Unravelling the Mechanisms of Electromagnetically Induced Absorption and Transparency in Open Degenerate Multilevel System: Effects of Neighboring Transitions

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Research Article

Keywords: Electromagnetically Induced Absorption, Transparency , degenerate two-level system (DTLS)

Posted Date: July 15th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-701938/v1>

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Unravelling the mechanisms of electromagnetically induced absorption and transparency in open degenerate multilevel system: effects of neighboring transitions

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ABSTRACT

Optical Bloch equations with and without neighboring hyperfine states near the degenerate two-level system (DTLS) in the challenging case of ^{85}Rb D2 transition that involves the Doppler broadening effect are solved herein. The calculated spectra agree well with the experimental results obtained using the coupling-probe scheme with orthogonal linear polarizations of the coupling and probe fields. The mechanisms of electromagnetically induced absorption (electromagnetically induced transparency) for the open $F_g = 3 \rightarrow F_e = 2$ and 3 transitions (open $F_g = 2 \rightarrow F_e = 2$ and 3 transitions) are clearly determined to be the effect of the strong closed $F_g = 3 \rightarrow F_e = 4$ transition line (strong closed $F_g = 2 \rightarrow F_e = 1$ transition line) based on the comparisons of the calculated absorption profiles of a DTLS without neighboring states and those of all levels with neighboring states depending on the coupling and probe power ratios. The crucial factors established based on comparisons of the calculated absorption profiles of DTLS with and without neighboring states, which enhance or reduce coherence effects and result in transformation between electromagnetically induced absorption and electromagnetically induced transparency, are the power ratios between coupling and probe beams, openness of the excited state, and effects of the neighboring states due to the Doppler broadening in a real atomic system.

Introduction

Since the initial reports on electromagnetically induced absorption (EIA)¹ and electromagnetically induced transparency (EIT)^{2,3}, many studies⁴⁻¹⁹ have been conducted on the transitions between EITs and EIAs and the mechanisms of transitions of EITs and EIAs due to quantum coherence and interference between coupled atomic states in coupling-probe and Hanle-type experiments. However, the mechanisms of transitions between EIAs and EITs depending on powers, polarization configurations of coupling and probe beams, openness of the transitions, and neighboring effects with Doppler broadening are still unclear⁴⁻¹⁹. The mechanisms of EIA transitions from EITs depending on coupling and probe powers in the case of the $F_e = F_g - 1$ open system of the ^{85}Rb D2 line have not been elucidated, and such EIAs at weak coupling and probe powers have not been observed to date.

Three necessary EIA conditions for EIAs by Lezama²⁰ for a degenerate two-level system (DTLS) were established based on first investigations of EIA resonance¹ using coupling and probe lasers: (i) the ground state must be degenerate; (ii) $F_e = F_g + 1$; (iii) the $F_g \rightarrow F_e$ transition must be closed, without considering contributions to absorption or transmission coherence strength from neighboring states embedded in Doppler broadening profiles, power ratios between the coupling and probe beams, polarization configurations, openness of the excited state, etc.

Observations and calculations of EIAs in a DTLS that partially do not satisfy the above three conditions^{4-6,8-17,19} and similarly those of EITs in a DTLS that partially satisfy the above three conditions^{7,9,10,18} have been performed. Thus, the above conditions for EIAs are satisfied in specific scenarios such that the EIA and EIT can be observed depending on the coupling and probe powers, openness of transition, polarization configurations, and effects of neighboring states in the cases of $F_e = F_g + 1$, $F_e = F_g$, and $F_e = F_g - 1$.

There also exist many reports^{4-7,12,14-17} on the transitions between EIA and EIT depending on the general EIA conditions of the $F_e = F_g + 1$ open system. However, expected EITs in the DTLS in the weak coupling and probe power regime and in the case of $F_e \leq F_g$, which violate the established EIA conditions²⁰, transforming into genuine and symmetric EIAs considering

the Doppler broadening effect have still not been reported. The first EIA resonances in the case of $F_e \leq F_g$ of the D1 and D2 transitions of $^{85,87}\text{Rb}$ were observed in the Hanle configuration, violating condition (iii) associated with closed transitions⁴ without any theoretical calculations for bright fluorescence profiles.

Kim *et al.*⁸ subsequently reported EIA resonances without a theoretical analysis in open systems of D1 lines of ^{85}Rb and ^{87}Rb , violating conditions (ii) and (iii). These EIA results obtained only from strong coupling and probe powers above the saturation power observed by several other groups also^{5,8,12,13,15–17}, result from merely enhanced absorption governed by strong coupling and probe powers, and are different from the EIAs observed and explained for the same transition configuration of $F_e = F_g - 1$ and F_g observed in this study using weak coupling and probe powers.

Chou *et al.*¹¹ qualitatively interpreted these EIA anomalies in open systems using a crude model in a high-power regime without a clear quantitative explanation. Zibrov *et al.*¹² also observed the EIA (EIT) resonances at open transitions $F_e = F_g + 1$ of D1 and D2 lines of ^{87}Rb atom on artificially shifting the laser frequency toward the blue end from the center of the Doppler profile (toward the red end from the center of the Doppler profile) in both Hanle and coupling-probe experiments except in the cases of $F_e = F_g - 1$ and $F_e = F_g$. Zhao *et al.*¹³ observed the EIA resonances in the strong coupling-probe regime for closed and open D2 transitions $F_g = 4 \rightarrow F_e = 3, 4$, and 5 of Cs in a coupling-probe experiment with an additional laser, wherein they referred to Goren *et al.*'s theoretical analysis¹⁴ for the EIA anomalies at open transitions without considering the effects of neighboring states.

Auzinsh *et al.* observed the EIA resonances in an atomic vapor cell in the case of the open $F_e = F_g + 1$ transition of $^{85,87}\text{Rb}$ -D1 lines¹⁶. Strong coupling and probe frequencies with powers greater than 100 mW/cm² were blue-shifted to escape the neighboring dark resonance in the Hanle experiment, wherein only strong coupling and probe powers govern the absorption phenomenon. They also confirmed that the resonance fluorescence observed in the extremely thin cell that escaped neighboring effects owing to the Doppler broadening could not reveal such EIA resonances¹⁷. Auzinsh *et al.* also observed sign reversals of bright resonances into dark resonances at closed transitions of D2 lines of ^{85}Rb and ^{87}Rb owing to high power and temperature in the Hanle experiment¹⁸.

Grewal *et al.*¹⁹ reported on the influence of closed neighboring hyperfine levels with strong EIA features owing to the increased ellipticities of the polarizations of coupling and probe lasers at the $F_e \leq F_g$ open transitions of D2 lines of ^{87}Rb in the case of the Hanle configuration. However, they could not theoretically explain the absorption profiles because of the computational complexities involved when considering the Doppler effect. Performing calculations of the absorption profiles for D2 transitions of ^{85}Rb have been proven to be a particularly challenging task because of strong neighboring effects due to Doppler profiles, wherein the total absorption of D2 transition lines with the inclusion of the Doppler effect should be calculated with the inclusion of all hyperfine levels of the ground and excited states.

In this study, we deduce that clear explanations for the transition of EIT into EIA in the case of ^{85}Rb D2 transition can be obtained based on a comparison of the calculated absorption profiles of DTLS without neighboring states and all energy levels of neighboring states with respect to the power ratios between the coupling and probe powers. To investigate the power effects on coherences, the coupling-probe experiment with two orthogonal linear polarizations from a single laser combined with two acousto-optic modulators (AOMs), instead of the Hanle-type experiment, is more suitable because the power ratios of the coupling and probe lasers and a wide scanning of the frequency in the Hanle-type experiment cannot be obtained.

Results

We compare the theoretical results while considering resonant and all neighboring transitions resulting in EIAs and EITs with the experimental results. We theoretically and experimentally investigate the resonance spectra for two spectrally unresolved groups of hyperfine transitions of ^{85}Rb D2 lines, i.e., $F_g = 3 \rightarrow F_e = 2, 3$, and 4 and $F_g = 2 \rightarrow F_e = 1, 2$, and 3, with a P-polarized weak-probe-beam power of 15 μW and S-polarized coupling beam with a scanning frequency of 5 MHz both at a low coupling power of 50 μW and strong coupling power of 4 mW, as shown in Fig. 1 and Fig. 2. For simplicity, we use simplified notations for the transitions; e.g., the $F_g = 3 \rightarrow F_e = 4$ transition is expressed as $3 \rightarrow 4'$ where unprimed (primed) integers represent the angular momentum quantum numbers in the ground (excited) states.

Figure 1 presents a comparison of the calculated spectra considering (a) a pure DTLS with transitions resonant at $3 \rightarrow 2'$, $3 \rightarrow 3'$, and $3 \rightarrow 4'$; (b) a transition resonant at $3 \rightarrow 2'$ with neighboring hyperfine transitions of $3 \rightarrow 3'$ and $4'$, a transition resonant at $3 \rightarrow 3'$ with neighboring hyperfine transitions of $3 \rightarrow 2'$ and $4'$, and a transition resonant at $3 \rightarrow 4'$ with neighboring hyperfine transitions of $3 \rightarrow 2'$ and $3'$; and (c) experimentally measured spectra with transitions resonant at $3 \rightarrow 2'$, $3 \rightarrow 3'$, and $3 \rightarrow 4'$ for two different weak (50 μW) and strong (4 mW) coupling powers as shown in the top and bottom traces, respectively.

First, we explain the cases of a weak coupling power as shown in the top trace of Fig. 1. In pure two-level calculations on the left side of the top trace, a closed $3 \rightarrow 4'$ transition satisfies all three necessary EIA conditions²⁰ and presents a relatively strong EIA amplitude with a linewidth of 57 kHz, as expected. For open transitions $3 \rightarrow 3'$ and $3 \rightarrow 2'$, EIT spectra with small amplitudes and a linewidth resolution of 46 kHz and 41 kHz are obtained, respectively. Considering all the neighboring states

Figure 1. Comparison of calculated and measured spectra considering: (a) pure two-level resonant transitions, i.e., $3 \rightarrow 2'$, $3 \rightarrow 3'$ and $3 \rightarrow 4'$, (b) a transition resonant at $3 \rightarrow 2'$ with neighboring hyperfine transitions of $3 \rightarrow 3'$ and $4'$, transition resonant at $3 \rightarrow 3'$ with neighboring transitions of $3 \rightarrow 2'$ and $4'$, transition resonant at $3 \rightarrow 4'$ with neighboring transitions of $3 \rightarrow 2'$ and $3'$, and (c) experimentally measured spectra for resonant transitions $3 \rightarrow 2'$, $3 \rightarrow 3'$ and $3 \rightarrow 4'$.

near the resonant transitions of $3 \rightarrow 2'$, $3 \rightarrow 3'$, and $3 \rightarrow 4'$, as shown in the upper trace of Fig. 1(b), all the resonant transitions show strong EIAs with similar amplitudes owing to a nearby closed $3 \rightarrow 4'$ transition, which exhibits strikingly similar trends in the spectra as the measured spectra, although the observed spectra are wider than the calculated ones. Measured ultra-narrow EIA dips at low coupling power are resolved with linewidths of 163 kHz, 156 kHz and 167 kHz, whereas the linewidths obtained using all the neighboring transitions calculation are 60 kHz, 60 kHz, and 58 kHz at the $3 \rightarrow 4'$, $3'$, and $2'$ transitions, respectively.

Second, we explain the case of a strong coupling power, as shown in the bottom trace of Fig. 1. In pure two-level calculations on the left side of the bottom trace, a closed $3 \rightarrow 4'$ transition satisfies all three necessary EIA conditions²⁰ and indicates a relatively strong EIA amplitude with a wide linewidth of 1.06 MHz and splits into two broad dips at the center of the spectra, resulting in the emergence of a narrow EIT-like peak with the 117 kHz linewidth resolution. This EIA spectra at a strong coupling power is attributed to the contributions of positive and negative atomic velocities in case of orthogonal polarizations, resulting in two identical EIA spectra separated at the right center after thermal averaging²¹. EIT spectra with small amplitudes and wide linewidths of 194 kHz and 122 kHz for open transitions $3 \rightarrow 3'$ and $3 \rightarrow 2'$, respectively, are obtained, as shown in lower traces of Fig. 1(a).

Including all the other adjacent transitions, such a symmetric EIA is transformed into asymmetric line profiles owing to the strong neighboring effects, which differ at the red and blue detuning regions. Considering all the neighboring states near the resonant transitions of $3 \rightarrow 2'$, $3 \rightarrow 3'$, and $3 \rightarrow 4'$, as shown in the lower trace of Fig. 1(b), owing to a nearby closed $3 \rightarrow 4'$ transition, all the resonant transitions exhibit strong EIAs with similar amplitudes, exhibiting strikingly similar trends in the spectra compared to the measured spectra for the closed $3 \rightarrow 4'$ transition. Asymmetric dips due to two separated EIAs at a strong power in the calculation (the measurement) are broad, with linewidths of 870 kHz, 848 kHz, and 842 kHz (607 kHz, 606 kHz, and 603 kHz) in the red detuning and narrow with linewidths of 297 kHz, 292 kHz, and 287 kHz (439 kHz, 402 kHz, and 377 kHz) in the blue detuning at the $3 \rightarrow 4'$, $3'$, and $2'$ transitions, respectively. A down-shift in relative strength of

Figure 2. Comparison of calculated and measured spectra considering: (a) pure two-level resonant transitions, i.e., $2 \rightarrow 1'$, $2 \rightarrow 2'$ and $2 \rightarrow 3'$, (b) transition resonant at $2 \rightarrow 1'$ with neighboring hyperfine transitions of $2 \rightarrow 2'$ and $3'$, transition resonant at $2 \rightarrow 2'$ with neighboring transitions of $2 \rightarrow 1'$ and $3'$, transition resonant at $2 \rightarrow 3'$ with neighboring transitions of $2 \rightarrow 1'$ and $3'$, and (c) experimentally measured spectra for resonant transitions $2 \rightarrow 1'$, $2 \rightarrow 2'$ and $2 \rightarrow 3'$.

the amplitude is evident from the narrow blue detuned side at the $3 \rightarrow 4'$ transition to the broad red detuned side at the $3 \rightarrow 2'$ transition because of the frequency shifts toward those transitions.

The amplitude of the total spectra across the $3 \rightarrow 4'$, $3'$, and $2'$ transitions decreases with decrease in F_e . The theoretical model that considers all neighboring hyperfine states as shown in the lower trace of Fig. 1(b) and experiment as illustrated in the lower trace of Fig. 1(c) agree well in terms of contrast and asymmetry, however, there are deviations in linewidths of approximately 100 kHz in both power regimes, which could be attributed to the effect of magnetic field, imperfect alignment of laser beams, and other effects that are not included in the calculation.

We further analyze the spectrally unresolved group of hyperfine transitions $2 \rightarrow 1'$, $2'$, and $3'$ of ^{85}Rb D2 lines instead of $F_g = 3$. Figure 2 presents a comparison of the calculated and measured spectra considering (a) pure two-level resonant transitions, i.e., $2 \rightarrow 1'$, $2 \rightarrow 2'$ and $2 \rightarrow 3'$, (b) a transition resonant at $2 \rightarrow 1'$ with neighboring hyperfine transitions of $2 \rightarrow 2'$ and $3'$, a transition resonant at $2 \rightarrow 2'$ with neighboring hyperfine transitions of $2 \rightarrow 1'$ and $3'$, a transition resonant at $2 \rightarrow 3'$ with neighboring hyperfine transitions of $2 \rightarrow 1'$ and $2'$, and (c) experimentally measured spectra for the resonant transitions of $2 \rightarrow 1'$, $2 \rightarrow 2'$ and $2 \rightarrow 3'$ for both weak (50 μW) and strong (4 mW) coupling powers as shown in the top and bottom traces, respectively.

The calculation for a DTLS in the low-power regime clearly reproduces ultra-narrow EIT resonances, as expected, at $2 \rightarrow 1'$, $2 \rightarrow 2'$ and $2 \rightarrow 3'$ transitions, as shown in the upper traces of Fig. 2. The obtained EIT spectra differ in relative amplitudes with the dominant EIT amplitude at the $2 \rightarrow 1'$ transition, as shown in the upper traces of Fig. 2(a). The obtained linewidth resolutions of the EIT spectra are 90 kHz, 60 kHz, and 130 kHz at the $2 \rightarrow 3'$, $2'$, and $1'$ hyperfine transitions, respectively.

The EIT spectra calculated while considering all the neighboring states near the resonant state are similar in amplitude and contrast owing to the strong EIT amplitude at the $2 \rightarrow 1'$ neighboring hyperfine transition, illustrated in the upper traces of Fig. 2(b). The trend in the measured spectra, as shown in Fig. 2(c), exhibits a striking similarity in amplitude and a contrast

that matches well with the calculation, as shown in Fig. 2(b), while considering neighboring states. The resolved linewidth in the low coupling power regime is approximately 114 kHz across the $2 \rightarrow 3'$, $2'$, and $1'$ transitions using all the neighboring calculations, as shown in Fig. 2(b); the resolved linewidths in the experiment, as presented in Fig. 2(c), are 157 kHz, 158 kHz, and 163 kHz at the $2 \rightarrow 3'$, $2'$, and $1'$ transitions, respectively.

In the strong coupling power regime, as shown in the lower traces of Fig. 2, the calculation that considers the resonant states shows increase in amplitudes and linewidths of the obtained spectra at the $2 \rightarrow 1'$ and $2 \rightarrow 2'$ hyperfine transitions. However, in violation of condition (iii) of Lezama's necessary EIA conditions, a weak-amplitude EIA with a linewidth resolution of 285 kHz is obtained at the $2 \rightarrow 3'$ hyperfine transition, as highlighted in the inset image of in the lower traces of Fig. 2(a).

Asymmetric EIT spectra of relatively similar amplitudes and linewidth resolutions are obtained owing to the contributions of all the neighboring hyperfine states with the resonant transition, as shown in the lower traces of Fig. 2(b), which matches well with the trend of the measured spectra, shown in the lower traces of Fig. 2(c). However, the experimentally measured spectra at higher powers could not reflect the fine contrast, in comparison to the calculation with all the neighboring transitions shown in the lower traces of Fig. 2(b). The resolved linewidths are 388 kHz, 407 kHz, and 435 kHz (441 kHz, 418 kHz, and 479 kHz) when using all the neighboring calculations (experiment).

The sign-inverting anomalies present at open transitions $3 \rightarrow 3'$ and $3 \rightarrow 2'$ in the previous cases, as shown in Figs. 1(b) and 1(c), are not relevant to the $2 \rightarrow 1'$, $2'$, and $3'$ group of spectrally resolved transitions as the EIT resonances at the $2 \rightarrow 3'$, $2'$, and $1'$ transitions are expected. Instead, anomalies in the relative strength of the amplitudes and linewidths at $2 \rightarrow 3'$, $2'$, and $1'$ are evident in the calculation on considering all the neighboring transitions and in the experiment, as shown in the lower traces of Figs. 2(b) and 2(c), respectively.

From both cases of $F_g = 2$ and 3, we observe that the power ratios between the coupling and probe beams, openness of the excited state, and effects of neighboring states due to Doppler broadening are crucial factors in enhancing or reducing coherence effects for transformation between EIA and EIT.

Discussion

In this study, we solved the optical Bloch equations with and without neighboring hyperfine states for all hyperfine transitions of the ^{85}Rb D2 lines both in weak- and strong-coupling-power regimes while considering the Doppler effect in an ordinary vapor cell, wherein the calculated spectra matched well with the observed spectra. Theoretical models based on time-dependent density matrix equations of a degenerate (a) two-level (resonant transitions) and (b) multilevel system including all neighboring hyperfine transitions are considered for calculating coherence effects such as EIT and EIA using thermal averaging over the Doppler profile. EITs without neighboring effects in the case of open $3 \rightarrow 2'$ and $3'$, i.e., a DTLS that violates Lezama's EIA conditions, transforms into genuine and symmetric EIAs owing to a strong $3 \rightarrow 4'$ EIA line with Doppler broadening in the weak coupling and probe power regime, which had remained theoretically unexplained and had not been observed previously in the case of ^{85}Rb D2 lines, while asymmetric and split EIAs are observed from calculated weak EITs in a DTLS in a weak probe and strong-coupling-power regime. The previously reported EIA resonances without clear quantitative explanations for open systems of D1 lines of ^{85}Rb and ^{87}Rb that violate conditions (ii) and (iii) of Lezama's EIA conditions are merely enhanced absorption phenomena governed by a strong coupling power^{7,8,11,13,16–18}. These are different from the EIAs observed and explained in the same transition configuration of $F_e = F_g - 1$ and F_g observed in this work using weak coupling-probe powers.

The EITs without neighboring effects in the DTLS in the case of $2 \rightarrow 1'$ ($2 \rightarrow 2'$) remain in the EITs owing to the $2 \rightarrow 2'$ ($2 \rightarrow 1'$) EIT line with the Doppler broadening in the weak probe and strong-coupling-power regime, while weak EIAs at $2 \rightarrow 3'$ in the weak probe and strong-coupling-power regime, which violates Lezama's EIA conditions because of openness, transform into EITs. Lezama's EIA conditions in the cycling case of $3 \rightarrow 4'$ with $F_g < F_e$ are also confirmed in strong coupling and weak probe regimes. With the comparisons of the calculated absorption profiles between a DTLS without neighboring states and all levels with neighboring states, the power ratio between probe and coupling beams, openness of the excited state, and effects of neighboring states due to Doppler broadening are crucial factors for enhancing or reducing coherence effects for transformations between EIA and EIT.

Methods

Theoretical Calculation

In this section, we describe a method of calculating the EIA spectra while considering the neighboring effect. As the details of the calculation have been reported previously^{21–25}, we briefly present the method of calculation. The energy-level diagram of D2 transition line of ^{85}Rb atoms is presented in Fig. 3. The coupling and probe beams that are linearly polarized with orthogonal directions propagate in the same directions. The Rabi frequency and effective detuning of the coupling (probe) beam are denoted by Ω_c (Ω_p) and δ_c (δ_p), respectively. The effective detunings are given by $\delta_c = d_c - kv$ and $\delta_p = d_p - kv$,

Figure 3. (a) Energy-level diagram of D2 transition lines of a ^{85}Rb atom, wherein the red and blue lines indicate transitions by the probe and coupling beams, respectively. (b) Transition scheme with two linearly polarized coupling and probe beams in the case of $F_g = 3 \rightarrow F_e = 4$ transition, where “0” (blue lines) and “ δ_d ” (red lines) imply the transitions excited by the coupling and probe beams, respectively. The excitations for the $F_g = 3 \rightarrow F_e = 2$ and 3 transitions are not shown to avoid confusion.

where d_c (d_p) denotes the frequency detuning of the coupling (probe) beam, $k(=2\pi/\lambda)$ is the wave vector, λ is the resonance wavelength of the lasers, and v is the atomic velocity. Here, d_c and d_p are the detunings relative to the resonance transition line under consideration.

Because the energy separation between the hyperfine states in $5S_{1/2}$ ground state is approximately six times the Doppler linewidth of the atoms, we can calculate the EIA spectra for the $F_g = 3 \rightarrow F_e = 2, 3$, and 4 transitions and $F_g = 2 \rightarrow F_e = 1, 2$, and 3 transitions separately. In the description of the calculation method, the $F_g = 3 \rightarrow F_e = 2, 3$, and 4 transitions are assumed. In a frame rotating with the coupling beam’s frequency, the density matrix describing the internal dynamics of the atoms is given by

$$\dot{\rho} = -\frac{i}{\hbar} [H_0 + V, \rho] + \dot{\rho}_{\text{relax}}, \quad (1)$$

where ρ is the density operator and H_0 (V) is the atomic (interaction) Hamiltonian.

In Eq. (1), the atomic Hamiltonian is given by

$$\begin{aligned} H_0 = & - \sum_{m=-4}^4 \hbar \delta_c |F_e = 4, m\rangle \langle F_e = 4, m| \\ & - \sum_{m=-3}^3 \hbar (\delta_c + \Delta_{43}) |F_e = 3, m\rangle \langle F_e = 3, m| \\ & - \sum_{m=-2}^2 \hbar (\delta_c + \Delta_{42}) |F_e = 2, m\rangle \langle F_e = 2, m|, \end{aligned} \quad (2)$$

where Δ_{4j} is the frequency spacing between the hyperfine states $|F_e = 4\rangle$ and $|F_e = j\rangle$ ($j = 2$ and 3). In Eq. (1), the interaction Hamiltonian is given by

$$\begin{aligned} V = & \frac{\hbar}{2} \Omega_p e^{-i\delta_d t} \sum_{q=-1}^1 \sum_{F_e=2}^4 \sum_{m=-3}^3 a_q C_{3,m}^{F_e, m+q} |F_e, m+q\rangle \langle F_g, m| \\ & + \frac{\hbar}{2} \Omega_c \sum_{F_e=2}^4 \sum_{m=-3}^3 C_{3,m}^{F_e, m} |F_e, m\rangle \langle F_g, m| + \text{h.c.}, \end{aligned} \quad (3)$$

where $F_g = 3$, $a_{\pm 1} = \mp 1/\sqrt{2}$, $a_0 = 0$, and h.c. denotes Hermitian conjugate. In Eq. (3), $C_{F_g, m_g}^{F_e, m_e}$ is the normalized transition strength between states $|F_e, m_e\rangle$ and $|F_g, m_g\rangle$ ²² and $\delta_d (\equiv \delta_p - \delta_c = d_p - d_c)$ is the difference in the detunings of the probe and coupling beams. In Eq. (1), $\dot{\rho}_{\text{relax}}$ represents the terms related to the relaxation mechanism such as spontaneous emission and transit time decay^{23,24}.

As reported previously^{21–25}, the density matrix elements are decomposed into various oscillation components. In the case of orthogonal linear polarization configuration, the coupling and probe beams excite the transitions with $\Delta m = 0$ and $\Delta m = \pm 1$, respectively, where Δm is the difference in the magnetic quantum numbers between the sublevels under consideration. In

Fig. 3, “0” and “ δ_d ” imply the transitions excited by the coupling and probe beams, respectively. As stated earlier, δ_d is the effective frequency of the probe beam relative to the frequency of the coupling beam. The method of determining the oscillation frequencies of the density matrix elements for the orthogonal linear polarization configuration have been described in detail in Ref. 25. Herein, only an explicit expansion of the density matrix elements that are responsible for the probe absorption is given by

$$\rho_{e_{m\pm 1},g_m}^{F_e} = \rho_{e_{m\pm 1},g_m}^{(1)} e^{-i\delta_d t} + \rho_{e_{m\pm 1},g_m}^{(2)} e^{i\delta_d t},$$

where the simplified notation for the density matrix elements is given by

$$\rho_{e_{m_e},g_{m_g}}^{F_e} \equiv \langle F_e, m_e | \rho | F_g = 3, m_g \rangle.$$

We have considered all the density matrix elements between the sublevels that are connected via photons numbers not greater than three. The absorption coefficient of the probe beam is thus given by

$$\alpha = -\frac{3\lambda^2}{2\pi} \frac{N_{\text{at}}}{\Omega_p} \int_{-\infty}^{\infty} \frac{dv}{\sqrt{\pi} v_{\text{mp}}} e^{-(v/v_{\text{mp}})^2} \times \text{Im} \left[\sum_{F_e=2}^4 \sum_{q=-1}^1 \sum_{m=-3}^3 a_q^* C_{3,m}^{F_e,m+q} \rho_{e_{m+q},g_m}^{(1)} \right], \quad (4)$$

where N_{at} is the atomic number density in the cell and v_{mp} is the most probable speed in the cell.

Figure 4. Experimental setup. Component symbols: OI: optical isolator; W: window; SAS: saturation absorption spectroscopy; HWP: half-wave plate; PBS: polarizing beam splitter; A: aperture; QWP: quarter-wave plate; L: lens; PD: photodiode; AOM: acousto-optic modulator.

Experimental Setup

The coupling and probe beams are generated using a single laser (DLPro, Toptica Inc.) combined with two AOMs in a single-pass configuration, as shown in Fig. 4. A combination of HWP and PBS-1 controls the ratio between the coupling and probe beam’s intensities and polarizations. A P-polarized weak-probe-beam power of $15 \mu\text{W}$ and an S-polarized coupling beam with a scanning frequency of 5 MHz at a low coupling power of $50 \mu\text{W}$ and strong coupling power of 4 mW were used. The coupling and probe beams were expanded by five times to obtain a uniform intensity across a 4-mm diameter. The coupling beam with the scanning detuning (Δ) from AOM-2 is combined with the weak probe at PBS-3 and co-propagates with orthogonal linear polarizations while maintaining an angle of intersection of approximately 0.1 mrad through the vapor cell shielded with five layers of μ -metal sheets. PBS-4 eliminates the coupling beam before the detection of the probe intensity at PD. The desired $5S_{1/2} \rightarrow 5P_{3/2}$ transition of ^{85}Rb D2 hyperfine line is locked using a saturation absorption spectroscopy (SAS) setup. The experiments are performed with ^{85}Rb atoms in a vapor cell at room temperature.

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Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A2C1005499 and No. 2021R1F1A1052487).

Author contributions statement

J.-T. conceived and supervised the experiments, Z.A.S. conducted the experiments and analysed the results, H.-R. performed theoretical calculations. All authors reviewed the manuscript.

Additional information

Competing interests

The authors declare no competing interests.