Optical pumping-assisted electromagnetically induced transparency

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(Received 14 January 2006; published 4 May 2006)

In this paper we report an observation of the two-photon absorption in a four-level system in hot ^{87}Rb vapor based on the proposal of Harris and Yamamoto [Phys. Rev. Lett. **81**, 3611 (1998)]. We show that this effect is reduced in hot atoms due to the non-Doppler-free nature of this scheme. Then we report a phenomenon that could be used in the same application of Harris and Yamamoto. The main result is a great enhancement of electromagnetically induced transparency (EIT) effect in hot ^{87}Rb vapor caused by optical pumping. We find that when the single photon detuning is near zero the EIT signal is dramatically enhanced by an optical pumping field. More interestingly when the single photon detuning is larger the signal can be changed from a sharp Raman peak to a sharp EIT dip. The full width at half maximum of the peak and dip are narrow and subnatural.

DOI: 10.1103/PhysRevA.73.053804 PACS number(s): 42.50.Gy, 32.80.Bx

I. INTRODUCTION

Electromagnetically induced transparency is one of the most fascinating phenomena in atomic physics [1]. In this effect, both the linear and nonlinear susceptibility of the medium are strongly modified by quantum interference. Numerous interesting applications based on this effect have been proposed [2–7]. One interesting application among them is the interference photon switch proposed by Harris and Yamamoto [3]. In this scheme, quantum interference inhibits single-photon absorption but enhances third-order, two-photon-type absorption in the four-level system. Experimental demonstrations of this scheme in cold atoms have been reported [8–10]. In this paper, we report an experimental demonstration of this absorptive photon switching by quantum interference in hot ^{87}Rb vapor. We will show that due to the influence of Doppler broadening, the result is not as dramatic as it is in cold atoms. However, this effect can still be clearly seen. Furthermore, we report a phenomenon that could be used to improve all optical switching. We call it optical pumping-assisted electromagnetically induced transparency (EIT). Unlike the scheme of Harris and Yamamoto, our scheme is unaffected by Doppler broadening. The main result is a great enhancement of EIT due to the optical pumping effect. We find that when the single photon detuning is near zero the EIT signal is dramatically enhanced by an optical pumping field. More interestingly when the single photon detuning is larger the signal can be changed from a sharp Raman peak to a sharp EIT dip by increasing optical pumping power. The full width at half maximums (FWHMs) of the peak and dip are very narrow and subnatural.

The remainder of this paper is organized into three parts. In Sec. II, we report the experiment of two-photon absorption in hot ^{87}Rb vapor. A theoretical calculation is given and is in good agreement with our experimental results. In Sec. III, we report the new phenomenon we observed. We end the paper with a discussion in Sec. IV.

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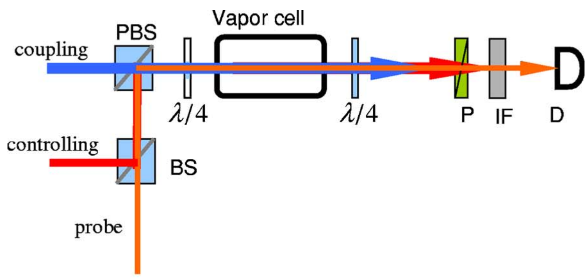
II. TWO-PHOTON ABSORPTION IN A FOUR-LEVEL SYSTEM

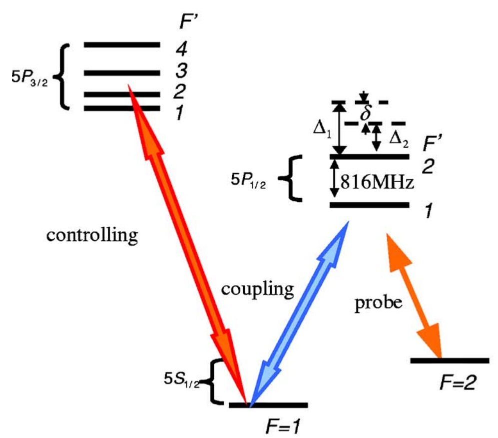
A. Experiment

Figure 1 is the schematic setup of our experiment and the energy diagram of ^{87}Rb. We use an isotopically pure ^{87}Rb cell. The temperature of the cell is about 50 °C, corresponding to an atomic density about 1.5×10^{11} cm^{-3}. The length of the cell is about 3 cm. The two ground hyperfine levels of $5S_{1/2}$ with $|5P_{1/2},F=2\rangle$ and $|5P_{3/2},F=2\rangle$ form a N-type four-level atomic system. The inside wall of the cell is paraffin coated. A 795 nm coupling field is a σ^+ field tuned to the $|5S_{1/2},F=1\rangle\rightarrow|5P_{1/2},F=2\rangle$ transition. It has a detuning Δ_1 relative to the $|5S_{1/2},F=1\rangle\rightarrow|5P_{1/2},F=2\rangle$ transition. We keep $\Delta_1=0$ throughout the experiment described in this section. A 795 nm probe field is a σ^- field tuned to the $|5S_{1/2},F=2\rangle\rightarrow|5P_{1/2},F=2\rangle$ transition. It has a detuning Δ_2 relative to the $|5S_{1/2},F=2\rangle\rightarrow|5P_{1/2},F=2\rangle$ transition. A third 780 nm controlling field with σ^- polarization is tuned to the $|5S_{1/2},F=1\rangle\rightarrow|5P_{3/2},F=2\rangle$ transition. These three fields are made to be copropagating. Their diameters inside the vapor cell are about 1 mm. After the cell the coupling field is separated from the probe field by a $\lambda/4$ wave plate and a polarizer. The controlling beam is blocked by a 3 nm interference plate with central wavelength 795 nm.The power of the coupling and probe field is 1.3 mW and 80 μW, respectively. The probe transmission spectrum is recorded with different controlling field powers.

Figure 2 shows the experimental result. The line (c) is the absorption spectrum without a controlling field. The spectrum shows a normal EIT dip at the two-photon resonance. The background is a Gaussian shape contributed by Doppler broadening plus a Lorentzian shape contributed by the hyperfine optical pumping effect of the coupling field. When the controlling field is added, the depth of the dip is notably reduced. When the power of the controlling field is 0.5 mW, the dip is only half of its original depth. When the power of the controlling field is increased to 1.0 mW, the depth of the dip is further reduced to about 24% of its original depth. When we increase the controlling power further, the spectrum shows some saturation and the depth of the dip is not



(a) Experimental setup



(b) Energy diagram of ^{87}Rb .

FIG. 1. (Color online) Experimental setup and the energy diagram of ^{87}Rb. (a) PBS: polarizing beam splitter; BS: beam splitter, P: polarizer; and IF: interference filter. (b) A 795 nm coupling field is a σ^{+} field tuned to the $|5S_{1/2},F=1\rangle \rightarrow |5P_{1/2},F=2\rangle$ transition ($\Delta_1=0$ MHz). A 795 nm probe field is a σ^{-} field whose frequency is scanned near the $|5S_{1/2},F=2\rangle \rightarrow |5P_{1/2},F=2\rangle$ transition. A third 780 nm controlling field with σ^{-} polarization is tuned to the $|5S_{1/2},F=1\rangle \rightarrow |5P_{3/2},F=2\rangle$ transition. These three fields are made to be copropagating, and the diameters inside the vapor cell are about 1 mm. After the cell the coupling field is separated from the probe field by a $\lambda/4$ wave plate and a polarizer.

reduced anymore. Comparing our results with previous works done in cold atoms, we can see that the Doppler broadening reduces the efficiency of the photon switch [8–10]. This is not surprising because the copropagating configuration is Doppler-free for EIT, but not so for the *N*-type four-level atomic system. Only atoms that are nearly resonant with the controlling field contribute to the two-photon absorption process. Other atoms simply act as an EIT medium for the probe field. Here we want to mention that this experimental result is not due to the optical pumping effect of the controlling laser. Since the coupling field is much stronger than the probe field, almost all atoms are in state $|5S_{1/2},F=2\rangle$ already. An additional controlling field, which is resonant with the $|5S_{1/2},F=1\rangle \rightarrow |5P_{3/2},F=2\rangle$ transition should have a negligible effect on the population distribution of the atoms. This can be seen from the experimental results. The background of the probe absorption profile is almost the same with and without the controlling laser. In the next section we present the theoretical model that explains these results.

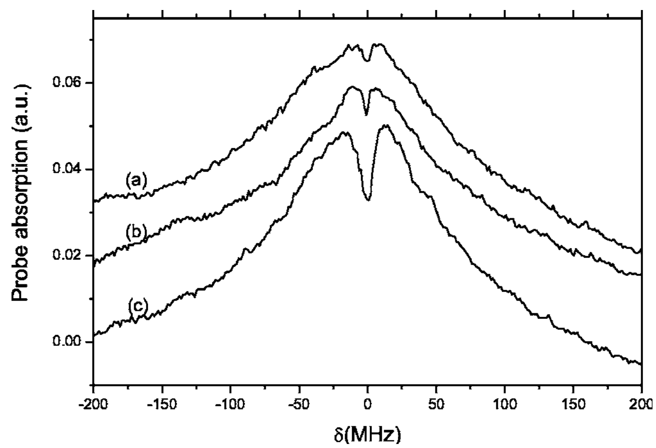


FIG. 2. Probe absorption with different controlling field power. The power of controlling field for (a), (b), and (c) is 1.0, 0.5, and 0 mW, respectively (the curves have been vertically shifted for clarity).

B. Theory

Consider a four-level atom shown in Fig. 3. The probe field is coupled to the $|1\rangle \rightarrow |3\rangle$ transition. The coupling field is coupled to the $|2\rangle \rightarrow |3\rangle$ transition. And the controlling field is coupled to the $|2\rangle \rightarrow |4\rangle$ transition. The Hamiltonian in the interaction picture is

$$H = -\Delta_p|3\rangle\langle 3| - \delta|2\rangle\langle 2| - \Delta_{24}|4\rangle\langle 4| - \frac{1}{2}(\Omega_p|1\rangle\langle 3| + \Omega_c|2\rangle\langle 3| + \Omega_{c'}|2\rangle\langle 4| + \text{H.c.}), \tag{1}$$

where $\Delta_p=\omega_p-\omega_{31}$, $\Delta_c=\omega_c-\omega_{32}$, $\delta=\Delta_p-\Delta_c$, and $\Delta_{24}=(\omega_p-\omega_{31})-(\omega_c-\omega_{32})+(\omega_{c'}-\omega_{42})$. Ω_p, Ω_c, and $\Omega_{c'}$ are the Rabi frequencies, respectively. Seeking the steady state solution of state amplitude equations and assuming that almost all atoms are in the ground state $|1\rangle$, we can find [3],

$$\chi(\omega_p) = \frac{K(4\tilde{\delta}\tilde{\Delta}_{24} - |\Omega_{c'}|^2)}{4\tilde{\Delta}_p\tilde{\delta}\tilde{\Delta}_{24} - |\Omega_c|^2\tilde{\Delta}_{24} - |\Omega_{c'}|^2\tilde{\Delta}_1}, \tag{2}$$

where $K=N|\mu_{13}|^2/\hbar\epsilon_0$ and N is the density of the atoms. The relaxations of the energy levels are introduced by defin-

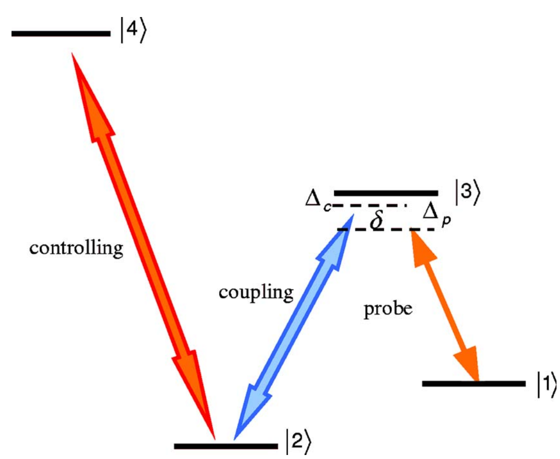


FIG. 3. (Color online) A four-level atom with *N*-type configuration.

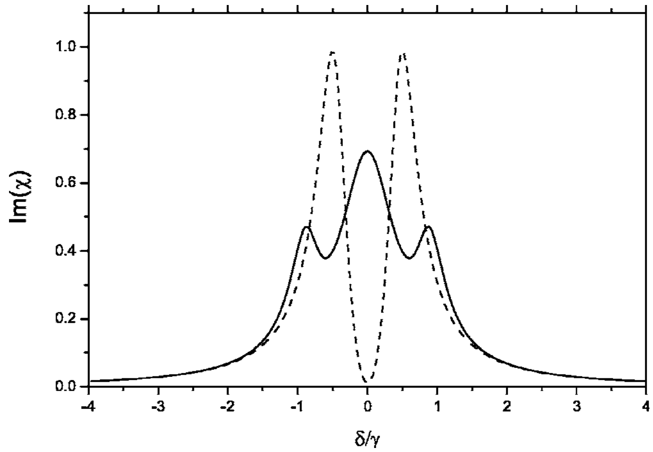


FIG. 4. Probe absorption with controlling field $\omega_{c'}$ on (solid line) and off (dashed line). Doppler broadening effect is not included in this plot. Parameters are $\Delta_1=0$, $\gamma_{13}=\gamma_{24}=\gamma$, $\gamma_{12}=0.01\gamma$, $\Omega_c=\gamma$, and $\Omega_{c'}=1.5\gamma$.

ing $\tilde{\Delta}_p=\Delta_p-k\cdot v+i\gamma_{13}$, $\tilde{\delta}=\delta-k\cdot v+i\gamma_{12}$, and $\tilde{\Delta}_{24}=\Delta_{24}-k\cdot v+i\gamma_{24}$, where $k\cdot v$ is the Doppler shift. Figure 4 shows the probe absorption profile with controlling field $\omega_{c'}$ on and off. In this calculation the coupling field is kept resonant with the $|2\rangle\rightarrow|3\rangle$ transition; and Doppler broadening is not included by setting $k=0$. When the controlling field is on, the original transparent window at two-photon resonance becomes opaque to the probe field. This is the essence of the scheme of Harris and Yamamoto.

Because our experiment is done in a hot atom system, the Doppler effect must be taken into account. The Doppler broadening is about 500 MHz in our case. We average χ in Eq. (2) over the velocity distribution. The optical pumping effect of the coupling field is included by introducing a Lorentzian term near the resonance of $\Delta_p=0$. Figure 5 shows the Doppler averaged probe absorption profile. We can see that the absorption at two-photon resonance induced by the controlling field is reduced in the presence of Doppler broadening. This reduction is due to the non-Doppler-free configuration of the experiment. However, the presence of the controlling field still significantly increases two-photon resonant absorption. Comparing Fig. 5 with Fig. 2 we can see they are in good agreement.

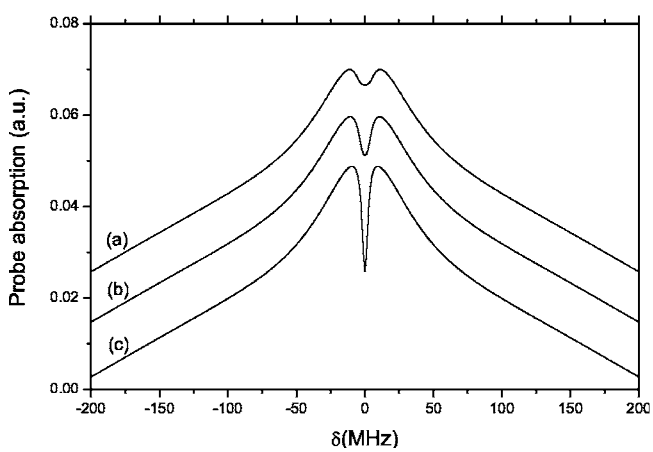


FIG. 5. Numerical simulation of probe absorption with different controlling field power. The effect of Doppler broadening and optical pumping are included. Parameters used for the plot are $\Delta_1=0$, $\Omega_c=35$ MHz. $\Omega_{c'}$ in (a)–(c) are 81 MHz, 57 MHz, and 0, respectively (the curves have been vertically shifted for clarity).

Experimentally we find that the probe absorption spectrum is insensitive to the detuning of the controlling laser as long as the frequency of the latter lies within the Doppler profile of the $|5S_{1/2},F=1\rangle\rightarrow|5P_{3/2},F=2\rangle$ transition. Numerical simulations confirm this. The explanation is that since only atoms that are nearly resonant with the controlling field contribute to the two-photon absorption process, small deviations from resonance will have little effect on the experiment, as long as this laser frequency lies well within the Doppler profile.

It is worth noting that in our numerical simulations, there is some power broadening effect caused by the controlling laser (see Fig. 5). When the power of the controlling laser is large, the dip is broadened considerably. This effect, however, is not observed in our experiment. In Fig. 2, the width of the dip is almost independent of the power of the controlling laser.

III. OPTICAL PUMPING-ASSISTED EIT

A. Experiment

In this section we report a phenomenon that could be used to improve all-optical switching in hot vapor. We call it optical pumping-assisted EIT. The experimental setup is the same as in Sec. II (see Fig. 1). The only difference is that we tune the controlling field to the $|5S_{1/2},F=2\rangle\rightarrow|5P_{3/2}\rangle$ transition. Since the controlling field is now used for optical pumping, we will refer to it as optical pumping field from now on.

Figure 6 shows the probe spectrum with and without the optical pumping field. We can see that the EIT dips are small without the optical pumping. When the optical pumping beam is added, the EIT signals are dramatically enhanced. At the same time the FWHM of the peaks remains unchanged. Another important effect is the change of the line shape of the absorption background from Gaussian to Lorentzian. Finally, the background is slightly reduced due to optical pumping.

Without optical pumping the probe absorption spectrum shows an EIT dip with an electromagnetically induced absorption (EIA) peak on it when $\Delta_1=-816$ MHz (coupling field is resonant with the $|5S_{1/2},F=1\rangle\rightarrow|5P_{1/2},F=1\rangle$ transition), a normal EIT dip when $\Delta_1=0$ MHz (coupling field is resonant with the $|5S_{1/2},F=1\rangle\rightarrow|5P_{1/2},F=2\rangle$ transition), and a sharp Raman absorption peak when $\Delta_1=-408$ MHz [11–13]. When the optical pumping field is on, the EIT effect is greatly enhanced. It is worth noting that the EIT dip with optical pumping is deeper than the background when the coupling field is resonant with the $|5S_{1/2},F=1\rangle\rightarrow|5P_{1/2},F=1\rangle$ transition ($\Delta_1=-816$ MHz). This means the probe field is not only transmitted but also experiences gain (see Fig. 6). The situation is more interesting when the coupling field is tuned to the middle of the two hyperfine levels of $|5P_{1/2}\rangle$. Figure 7 shows the probe absorption with different

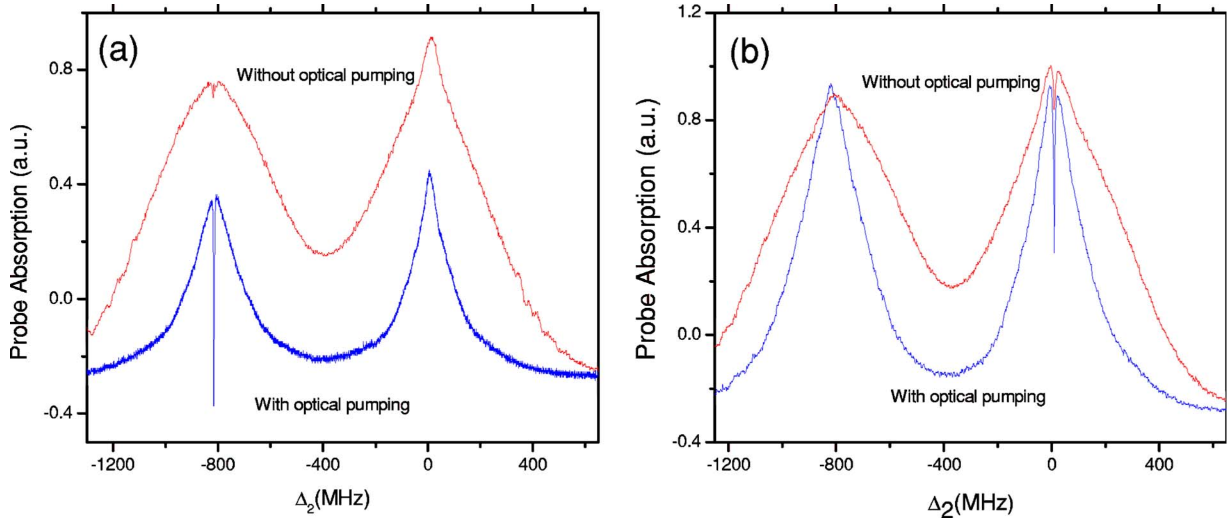


FIG. 6. (Color online) Probe absorption with and without optical pumping field. The EIT effect is greatly enhanced by the optical pumping field. Δ_1 in (a) and (b) is −816 MHz (coupling field is resonant with the $|5S_{1/2},F=1\rangle \to |5P_{1/2},F=1\rangle$ transition) and 0 MHz (coupling field is resonant with the $|5S_{1/2},F=1\rangle \to |5P_{1/2},F=2\rangle$ transition), respectively.

optical pumping power when $\Delta_1 \approx -408$ MHz. When the optical pumping field is off, we observe a very sharp Raman absorption peak near the two-photon resonance. The absorption is comparable with the Doppler broadened peaks at wings. Here we want to point out that both upper energy levels of $5P_{1/2}$ manifold contribute to this Raman absorption peak. The total effect is a constructive interference of two paths which leads to a large Raman absorption peak. This absorption is not an EIA. We will explain this in detail below. When we gradually increase the power of the optical

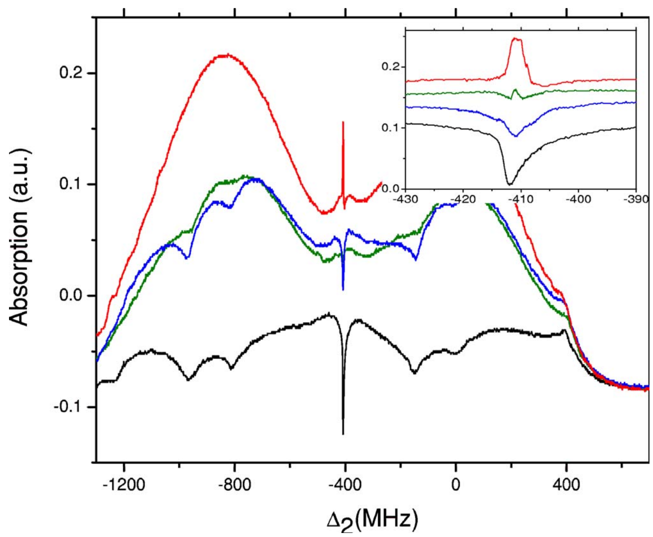


FIG. 7. (Color online) Probe absorption with different optical pumping power. $\Delta_1 \approx -408$ MHz. Optical pumping power for black, blue, green, and red curves (from up to down) are 0, 44 μW, 170 μW, and 3.4 mW, respectively. The peak first decreases and then changes to a sharp EIT dip. The Doppler broadened absorption peaks at the wings are also reduced due to optical pumping. The FWHMs of the peaks and dip are about 3 MHz. Inset, enlarged figure near the two-photon resonance (the curves have been vertically shifted for clarity).

pumping field, the peak first decreases and then changes to a sharp EIT dip. The Doppler broadened absorption peaks at the wings are notably reduced due to the optical pumping. The inset of Fig. 7 gives an enlarged figure near the two-photon resonance. The FWHMs of the peak and dip are about 3 MHz. This is a factor of 2 less than the natural linewidth of the rubidium D1 transition. The four shallow dips on the Doppler wings are due to the hole burning effect of the optical pumping beam.

The reason we call it optical pumping-assisted EIT is that this phenomenon is not sensitive to the frequency of the pumping beam and the angle between the pumping beam and the probe beam. As we change the angle from 0°to 15°, the probe spectrum changes only slightly. Therefore we think this phenomenon is caused by the population difference induced by the optical pumping field.

B. Theory

In this section we give a simple model which can include the optical pumping effect. Consider an atom with the energy diagram shown in Fig. 8. Working in the interaction picture, the Hamiltonian of this system is given by

$$H = -\Delta_c|2\rangle\langle 2| - (\Delta_c - \Delta_p)|3\rangle\langle 3| - \frac{1}{2}(\Omega_p|3\rangle\langle 2| + \Omega_c|1\rangle\langle 2| + \text{H.c.}), \tag{3}$$

where Ω_p and Ω_c are Rabi frequency of probe field and coupling field, respectively. Thus we can get the master equations as

$$i\dot{\rho}_{11} = -\frac{\Omega_c}{2}(\rho_{21} - \rho_{12}) + i\gamma_{21}\rho_{22} + R_{op}\rho_{33},$$

$$i\dot{\rho}_{22} = \frac{\Omega_c}{2}(\rho_{21} - \rho_{12}) + \frac{\Omega_p}{2}(\rho_{23} - \rho_{32}) - i\gamma_{21}\rho_{22} - i\gamma_{23}\rho_{22},$$

$$i\dot{\rho}_{33} = \frac{-\Omega_p}{2}(\rho_{23} - \rho_{32}) + i\gamma_{23}\rho_{22} - R_{op}\rho_{33},$$

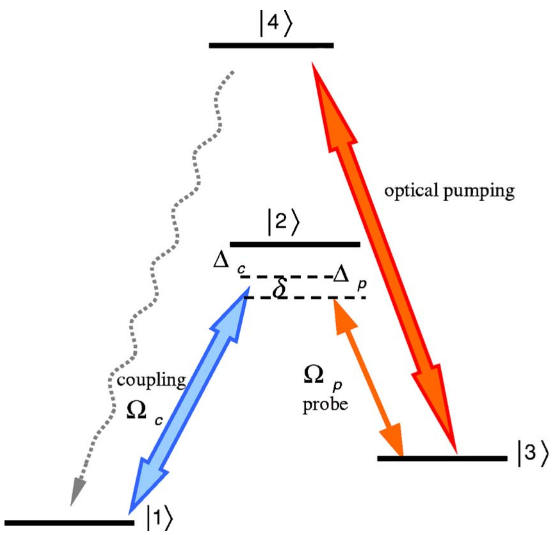


FIG. 8. (Color online) Energy level diagram of a four-level atom. A coupling laser is tuned near the $|1\rangle \rightarrow |2\rangle$ transition. A probe laser coupled to the $|2\rangle \rightarrow |3\rangle$ transition. An optical pumping field coupled to the $|3\rangle \rightarrow |4\rangle$ transition.

$$
\begin{aligned}
i\dot{\rho}_{12} &= \left[\Delta_c - \frac{i}{2}(\gamma_{21} + \gamma_{23} + \gamma_{2ph}) \right] \rho_{12} \\
&\quad - \frac{\Omega_c}{2}(\rho_{22} - \rho_{11}) + \frac{\Omega_p}{2}\rho_{13}, \\
i\dot{\rho}_{13} &= \left[\Delta_c - \Delta_p - \frac{i}{2}\gamma_{13} \right] \rho_{13} - \frac{\Omega_c}{2}\rho_{23} + \frac{\Omega_p}{2}\rho_{12}, \\
i\dot{\rho}_{23} &= \left[-\Delta_p - \frac{i}{2}(\gamma_{21} + \gamma_{23} + \gamma_{2ph}) \right] \rho_{23} \\
&\quad - \frac{\Omega_c}{2}\rho_{13} - \frac{\Omega_p}{2}(\rho_{33} - \rho_{22}),
\end{aligned} \tag{4}
$$

where γ_{21} and γ_{23} are decay rates of level 2, γ_{2ph} and γ_{13} are dephasing rates. The optical pumping field is not included in the Hamiltonian in Eq. (3). Its effect is introduced by the last terms of the first and third equations in Eq. (4). R_{op} is the rate of optical pumping. Because optical pumping is an incoherent process, we find it is good enough to directly introduce this term into the master equations. The coherent effect of the optical pumping field is not included in this model. Figure 9 shows the probe absorption profile as a function of two-photon detuning computed using Eq. (4). We can see the main phenomena of our observation are reproduced. (i) The EIT dip is enhanced by the optical pumping. (ii) When optical pumping is strong enough the dip can be deeper than the background, i.e., the probe field can experience amplification. (iii) The line shape of the background is changed from Gaussian to Lorentzian. The background is also reduced due to optical pumping.

We can easily extend this model to the case where there are two upper energy levels. This extension is needed because both upper energy levels contribute to the Raman absorption peak when the coupling field has a

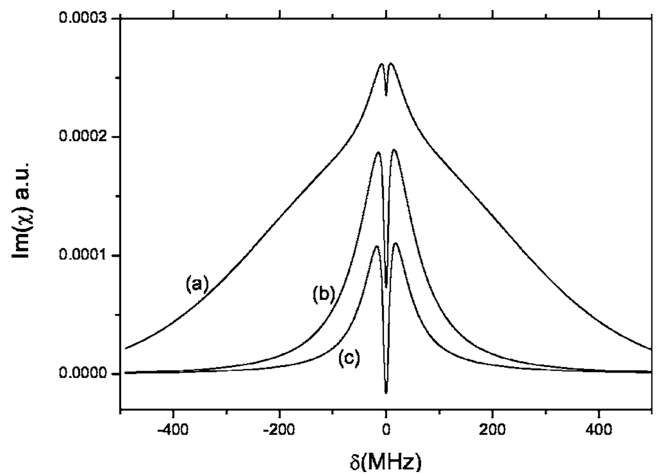


FIG. 9. Im(χ) vs two-photon detuning δ at different optical pumping rates. R_{op} for curves (a), (b), and (c) is 0, 1.3 MHz, and 6 MHz, respectively. Other parameters are $\gamma_{21}=\gamma_{23}=6$ MHz, $\gamma_{13}=3$ MHz, $\gamma_{2ph}=1.5$ MHz, $\Delta_c=0$, and $\Omega_c=25$ MHz.

large detuning ($\Delta_1 \approx -408$ MHz). There are two paths. One is $|5S_{1/2}, F=1\rangle \leftrightarrow |5P_{1/2}, F=1\rangle \leftrightarrow |5S_{1/2}, F=2\rangle$. The other is $|5S_{1/2}, F=1\rangle \leftrightarrow |5P_{1/2}, F=2\rangle \leftrightarrow |5S_{1/2}, F=2\rangle$. These two paths experience a constructive interference and give a large Raman absorption peak. The condition for this constructive interference is that these two paths have opposite phases. Figure 10 illustrates a simple model. The coupling field with frequency ω_c is coupled to $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |2'\rangle$ transitions. The Rabi frequencies are Ω_c and $\Omega_{c'}$, respectively. The probe field with frequency ω_p is coupled to $|3\rangle \leftrightarrow |2\rangle$ and $|3\rangle \leftrightarrow |2'\rangle$ transitions. The Rabi frequencies are Ω_p and $\Omega_{p'}$,

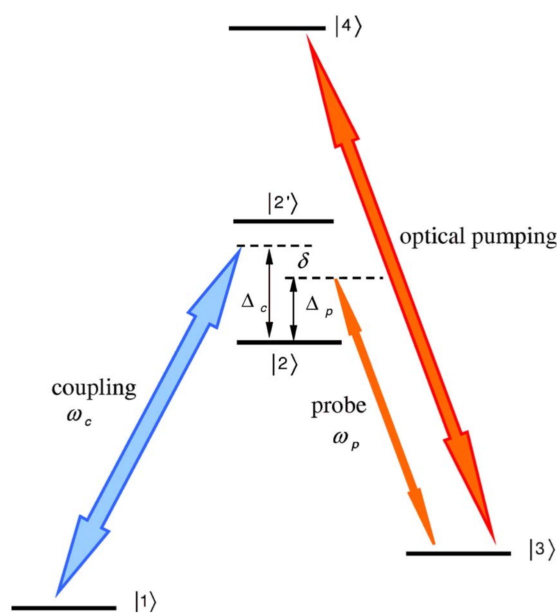


FIG. 10. (Color online) A four level model with two upper energy levels. The coupling field with frequency ω_c is coupled to $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |2'\rangle$ transitions. The Rabi frequencies are Ω_c and $\Omega_{c'}$, respectively. The probe field with frequency ω_p is coupled to $|3\rangle \leftrightarrow |2\rangle$ and $|3\rangle \leftrightarrow |2'\rangle$ transitions. The Rabi frequencies are Ω_p and $\Omega_{p'}$, respectively.

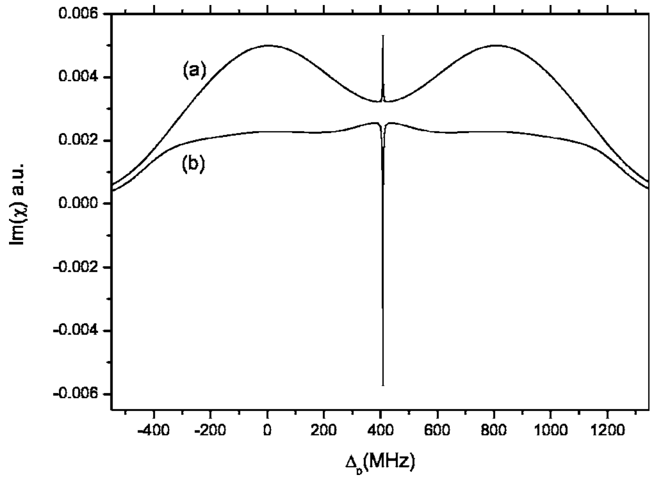


FIG. 11. Theoretical calculations of Im(χ) vs probe detuning Δ_p for Δ_c=408 MHz. (a) Without optical pumping. (b) With optical pumping. R_{op}=0.45 MHz. Other parameters are the same as in Fig. 9.

respectively. The condition for a constructive interference is that Ω_p/Ω_c and $\Omega_{p'}/\Omega_{c'}$ have opposite signs, i.e., these two paths have opposite phases. In our experiment the coupling field and the probe field are left circular polarized and right polarized, respectively. The two upper energy levels are $|5P_{1/2},F=1\rangle$ and $|5P_{1/2},F=2\rangle$. The two ground states are $|5S_{1/2},F=1\rangle$ and $|5S_{1/2},F=2\rangle$. This kind of configuration fulfills the condition mentioned above exactly. Actually it is also utilized in other applications, such as enhancing a four-wave-mixing process [14,15].

Figure 11 shows the calculated probe absorption profile as a function of two-photon detuning (Δ_c=−408 MHz). We can see the behavior is quite similar to our observation. However, the calculated EIT dip in the presence of the optical pumping field is deeper than the signal we observed. We think this is due to the imperfect alignment of the probe field and coupling field. The divergence of the beam may also reduce the amplitude of the signal.

IV. DISCUSSION

The phenomenon of optical pumping assisted EIT described in the previous section may be used for the all-optical switching application. The requirement for the power of optical pumping is modest. From Fig. 7 we can see that a few hundred μW is enough to turn the medium from opaque to transparent. However, this scheme may not be extended to the single-photon level. The reason is that this scheme utilizes the incoherent optical pumping. This process mus t be cycled several times before it has a notable effect. So a single photon is not sufficient to make it work. Although the hot atomic system is surpassed by its cold counterpart in many aspects, one cannot conclude that the hot atomic system is unsuitable for single-photon level all-optical switching. In fact, a recent publication demonstrates all-optical switching in hot rubidium vapor with very low switching energy density [16]. Another benefit is that the sharp feature we observed is unaffected by Doppler broadening and can, thus, be obtained with a hot atomic system. This will greatly reduce the complexity of the system compared to cold atom setups.

In conclusion we report an observation of the two-photon absorption in a four-level system in hot ^{87}Rb vapor, based on the proposal of Harris and Yamamoto. We show that this effect is reduced in hot atoms due to the non-Doppler-free nature of this scheme. Then we report a phenomenon that could be used in the same application of Harris and Yamamoto. We call it optical pumping-assisted EIT. A simple model is given and can explain most of the observations. This phenomenon is essentially Doppler-free and is insensitive to the misalignment of the optical pumping field. This robustness to misalignment is very important for practical concern. Furthermore, due to the good signal-to-noise ratio, this phenomenon could find applications in precise spectroscopy and laser frequency stabilization.

ACKNOWLEDGMENTS

This work was funded by National Fundamental Research Program (2001CB309300), National Natural Science Foundation of China (Grant Nos. 60121503 and 10304017), the Innovation funds from Chinese Academy of Sciences, and Program for New Century Excellent Talents in University.

[1] For a review see S. E. Harris, Phys. Today **50**, 36 (1997); E. Arimondo, Prog. Opt. **35**, 259 (1996); M. D. Lukin and A. Imamoglu, Nature (London) **413**, 273 (2001); M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. **77**, 633 (2005).
[2] H. Schmidt and A. Imamoglu, Opt. Lett. **21**, 1936 (1996).
[3] S. E. Harris and Y. Yamamoto, Phys. Rev. Lett. **81**, 3611 (1998).
[4] S. E. Harris and L. V. Hau, Phys. Rev. Lett. **82**, 4611 (1999).
[5] M. O. Scully, S. Y. Zhu, and A. Gavrielides, Phys. Rev. Lett. **62**, 2813 (1989).
[6] A. Andre and M. D. Lukin, Phys. Rev. Lett. **89**, 143602 (2002).
[7] A. Andre, M. Bajcsy, A. S. Zibrov, and M. D. Lukin, Phys. Rev. Lett. **94**, 063902 (2005).
[8] M. Yan, E. G. Rickey, and Y. Zhu, Phys. Rev. A **64**, 041801(R) (2001).
[9] D. A. Braje, V Balic, G. Y. Yin, and S. E. Harris, Phys. Rev. A **68**, 041801(R) (2003).
[10] Y.-F. Chen, Z.-H. Tsai, Y.-C. Liu, and I. A. Yu, Opt. Lett. **30**, 3207 (2005).
[11] A. M. Akulshin, S. Barreiro, and A. Lezama, Phys. Rev. A **57**, 2996 (1998).
[12] A. Lezama, S. Barreiro, and A. M. Akulshin, Phys. Rev. A **59**,

4732 (1999).

[13] W. Jiang, Q.-F. Chen, Y.-S. Zhang, and G.-C. Guo (unpublished).

[14] M. Johnsson, E. Korsunsky, and M. Fleischhauer, Opt. Commun. **212**, 335 (2002).

[15] M. T. Johnsson and M. Fleischhauer, Phys. Rev. A **68**, 023804 (2003).

[16] A. M. C. Dawes, L. Illing, S. M. Clark, and D. J. Gauthier, Science **308**, 672 (2005).