Analytical solutions for a doubly driven two-level atom*

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We have deduced analytical solutions of an energy level diagram of the doubly driven/dressed atom for a two-level atom exposed to a strong near-resonant bichromatic laser field in a special case, i.e., the bichromatic field with frequencies ω_1 and ω_2, and Rabi frequencies Ω_1 and Ω_2, in which the first coupling field of Ω_1 acts on the bare atomic levels, and then the resulting singly dressed states are driven by the second coupling field of Ω_2, thus resulting in the doubly dressed atom. We have measured the probe absorption spectra of a doubly driven two-level atom. The system consists of 5 $^2S_{1/2}, F = 2$ and 5 $^2P_{3/2}, F' = 3$ states of ^{87}Rb atoms in a magneto-optical trap (MOT) as well as the cooling/trapping beams and an additional coupling field. As for the spectroscopic properties of the doubly driven two-level atom, theoretical analytical solutions are in general agreement with the experimental spectrum as a whole.

Keywords: the doubly driven/dressed atom, near-resonant bichromatic laser field, energy level

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1. Introduction

A two-level system driven by a strong bichromatic laser field would lead to novel features which are not present in the monochromatic case. Complicated dynamics in new regimes of light–matter interactions, such as interference-induced spectral line elimination and the fluorescence or probe absorption spectra, have also been studied extensively both theoretically and experimentally. Previous works in these regions have been reported by many groups.[1–6] There are also some meaningful researches for resonant bichromatic laser fields.[7,8] The very recent work by He *et al.*[9] is the first demonstration of spontaneously induced spectral cancelation using the transitions of a solid-state quantum emitter. In 2014, Ruan *et al.*[10] measured the spectroscopic properties of singly dressed states in a strong monochromatic field, but no quantitative theoretical calculation was given. This paper is the further work of Ruan *et al.*[10] We concentrate on the cases where analytical solutions for a doubly driven two-level atom can be found and give a quantitative comparison of theoretical and experimental data.

2. Theoretical model and experimental method

It is well known that the analysis formula for the energy level diagram of a singly driven two-level system can be given by the two-level dressed-atom approach.[11,12] Therefore, the analytical solutions for a system of a two-level atom driven by a strong bichromatic laser field would be expected if the light–matter interactions in such system can be simplified as a two-step process: the first step is that the first coupling field acts on the bare atomic levels, and then leads to the singly dressed states. The second step is that the second coupling field acts on the singly dressed states and results in doubly dressed states. The quantum system of the singly dressed states in a quasi-resonant coupling field is similar to a quantum system of atoms in a coupling field, i.e., a natural generalization of the two-level dressed-atom approach. Therefore, the analysis formula of an energy level diagram for a two-level system exposed to a strong near-resonant bichromatic laser field can be obtained. More specifically, the Hamiltonian of a two-level atomic system interacting with a strong near-resonant bichromatic laser field and decomposed as a two-step process is as follows:

$$\begin{aligned}\hat{H} &= \hat{H}_{\text{atom}} + \hat{H}_{\omega_1} + \hat{H}_{\omega_2} + \hat{V}_{\text{atom}+\omega_1+\omega_2} \\ &= \hat{H}_{\text{singly-dressed}} + \hat{H}_{\omega_2} + \hat{V}', \end{aligned} \tag{1}$$

where $\hat{H}_{\text{atom}} = \hbar\omega_0 |e\rangle\langle e|$ is the atomic Hamiltonian, having eigenstates $|e\rangle$ and $|g\rangle$ with energies $\hbar\omega_0$ and 0. $\hat{H}_{\omega_1} = \hbar\omega_1(\hat{a}^\dagger_{\omega_1}\hat{a}_{\omega_1} + 1/2)$ is the Hamiltonian of the first coupling field, with $\hat{a}^\dagger_{\omega_1}$ and $\hat{a}_{\omega_1}$ being the creation and annihilation operators. $\hat{H}_{\omega_2} = \hbar\omega_2(\hat{a}^\dagger_{\omega_2}\hat{a}_{\omega_2} + 1/2)$ is the Hamiltonian of the second coupling field, with $\hat{a}^\dagger_{\omega_2}$ and $\hat{a}_{\omega_2}$ being the creation and annihilation operators. The atom is coupled by the Hamiltonian $\hat{V}_{\text{atom}+\omega_1+\omega_2}$ to the bichromatic laser field. In the

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first step, $\hat{H}_{\text{singly-dressed}} = \hat{H}_{\text{atom}} + \hat{H}_{\omega_1} + \hat{V}_{\text{atom}+\omega_1}$. $\hat{V}_{\text{atom}+\omega_1} = -\boldsymbol{d} \cdot \boldsymbol{E}_{\omega_1}$ is the interaction Hamiltonian between the atom and the first coupling laser, where $\boldsymbol{d}$ is the dipolar transition matrix between states $|g\rangle$ and $|e\rangle$, and $\boldsymbol{E}_{\omega_1}$ is the laser field operator. The solution of the first step is obtained by the two-level dressed-atom approach[11,12] developed by Cohen–Tannoudji and collaborators for the coupled atom within a drive/coupling field system. Certainly, the solution of the second step is similar to that for the first step. Hamiltonian $\hat{V}' = \hat{V}_{\text{atom}+\omega_1+\omega_2} - \hat{V}_{\text{atom}+\omega_1}$ is the interaction Hamiltonian between the singly dressed states and the second coupling laser.

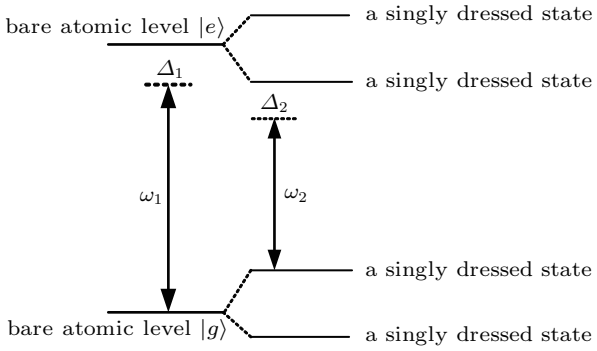


Fig. 1. A quantum system of a two-level atom driven by a strong bichromatic laser field, which can be simplified as a two-step process.

Figure 1 gives a simple and intuitive picture of the energy exchanges in the coupled atom within a drive/coupling bichromatic laser field system for the two-step process. In the drive/coupling bichromatic laser field, the first coupling field frequency ω_1 is quasi-resonant with the transition between the two bare atomic levels, and the second coupling field frequency ω_2 is quasi-resonant with the transition connecting two singly dressed levels. A natural generalization of the two-level dressed-atom approach for the singly dressed states in a quasi-resonant coupling field is shown in Figs. 2–4. The energy formulas for the doubly dressed levels are listed in Table 1.

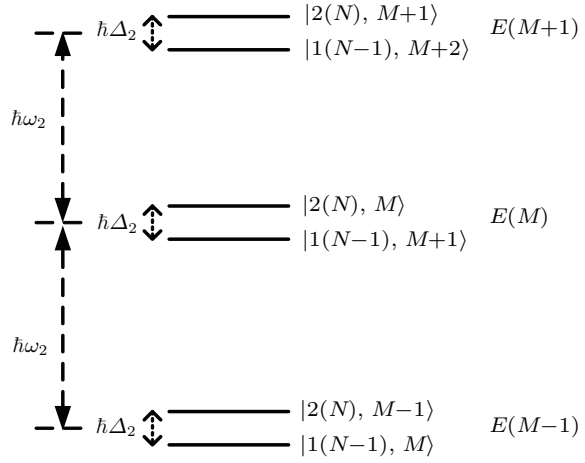


Fig. 2. Manifolds $E(M+1), E(M)$, and $E(M-1)$ of uncoupled states of the singly dressed states plus laser photons system. The energy difference $\hbar\Delta_2$ between the two levels of a given manifold is very small compared with the gap $\hbar\omega_2$ between two adjacent manifolds. The manifold formed by these two singly dressed states $|2(N)\rangle$ and $|1(N-1)\rangle$ (N is the number of laser photons of the first coupling field and M is the number of laser photons of the second coupling field) is written as $E(M) = \{|2(N), M\rangle, |1(N-1), M+1\rangle\}$.

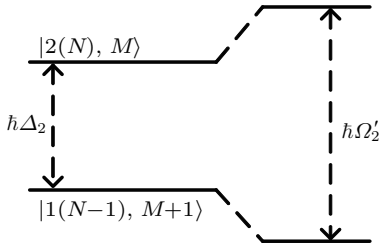


Fig. 3. Uncoupled levels and perturbed levels of the manifolds $E(M)$. $\hbar\Omega_2' = \hbar\sqrt{\Delta_2^2 + \Omega_2^2}$, where Ω_2 is the Rabi frequency of the coupling field for the corresponding singly dressed levels and Δ_2 represents the detuning of the second coupling field frequency from the transition connecting two singly dressed levels.

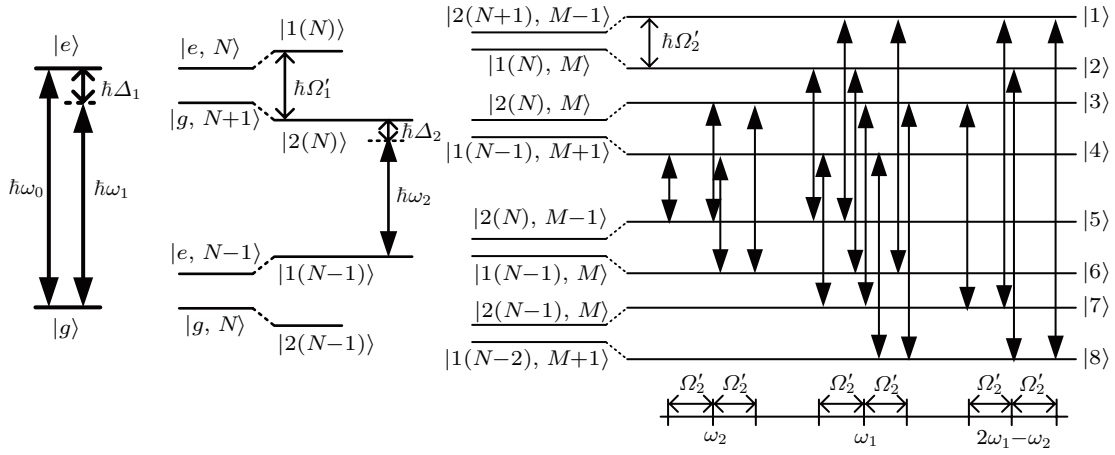


Fig. 4. Doubly dressed levels for a two-level system exposed to a strong near-resonant bichromatic laser field. Here $\Omega_1' = \sqrt{\Omega_1^2 + \Delta_1^2}$, where ω_1, Δ_1, and Ω_1 represent the frequency, detuning, and Rabi frequency for the first coupling field acting on the bare atomic levels, respectively. N and M are the numbers of laser photons of the first and the second coupling fields, respectively.

Table 1. The theoretical energy formulas for the doubly dressed levels.

Level	Energy formula
1	$E(\|g\rangle)+(N+2)\hbar\omega_1-\frac{\hbar(\Omega_1'+\Delta_1)}{2}+(M-1)\hbar\omega_2+\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
2	$E(\|e\rangle)+N\hbar\omega_1+\frac{\hbar(\Omega_1'+\Delta_1)}{2}+M\hbar\omega_2-\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
3	$E(\|g\rangle)+(N+1)\hbar\omega_1-\frac{\hbar(\Omega_1'+\Delta_1)}{2}+M\hbar\omega_2+\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
4	$E(\|e\rangle)+(N-1)\hbar\omega_1+\frac{\hbar(\Omega_1'+\Delta_1)}{2}+(M+1)\hbar\omega_2-\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
5	$E(\|g\rangle)+(N+1)\hbar\omega_1-\frac{\hbar(\Omega_1'+\Delta_1)}{2}+(M-1)\hbar\omega_2+\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
6	$E(\|e\rangle)+(N-1)\hbar\omega_1+\frac{\hbar(\Omega_1'+\Delta_1)}{2}+M\hbar\omega_2-\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
7	$E(\|g\rangle)+N\hbar\omega_1-\frac{\hbar(\Omega_1'+\Delta_1)}{2}+M\hbar\omega_2+\frac{\hbar(\Omega_2'+\Delta_2)}{2}$
8	$E(\|e\rangle)+(N-2)\hbar\omega_1+\frac{\hbar(\Omega_1'+\Delta_1)}{2}+(M+1)\hbar\omega_2-\frac{\hbar(\Omega_2'+\Delta_2)}{2}$

These energy level diagram properties can be probed by a third laser field, i.e., record transmitted intensity as a function of frequency ω_p for a low-intensity probe beam focused through the atom sample. As shown in Fig. 4, our theoretical analysis predicts that the absorption spectrum of the probe beam for such a system is composed of three characteristic triplet structures, formed by central lines at ω_1, ω_2, and $2\omega_1-\omega_2$, respectively, and two sidebands symmetrically distributed at $\pm\Omega_2'$. Here $\hbar\Omega_2'=\hbar\sqrt{\Delta_2^2+\Omega_2^2}$, where ω_2, Δ_2, and Ω_2 represent the frequency, detuning, and Rabi frequency for the second coupling field acting on the singly dressed levels, respectively. While the probe absorption spectrum of a singly driven two-level atom is composed of a dispersion-like structure located at the coupling field frequency and two symmetrically distributed side-band spectral features termed the absorption peak and the gain peak.

As for the experimental verification, cold atoms produced by a magneto-optical trap (MOT)[13] offer great opportunities for the studies of precise spectroscopic measurements due to significantly reduced Doppler broadening and low collision rates. In this paper and the work of Ruan *et al.*,[10] we take the 5 $^2S_{1/2}, F=2$ and 5 $^2P_{3/2}, F'=3$ states of ^{87}Rb atoms as a two-level atom system. Cold ^{87}Rb atoms are produced in a standard MOT. Details of the apparatus were described in our previous work.[14–16] Thus, the 5 $^2S_{1/2}, F=2$ and 5 $^2P_{3/2}, F'=3$ states of ^{87}Rb atoms as well as the cooling/trapping beams and an additional coupling field constitute the degenerate two-level atomic system in two strong monochromatic coupling fields. The cooling/trapping beams play the role of the first coupling field which acts on the bare atomic levels, and the second coupling field acting on the dressed levels is provided by an independent frequency-stabilized diode laser of Toptica DL100. The probe beam is derived from the Toptica DL100 laser and is independently tuned over a limited range in frequency by acousto-optic modulators (AOM). Following the method adopted by Ruan *et al.*,[10] we have measured the probe spectrum in the presence of two coupling fields and the probe spectrum with only one coupling field, aiming to compare and identify these spectral features resulting from the transition connecting one pair of doubly dressed levels. In this scheme, the detuning $\Delta_1/2\pi$ of the first coupling field frequency from the transition 5 $^2S_{1/2}, F=2 \rightarrow 5\ ^2P_{3/2}, F'=3$ is fixed at -12 MHz. The frequency of the second coupling field is quasi-resonant with the gain peak formed only by the first coupling field and the frequency of the second coupling field varies by an AOM. Note that the second coupling field propagates through the cold ^{87}Rb atoms in two cases. (i) Similar to the work of Ruan *et al.*,[10] the second coupling field passes the atom sample once. A typical probe absorption spectrum is shown in Fig. 5. (ii) The second coupling field is a counterpropagating beam acting on the atom sample by adding a totally reflecting mirror. A typical probe absorption spectrum is shown in Fig. 6. The present uncertainties in frequency calibration mainly result from the frequency jitter ~ 1 MHz of lasers in this work, and the errors (less than 1%) from the frequency calibration procedure.

3. Results and discussion

Figures 5 and 6 display that these spectral features resulting from the transition connecting one pair of doubly dressed levels agree with the present theoretical prediction. More specifically, we observe a characteristic triplet structure formed by a central line at ω_2, and two sidebands symmetrically distributed in the case that the second coupling field passes the atom sample once. While in the case that the second coupling field is a counterpropagating beam acting on the atom sample, we observe two characteristic triplet structures formed by central lines at ω_2 and ω_1, respectively, and two sidebands symmetrically distributed. Although the present theoretical analysis predicts that the absorption spectrum of the probe beam for a such system is composed of three characteristic triplet structures, the intensities of these spectral features are determined by nonzero transition matrix elements and the corresponding populations, thus it is understandable that not all of the spectral features can be observed. In the two cases, while the intensity of the second coupling field is the same, the Rabi frequency Ω_2 is different, thus the probe absorption spectrum is different. Furthermore, we give a comparison of quantitative theoretical and experimental data in Table 2 and Figs. 7–9. Table 2 gives experimental energy levels for these spectral features resulting from the transition connecting one pair of doubly dressed levels as a function of the second coupling field frequency and the deduced Rabi frequency Ω_2 of the second coupling field. Certainly, Rabi frequency Ω_2 is independent of Δ_2 if the intensity of the second coupling field is fixed. In the present work, we fix the intensity of the second coupling field at 344 mW/cm^2 in the two cases, while the intensity of the second coupling field is about 254.8 mW/cm^2 in the work of Ruan *et al.*[10] As shown in Table 2 and Figs. 7–9,

the deduced Rabi frequency Ω_2 from the experimental energy levels is independent of Δ_2. It is consistent with our theoretical prediction. In addition, as shown in Table 2 and Fig. 7,

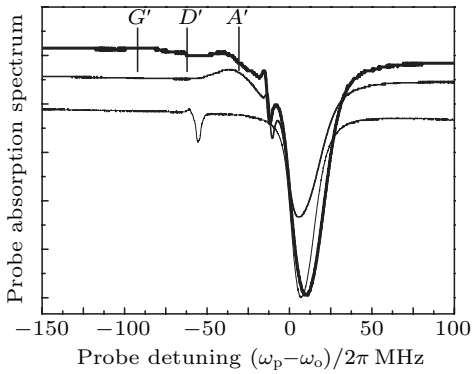


Fig. 5. The probe absorption spectrum measured in a two-level atomic system with two coupling fields. The frequency of the second coupling field is red-shifted with respect to the energy position of the gain peak formed only by the first coupling field. The peaks labeled as G', D', and A' represent the spectroscopic properties resulting from the transition connecting one pair of doubly dressed levels. The thick curve is the probe absorption spectrum in the presence of two coupling fields. The detunings of the two coupling fields are -12 MHz and -63 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$, respectively. The second coupling field passes through the atom sample once. The medium thickness curve is the pump–probe spectrum measured in the presence of the first coupling field. The first coupling field is provided by the cooling/trapping beams with the detuning of -12 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$. The thin curve is the pump–probe spectrum measured in the presence of the second coupling field. In this case, the cooling/trapping beams are switched off and the second coupling field is provided by an independent frequency-stabilized diode laser. The detuning of the coupling field is -63 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$.

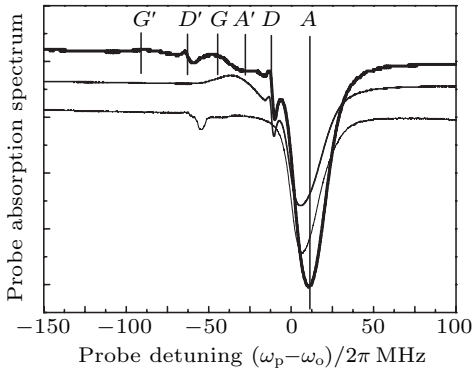


Fig. 6. The probe absorption spectrum measured in a two-level atomic system with two coupling fields. The frequency of the second coupling field is red-shifted with respect to the energy position of the gain peak formed only by the first coupling field. The peaks labeled as G', D', and A' (G, D, and A) represent the spectroscopic properties resulting from the transition connecting one pair of doubly dressed levels. The thick curve is the probe absorption spectrum in the presence of two coupling fields. The detunings of the two coupling fields are -12 MHz and -63 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$, respectively. The second coupling field is a counterpropagating beam acting on the atom sample. The medium thickness curve is the pump–probe spectrum measured in the presence of the first coupling field. The first coupling field is provided by the cooling/trapping beams with the detuning of -12 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$. The thin curve is the pump–probe spectrum measured in the presence of the second coupling field. In this case, the cooling/trapping beams are switched off and the second coupling field is provided by an independent frequency-stabilized diode laser. The detuning of the coupling field is -63 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$.

Ω_2 deduced from the triplet structure with a central line at ω_2 is consistent with that deduced from the triplet structure with a central line at ω_1 within the experimental errors in the case that the second coupling field is a counterpropagating beam. The Ω_2 from the case that the second coupling field is a counterpropagating beam is larger than that for the other case. It is reasonably and displayed in Table 2 and Figs. 7 and 8.

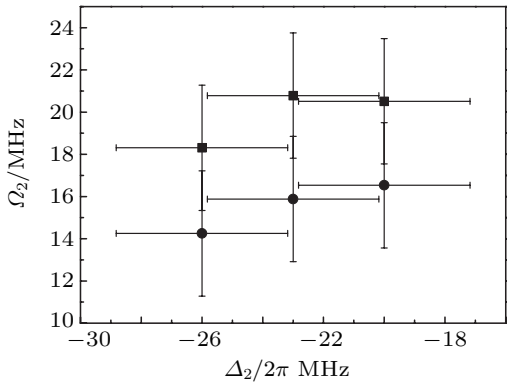


Fig. 7. The present Rabi frequency Ω_2 as a function of the detuning Δ_2 in the case that the second coupling field passes through the atom sample with a counterpropagating beam.

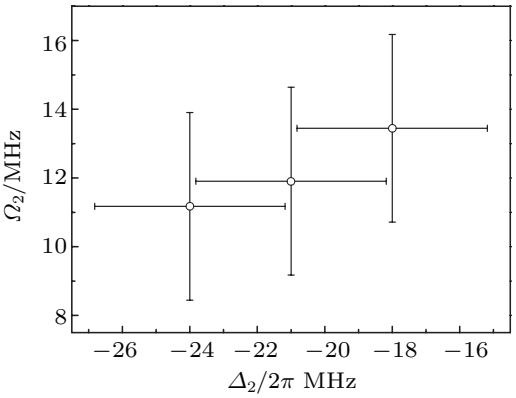


Fig. 8. The present Rabi frequency Ω_2 as a function of the detuning Δ_2 in the case that the second coupling field passes through the atom sample once.

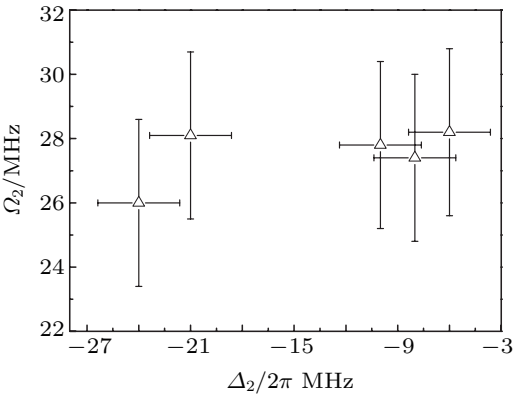


Fig. 9. The Rabi frequency Ω_2 as a function of the detuning Δ_2 in the case that the second coupling field passes through the atom sample once for the work of Ruan *et al.*[10]

Table 2. Experimental energy levels (estimated errors in parentheses) for these spectral features resulting from the transition connecting one pair of doubly dressed levels. The detuning of the first coupling field (cooling/trapping beams) $\Delta_1/2\pi$ is -12 MHz with respect to the transition $5\ ^2S_{1/2}, F = 2 \rightarrow 5\ ^2P_{3/2}, F' = 3$. The frequency ω_2 of the second coupling field is quasiresonant with the gain peak formed only by the first coupling field.

The second coupling field passes the atom sample once				
Δ_2	$\omega_{\rm gain}-\omega_2$	$\omega_{\rm dis.}-\omega_2$	$\omega_{\rm abs.}-\omega_2$	Ω_2 [a]
/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)
This work [b]				
–20(2.8)	–24.1(2.5)	–	–	13.4(2.7)
–23(2.8)	–25.9(2.5)	–	–	11.9(2.7)
–26(2.8)	–28.3(2.5)	–	–	11.2(2.7)
Ruan *et al.* [10] [c]				
–6(2.4)	–27.4(2.1)	–0.4(1.3)	+30.3(1.6)	28.2(2.6)
–8(2.4)	–29.8(2.1)	–1.6(1.3)	+27.2(1.6)	27.4(2.6)
–10(2.4)	–30.9(2.1)	–1.4(1.3)	+28.1(1.6)	27.8(2.6)
–21(2.4)	–36.7(2.1)	–2.1(1.3)	+33.4(1.6)	28.1(2.6)
–24(2.4)	–33.8(2.1)	+1.3(1.3)	+37.0(1.6)	26.0(2.6)
This work, the second coupling field is a counterpropagating beam				
Δ_2	$\omega_{\rm gain}-\omega_2$	$\omega_{\rm dis.}-\omega_2$	$\omega_{\rm abs.}-\omega_2$	Ω_2 [c]
/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)
–20(2.8)	–24.0(2.5)	0.7(1.3)	33.3(1.6)	20.5(3.0)
–23(2.8)	–36.7(2.5)	0.9(1.3)	25.3(1.6)	20.8(3.0)
–26(2.8)	–28.0(2.5)	1.1(1.3)	35.6(1.6)	18.3(3.0)
Δ_2	$\omega_{\rm gain}-\omega_1$	$\omega_{\rm dis.}-\omega_1$	$\omega_{\rm abs.}-\omega_1$	Ω_2 [c]
/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)	/($2\pi\times$MHz)	
–20(2.8)	–29.9(2.5)	1.6(1.3)	22.0(1.6)	16.5(3.0)
–23(2.8)	–32.8(2.5)	0.8(1.3)	23.1(1.6)	15.9(3.0)
–26(2.8)	–35.9(2.5)	0.3(1.3)	23.4(1.6)	14.2(3.0)

[a] Obtained from the present theoretical prediction that a central line $\omega_{\rm dis}$ is at ω_2 and ω_1 respectively, and the two sidebands termed the absorption peak and the gain peak are symmetrically distributed at $\pm\Omega_2'$ with $\hbar\Omega_2' = \hbar\sqrt{\Delta_2^2+\Omega_2^2}$.

[b] No data for the central line and absorption peak due to too larger error. Ω_2 is obtained from the energy position of the gain peak.

[c] Ω_2 is obtained from the energy difference between the gain peak and the absorption peak.

4. Conclusion

In summary, as shown in Table 1 and Fig. 4, we have deduced analytical solutions of energy level diagram of the doubly driven/dressed atom for a two-level system exposed to a strong near-resonant bichromatic laser field in the special case that such a system can be simplified as a two-step process. The present theoretical analysis predicts that the absorption spectrum of the probe beam for such a system is composed of three characteristic triplet structures, formed by central lines at ω_1, ω_2, and $2\omega_1-\omega_2$, respectively, and two sidebands symmetrically distributed at $\pm\Omega_2'$. We take $5\ ^2S_{1/2}, F = 2$ and $5\ ^2P_{3/2}, F' = 3$ states of ^{87}Rb atoms in an MOT as well as the cooling/trapping beams and an additional coupling field as a quantum system of a two-level atom driven by a strong bichromatic laser field. We have measured the probe absorption spectra of the doubly driven two-level atom. The comparison of theoretical and experimental results shows good qualitative agreement between the predications and experimental data, as shown in Table 2 and Figs. 7–9.

References

[1] Greentree A D, Chang J W, Holmstrom S A, Martin J P D, Manson N B, Catchpole K R and Savage C 1999 *J. Opt. B: Quantum Semiclass. Opt.* **1** 240

[2] Lipsich A, Barreiro S, Akulshin A M and Lezama A 2000 *Phys. Rev. A* **61** 053803

[3] Lezama A, Barreiro S, Lipsich A and Akulshin A M 1999 *Phys. Rev. A* **61** 013801

[4] Ficek Z and Freedhoff H S 1996 *Phys. Rev. A* **53** 4275

[5] Ficek Z and Rudolph T 1999 *Phys. Rev. A* **60** 4245

[6] Rudolph T, Freedhoff H S and Ficek Z 1998 *J. Opt. Soc. Am. B* **15** 2325

[7] Jing H, Cheng J and Meystre P 2008 *Phys. Rev. Lett.* **114** 097402

[8] Jing H, Cheng J and Meystre P 2007 *Phys. Rev. Lett.* **99** 133002

[9] He Y, He Y M, Liu J, Wei Y J, Ramírez H Y, Atatüre M, Schneider C, Kamp M, Höfling S, Lu C Y and Pan J W 2015 *Phys. Rev. Lett.* **114** 097402

[10] Ruan Y P, Jia F D, Sun Z, Lv S F, Qing B, Huang W, Xue P, Xu X Y, Dai X C and Zhong Z P 2014 *Phys. Rev. A* **90** 033811

[11] Cohen-Tannoudji C, Dupont-Roc J and Grynberg G 1992 *Atom-Photon Interactions: Basic Processes and Applications* (New York: Wiley)

[12] Grynberg G and Cohen-Tannoudji C 1993 *Opt. Commun.* **96** 150

[13] Chu S, Hollberg L, Bjorkholm J E, Cable A and Ashkin A 1985 *Phys. Rev. Lett.* **55** 48

[14] Lv S F, Jia F D, Liu J Y, Xu X Y, Xue P and Zhong Z P 2017 *Chin. Phys. Lett.* **34** 013401

[15] Liu L W, Jia F D, Ruan Y P, Huang W, Lv S F, Xue P, Xu X Y, Dai X C and Zhong Z P 2013 *Chin. Phys. Lett.* **30** 043201

[16] Sun Z, Jia F D, Lv S F, Ruan Y P, Qing B, Xue P, Xu X Y, Dai X C and Zhong Z P 2014 *Chin. Phys. Lett.* **31** 043201