Level-crossing absorption with narrow spectral width in Rb vapor with buffer gas

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We present the transformation in the Hanle configuration of the transmission that results from coherent population trapping (CPT) into the level-crossing absorption (LCA) that results from the single-photon optical pumping in the ^{87}Rb D_1 line of a Rb vapor cell with a Ne buffer gas when the polarization of the laser field is changed from linear to circular. The LCA spectrum, with a narrow spectral width of 2.4 mG (1.7 kHz), was observed in the $F_g \rightarrow F_e \leqslant F_g$ transition with the circularly polarized laser. This may be because the LCA is both related to the transverse magnetic field and the atom-laser interaction time resulting from diffusive atomic motion in the cell with the buffer gas. The CPT and LCA spectra were calculated numerically using the full density matrix equations for the relevant magnetic sublevels of the hyperfine levels, considering the residual magnetic fields perpendicular to laser propagation and the collision effects resulting from the buffer gas. There was good qualitative agreement between theoretical and experimental results.

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I. INTRODUCTION

Atomic coherence has various applications, such as the atomic clock, laser cooling, light storage, and quantum teleportation [1–8]. Electromagnetically induced transparency (EIT) is one of the phenomena associated with coherent effects [9–13]. In general, EIT has been studied in a three-level Λ system with two long-lived ground states and a short-lived excited state. When the two ground states are coupled to an excited state by the resonant fields at a certain time, reaching a steady state, the population of atoms in the two ground states does not change. In this situation, the atoms are in a so-called coherent-population-trapping (CPT) configuration [14]. The resonant field is transparent in an atomic medium without absorption. The spectral width of the transmittance spectrum is related to the coherence decay rate of the coherent superposition of the ground states. In particular, the atomic coherence between the Zeeman sublevels with Hanle configuration is useful for developing an atomic magnetometer. Many previous studies of the Hanle configuration employed electromagnetically induced transparency (EIT) resonance on an $F_g \rightarrow F_e \leqslant F_g$ transition [14,15].

However, the phenomenon opposite of EIT is electromagnetically induced absorption (EIA) with low-frequency Zeeman coherences in a near-degenerate two-level atomic system [16–18]. EIA in the Hanle configuration has been investigated in the resonance on an $F_g \rightarrow F_e = F_g + 1$ transition using a pure atomic vapor cell [19–21]. Unlike EIT, EIA was explained by the atomic coherence between the degenerate excited levels transferring spontaneously to the degenerate ground levels [17]. Observation of EIA is difficult in an atomic vapor cell with a buffer gas because the features of EIA are related to the emission of the excited states. EIA resonances may be suppressed when the coherence of the excited state is destroyed by collisions [22]. With the exception of EIA resulting from spontaneous coherent transfer in the resonance on an $F_g \rightarrow F_e = F_g + 1$ transition, the absorption spectrum with a below-natural width occurs because of a collision-induced coherent effect, two-photon Raman resonance, and double-Λ-level configuration [23–26]. Recently, A. Huss *et al.* reported both the width and the contrast of single-frequency level-crossing CPT resonances in the presence of an additional magnetic field orthogonal to the laser propagation direction [26].

In this article, we present the transformation of the transmission due to CPT into the absorption due to single-photon transition in the Hanle configuration using the polarization of a laser field of ^{87}Rb D_1 line with a Rb vapor cell with a buffer gas. The absorption spectra were examined as the function of the hyperfine transition, and the features of the spectra in the buffer gas cell were compared with those of a pure cell. In addition, the Hanle spectrum in a vapor cell with buffer gas was calculated numerically using full density matrix equations for the relevant magnetic sublevels of the hyperfine levels.

II. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup for the transmittance and the absorption spectrum in the Hanle configuration according to the polarization of laser. An external cavity laser diode on the $5S_{1/2} \rightarrow 5P_{1/2}$ transition in ^{87}Rb D_1 line was used for the experiment and was monitored using the conventional technique for saturated absorption spectroscopy (SAS) in a 5-cm-long Rb vapor cell. A 5-cm-long pure Rb vapor cell at room temperature and a Rb vapor cell with 50 Torr of Ne as buffer gas at temperatures ranging from 50°C to 90°C were used to examine the collision effect. The effect of the earth's magnetic field was minimized by wrapping the Rb cell three times with a μ-metal sheet. The residual magnetic field was measured to be several milligauss (mG). A solenoid coil was installed in the μ-metal sheets, and the magnetic field parallel to the laser's propagation was scanned around the zero value to obtain the spectrum in the Hanle configuration. The residual magnetic field was reduced by controlling the x- and y-axial magnetic field using a compensation coil. In this experiment, the residual magnetic field is important for the absorption spectrum with a circularly polarized laser. The dependence

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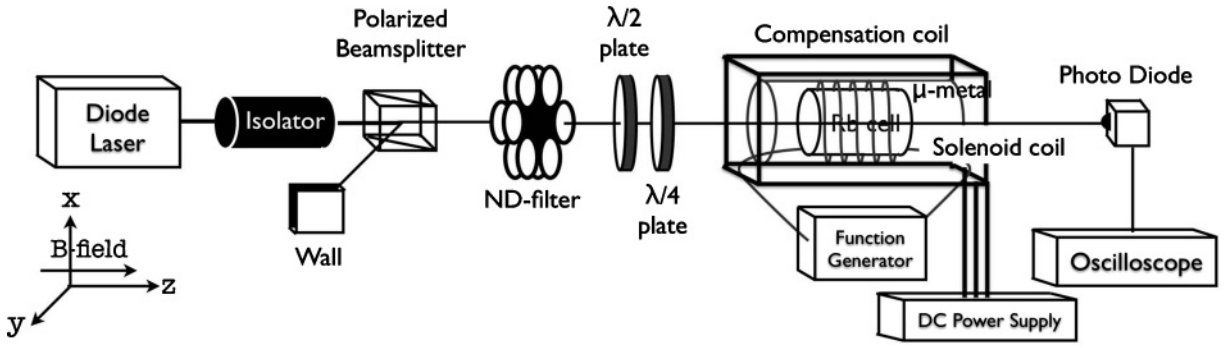

FIG. 1. Experimental setup for the transmittance and the absorption spectrum in the Hanle configuration according to the laser polarization.

of the Hanle spectrum on the polarization of the laser was investigated by varying the laser polarization from linear to circular by a half-wave plate and a quarter-wave plate. The laser intensity was also adjusted using neutral density (ND) filters.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the typical CPT spectrum of the $5S_{1/2}(F = 2)$ to $5P_{1/2}(F' = 1)$ transition of ^{87}Rb in the Hanle configuration, where the horizontal axis of the figure is a z-axis magnetic field parallel to the laser's propagation generated by the solenoid coil. The z-axis magnetic field was scanned in the region near the zero value, where the laser intensity was 126 μW/cm^2, the laser polarization was linear, and the temperature of the vapor cell with the Ne buffer gas (50 Torr) was 70°C. In Fig. 2, the spectral width and contrast of the CPT spectrum was 1.2 mG (0.85 kHz) and approximately 6%, respectively. The contrast was defined as the CPT signal intensity divided by the background intensity. The asymmetrical resonance line in Fig. 2 is the result of the temporal evolution effect of due to magnetic field scanning generated by the solenoid coil. This phenomenon arises from

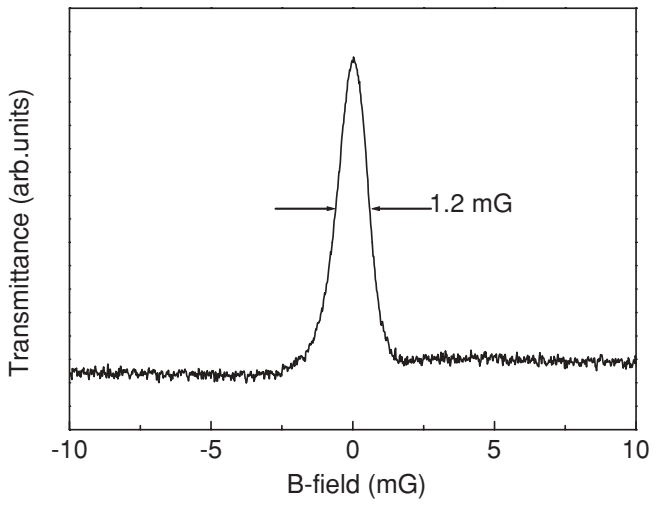

FIG. 2. Typical CPT spectrum of the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transition of ^{87}Rb in the Hanle configuration, where the horizontal axis of the figure is the z-axis magnetic field parallel to the laser's propagation generated by the solenoid coil.

temporal evolution of the CPT signal when Raman detuning is changed suddenly [27,28].

The Hanle spectra in the vapor cell with a buffer gas were investigated according to the transition between the hyperfine states. There are four transitions between the two hyperfine ground states ($F = 1$ and 2) and two hyperfine excited states ($F' = 1$ and 2) in the D_1 line of ^{87}Rb atoms. The transmittance spectra due to CPT in all hyperfine transitions were observed when the laser frequency was fixed at each hyperfine transition and the z-axis magnetic field was scanned, as shown in Fig. 3. These results were obtained under the conditions of the linearly polarized laser and the vapor cell with the Ne buffer gas.

As shown in Figs. 3(a) and 3(b), the magnitude of the transmittance spectra in the $F = 1 \rightarrow F' = 1$ and 2 transitions was smaller than those in the $F = 2 \rightarrow F' = 1$ and 2 transition because of the lower transition probability. The contrast of the two spectra in the $F = 1 \rightarrow F' = 1$ and 2 transitions was measured to be approximately 0.5% and 0.1%, respectively. Transmittance instead of absorption was observed, even though the condition for the EIA (due to spontaneous coherent transfer) was satisfied in the $F = 1 \rightarrow F' = 2$ transition. This can be explained by destruction of the coherence of the excited state by collisions with the buffer gas. Spontaneous coherent transfer can be suppressed and CPT may be dominant because of the short lifetime of the excited state [20].

A comparison of the two spectra of the $F = 2 \rightarrow F' = 1$ and 2 transitions revealed that the magnitude, contrast, and spectral width of the transmittance spectrum in the $F = 2 \rightarrow F' = 1$ transition were similar to those in the $F = 2 \rightarrow F' = 2$ transition, as shown in Figs. 3(c) and 3(d). The measured contrast and spectral width was approximately 5% and approximately 1.2 mG, respectively. However, in the case of the $F = 2 \rightarrow F' = 2$ transition, there was an absorption around the CPT resonance, as shown in Fig. 3(d). This absorption was attributed to the residual magnetic field, the uncompleted linearly polarized laser and the collision effect.

A transformation of the transmission into absorption in the four transitions of the D_1 line of ^{87}Rb atoms was observed when the laser polarization was changed from linear to circular. Figure 4 shows the Hanle spectra in the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transition according to the polarization of the laser, where the degree is the angle between the direction of linear polarization and the fast axis of the quarter-wave plate. In the case of the right circular polarization, because the atoms are optically pumped by the circularly polarized light to the

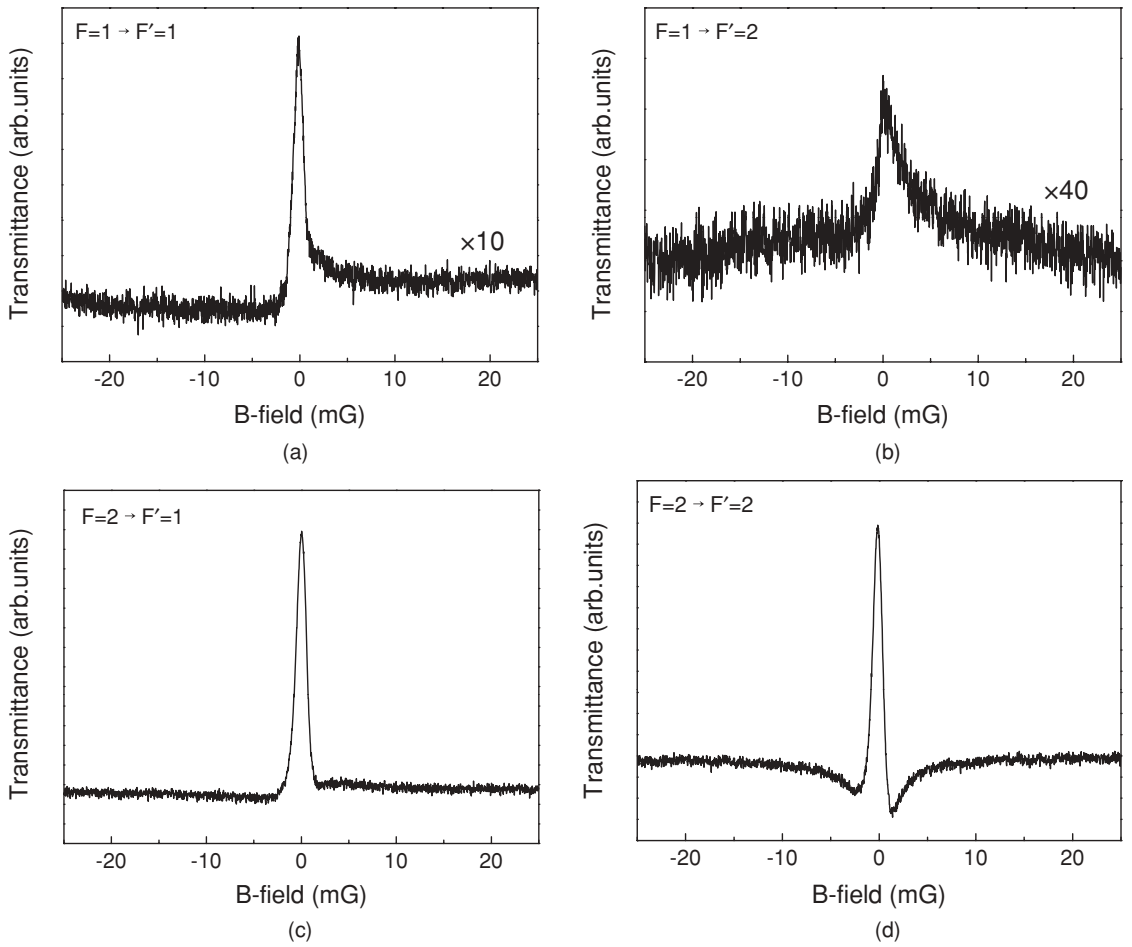

FIG. 3. Transmittance spectra due to CPT in the four transitions with a linearly polarized laser and a vapor cell with the Ne buffer gas: (a) $F = 1 \rightarrow F' = 1$ transition, (b) $F = 1 \rightarrow F' = 2$ transition, (c) $F = 2 \rightarrow F' = 1$ transition, and (d) $F = 2 \rightarrow F' = 2$ transition in the D_1 line of ^{87}Rb atoms.

magnetic sublevels $m_F = 1$ and $m_F = 2$ of the $5S_{1/2}(F = 2)$ ground state and which then cease to interact with the laser light, we may not expect any transmission or absorption signal. However, a distinct absorption spectrum with a narrow spectral width was observed when using the circularly polarized laser, as shown at the 45° mark of Fig. 4. The absorption spectrum with the narrow spectral width is the result of a redistribution of the ground-state populations caused by the transverse magnetic field and not by an atomic coherence effect due to two-photon coherence. The atomic magnetic momentum is generated collinearly to the z-axis magnetic field because the atoms are pumped into the particular Zeeman sublevels of the ground state without atom-laser interaction from the circularly polarized laser. However, when there is a weak transverse residual magnetic field, the atomic magnetic momentum is changed around the zero value of the z-axis magnetic field directed to the laser's propagation. The transverse residual magnetic field crosses the Zeeman sublevels in the ground state and redistributes the populations of Zeeman sublevels, which results in an absorption signal [26].

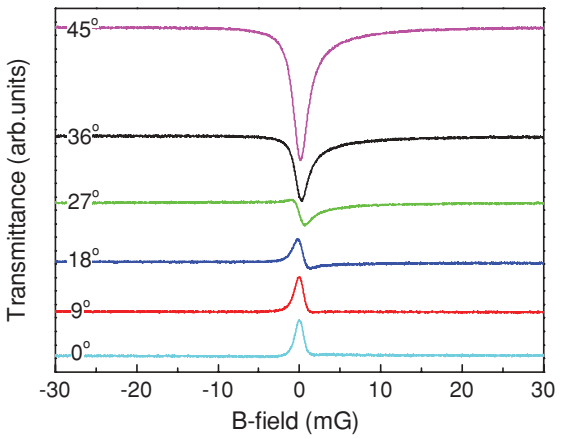

FIG. 4. (Color online) Hanle spectra of the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transition in the Rb vapor cell with Ne 50-Torr buffer gas according to the laser polarization, where the degree is the angle between the direction of linear polarization and the fast axis of the quarter-wave plate.

Although the absorption is due to optical pumping by the single-photon coherence, a narrow absorption spectrum with a weak transverse residual magnetic field can be obtained. In particular, the narrow spectral width is caused by the level crossing due to the transverse magnetic field generated when the z-axis magnetic field is smaller than the transverse magnetic field. The transverse residual magnetic field is weaker, and the LCA resonance is narrower. The spectral width of the absorption spectrum is related to the magnitude

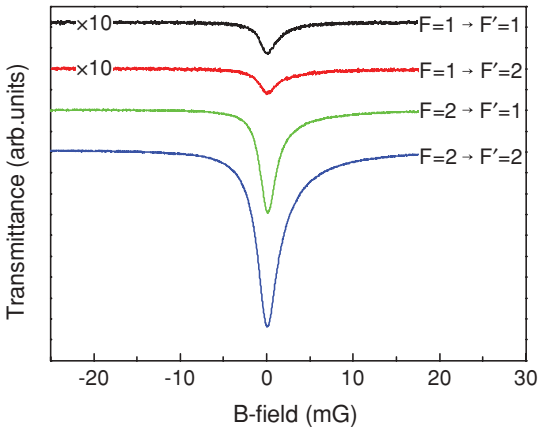

FIG. 5. (Color online) Narrow LCA spectra in the four transitions under the conditions on the circularly polarized laser and the vapor cell with Ne buffer gas: From the top to the bottom, $F = 1 \rightarrow F' = 1$, $F = 1 \rightarrow F' = 2$, $F = 2 \rightarrow F' = 1$, and $F = 2 \rightarrow F' = 2$ transitions in the D_1 line of ^{87}Rb atoms.

of the transverse magnetic field. Spectral distortion due to the transmittance of CPT and the LCA was observed when the laser polarization was elliptic by adjusting the quarter-wave plate in the experimental setup in Fig. 1, as shown between the 9° and 36° marks in Fig. 4. Because the laser polarizations at 27° and 36° in Fig. 4 have larger circular components than linear components, absorption dominates over transmittance. On the other hand, in the cases at the 9° and 18° marks in Fig. 4, transmittance dominates over absorption. At the 27° and 18° positions in Fig. 4, dispersive features were observed as a result of the transmittance of CPT and LCA. The origin of the complicated shape in the cases at the 27° and 18° marks in Fig. 4 are discussed when the calculated results are explained.

Figure 5 shows the narrow LCA spectra with the circular polarization for each hyperfine transition. LCA spectra could be observed in all hyperfine transitions when the experimental process and conditions were the same as those in Fig. 3. The magnitude of the absorption spectra in the $F = 2 \rightarrow F' = 1$ and 2 transitions was approximately thirty times more than those of the $F = 1 \rightarrow F' = 1$ and 2 transitions. In the case of the $F = 2 \rightarrow F' = 2$ transitions, the LCA spectrum was the largest in the spectra of the four transitions because of the difference in the transition probability and number of hyperfine states. Although the magnitude of the LCA spectra is considerably different, the spectral width of the four spectra was almost 2.5 mG.

In order to investigate the LCA dependence on the collision effects, the Hanle spectra was obtained using a pure Rb cell with the laser polarization under the same conditions used for the cell with the buffer gas. Figure 6 shows the Hanle spectra of the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transition in the pure Rb cell with the laser polarization. When the laser polarization was changed from linear to circular, the magnitude of the transmittance spectrum due to CPT was just reduced, and it was difficult to observe the LCA in the pure Rb cell. However, a very weak LCA spectrum was observed in the case of circular polarization, as shown in Fig. 6(b), because the interaction time for the population redistribution due to the level crossing by the transverse magnetic field in the cell with the buffer gas is longer than that in the pure cell. By comparing the LCA spectra

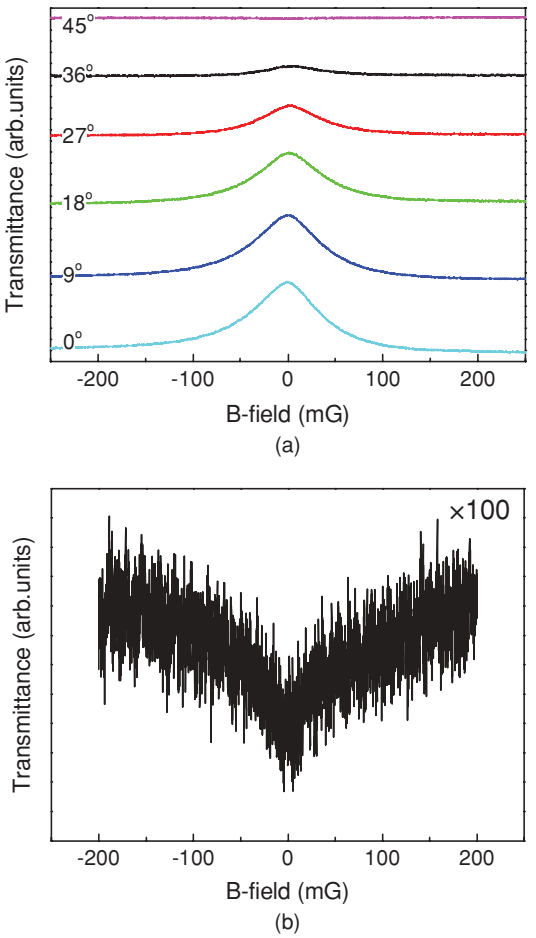

FIG. 6. (Color online) (a) Hanle spectra of the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transition in the pure Rb vapor cell according to the polarization of the laser, where the degree is the angle between the direction of linear polarization and the fast axis of the quarter-wave plate, (b) weak LCA spectrum in the case of circular polarization, which is 100 times larger signal than that in (a).

of the pure Rb cell and the cell with the buffer gas, we found that the LCA spectrum depends not only on the transverse magnetic field but also on the atom-laser interaction time due to the diffusive atomic motion in the cell with the buffer gas.

In order to perform a theoretical study of the transformation of transmittance due to CPT into LCA due to single-photon optical pumping according to the laser polarization, it is important to consider the atomic coherence, transverse magnetic field, and collision effects in the eight-level atomic system, including all the degenerate magnetic sublevels in the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transitions of ^{87}Rb. By considering the residual magnetic fields perpendicular to laser propagation and the collision effects due to the buffer gas, the Hanle spectra in the vapor cell with buffer gas were numerically calculated by the full density matrix equations for the $5S_{1/2}(F = 2) \rightarrow 5P_{1/2}(F' = 1)$ transitions of ^{87}Rb, as shown in Fig. 7. In order to numerically simulate the experimental results of Fig. 4, the parameters for the numerical calculation of Fig. 7 are a laser intensity of 126 μW/cm^2, laser beam diameter of 4.5 mm, transverse magnetic field of 1 mG, atom-laser interaction time of 3.75 ms, and collision broadening of 250 MHz.

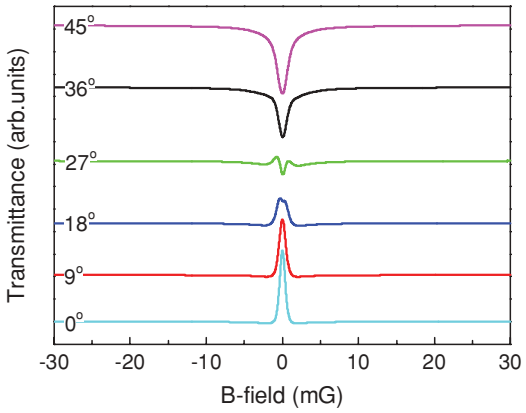

FIG. 7. (Color online) Numerically calculated Hanle spectra of the $5S_{1/2}(F=2) \rightarrow 5P_{1/2}(F'=1)$ transition according to the laser polarization in which the transverse magnetic field and collision effects of a buffer gas are considered.

A comparison of the numerical results in Fig. 7 with the experimental results in Fig. 4 showed good qualitative agreement. As shown in Figs. 4 and 7, a narrow transmission (absorption) peak was observed when the polarization was linear (circular) in both the experiment and calculation. As the polarization was changed from the linear to circular, the height of the transmission peak decreased and the shape of the signal became the absorption peak. However, the calculated result for the 27° angle showed a complicated asymmetric line shape and to a certain extent was different from the experimental result. This is why the line shape was composed of neither simple absorptive nor dispersive function; instead, it consisted of many Lorentzian and dispersive functions with different widths and amplitudes.

The absence of LCA from the calculated results was confirmed when the transverse magnetic field was zero. The experimental and theoretical results in Figs. 4 and 7, respectively, showed that the transverse magnetic field was the most important reason for LCA. The Hanle spectra in the pure Rb cell were calculated as shown in Fig. 8. The parameter for the atom-laser interaction time was 15.6 μs. The

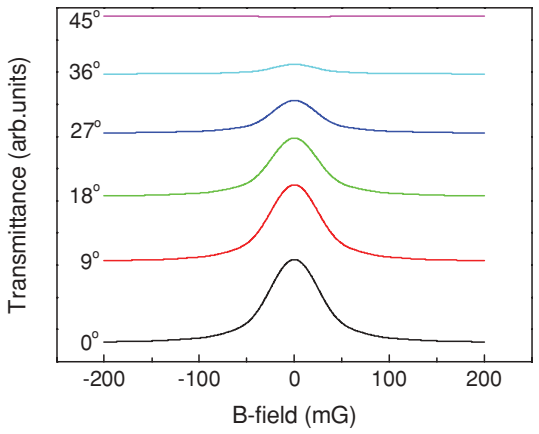

FIG. 8. (Color online) Numerically calculated Hanle spectra of the $5S_{1/2}(F=2) \rightarrow 5P_{1/2}(F'=1)$ transition according to the laser polarization for the pure cell, in which the transverse magnetic field is considered.

theoretical results were in good qualitative agreement with the experimental results shown in Fig. 6(a). When the transverse magnetic field was sufficiently large, an LCA spectrum could be obtained with a pure Rb cell. The LCA was related not only to the transverse magnetic field but also to the atom-laser interaction time due to diffusive atomic motion in the cell with the buffer gas. Under the same conditions, the atom-laser interaction time in the cell with the buffer gas is longer than that in the pure cell. The spectral width is narrower, as expected, because of the increase in the atom-laser interaction time. Also, the interaction time for the population redistribution due to the level crossing by the transverse magnetic field in the cell with the buffer gas is longer than that in the pure cell. Therefore, both the magnitude of the transverse magnetic field and atom-laser interaction time should be considered in order to better understand the LCA.

IV. CONCLUSION

This study examined the LCA caused by the single-photon optical pumping in a Rb vapor cell with Ne buffer gas. In the Hanle configuration, a transformation of the transmission due to CPT into the LCA due to single-photon optical pumping in the ^{87}Rb D_1 line was observed when the polarization of the laser field was changed from linear to circular. In the linearly polarized laser, CPT spectra were obtained in all four hyperfine transitions of the ^{87}Rb D_1 line. The measured spectral width and contrast of the CPT spectrum of the $F=2 \rightarrow F'=1$ transition were 1.2 mG (0.85 kHz) and approximately 6%, respectively. In the $F=1 \rightarrow F'=2$ transition, transmittance was observed instead of absorption because of the collision effects by the buffer gas. In the circularly polarized laser, despite the optical pumping by the single-photon coherence without the quantum interference effect by two-photon coherence, a narrow absorption spectrum (LCA) with a weak residual transverse magnetic field was obtained, which was generated by the level-crossing attributable to the transverse magnetic field. The measured spectral width of the LCA spectrum on the $F=2 \rightarrow F'=1$ transition was 2.4 mG (1.7 kHz) by the residual transverse magnetic field. The spectral width of the LCA was strongly related to the magnitude of the transverse magnetic field. In addition, the LCA spectra were observed in all four hyperfine transitions, even though the magnitude of the LCA spectra was significantly different in each transition.

A comparison of the LCA spectra in the pure Rb cell with that of a Rb cell with Ne buffer gas showed that the LCA was dependent on the atom-laser interaction time and the collision effects of the buffer gas. By considering the residual magnetic field and collision effects due to the buffer gas, the Hanle spectrum in the vapor cell with buffer gas was calculated numerically using the full density matrix equations for all relevant magnetic sublevels of the hyperfine levels. The theoretical and experimental results showed good qualitative agreement. We explained that the LCA was related not only to the transverse magnetic field but also to the atom-laser interaction time resulting from the diffusive atomic motion in the cell with the buffer gas. It is expected that the LCA can be applied to an atomic magnetometer to measure weak transverse magnetic fields using the spectral width variable magnetic resonance.

ACKNOWLEDGMENTS

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