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Narrow-linewidth double-resonance optical pumping spectrum due to electromagnetically induced transparency in ladder-type inhomogeneously broadened media

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Based on the cesium $6S_{1/2}$-$6P_{3/2}$-$8S_{1/2}$ ladder-type atomic system, double-resonance optical pumping (DROP) spectra including electromagnetically induced transparency (EIT) effects have been investigated with a room-temperature cesium vapor cell. For both cases of the probe and the coupling laser beams passing through the cesium vapor cell with the counter-propagation (CTP) and co-propagation (CP) configurations, the DROP spectra measured in the experiment display explicitly different linewidths. Thanks to the EIT effect, the linewidth of the DROP spectrum is explicitly narrower for the CTP configuration than for the CP configuration. Experimental results agree with the theoretical analysis considering Doppler averaging. Furthermore, when the coupling laser has moderate power, the DROP spectrum for the CTP configuration clearly shows two components: the narrow part due to the EIT effect and the broad part caused by optical pumping (but these two different components are never seen in the CP configuration). Also, the effect of the intensity of the coupling and probe lasers on the DROP spectra is investigated.

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I. INTRODUCTION

The investigation of high-resolution spectroscopy is a very important field in physics, and it promotes the rapid development of atomic and molecular physics, laser physics, optoelectronics, and so on, and it also has great significance in the quantum frequency standard. The spectra between the excited states with the natural characteristic of being Doppler-free due to the velocity-selective mechanism have been used in high-resolution spectroscopy, laser frequency stabilization, frequency references in optical communication, and precision measurement [1–4]. The excited spectra can be usually acquired by the optical-optical double resonance (OODR) technique, but sometimes they have low signal-to-noise ratios (SNRs) [5].

In 2004, Moon *et al.* used the double-resonance optical pumping (DROP) technique to get the excited spectra, which is performed by velocity-selective optical pumping from one of the ground-state hyperfine components to another via the two-photon excitation process and spontaneous decay through the intermediate states and the higher excited state in the ladder-type atomic system [5]. The DROP technique differs from the OODR method in that it detects the variation of the ground-state population instead of the intermediate-state population as in the OODR technique, so the DROP spectra have a higher SNR. DROP spectra have already been investigated and applied to laser frequency stabilization [6,7]. In fact, in a DROP experimental system, there exists an atomic coherence effect such as electromagnetically induced transparency (EIT), which has received less attention. Just recently, the optical pumping effect in EIT has been brought into focus [8,9]. For a Λ-type atomic system, Ye and Zibrov studied the effect on the EIT signal from optical pumping by the coupling laser [10]. Jiang *et al.* investigated enhancement of the EIT signal by an additional optical pumping field [11]. However, in some EIT experiments with ladder-type atomic systems, DROP is often neglected because of the weak optical pumping caused by using a weak probe [12,13]. For the atomic coherence effect (EIT) in a ladder-type system, the physical picture can be interpreted as that the atoms are prepared in a dark superposition state of the ground state and a higher excited state, therefore reduced absorption of the probe beam will be observed; whereas the DROP spectrum is based on velocity-selective optical pumping, which transfers the population on one of the ground-state hyperfine components to another via the two-photon excitation process and spontaneous decay, and also will reduce the absorption of the probe beam whose frequency is locked between the ground state and one of the intermediate states. So it is difficult to distinguish these two effects. Moreover, we note that for a ladder-type atomic system, the EIT signal profile without the Doppler background in the case of scanning the coupling laser over the transition between the intermediate state and a higher excited state but keeping the probe laser locked between the ground state and one of the intermediate states, instead of keeping the coupling laser fixed but scanning the probe laser in normal EIT experiments, is so similar to the DROP signal that it is a bit more difficult to distinguish them. A recent theoretical study on DROP spectra [14] was presented on the basis of the density-matrix equations, and discrimination of the atomic coherence effect and the optical pumping effect in DROP spectra for co-propagation (CP) of the probe and coupling laser beams was done by comparing the experimental results with theoretical simulations with or without the two-photon coherent term between the ground state and higher excited state.

In this paper, based on the cesium $6S_{1/2}$-$6P_{3/2}$-$8S_{1/2}$ ladder-type atomic system, demonstration and discrimination of the atomic coherence effect and the optical pumping effect in DROP spectra as well as relevant theoretical analysis are presented. The atomic coherence effect, EIT, makes the linewidth of the DROP spectrum explicitly narrower for the counter-propagation (CTP) configuration than for the

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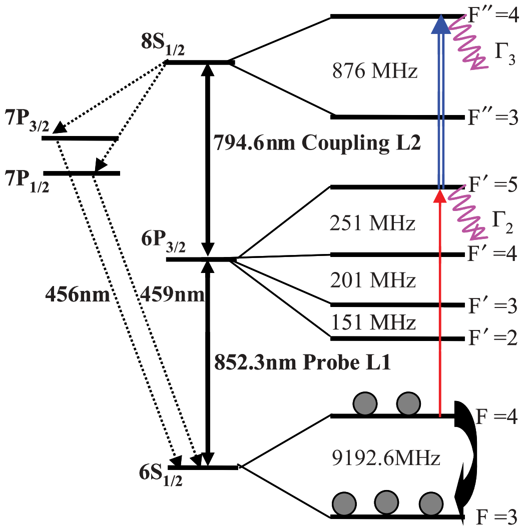

FIG. 1. (Color online) Relevant energy levels of cesium atoms. The probe laser (L1) is locked to the $F = 4 - F' = 5$ cycling transition, while the coupling laser (L2) is scanned over $F' = 5 - F'' = 4$ hyperfine transition. DROP spectrum can be obtained by recording probe transmission as function of the coupling laser's detuning.

CP configuration. In Sec. II we present the experimental setup, and in Sec. III we discuss the experimental result and compare it with the theoretical analysis. Section III is further divided into two subsections dealing with the EIT effect on DROP spectra theoretically and experimentally, and the influence of the intensity of the coupling and probe lasers on the DROP spectra. Finally, we give a conclusion.

II. EXPERIMENTAL SETUP

Figure 1 shows the relevant energy levels of cesium atoms. The center wavelengths of the transitions of $6S_{1/2}$-$6P_{3/2}$ and $6P_{3/2}$-$8S_{1/2}$ are 852.3 and 794.6 nm, respectively; while the wavelengths of the transitions of $7P_{1/2}$-$6S_{1/2}$ and $7P_{3/2}$-$6S_{1/2}$ are 459 and 456 nm, respectively. The spontaneous decay rate from the $6P_{3/2}$ to the $6S_{1/2}$ state is $\Gamma_2 = 5.22$ MHz, and that from $8S_{1/2}$ to $6P_{3/2}$ is $\Gamma_3 = 2.18$ MHz. The probe laser (L1) is locked to the $F = 4$ to $F' = 5$ cycling transition, while the coupling laser (L2) is scanned over the $F' = 5$ to $F'' = 4$ hyperfine transition. By recording probe transmission as function of the coupling laser's detuning, the population variation of atoms around zero velocity along the probe laser direction on the $F = 4$ ground state can be obtained yielding a DROP spectrum.

Figure 2 shows the schematic diagram of the experimental arrangement. Two grating-feedback external-cavity diode lasers (ECDLs) with typical linewidth of ~500 kHz are used as the coupling laser and the probe laser. The home-made ECDL (L1) @ 852.3 nm used as the probe beam with a diameter of ~1.5 mm is locked to the $F = 4 - F' = 5$ cycling transition using the conventional frequency-modulation technique for avoiding single-resonance optical pumping via $F' = 3$ and $F' = 4$ intermediate states to $F = 3$ ground state, and populates the $F' = 5$ state. Another ECDL (Toptica DL100) (L2) @ 794.6 nm used as the coupling beam with a diameter of ~2.0 mm is utilized to populate the $F'' = 4$ state, therefore the population of atoms around zero velocity along the probe laser direction on the $F = 4$ ground state can be optically pumped to the $F = 3$ ground state via this two-photon excitation and spontaneous decay. The two beams are overlapped and then separated by dichroic filters (DFs) in a cesium vapor cell (length of ~5 cm, diameter of ~2.5 cm) at room temperature. The coupling beam can take the path of beam 1 by blocking beam 2 for a CP configuration, it also can take the path of beam 2 by blocking beam 1 for a CTP configuration. Two sets of adjustable beam-splitting modules consisted of one half-wave plate ($\lambda/2$) and one polarization beam-splitter cube (PBS) are used to change the optical power of the coupling and probe beams. DROP spectrum is observed by use of a photodiode (PD, New Focus, Model 2001), and the linewidth of the DROP spectrum is measured using a confocal Fabry-Perot cavity (not shown in Fig. 2) with a calibrated free spectra range of 503 MHz.

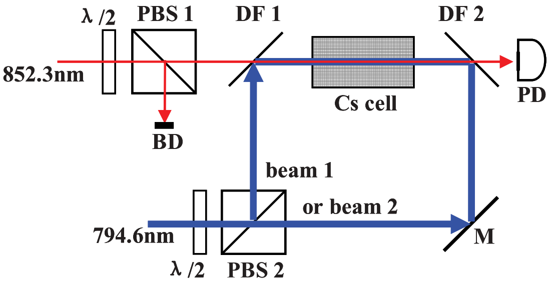

FIG. 2. (Color online) Schematic diagram of experimental arrangement. The coupling laser @794.6 nm takes the path of beam 1 for co-propagation (CP) configuration, and it takes the path of beam 2 for counter-propagation (CTP) configuration. The key to labels: $\lambda/2$, half-wave plate; PBS, polarization beam splitting cube; BD, beam dump; DF, dichroic filter; PD, photodiode; M, 45° full-reflection mirror.

III. THEORETICAL ANALYSES AND EXPERIMENTAL RESULTS

When the frequency of the probe laser is locked to the $F = 4 - F' = 5$ cycling transition, some atoms with velocity direction perpendicular to the probe beam are populated to the $F' = 5$ state from the $F = 4$ ground state, and are further excited to the $F'' = 4$ state when the coupling laser is scanning on the $F' = 5 - F'' = 4$ transition. Some of the atoms on the $F'' = 4$ state spontaneously decay to $F' = 3$ and $F' = 4$ states, and $7P_{1/2}$ and $7P_{3/2}$ states, then spontaneously decay to the $F = 3$ ground state. Strong blue fluorescence caused by the spontaneous decay for the $7P_{3/2}$–$6S_{1/2}$ transition (corresponding to 456 nm) and $7P_{1/2}$–$6S_{1/2}$ transition (corresponding to 459 nm) is clearly observed in experiment. Due to this two-photon excitation and spontaneous decay, the population of the $F = 4$ ground state are optically pumped to the $F = 3$ ground state, therefore absorption of the probe beam accordingly decreases, forming the DROP spectrum [5–7]. Figure 3 compares the DROP signals of the $F' = 5 - F'' = 4$ transition for CTP and CP configurations, where the probe beam's power is ~120 μW as large as that of the coupling beam. An obvious difference between the two configurations

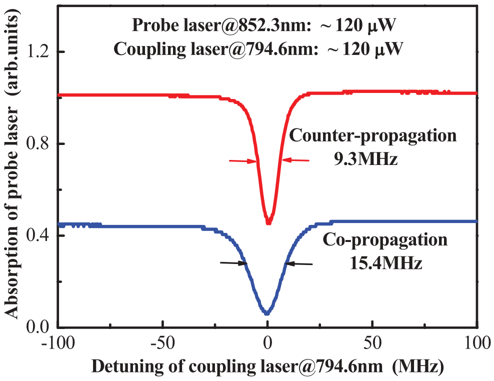

FIG. 3. (Color online) Comparison of the DROP spectra of cesium $F' = 5 - F'' = 4$ hyperfine transition under the same coupling and probe laser intensities for CTP and CP configurations.

in Fig. 3 is that the magnitude of the DROP spectrum for CTP is little bit higher than that for CP, because for the CTP case more atoms will contribute to the DROP spectrum in which the Doppler effect can be partially eliminated. In other words, the CTP configuration is a two-photon Doppler-free arrangement [15].

Another explicit difference between the two configurations is that the linewidth of the DROP spectrum is ∼9.3 MHz for the CTP configuration, which is narrower than that for the CP configuration (∼15.4 MHz). We note that for a Doppler-broadened ladder-type atomic system, a DROP experimental setup for CTP configuration is the same as that for an EIT experiment. Only one different point is that in a normal EIT experiment, the coupling laser's is fixed while the probe laser's frequency scans between the ground and intermediate states [15], whereas in the DROP experiment, the coupling laser's frequency scans between the intermediate and higher excited states while the probe laser is locked on resonance [6,7]. But when two-photon detuning between the coupling and probe beams is around zero, DROP and EIT will take effect simultaneously, yielding probe absorption reducing. To understand the results in Fig. 3, the EIT effect in a ladder-type three-level atomic system should be taken into account, and we believe that the EIT effect makes the linewidth of the DROP spectrum narrower for a CTP configuration than for a CP configuration. The detailed explanation and analysis follow.

A. Effect of EIT on DROP spectrum

DROP is a kind of optical pumping spectrum based upon the multilevel model [6,7], which is composed of two levels in the ground state, at least two levels in the intermediate state, and one level in a higher excited state (see Fig. 1). In theoretical treatment, DROP can be described by density-matrix equations considering all relevant hyperfine levels. A recent paper [14] theoretically deals with DROP spectra for the CP configuration along this line, and their numerical simulation indicates that the dominant operating mechanism for DROP signals is the optical pumping rather than the two-photon coherence. But the equations are too complicated to give approximate analytical results, and it is hard to show a clear physical picture, especially one that indicates the reasons for the different results obtained for the CTP and CP configurations, as shown in Fig. 3. We simplify our system into a three-level model with cesium $F = 4 - F' = 5 - F'' = 4$ transitions (see Fig. 1) without regard to optical pumping, so the influence of the two-photon coherent part (EIT) in this system on the DROP spectrum is obviously discovered. Here ω_{21} is the frequency of the $F = 4 - F' = 5$ transition, ω_P is the probe laser's frequency, and $\Delta_1 = \omega_P - \omega_{21}$ is probe detuning. Similarly, ω_{32} is the frequency of the $F' = 5 - F'' = 4$ transition, ω_C is the coupling laser's frequency, and $\Delta_2 = \omega_C - \omega_{32}$ is coupling detuning. N is cesium atomic density in the vapor cell, and g_{21} is the dipole moment matrix element for the $F = 4 - F' = 5$ transition, and Ω_C is the Rabi frequency of the coupling laser. If collisional dephasing is negligible, the decay rates are given by $\gamma_{ij} = (\Gamma_i + \Gamma_j)/2$, where $\Gamma_{i(j)}$ is the spontaneous decay rate of level $i(j)$. When neglecting the Doppler effect, the complex susceptibility $\chi = \chi' + i\chi''$ can be obtained from the standard semiclassical methods [15], and the real part χ' and imaginary part χ'' are related to the dispersion and absorption of the atomic medium:

$$\chi = \frac{4i\hbar N g_{21}^2/\varepsilon_0}{\gamma_{21} - i\Delta_1 + \frac{\Omega_C^2/4}{\gamma_{31} - i(\Delta_1 + \Delta_2)}}. \tag{1}$$

Here, we can get an EIT signal at the condition of zero two-photon detuning by locking the probe laser's frequency to the $F = 4 - F' = 5$ transition and scanning the coupling laser over the $F' = 5 - F'' = 4$ transition, instead of scanning the probe laser and keeping the coupling laser's frequency fixed as in normal EIT experiments. We call it the unusual EIT to just distinguish it from the normal EIT, but the physical mechanism is the same for both cases. Figure 4 shows the difference between them by numerical simulation based on Eq. (1). Compared with the shape of normal EIT, the unusual EIT has a distinct characteristic without the Doppler background, which is very similar to the DROP spectrum in Fig. 3, and it is difficult to distinguish the difference between them.

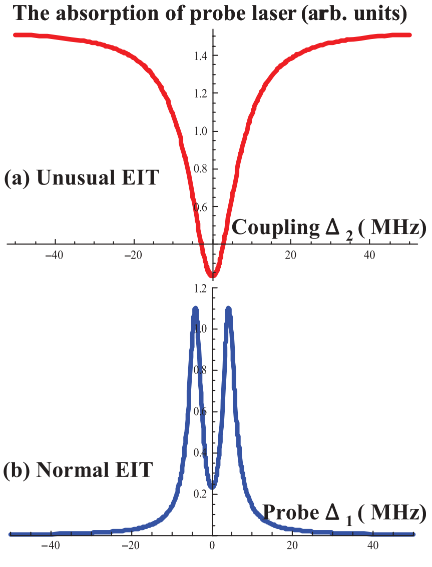

FIG. 4. (Color online) Comparison of the unusual EIT and the normal EIT of cesium $F = 4 - F' = 5 - F'' = 4$ ladder-type system. Simulation parameters: $\gamma_{21} = 2.61$ MHz, $\gamma_{31} = 1.09$ MHz, $\Omega_C = 8$ MHz.

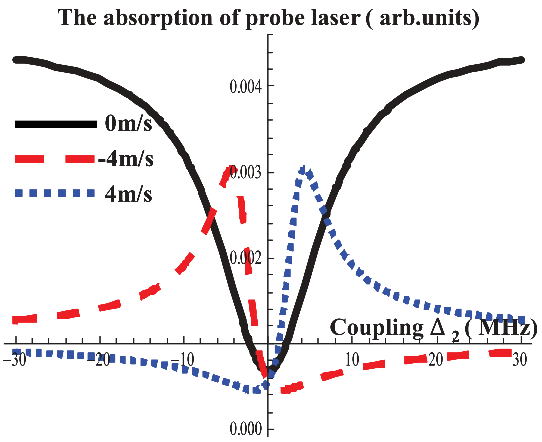

FIG. 5. (Color online) Effect of velocity on the unusual EIT signal in ladder-type system while scanning the coupling laser and locking the probe laser for CTP configuration. Simulation parameters: $\gamma_{21} = 2.61$ MHz, $\gamma_{31} = 1.09$ MHz, $\Delta_1 = 0$, $\Omega_C = 8$ MHz, $T = 300$ K.

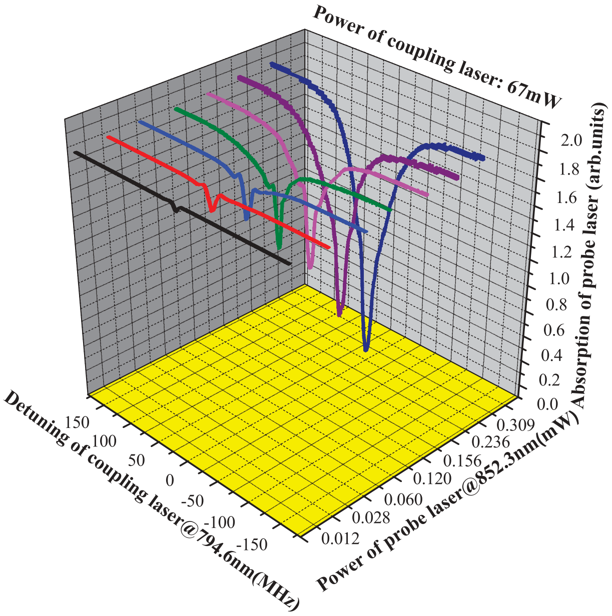

FIG. 7. (Color online) DROP signals including EIT effect for CTP configuration. The coupling laser's power is fixed to ∼67 mW ($\Omega_C \sim 95.1$ MHz), while the probe laser's power is changed from ∼0.012 to ∼0.309 mW (Ω_p from ∼ 2.9 to ∼14.6 MHz).

The above analysis is valid only for a stationary atom. In fact, our experiment is done in a cesium vapor cell at room temperature. There exists a very wide distribution range of atomic velocity, and the Doppler effect must be taken into account. The moving of the atoms results in the changes of detunings for both the probe and coupling lasers. Therefore, the following transformations are performed based on Eq. (1): $\Delta_1 \to \Delta_1 + (\omega_P/c)v$ and $\Delta_2 \to \Delta_2 \pm (\omega_C/c)v$, where c is the light speed, and v is the atomic velocity along the direction of the probe beam ("+" for CP configuration and "−" for CTP configuration). Considering the one-dimensional Maxwell-Boltzmann distribution of velocities $N(v)$, we have

$$\chi(v)dv = \frac{4i\hbar g_{21}^2/\varepsilon_0}{\gamma_{21} - i\Delta_1 - i\frac{\omega_p}{c}v + \frac{\Omega_C^2/4}{\gamma_{31} - i(\Delta_1+\Delta_2) - i(\omega_p \pm \omega_c)v/c}} \times N(v)\,dv, \tag{2}$$

where $N(v) = \frac{N}{u\sqrt{\pi}}e^{-v^2/u^2}, u = \sqrt{\frac{2kT}{m}}$ and is the most probable velocity. k is the Boltzmann constant, T is temperature, and m is the mass of the cesium atom.

We discuss the influence of the atom's motion on the unusual EIT spectrum based on Eq. (2) in the CTP configuration. Figure 5 shows the unusual EIT signal shapes. The solid curve is for the stationary atoms, while the dotted and dashed curves with dispersive profiles are for the atoms with $v \sim 4$ and -4 m/s, which will increase the absorption on both sides of the central transparent signal for stationary atoms. So the overall transparency window shrinks, and the effective EIT linewidth decreases. When velocities are integrated from ∼−500 to ∼+500 m/s with a step of 1 m/s, the simulation result is shown in curve (a) in Fig. 6. The linewidth for the unusual EIT is becoming narrower compared to that for the stationary atoms, as shown in curve (c) in Fig. 6,

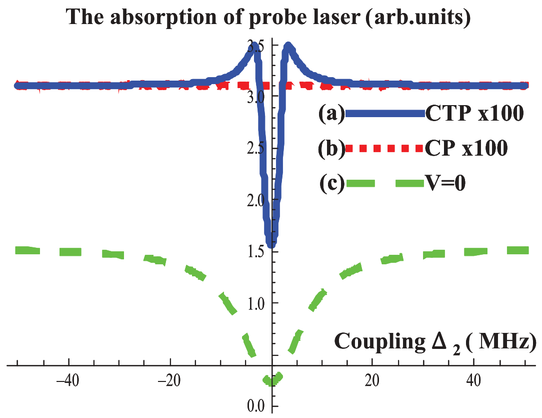

FIG. 6. (Color online) Unusual EIT signal in ladder-type system while scanning the coupling laser and locking the probe laser with integrating the Doppler velocity group for CTP configuration (a), CP configuration (b), and without integral (c). Curve (a) and (b) are enlarged by a factor 100 for comparison in the same scale with curve (c).

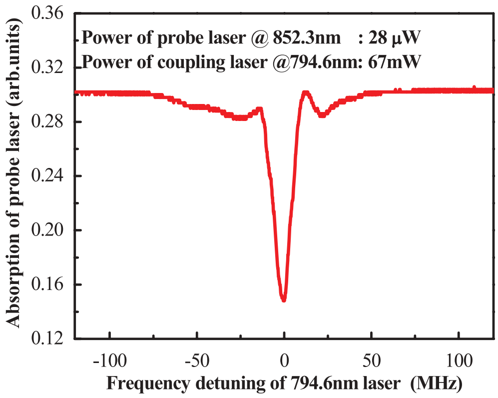

FIG. 8. (Color online) Nearly pure unusual EIT signal for the weak probe laser for CTP configuration.

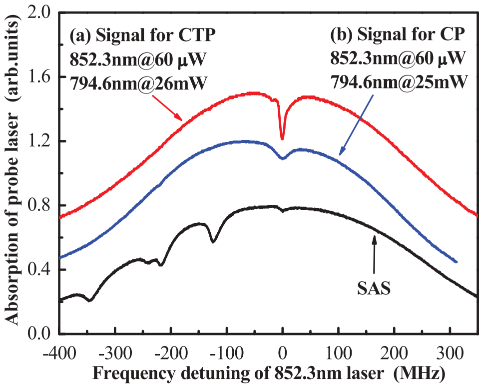

FIG. 9. (Color online) Probe absorption signals for CTP (a) and CP (b) configurations while scanning the probe laser and keeping the coupling laser locked. The $F=4-F'=5$ cycling transition is reasonably selected for reference of frequency detuning.

because of Doppler averaging. Similar results have also been reported in the normal EIT experiment [16]. In addition, curve (a) obviously shows additional absorption wings on both sides [two peaks of curve (a) in Fig. 6], accompanying the central transparent signal, which are due to the wavelength-mismatch between the probe and coupling lasers [17], and confirmed by calculation especially for the strong coupling laser. Actually, the optical pumping cannot be removed in the experiment, so the unusual EIT will always be mixed with optical pumping in the DROP spectrum for the CTP configuration.

However, for the CP configuration, the EIT signal is difficult to observe in a ladder-type Doppler-broadened media [see curve (b) in Fig. 6, which has the same parameters as curve (a)]. Equation (2) indicates that the two-photon Doppler-free condition requires the probe and coupling beams to counter-propagate, then the small term $(\omega_P - \omega_C)v/c$ can be approximately neglected. But for the CP configuration, the term $(\omega_P + \omega_C)v/c$ cannot be ignored. Thus, the CP configuration does not fulfill the two-photon Doppler-free condition for ladder-type Doppler-broadened media, and the signals of moving atoms will fully fill in the transparency window for stationary atoms, so the unusual EIT signal is almost submerged by the Doppler effect. This is why people need a very intense coupling laser ($\Omega_C > \Delta\omega_D$, $\Delta\omega_D$ is the Doppler broadening) to observe ladder-type EIT in previous experiment [18]. We ascribe the DROP spectrum for the CP configuration mainly to optical pumping; the EIT effect is almost submerged by the Doppler effect and therefore has a nearly negligible influence on the DROP spectrum. Here we noted that numerical simulations in Ref. [14] pointed out that the two-photon coherence between the ground state and the upper excited state has a weak influence on the linewidth of the DROP spectrum for the CP configuration. This difference probably comes from the simplified ladder-type three-level model we used, in which other hyperfine levels in the ground and intermediate states are ignored approximately. Although these hyperfine levels do not directly interact with the coupling and probe lasers, they still take effect via two-photon excitation and spontaneous decay. Thus, maybe they can still make the two-photon coherence be not fully submerged by the Doppler effect even for the CP configuration. This point needs to be further investigated in detail.

Both optical pumping and the EIT effect contribute to the DROP spectrum. For the CTP configuration, both optical pumping and EIT simultaneously affect the DROP spectrum; whereas for the CP configuration, the DROP spectrum mainly comes from optical pumping, and the EIT effect has a nearly negligible influence on the DROP spectrum. As we know, EIT is a quantum coherence process with narrow linewidth especially for Doppler averaging, while DROP is due to optical pumping accompanied by a spontaneous decay process with a broad linewidth. This is the physical reason for the different linewidths of the CP and CTP configurations in Fig. 3.

Furthermore, when the coupling laser has moderate power, for example, ~67 mW ($\Omega_C \sim 95.1$ MHz), the DROP spectrum for the CTP configuration clearly shows two components: the narrow part due to the EIT effect and the broad part due to optical pumping, as shown in Fig. 7. But these two different components are never seen in the CP configuration. The stronger the intensity of the coupling laser, the more prominent the EIT effect. On the other hand, when the probe laser's power increases from 0.012 to ~0.309 mW (Rabi frequency of the probe beam Ω_p from ~2.9 to ~14.6 MHz), optical pumping is remarkably enhanced, and the bottom of the spectrum is obviously broadened (see Fig. 7). When the probe laser's power is ~28 μW ($\Omega_p \sim 4.4$ MHz) or lower, optical pumping can be nearly neglected because of the low population in

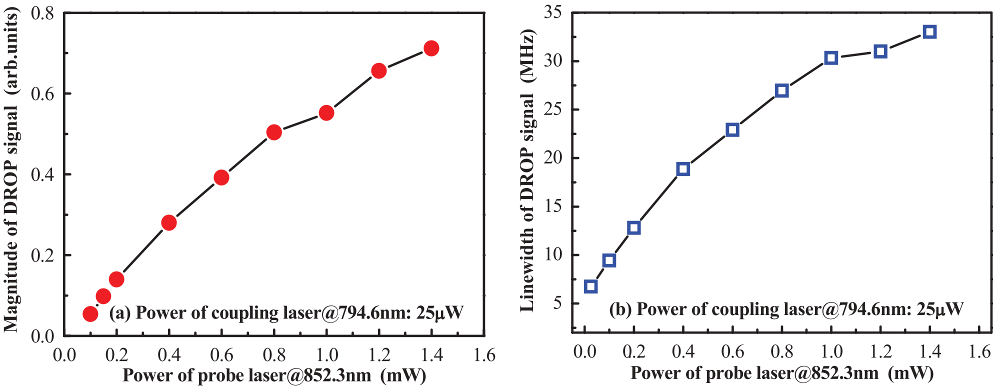

FIG. 10. (Color online) Effect of the probe laser's intensity on the magnitude and linewidth of DROP spectra for CTP configuration. The solid lines are for guiding eyes.

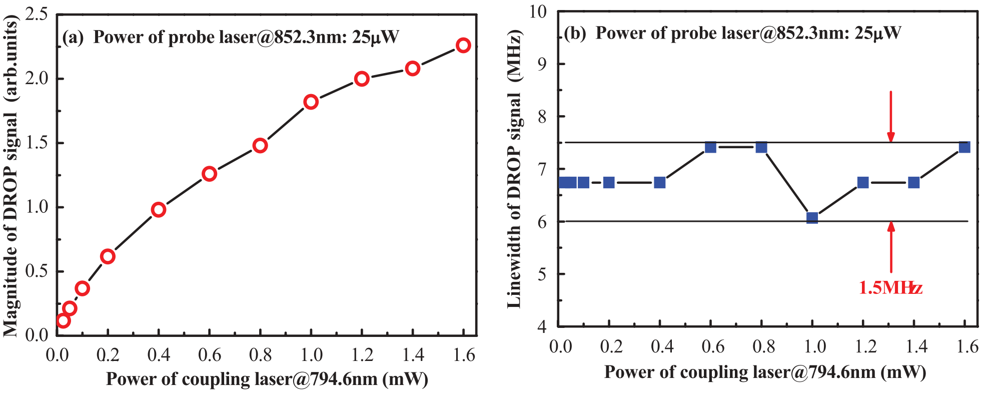

FIG. 11. (Color online) Effect of the coupling laser's intensity on the magnitude and linewidth of DROP spectra for CTP configuration. The solid lines are for guiding the eyes.

the $F' = 5$ state. In this case, the spectrum is due almost entirely to the EIT effect, so the spectral profile shown in Fig. 8 is very similar to the theoretical simulation [curve (a) in Fig. 6].

The spectra with two components also can be observed in normal EIT arrangement (CTP configuration) [9], where the coupling laser's frequency is fixed while the probe laser is scanned over the transition from the ground state to the intermediate state. We record the results as shown in trace (a) in Fig. 9, in which both EIT and optical pumping contribute to the absorption reduction dip on the Doppler background. The saturation absorption spectra (SAS) in Fig. 9 are for frequency reference. For the CP configuration, we also observe a dip [see trace (b) in Fig. 9], which is mainly due to DROP instead of EIT. Moreover, we never see a signal composed of two components in the CP configuration.

B. Influence of the coupling and probe laser intensities on DROP spectra

We have also confirmed the EIT effect in the DROP spectrum for the CTP configuration in experiment by observing the influence of the intensity of the probe and coupling lasers on the linewidth and magnitude of the DROP spectrum. Figures 10 and 11 show the influence of the probe and coupling laser intensities on DROP spectra. From Figs. 10(a) and 11(a), we can see that the DROP-spectrum magnitude is clearly enhanced when laser intensity increases, but the influence of laser intensity on the DROP-spectrum linewidth has a remarkably different behavior. We note that the linewidth is clearly broadened when the probe laser intensity increases, whereas with the coupling laser intensity increase, the linewidth keeps roughly the same within experimental error range [see Figs. 10(b) and 11(b)]. When the probe laser's power is increased from several tens of μW to ∼1.4 mW, the linewidth broadens from ∼6 to ∼32 MHz [see Fig. 10(b)]. However, when the coupling laser's power is changed from several tens of μW to ∼1.6 mW, the linewidth stays around ∼6.7 MHz with only a fluctuation of ∼1.5 MHz [Fig. 11(b)]. Even if the coupling laser's power is 67 mW, a signal is obtained with linewidth of 11.6 MHz (see Fig. 8) which only increases slightly compared with Fig. 11(b). This means that the coupling laser intensity has a weak influence on the linewidth. We ascribe this behavior to the EIT effect.

We know that both EIT and optical pumping contribute to DROP spectra for CTP configuration. Because DROP depends mainly on the optical pumping rate, the population transfer rate from $F = 4$ to $F = 3$ state accordingly increases while increasing both laser intensities, yielding the enhanced magnitude of the DROP spectrum. For the EIT effect, when the coupling laser has a moderate power, the EIT effect is more prominent. Moreover, due to the Doppler averaging in a room-temperature vapor cell, the EIT signal with subnatural linewidth still can be obtained even if the Rabi frequency of the coupling laser is $\Omega_C \gg 2\Gamma_3$. So the linewidth is not broadened obviously while increasing the coupling laser intensity. Similar experimental results were also reported in Ref. [16].

IV. CONCLUSION

In conclusion, based on the cesium $6S_{1/2}$-$6P_{3/2}$-$8S_{1/2}$ ladder-type atomic system, we have investigated DROP spectra with cesium vapor cell considering the ladder-type EIT effect. Although DROP spectral profile is similar to the shape of unusual EIT, the difference between them has been recognized and demonstrated in experiment and confirmed in theoretical analysis. The EIT effect mixed with optical pumping in DROP spectra can be easily observed for the CTP configuration, but it has nearly negligible influence on DROP spectra for the CP configuration. For the CP configuration, DROP spectra are mainly attributed to optical pumping, because the EIT effect is almost submerged by the Doppler effect. Comparing with the CP configuration, EIT makes the linewidth of DROP spectra narrow for the CTP configuration, because the Doppler effect is partly eliminated. In particular, when the coupling laser has moderate power for the CTP configuration, an interesting spectrum with two different components is observed, in which the narrow part is due to the EIT effect and the broad part to optical pumping. However, these two different components are never seen for the CP configuration for the dominant optical pumping. Finally, from the influence of the two laser intensities on DROP spectra for the CTP configuration, we can clearly see that the linewidth is nearly not changed by increasing the coupling laser's intensity. We ascribe this point to the EIT effect in DROP spectra.

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[1] H. Sasada, IEEE Photonics Technol. Lett. **4**, 1307 (1992).
[2] R. Boucher, M. Breton, N. Cyr, C. Julien, and M. Tetu, IEEE Photonics Technol. Lett. **4**, 327 (1992).
[3] M. Breton, N. Cyr, P. Tremblay, M. Tetu, and R. Boucher, IEEE Trans. Instrum. Meas. **42**, 162 (1993).
[4] K. Pandey, P. V. Kiran Kumar, M. V. Suryanarayana, and V. Natarajan, Opt. Lett. **33**, 1675 (2008).
[5] H. S. Moon, W. K. Lee, L. Lee, and J. B. Kim, Appl. Phys. Lett. **85**, 3965 (2004).
[6] H. S. Moon, L. Lee, and J. B. Kim, J. Opt. Soc. Am. B **24**, 2157 (2007).
[7] B.-D. Yang, J.-Y. Zhao, T.-C. Zhang, and J.-M. Wang, J. Phys. D **42**, 085111 (2009).
[8] S. Chakrabarti, A. Pradhan, B. Ray, and P. N. Ghosh, J. Phys. B **38**, 4321 (2005).
[9] H. S. Moon, L. Lee, and J. B. Kim, Opt. Express **16**, 12163 (2008).
[10] C. Y. Ye, and A. S. Zibrov, Phys. Rev. A **65**, 023806 (2002).
[11] W. Jiang, Q.-F. Chen, Y.-S. Zhang, and G.-C. Guo, Phys. Rev. A **73**, 053804 (2006).
[12] H. S. Moon, L. Lee, and J. B. Kim, J. Opt. Soc. Am. B **22**, 2529 (2005).
[13] D. McGloin, M. H. Dunn, and D. J. Fulton, Phys. Rev. A **62**, 053802 (2000).
[14] H. R. Noh and H. S. Moon, Phys. Rev. A **80**, 022509 (2009).
[15] J. Gea-Banacloche, Y.-Q. Li, S.-Z. Jin, and M. Xiao, Phys. Rev. A **51**, 576 (1995).
[16] S. M. Iftiquar, G. R. Karve, and V. Natarajan, Phys. Rev. A **77**, 063807 (2008).
[17] T. H. Yoon, C. Y. Park, and S. J. Park, Phys. Rev. A **70**, 061803 (2004).
[18] J. E. Field, K. H. Hahn, and S. E. Harris, Phys. Rev. Lett. **67**, 3062 (1991).