1/2},F=3$ manifold (third trace from the top). Finally, we probe the manifold after two optical pumping process but use an on-resonance $\sigma_p^{(-)}$ probe (bottom trace). Using these two absorption curves it can be shown that the upper bound of the *total residual population* in the $m_F=-3,\ldots,+1$ substates combined (gray dots) is $\leq 10\%$ of the population in the $m_F=+2$ level which is about a factor of 3 less than the "dark" population in the state $m_F=+3$. This validates our claim of a single-Λ scheme in a medium with overlapping Doppler-broadened hyperfine levels. Indeed, using our state preparation excellent EIT two-photon resonance signals can be obtained for an atomic medium having narrow hyperfine separation. Under the same weak driving conditions, however. the conventional orthogonal-polarization EIT configuration fails to yield any EIT signal (see Fig. 3 below).

To demonstrate the advantages of the parallel-polarization EIT scheme with the above described state preparation we use right-circularly polarized probe and control fields [see Fig. 1(a)]. In this $\sigma^{(+)}_{\rm probe}-\sigma^{(+)}_{\rm control}$ configuration the probe field couples the $|1\rangle=|5S_{1/2},F=3,m_F=2\rangle\rightarrow|2\rangle=|5P_{1/2},F'=3,m_F=3\rangle$ transition only whereas the control field couples the $|3\rangle=|5S_{1/2},F=2,m_F=2\rangle\rightarrow|2\rangle=|5P_{1/2},F'=3,m_{F'}=3\rangle$ transition only. Note that because of the small energy spacing (364 MHz) the $F'=2$ and $F'=3$ levels of the $5P_{1/2}$ manifold overlap strongly due to the Doppler broadened profiles at room-temperature. Thus, if the polarizations of the probe and control fields are chosen as in the popular $\sigma^{(-)}_{\rm probe}-\sigma^{(+)}_{\rm control}$ configuration both levels contribute significantly to one-photon processes that involve the probe light [Fig. 1(b)]. With our state preparation and our choice of laser polarizations the electric dipole transition selection rules dictate that the probe and control fields can *only* excite the atomic transitions depicted in Fig. 1(a). That is, even though the Doppler-broadened line widths of all nearby hyperfine states overlap strongly with the laser bandwidth they make *no* contribution to the absorption of the probe field due to the selection rules, and we have a single, closed three-state Λ system that behaves like a cold medium.

We use a single diode laser and a 3 GHz acousto-optical modulator to generate both probe and control beams.[22] A

^{85}Rb cell of length $L=100$ mm and diameter $d=25$ mm filled with a 10 mBar neon buffer gas is placed in a magnetically shielded and temperature controlled housing with a solenoid that provides a stable unidirectional magnetic field of $\approx 1.0\times 10^{-5}$ Tesla. After the cell, a spatial filter blocks the control light and only probe light can reach the detector.

In Fig. 3, we show probe light transmittance as a function of two-photon detuning. Here, the control laser frequency is fixed to the one-photon resonance and the probe frequency is scanned across the two-photon resonance. The upper trace shows the EIT transmission using parallel polarization scheme [Fig. 1(a)] whereas the lower trace corresponds to the widely used orthogonal polarization scheme [Fig. 1(b)]. The EIT transmission peak for the parallel-polarization scheme has an excellent signal-to-noise ratio but no EIT transmission peak is detectable for orthogonal-polarization scheme. In fact, the absorption due to nearby states is so severe that no probe light can be detected in the latter case. These measurements establish the fact that under weak driving conditions the parallel polarization scheme is superior to the orthogonal polarization scheme. Indeed, with the commonly used orthogonal scheme effects due to nearby states and multiple off-resonance Λ channels have completely incapacitated any EIT effect using ^{85}Rb at elevated concentration (room-temperature). It is rather remarkable that such a pronounced two-photon resonance can be obtained in our scheme with only small a population in the ground state $|5S_{1/2},F=3,m_F=2\rangle$.

With high-quality EIT signal shown in Fig. 3 we have carefully studied probe field propagation dynamics and we can make accurate comparison with predictions based on a "life-time broadened" single-Λ system. Such an accurate comparison is not possible for the conventional EIT polarization configuration for the atomic specie studied here. For instance, by fitting the group velocity measurement[23] we obtain an *effective* atom number density $N_{\rm eff}\approx 1.4\times 10^{17}/{\rm m}^3$, a result that agrees well with our residual population verification after proper optical pumping procedures. We note that the atom number density obtained based on the cell temperature is $N\approx 3.8\times 10^{17}/{\rm m}^3$ at $T=61.5$ °C. Thus, $N_{\rm eff}<N$ indicates that only a fraction of the total population (therefore, the *effective* density) resides in the ground state $|5S_{1/2},F=3,m_{\rm F}=2\rangle$ as discussed before. A large fraction is in the $5S_{1/2},F=3,m_{\rm F}=+3$ dark state that does not contribute. Due to space limitation propagation dynamics measurements and population analysis will be published elsewhere.

In conclusion, we have demonstrated experimentally that by appropriate atomic state preparation and laser polarizations selection it is possible to realize a single, closed three-state Λ-system in a room-temperature gaseous phase atomic element that has narrow (smaller than average Doppler line width) hyperfine level separations. We have shown a clear EIT signal with excellent signal-to-noise ratio under the driving conditions where the commonly used EIT excitation scheme fails completely. The state preparation, laser polarizations, and excitation scheme reported here open the possibility for blue-light Λ-type EIT processes, which requires higher $nP_{1/2}$ states as the upper excited state, using Doppler-broadened alkali vapors, which is a possibility that does not exist for the conventional EIT configuration.

[1] S. E. Harris, Phys. Today **50** (7), 36 (1997).
[2] Where $2|\Omega_C|<10\Gamma$, where $2\Omega_C$ is the driving field Rabi frequency, Γ is the upper state lifetime.
[3] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett. **86**, 783 (2001).
[4] Y. Q. Li and M. Xiao, Phys. Rev. A **51**, 4959 (1995).
[5] M. M. Kash, V. A. Sautenkov, A. S. Zibrov, L. Hollberg, G. R. Welch, M. D. Lkin, Y. Rostovtsev, E. S. Fry, and M. O. Scully, Phys. Rev. Lett. **82**, 5229 (1999).
[6] A. S. Zibrov, M. D. Lukin, D. E. Nikonov, L. Hollberg, M. O. Scully, V. L. Velichansky, and H. G. Robinson, Phys. Rev. Lett. **75**, 1499 (1995).
[7] O. Schmidt, R. Wynands, Z. Hussein, and D. Deschede, Phys. Rev. A **53**, R27 (1996).
[8] We note that no room-temperature, weakly driven (ultraslow-wave) EIT experiment using ^{23}Na or ^{85}Rb can be found in literature. Even for ^{87}Rb (about 800 MHz hyperfine splitting) the loss of the probe field using common EIT beam scheme is still significant at elevated temperature due to the presence of multiple Λ channels.
[9] F. Levi, A. Godone,J. Vanier, S. Micalizio, and G. Modugno, Eur. Phys. J. D **12**, 53 (2000).
[10] T. Zanon, S. Guerandel, E. de Clercq, D. Holleville, N. Nimarcq, and A. Clairon, Phys. Rev. Lett. **94**, 193002 (2005).
[11] A. Godone, F. Levi, and S. Micalizio, Phys. Rev. A **66**, 043804 (2002).
[12] E. E. Mikhailov, V. A. Sautenkov, I. Novikova, and G. Welch, Phys. Rev. A **69**, 063808 (2004).
[13] S. Brandt, A. Nagel, R. Wynands, and D. Meschede, Phys. Rev. A **56**, R1063 (1997).
[14] M. Erhard and H. Helm, Phys. Rev. A **63**, 043813 (2001).
[15] A. B. Matsko, D. Strekalov, and L. Maleki, Opt. Express **13**, 2210 (2005).
[16] R. Wynands and A. Nagel, Appl. Phys. B: Lasers Opt. **68**, 1 (1999).
[17] Y. Y. Jau, E. Miron, A. B. Post, N. N. Kuzma, and W. Happer, Phys. Rev. Lett. **93**, 160802 (2004).
[18] R. Meshulam, T. Zigdon, A. D. Wilson-Gordon, and H. Friedmann, Opt. Lett. **32**, 2318 (2007).
[19] Indeed, state preparation schemes employed in these studies all result in the media being in a ground state where multiple Λ-channels and near-by states contributions cannot be avoided.
[20] Note that $m_F=+3$ is a "dark" state which does not contribute to the absorption.
[21] H. J. Metchalf and P. V. der Straten, *Laser Cooling and Trapping* (Springer, New York, 1999).
[22] The beams have a crossing angle of ≈ 2.0 mrad in the atomic medium. The popular EIT scheme [Fig. 1(b)] could not yield any detectable signal under our weak driving conditions even with zero crossing angle.
[23] By measuring delay time one obtains group velocity. Using group velocity expression one obtains density, see L. Deng, E. W. Hagley, M. Kozuma, and M. G. Payne, Phys. Rev. A **65**, 051805(R) (2002).