Polarization dependence of double-resonance optical pumping and electromagnetically induced transparency in the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transition of ^{87}Rb atoms

Han Seb Moon[1,*] and Heung-Ryoul Noh[2,†]

[1]*Department of Physics, Pusan National University, Busan 609-735, Korea*

[2]*Department of Physics, Chonnam National University, Gwangju 500-757, Korea*

(Received 8 February 2011; published 15 September 2011)

The polarization dependence of double-resonance optical pumping (DROP) in the ladder-type electromagnetically induced transparency (EIT) of the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transition of ^{87}Rb atoms is studied. The transmittance spectra in the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=2,3,4)$ transition were observed as caused by EIT, DROP, and saturation effects in the various polarization combinations between the probe and coupling lasers. The features of the double-structure transmittance spectra in the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=4)$ cycling transition were attributed to the difference in saturation effect according to the transition routes between the Zeeman sublevels and the EIT according to the two-photon transition probability.

DOI: 10.1103/PhysRevA.84.033821 PACS number(s): 42.50.Gy, 32.10.Fn, 32.80.Xx, 32.80.Qk

I. INTRODUCTION

In high-resolution spectroscopy, atomic coherence and optical pumping play an important role in an optical medium with light [1]. The atomic coherent phenomena are counterintuitive and caused by quantum interference between the atomic states. Electromagnetically induced transparency (EIT) is an example of atomic coherent phenomenon [2–4]. Using the characteristics of EIT with a narrow spectral width and transparency, EIT has been applied to potentially important areas, including light storage [5,6], precision magnetometers [7,8], and quantum optics [9–11].

Although many optical pumping phenomena may be understood intuitively by the rate equation described as the change in the population by optical pumping, the spontaneous process due to optical pumping affects the decay of the atomic coherence significantly. The spectrum can occur not only through quantum interference due to the atomic coherence, but also via a population change in the state that results from optical pumping. The EIT spectrum also includes an optical pumping effect by the coupling laser. In the case of the atoms in the Λ-type atomic system, composed of two ground states and a common excited state, most of the population in one ground state may be optically pumped into another ground state by single-photon resonance. The role of optical pumping in the EIT spectrum of an atomic vapor has already been discussed [12].

The ladder-type atomic system represents an excitation from a ground state to a high-lying state via a common intermediate state, as shown in Fig. 1. Before lasers were developed, Bitter proposed to detect very small changes of Zeeman sublevels using the optical detection of radio frequency resonance [13]. Double-resonance spectroscopy has already been applied to the study of atomic transitions [14]. In the case of a ladder-type atomic system with a double-resonance transition [15–17], there is optical pumping in the ladder-type atomic system due to the so-called double-resonance optical pumping (DROP) phenomenon [18–20]. The magnitude of optical pumping is proportional to a two-photon transition probability and the frequency of the optical pumping is under the condition of the two-photon resonance similar to the two-photon atomic coherence. It was reported that the ladder-type EIT is not free from the optical pumping effect, which was more serious in the ladder-type EIT than in the Λ-type EIT [20]. As is well known, the atomic coherence and optical pumping affect the polarization of the interacting lasers with atoms significantly due to the different transition probabilities according to the laser polarization and hyperfine states. Although the DROP effect on the ladder-type EIT has been reported [18], the dependence of the polarization of the lasers between the DROP and EIT in a ladder-type atomic system has not been reported. Also, the transmittance spectrum due to EIT and saturation effect according to the laser's polarization has never been investigated in the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=4)$ cycling transition.

In the present work we study the influence of polarization combination on EIT, DROP, and saturation effect in a $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ ladder-type system with use of room-temperature rubidium atoms in a vapor cell. The relative intensity and the spectral-shape features of the transmittance spectra in the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=4)$ cycling transition were investigated with various polarization combinations of the laser. We also discuss how polarization affects the spectra. In addition, the transmittance spectra were simulated by considering the two-photon transition probability and optical pumping.

II. EXPERIMENTAL SETUP

Figure 1 shows the energy-level diagram of the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transitions of ^{87}Rb atoms. The $5S_{1/2}$-$5P_{3/2}$ transition is resonant on the probe laser at 780 nm and the $5P_{3/2}$-$5D_{5/2}$ transition is resonant on the coupling laser at 776 nm. The natural line widths of the $5P_{3/2}$ and $5D_{5/2}$ states are approximately 6.0 MHz and 0.67 MHz, respectively. When the atoms are resonant with the fields of the coupling and probe lasers, the population of the $5S_{1/2}(F=2)$ state may be depleted because many atoms excited to the $5D_{5/2}$ states $(F''=2,3)$ can be optically pumped to the

*hsmoon@pusan.ac.kr

†hrnoh@chonnam.ac.kr

 ©2011 American Physical Society

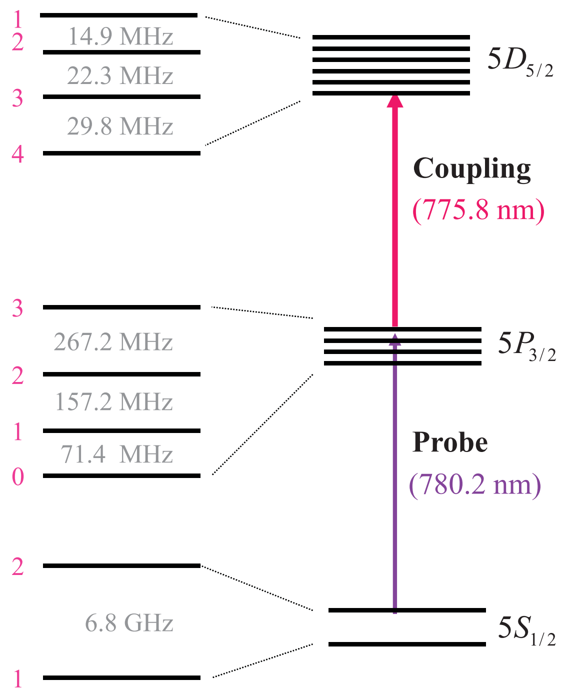

FIG. 1. (Color online) Energy-level diagram of the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ states of ^{87}Rb ($I = 3/2$). The total angular momentum F values are given to the left of the levels.

other ground state, $5S_{1/2}(F = 1)$, through the intermediate states, $5P_{3/2}(F' = 1,2)$. In particular, the cycling transition of $5S_{1/2}(F = 2)$-$5P_{3/2}(F' = 3)$-$5D_{5/2}(F'' = 4)$ is important for EIT because optical pumping to another $5S_{1/2}(F = 1)$ ground state never occurs due to the selection rules, even though the excited state has a decay channel to the $6P_{3/2}$ state. This cycling transition may be an example of a simple three-level ladder-type atomic system. However, the population of the $5S_{1/2}(F = 2)$ state may be changed by saturation effect caused by the strong coupling laser in the $5P_{3/2}(F'' = 3)$-$5D_{5/2}(F' = 4)$ transition.

Figure 2 shows the experimental setup for the DROP and EIT in the ladder-type atomic system. The frequency of the probe laser (780 nm) was scanned over the range of $5S_{1/2}(F = 2)$-$5P_{3/2}(F' = 1,2,3)$ transitions in the ^{87}Rb D_2 line and monitored using a conventional technique for saturated absorption spectroscopy (SAS). The frequency of the coupling laser (776 nm) was fixed on the $5P_{3/2}(F' = 3)$-$5D_{5/2}(F'' = 4)$ transition. Both the probe and coupling lasers were extended cavity laser diodes (ECLDs). The probe and coupling lasers were made to overlap and counterpropagate through a 2-mm diameter aperture and 5-cm room-temperature rubidium vapor cell. The earth's magnetic field was cancelled by wrapping three layers of a mu-metal sheet around the rubidium vapor cell. The optical power of both lasers was controlled with use of a neutral-density (ND) filter, and the polarization was controlled by the respective quarter wave plate (QWP)-half wave plate (HWP) pairs.

III. EXPERIMENTAL RESULTS

We observed the transmittance signal in the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transition of ^{87}Rb atoms, where the horizontal axis of Fig. 3 was detuning from the two-photon resonance between $5S_{1/2}(F = 2)$ and $5D_{5/2}(F'' = 4)$ of ^{87}Rb. The two lasers were linearly polarized in parallel. The probe and coupling powers were 15 μW and 8.2 mW, respectively. Although this transmittance spectrum is the so-called ladder-type EIT spectrum due to two-photon atomic coherence between the $5S_{1/2}$ and $5D_{5/2}$ states [15–17], this transmittance signal is due to not only a quantum destructive interference resulting from the atomic coherence, but also a population change in the state resulting from optical pumping. Because DROP due to optical pumping is proportional to a two-photon transition probability and is under the condition of the two-photon resonance similar to one of EIT [20], it is difficult to discriminate between EIT and DROP in the transmittance spectra for $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transition of ^{87}Rb atoms.

The transmittance peak of the cycling transition $5S_{1/2}(F = 2)$-$5P_{3/2}(F' = 3)$-$5D_{5/2}(F'' = 4)$ has a double structure, as shown in Fig. 4. The double-structure spectrum means superposition of two spectral profiles with different spectral widths, comprised of the narrow spectrum due to atomic coherence and

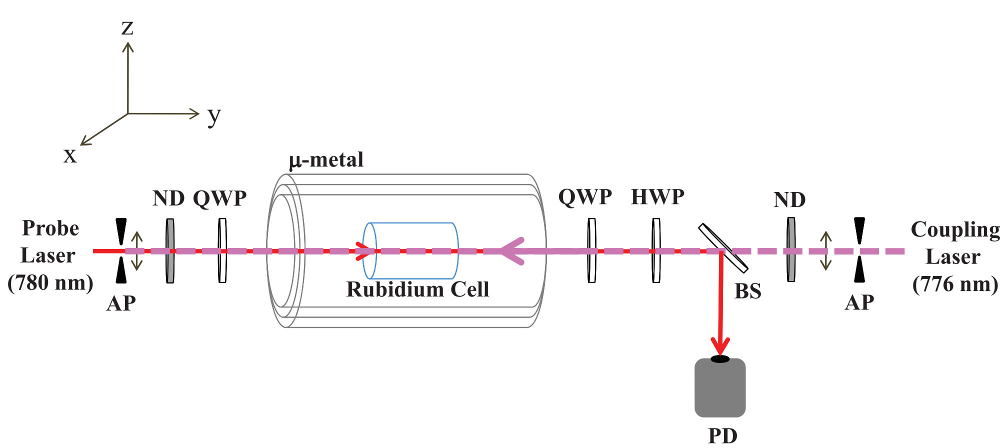

FIG. 2. (Color online) Experimental setup for examining the influence of the polarization combination of the lasers on DROP and EIT in the ladder-type atomic system of ^{87}Rb. (AP: aperture; ND: neutral density filter; BS: beam splitter; HWP: half-wave plate; QWP: quarter-wave plate; PBS: polarizing beam splitter; PD: Si photodiode.)

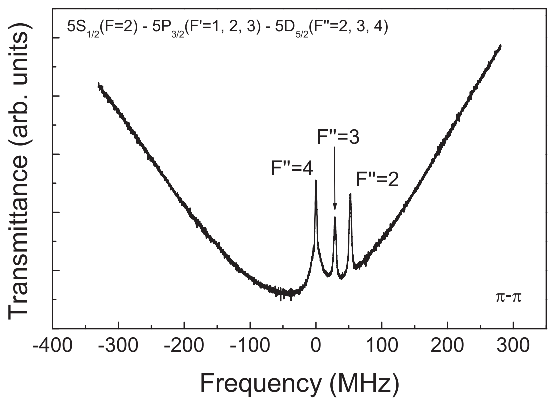

FIG. 3. Ladder-type transmittance spectrum of the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transitions of ^{87}Rb atoms in the case of a π-linearly polarized coupling laser and a π-linearly polarized probe laser.

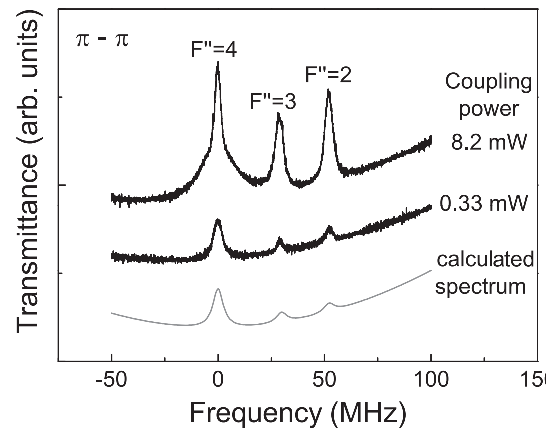

FIG. 4. Transmittance spectra of the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transitions at the coupling powers, 0.33 mW and 8.3 mW (black curves); the calculated spectrum with the two-photon transition probability (gray curve).

the broad spectrum due to saturation effect, respectively [20]. As explained in the discussion of the energy-level diagram in Fig. 1, the cycling transition may be modeled by a simple three-level ladder-type atomic system because the population of the $5S_{1/2}(F = 2)$ ground state is not transferred spontaneously to the other $5S_{1/2}(F = 1)$ ground state. In the cycling transition, the EIT due to atomic coherence has a larger effect than DROP.

However, in the case of the transmittance peaks of the $5D_{5/2}(F'' = 2$ and $3)$ states, an atom of the ground state $(F = 2)$ was excited to the $5D_{5/2}(F'' = 2$ or $3)$ state via the $5P_{3/2}$ intermediate state. Moreover, the atom can then be optically pumped into the $F = 1$ ground state via the intermediate $5P_{3/2}$ state. The different velocity components of the atoms in the rubidium vapor cell can contribute to the transmittance signal through all hyperfine states $(F' = 1,2,3,4)$ in the $5P_{3/2}$ intermediate state because of the Doppler broadening. Therefore, the DROP is the dominant effect for those transmittance peaks.

The relative intensities of the transmittance peaks depend on the laser power. Figure 4 shows two experimental spectra (black curves) and one calculated spectrum (gray curve) for the π-linearly polarized coupling laser and probe laser (lin-parallel-lin). The calculated spectrum of Fig. 4 was simulated by superposing one Gaussian curve and three Lorentzian curves proportional to the two-photon transition probability by considering the Clebsch-Gordan coefficients [16], as shown in Table I. The relative intensities of the two experimental spectra were considerably different in both cases of coupling power of 8.2 mW and 0.33 mW. In the case of 0.33 mW coupling power, the relative intensities of the peaks of the $5D_{5/2}(F'' = 2$ and $3)$ states were significantly lower than the one of the $5D_{5/2}(F'' = 4)$ state. Because the DROP effect in the transmittance signals of those transitions is dominant, the optical pumping from the $5S_{1/2}(F = 2)$ and $5S_{1/2}(F = 1)$ states due to DROP decreases when the power of the coupling laser is weaker. The relative intensity of the transmittance spectrum with 0.33 mW coupling power is in good agreement with the calculated result (gray curve) with the two-photon transition probabilities. The ratios of the relative transition probabilities of the $5S_{1/2}(F = 2)$-$5P_{3/2}(F' = 1,2,3)$-$5D_{5/2}(F'' = 2,3,4)$ transitions are approximately 1:1:3 to the $F'' = 2$, 3, and 4 states, when the $\Delta m = 0$ transition is considered. The experimental intensity ratios of the transmittance spectrum shown in Fig. 4 were approximately 1.2:1:1.8. There are two reasons for the difference between the experimental and the calculated transition probabilities. The first is the difference between the one-photon and two-photon transition probabilities. The second is the different optical pumping routes. As noted above, the atoms in the $F'' = 2$ state have an extra optical pumping route from $5D_{5/2}(F'' = 2)$ to $5S_{1/2}(F = 1)$ via the $5P_{3/2}(F' = 1)$ state. However, when the power of the coupling laser is 0.33 mW, the double structure of the transmittance spectrum cannot be seen in Fig. 4 because

TABLE I. The relative two-photon transition probability and the relative intensities of transmittance spectra of Fig. 5 as a function of the polarization combinations of the coupling and probe lasers.

Coupling- probe	Calculated values relative two-photon transition probability [16]			Measured values relative intensities of spectra of Fig. 5		
	$F'' = 4$	$F'' = 3$	$F'' = 2$	$F'' = 4$	$F'' = 3$	$F'' = 2$
π-π	36	12	12	37	20	24
π-$\sigma^{\pm}$	27	20	7	31	26	11
π-σ^{+}	27	20	7	58	46	36
σ^{+}-σ^{+}	54	18	7	70	21	0
σ^{+}-σ^{-}	9	14	12	57	60	53
σ^{+}-$\sigma^{\pm}$	27	20	7	39	18	12

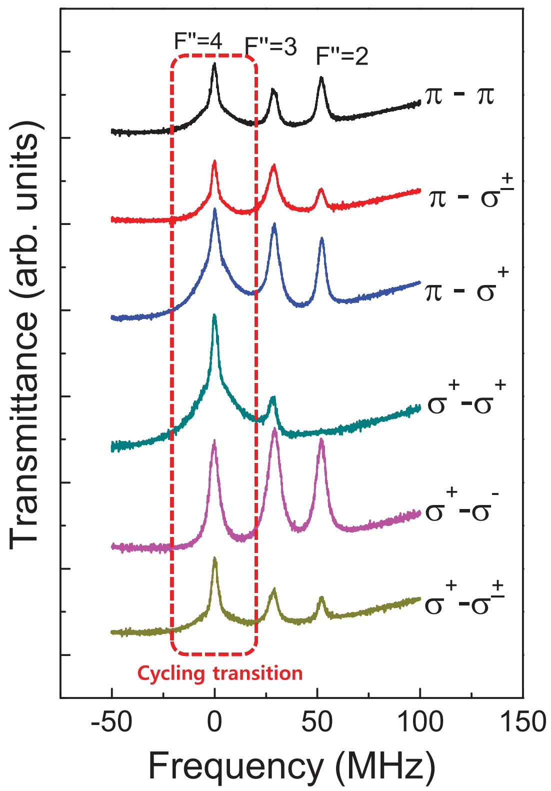

FIG. 5. (Color online) Measured transmittance spectra composed of DROP and EIT as a function of the polarization combinations of the coupling and probe lasers in the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transitions.

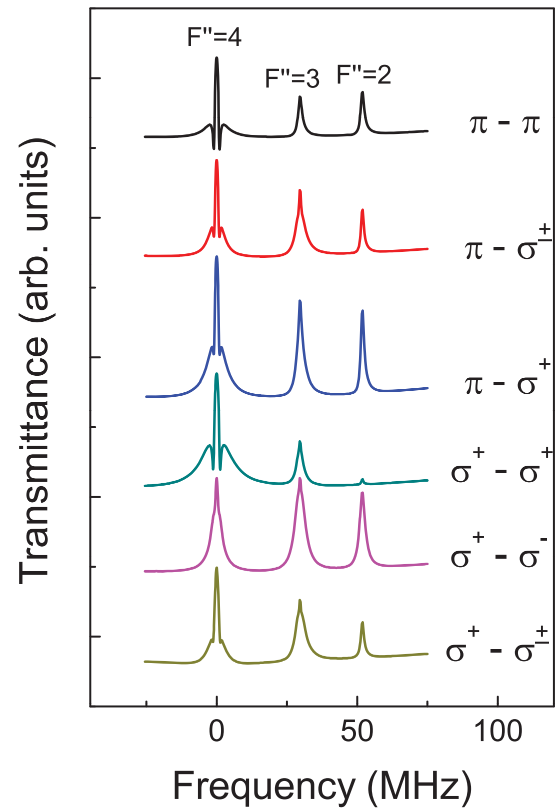

FIG. 6. (Color online) Numerically calculated transmittance spectra as a function of the polarization combinations of the coupling and probe lasers in the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transitions.

the atomic coherence is related to the power of the coupling laser.

Figure 5 shows the transmittance spectra of the $5S_{1/2}(F = 2)$-$5P_{3/2}(F' = 1,2,3)$-$5D_{5/2}(F'' = 2,3,4)$ transitions as a function of the polarization combination of the probe and coupling lasers. The experimental spectra of Fig. 5 were obtained using a 15 μW probe laser and an 8.2 mW coupling laser. When the polarization of the probe laser is π-linearly polarized light (z axis), the polarization combination of the coupling laser is comprised of π-linearly polarized light (z axis), $\sigma^{\pm}$-linearly polarized light (x axis), and σ^{+}-right-circularly polarized light $[(\hat{z} - i\hat{x})/\sqrt{2}]$. Also, when the polarization of the probe laser is σ^{+}-right-circularly polarized light $[(\hat{z} - i\hat{x})/\sqrt{2}]$, the polarization combination of the probe laser is comprised of π-linearly polarized light (z axis), $\sigma^{\pm}$-linearly polarized light (x axis) and σ^{+}-right-circularly polarized light $[(\hat{z} - i\hat{x})/\sqrt{2}]$.

This study focused the variations in the double-structure feature of the cycling transition according to the polarization combination of the laser. The double-structure spectrum clearly showed the cycling transition except in the case of the σ^{+}-polarized coupling laser and σ^{-}-polarized probe laser. As shown in Fig. 5, the entire spectral profile and intensity of the transmittance spectrum in the cycling transition are dependent on the polarization combination of the laser. A comparison of the cases of the σ^{+}-σ^{+} polarization with the case of σ^{+}-σ^{-} polarization revealed a difference in the spectral features of the two spectra. In the spectrum, the important difference from the case of σ^{+}-σ^{-} polarization is the double structure in the case of σ^{+}-σ^{+} polarization. The difference can be attributed to the two-photon transition probability and different transition routes between the Zeeman sublevels. The transitions between Zeeman sublevels with the σ^{+}-polarized coupling laser and σ^{-}-polarized probe laser should be considered as the $\Delta m_F = +1$ and -1 selection rule, respectively. In the case of σ^{+}-σ^{-} polarization, the two-photon transition probability is lower than in the case of the other polarization combination and the population accumulates in the uncoupled Zeeman sublevels of the intermediate state. Therefore, the saturation effect is dominant in the transmittance spectrum.

The two-photon transition probability and the transmittance peak in the cycling transition was highest in the σ^{+}-σ^{+} polarization combination. The narrow EIT signal caused by atomic coherence was higher when the two-photon transition probability was higher because the two-photon transition probability is related to the atomic coherence. In the case of the σ^{+}-σ^{-} polarization combination, although the two-photon transition probability was lowest in the cycling transition, the transmittance peak of the cycling transition was larger than in the case of the linearly polarized laser. This transmittance spectrum was attributed to saturation because it is dependent on the transition routes in the Zeeman sublevels. This is because the population can be accumulated in the uncoupled Zeeman sublevels of the intermediate state because of the optical pumping process. However, although the two-photon transition probability is low, we can see the weak atomic coherence effect from the acuminate spectral shape of the transmittance spectrum.

The difference between the relative two-photon transition probability of Table I and the relative intensities of the transmittance spectra of Fig. 5 is significant. To understand a theoretical study of the change of transmittance according to the polarization combination between the probe and coupling lasers, we calculated the density-matrix equation including all the degenerate magnetic sublevels of the hyperfine states in the $5S_{1/2}$,$5P_{3/2}$,$5D_{5/2}$, and $6P_{3/2}$ fine structure states. The calculated transmittance spectra were averaged over the Maxwell-Boltzmann velocity distribution in order to consider the Doppler-broadened atomic medium. The transmittance spectra in the vapor cell were calculated numerically by the full density matrix equations [21], as shown in Fig. 6. In order to numerically simulate the experimental results of Fig. 5, the parameters for the numerical calculation of Fig. 6 are a probe laser power of 15 μW, a coupling laser power of 8.2 mW, and laser beam diameter of 2 mm.

A comparison of the calculated results in Fig. 6 with the experimental results in Fig. 5 shows a quite reasonable agreement. As shown in Figs. 5 and 6, a double structure of the cycling transition was observed in both the experiment and calculation. However, the calculated result for the transmittance spectra showed the very narrow dips near the narrow peak in double structure. This is because the line width of the two independent lasers used in our experiment were not considered: they were estimated as 1 MHz, respectively.

IV. CONCLUSION

This study examined the polarization effect of DROP, saturation effect, and EIT in a $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ ladder-type system in ^{87}Rb. When the transmittance spectra were measured according to the polarization combination of the lasers, the transmittance peak of the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=4)$ cycling transition showed a double structure except in the case of the σ^+-σ^- polarization combination. The polarization dependence of DROP and EIT was analyzed by measuring the relative intensities of the entire transmittance spectrum. The EIT effect was observed on only the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=4)$ cycling transition and the transmittance of the $5S_{1/2}(F=2)$-$5P_{3/2}(F'=3)$-$5D_{5/2}(F''=2$ and $3)$ transitions was due to DROP effect. In the case of the σ^+-σ^- polarization combination, the large transmittance spectrum was measured despite the low two-photon transition probability that results from the population accumulated in the uncoupled Zeeman sublevels of the intermediate state. In the case of the cycling transition, despite the residual B field in the cell and the incomplete polarization of the lasers, the EIT due to atomic coherence was strongly related to the two-photon transition probability. However, the DROP due to optical pumping was dependent on the two-photon transition probability and the transition routes between Zeeman sublevels. Finally, the ladder-type atomic systems were used in many studies of Rydberg states, nonclassical photon pair generation, multiwave mixing, and coherent control. Our results are expected to help to better understand the causes of the transition between the states in ladder-type atomic systems, which are quantum interference due to the atomic coherence and population changes in the states due to optical pumping.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (Grant No. 2009-0066070).

[1] W. Demtröder, *Laser Spectroscopy*, 3rd ed. (Springer, Berlin, 2003).
[2] K. J. Boller, A. Imamoglu, and S. E. Harris, Phys. Rev. Lett. **66**, 2593 (1991).
[3] H. Schmidt and A. Imamoglu, Opt. Lett. **21**, 1936 (1996).
[4] M. Xiao, Y. Q. Li, S. Z. Jin, and J. Gea-Banacloche, Phys. Rev. Lett. **74**, 666 (1995).
[5] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, Nature (London) **409**, 490 (2001).
[6] M. Bajcsy, A. S. Zibrov, and M. D. Lukin, Nature (London) **426**, 638 (2003).
[7] T. W. Kornack, J. C. Allred, and M. V. Romalis, Nature (London) **422**, 596 (2003).
[8] D. Budker and M. V. Romalis, Nature Phys. **3**, 227 (2007).
[9] C. W. Chou, H. de Riedmatten, D. Felinto, S. V. Polyakov, S. J. van Enk, and H. J. Kimble, Nature (London) **438**, 828 (2005).
[10] H. J. Kimble, Nature (London) **453**, 1023 (2007).
[11] P. Kolchin, Phys. Rev. A **75**, 033814 (2007).
[12] C. Y. Ye and A. S. Zibrov, Phys. Rev. A **65**, 023806 (2002).
[13] F. Bitter, Phys. Rev. **76**, 833 (1949).
[14] J. Brossel and F. Bitter, Phys. Rev. **86**, 308 (1952).
[15] R. R. Moseley, S. Shepherd, D. J. Fulton, B. D. Sinclair, and M. H. Dunn, Opt. Commun. **119**, 61 (1995).
[16] D. McGloin, M. H. Dunn, and D. J. Fulton, Phys. Rev. A **62**, 053802 (2000).
[17] A. K. Mohapatra, T. R. Jackson, and C. S. Adams, Phys. Rev. Lett. **98**, 113003 (2007).
[18] H. S. Moon, W. K. Lee, L. Lee, and J. B. Kim, Appl. Phys. Lett. **85**, 3965 (2004).
[19] H. S. Moon, L. Lee, and J. B. Kim, J. Opt. Soc. Am. B **24**, 2157 (2007).
[20] H. S. Moon, L. Lee, and J. B. Kim, Opt. Express **16**, 12163 (2008).
[21] H.-R. Noh and H. S. Moon, Phys. Rev. A **80**, 022509 (2009).