Dual-dressed four-wave mixing and dressed six-wave mixing in a five-level atomic system

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We study the co-existing four-wave mixing (FWM) process with two dressing fields and the six-wave mixing (SWM) process with one dressing field in a five-level system with carefully arranged laser beams. We also show two kinds of doubly dressing mechanisms in the FWM process. FWM and SWM signals propagating along the same direction compete with each other. With the properly controlled dressing fields, the FWM signals can be suppressed, while the SWM signals have been enhanced.

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Four-wave mixing (FWM) and six-wave mixing (SWM) with electromagnetically induced transparency (EIT)[1−7], and Autler-Townes (AT) splitting[8−11] due to atomic coherence in multi-level system have attracted a lot of attention recently. In this letter, we consider an opening five-level system in Fig. 1(a), in which states between $|0\rangle$ and $|1\rangle$, $|1\rangle$ and $|2\rangle$, $|1\rangle$ and $|3\rangle$, $|0\rangle$ and $|4\rangle$ are dipole-allowed transitions coupled by dipolar transitions with resonant frequencies Ω_i and laser field $E_i(E_i')$ (ω_i, $\mathbf{k}_i$, $\mathbf{k}_i'$), and Rabi frequencies $G_i(G_i')$ ($i = 1,2,3,4$). The Rabi frequencies are defined as $G_i = \varepsilon_i\mu_{ij}/\hbar$ and $G_i' = \varepsilon_i'\mu_{ij}/\hbar$ ($j = 1,2,3,4$ and $i \neq j$), where μ_{ij} are the transition dipole moments between level i and level j. One possible experimental candidate for the proposed system is ^{85}Rb atoms with states $|0\rangle = |5S_{1/2}\rangle$, $|1\rangle = |5P_{3/2}\rangle$, $|2\rangle = |5D_{3/2}\rangle$, $|3\rangle = |5D_{5/2}\rangle$, $|4\rangle = |5P_{1/2}\rangle$, and $|5\rangle = |6P_{1/2}\rangle$. The transverse relaxation rate Γ_{ij} between states $|i\rangle$ and $|j\rangle$ can be obtained by $\Gamma_{ij} = (\Gamma_i + \Gamma_j)/2$ ($\Gamma_0 = \gamma_{0G} = \gamma_{G0} = \Gamma_G$, $\Gamma_1 = \gamma_{10}+\gamma_{1G}$, $\Gamma_2 = \gamma_{21}+\gamma_{24}+\gamma_{25}$, $\Gamma_3 = \gamma_{31}+\gamma_{34}+\gamma_{35}$, $\Gamma_4 = \gamma_{40} + \gamma_{4G}$and $\Gamma_5 = \gamma_{50} + \gamma_{5G}$), where γ_{ij} is the term due to spontaneous emission (longitudinal relaxation rate) between states $|i\rangle$ and $|j\rangle$, γ_{0G} and $\gamma_{G0}$are the nonradiative decay rates between $|0\rangle$ and $|G\rangle$. The atoms are pumped from $|G\rangle$ to $|5\rangle$ by beam 5 to maintain the magnitude of atoms on $|0\rangle$. Fields E_i and E_i' with the same frequency propagate along beams 2 and 3 with a small angle (Fig. 1(b)), while a weak probe field E_1 (beam 1) propagates along the opposite direction of beam 2. By blocking two different fields in the beam 3 and using the corresponding two fields in the beam 2 as the dressing fields, the doubly dressed FWM (DDFWM), dressed SWM (DSWM), and eight-wave mixing (EWM) signals of the frequency ω_1 are generated along beam 4. The direction of beam 4 is opposite to beam 3. We have three choices of using the two fields as the dressing fields in the beam 2 and blocking the corresponding ones in the beam 3. Every case presents two mechanisms which we call the parallel-cascade and sequent-cascade mechanisms. The different mechanisms have different correlations between the two dressing fields. For EWM is too weak to be observed, we mainly consider DDFWM and DSWM. These two kinds of signals share the atoms on the common levels and compete with each other.

The case of blocking E_2' and E_4' is similar to the one of blocking E_3' and E_4', which can be understood in energy-level picture shown in Fig. 1(c1). We just discuss the result of blocking E_3' and E_4'. There are 12 DDFWM (DDF1E2: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{\omega_2} \rho_{20}^{(2)} \xrightarrow{-\omega_2} \rho_{G_3\pm G_4\pm}^{(3)}$ etc.),

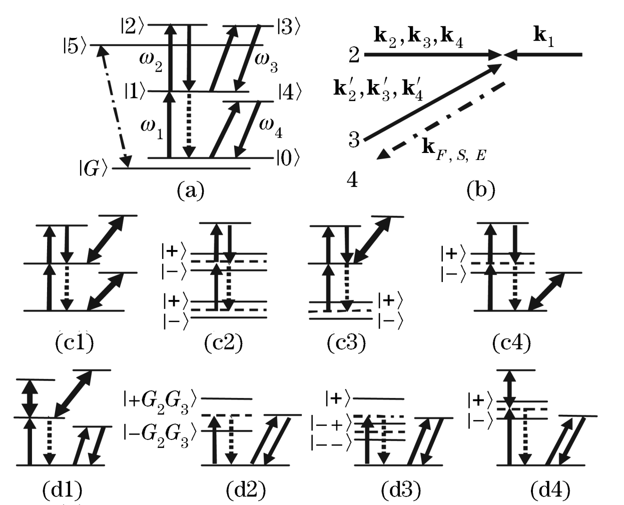

Fig. 1. (a) Energy-level diagram of an open five-level system; (b) phase-conjugate schematic diagram of phase-matched multi-wave mixing; (c1) five-level atomic system with blocking fields E_3' and E_4' or E_2' and E_4'; (c2) parallel-cascade DDFWM dressed-state picture; (c3),(c4) DSWM dressed-state pictures with blocking fields E_3' and E_4' or E_2' and E_4'; (d1) five-level atomic system with blocking fields E_3' and E_2'; (d2),(d3) sequential-cascade DDFWM dressed-state pictures; (d4) DSWM dressed-state picture with blocking fields E_3' and E_2'.

46 DSWM (DS1E1: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{\omega_2} \rho_{2G_4\pm}^{(2)} \xrightarrow{-\omega_2} \rho_{10}^{(3)} \xrightarrow{\omega_3} \rho_{30}^{(4)} \xrightarrow{-\omega_3} \rho_{10}^{(5)}$ etc.), and 44 EWM (E1: $\rho_{00} \xrightarrow{\omega_1} \rho_{10} \xrightarrow{\omega_2} \rho_{20} \xrightarrow{-\omega_4} \rho_{24} \xrightarrow{\omega_4} \rho_{20} \xrightarrow{-\omega_2} \rho_{10} \xrightarrow{\omega_3} \rho_{30} \xrightarrow{-\omega_3} \rho_{10}$ etc.). Because of the limitation of the length of this letter, we just discuss only two DDFWM chains representing two mechanics and one DSWM chain respectively. When the fields E_3' and E_4' are blocked, we consider two-photon resonant FWM process in the $|0\rangle$-$|1\rangle$-$|2\rangle$ which represents a cascade three-level system satisfying the phase-matching condition $\mathbf{k}_A = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_2'$ (Fig. 1(c1)). Two strong dressing fields E_3 and E_4 are added between $|1\rangle$ to $|3\rangle$ and $|0\rangle$ to $|4\rangle$. We firstly show the parallel cascade mechanism. In the chain E1, two sub-processes about the dressing fields ("$\rho_{10} \xrightarrow{\omega_3} \rho_{30} \xrightarrow{-\omega_3} \rho_{10}$" and "$\rho_{20} \xrightarrow{-\omega_4} \rho_{24} \xrightarrow{\omega_4} \rho_{20}$") lie parallel. The coupling fields E_3 and E_4 dress states $|1\rangle$ and $|0\rangle$, and vary the ket "1" of ρ_{10} and the bra "0" of ρ_{20}, respectively. In other words, the fields E_3 and E_4 influence the atomic coherence between states $|1\rangle$ and $|0\rangle$, $|2\rangle$ and $|0\rangle$ correspondingly. According to the FWM chain F1: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{\omega_2} \rho_{20}^{(2)} \xrightarrow{-\omega_2} \rho_{10}^{(3)}$, the two dressed states are represented as $\rho_{20}^{(2)}$ and $\rho_{10}^{(3)}$, hence we get $\rho_{2G_4\pm}^{(2)}$ and $\rho_{G_3\pm 0}^{(3)}$ in the DDFWM chain DDF1E1: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{\omega_2} \rho_{2G_4\pm}^{(2)} \xrightarrow{-\omega_2} \rho_{G_3\pm 0}^{(3)}$. Secondly, we show the sequential cascade mechanism. Consider the other EWM chain E2: $\rho_{00} \xrightarrow{\omega_1} \rho_{10} \xrightarrow{\omega_2} \rho_{20} \xrightarrow{-\omega_2} \rho_{10} \xrightarrow{\omega_3} \rho_{30} \xrightarrow{-\omega_3} \rho_{10} \xrightarrow{-\omega_4} \rho_{14} \xrightarrow{\omega_4} \rho_{10}$ in this case which corresponds to DDFWM chain DDF1E2 with two sub-processes about dressing fields joining together ("$\rho_{10} \xrightarrow{\omega_3} \rho_{30} \xrightarrow{-\omega_3} \rho_{10} \xrightarrow{-\omega_4} \rho_{14} \xrightarrow{\omega_4} \rho_{10}$"). Different from the parallel mechanism, though the coupling fields E_3 and E_4 still dress states $|1\rangle$ and $|0\rangle$ respectively, they vary the ket "1" and the bra "0" of the same element of density matrix ρ_{10} respectively. It means this dressed state will affect the same atomic coherence between $|0\rangle$ and $|1\rangle$ represented by $\rho_{10}^{(3)}$ in the FWM chain F1, thus we get $\rho_{G_3\pm G_4\pm}^{(3)}$ in the DDFWM chain DDF1E2. Finally, we consider the DSWM chain DS1E1. The SWM process in the $|0\rangle$-$|1\rangle$-$|2\rangle$-$|3\rangle$ which represents a Y-type four-level system satisfies the phase-matching condition $\mathbf{k}_{\mathrm{DS1E1}} = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_2' + \mathbf{k}_3 - \mathbf{k}_3$ with one dressing field E_4 added between $|0\rangle$ and $|4\rangle$. The sub-process about dressing field of the EWM chain E1 ("$\rho_{20} \xrightarrow{-\omega_4} \rho_{24} \xrightarrow{\omega_4} \rho_{20}$") means that the dressed state affect atomic coherence between $|0\rangle$ and $|2\rangle$ represented by $\rho_{20}^{(2)}$ in the SWM chain S1: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{\omega_2} \rho_{20}^{(2)} \xrightarrow{-\omega_2} \rho_{10}^{(3)} \xrightarrow{\omega_3} \rho_{30}^{(4)} \xrightarrow{-\omega_3} \rho_{10}^{(5)}$. Correspondingly, We get $\rho_{2G_4\pm}^{(2)}$ in the DSWM chain.

In the parallel mechanism, the density-matrix dynamic equations in the steady state, using partially rotate wave approximation (PRWA) can be simplified as follows:

$$\partial\rho_{20}/\partial t = -D_2\rho_{20} + iG_2\rho_{10} - iG_4\rho_{24}, \tag{1}$$

$$\partial\rho_{24}/\partial t = -D_4\rho_{24} - iG_4^*\rho_{20}, \tag{2}$$

$$\partial\rho_{10}/\partial t = -D_1\rho_{10} + iG_2'^*\rho_{20} + iG_3\rho_{30}, \tag{3}$$

$$\partial\rho_{30}/\partial t = -D_3\rho_{30} + iG_3^*\rho_{10}. \tag{4}$$

By solving the above four equations with the FWM perturbation chain F1, we can deduce the result of ρ_{DDF1E1} as

$$\rho_{\mathrm{DDF1E1}} = \rho_{10}^{(3)} = \frac{-iA_1D_4D_3}{D_1(|G_4|^2 + D_2D_4)(|G_3|^2 + D_1D_3)}, \tag{5}$$

where $A_1 = G_1G_2G_2'^*$, $D_1 = \Gamma_{10} + i\Delta_1$, $D_2 = \Gamma_{20} + i(\Delta_1 + \Delta_2)$, $D_3 = \Gamma_{30} + i(\Delta_1 + \Delta_3)$, $D_4 = \Gamma_{24} + i(\Delta_1 + \Delta_2 - \Delta_4)$. Γ_{ij} is the decay rate between two states $|i\rangle$ and $|j\rangle$ and the detuning $\Delta_i = \Omega_i - \omega_i$. The signal intensity of the chain DDF2E2: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{(G_2\pm G_3\pm)0}^{(1)} \xrightarrow{-\omega_4} \rho_{14}^{(2)} \xrightarrow{\omega_4} \rho_{10}^{(3)}$ is proportional to $|\rho_{\mathrm{DDF1E1}}|^2$ and propagates along the direction $\mathbf{k}_A = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_2'$.

Using the similar PRWA method, we can also get the final result of sequential-cascade mechanism ρ_{DDF1E2}. Then the applicable equations are as follows:

$$\dot\rho_{10} = -D_1\rho_{10} + iG_2'^*\rho_{20} + iG_3\rho_{30} - iG_4\rho_{14}, \tag{6}$$

$$\dot\rho_{14} = -D_5\rho_{14} - iG_4^*\rho_{10}. \tag{7}$$

Under the steady state condition, we solve the equations by the perturbation chain F1 and have

$$\rho_{\mathrm{DDF1E2}} = \rho_{10}^{(3)} = \frac{-iA_1D_5D_3}{D_1D_2(|G_3|^2D_5 + |G_4|^2D_3 - D_1D_5D_3)}, \tag{8}$$

where $D_5 = \Gamma_{14} + i(\Delta_1 - \Delta_4)$. The signal intensity of the chain DDF1E2 is proportional to $|\rho_{\mathrm{DDF1E2}}|^2$ and propagates along the same direction $\mathbf{k}_A = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_2'$ as $|\rho_{\mathrm{DDF1E1}}|^2$.

Similarly, we can get the result of ρ_{DS1E1} of DSWM with PRWA method at the steady state: $\rho_{\mathrm{DS1E1}} = \rho^{(5)} = \frac{iA|G_3|^2D_4}{D_1^2D_3(D_4D_2 + |G_4|^2)}$. The signal intensity of the chain DS1E1 is proportional to $|\rho_{\mathrm{DS1E1}}|^2$ and propagates along the same direction with DDFWM signals.

As the fields E_2' and E_3' are blocked and E_2 and E_3 are used as dressing fields, the two-photon resonant FWM process in the $|0\rangle$-$|1\rangle$-$|4\rangle$ which represents a V-type three-level system satisfying the phase-matching condition $\mathbf{k}_B = \mathbf{k}_1 + \mathbf{k}_4 - \mathbf{k}_4'$ (Fig. 1(d1)). The two strong dressing fields E_3 and E_2 are applied between $|1\rangle$ to $|3\rangle$ and $|1\rangle$ to $|2\rangle$ respectively. Here, we just consider two chains (ρ_{DDF2E2} and DDF2E3: $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{G_3\pm 0}^{(1)} \xrightarrow{-\omega_4} \rho_{14}^{(2)} \xrightarrow{\omega_4} \rho_{G_2\pm 0}^{(3)}$) representing two mechanics respectively. Similarly, we can obtain the final results of DDFWM in the third case as $\rho_{\mathrm{DDF2E3}} = \rho_{10}^{(3)} = \frac{-iA_2D_3D_2}{D_5(|G_2|^2 + D_1D_2)(|G_3|^2 + D_1D_3)}$ and $\rho_{\mathrm{DDF2E2}} = \rho_{10}^{(3)}\frac{iA_2D_3D_2}{D_1D_5(|G_2|^2D_3 + |G_3|^2D_2 + D_1D_2D_3)}$, where $A_2 = G_1G_4G_4'^*$.

Firstly, Fig. 2(a) presents the parallel DDFWM (ρ_{DDF1E1}) signal intensity versus Δ_1/Γ_{20} when the two different dressing fields (E_3 and E_4) vary respectively. When increasing G_3 and keeping G_4 constant as shown in the dashed line, the inner pair of peaks shift apart from resonate point symmetrically, on the other hand, the peripheral pair of peaks stand fixed in original place. On the contrary, when G_3 keeps constant and G_4 increases, the inner pair of peaks stand still while the peripheral

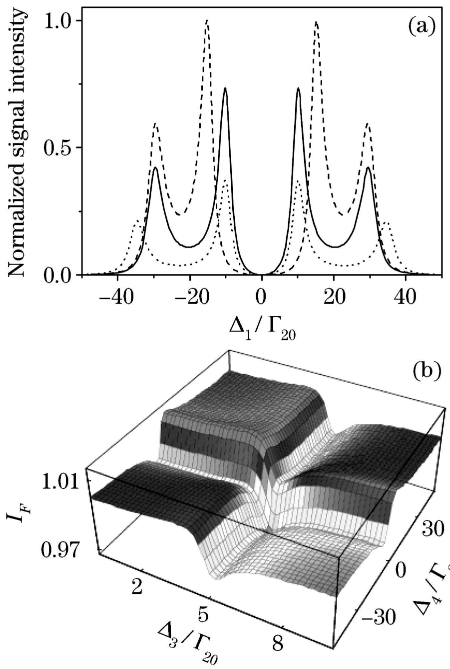

Fig. 2. Parameters are $\Gamma_{24}/\Gamma_{20} = 4.05$, $\Gamma_{30}/\Gamma_{20} = 0.55$, $\Gamma_{10}/\Gamma_{20} = 3.33$. (a) Parallel DDFWM signal intensity versus Δ_1/Γ_{20}, where $G_3/\Gamma_{20} = 10$, $G_4/\Gamma_{20} = 30$ (solid line); $G_3/\Gamma_{20} = 15$, $G_4/\Gamma_{20} = 30$ (dashed line); $G_3/\Gamma_{20} = 10$, $G_4/\Gamma_{20} = 35$ (dotted line). when $\Delta_4 = 0$, $\Delta_3 = 0$, $\Delta_2 = 0$. The maximum of the DDFWM signal intensity is normalized to 1; (b) parallel DDFWM signal intensity versus Δ_3/Γ_{20} and Δ_4/Γ_{20}. The FWM signal intensity with no coupling field is normalized to 1.

pair of peaks shift similarly. Furthermore, when the two peaks converge to each other the intensity of both peaks enforces and decrease as the two peaks separate from each other. On basis of this picture, the conclusion can be drawn that the dressing fields E_3 and E_4 control different splitting peaks respectively. As shown in Fig. 1(c2), in the parallel mechanism, the two dressing fields E_3 and E_4 dress the energy level $|1\rangle$ and $|0\rangle$ into $|+\rangle$, $|-\rangle$, which well match these two pair of splitting peaks in Fig. 2(a). Moreover, these distance of two splitting peaks can be expressed as $\Delta_{G_3-\mathrm{AT}} = 2\{G_3[G_3^2 + 2\Gamma_{30}(\Gamma_{10} + \Gamma_{30})]^{1/2} - \Gamma_{30}^2\}^{1/2}$ and $\Delta_{G_4-\mathrm{AT}} = 2\{G_4[G_4^2 + 2\Gamma_{24}(\Gamma_{20} + \Gamma_{24})]^{1/2} - \Gamma_{24}^2\}^{1/2}$, respectively. We have $\Delta_{G_3-\mathrm{AT}}(\Delta_{G_4-\mathrm{AT}}) \propto G_3(G_4)$ approximately. Thus, as the increase of fields intensity, the separation between splitting peaks will increase correspondingly. When $\Delta_4 > 0$ ($\omega_4 < \Omega_4$), the dressing field E_4 will dress the energy level above $|0\rangle$. Thus, the splitting level $|+\rangle$ and $|-\rangle$ are not separated symmetrically on both side of $|0\rangle$, on the other hand, $|-\rangle$ is more close to $|0\rangle$ than $|+\rangle$. In other words, the left peak of the splitting $|-\rangle$ shifts close to resonant point $\Delta_1 = 0$ while the right peak of the splitting $|+\rangle$ removes from that point.

Figure 2(b) shows the signal intensity ρ_{DDF1E1} versus both Δ_3 and Δ_4 with no dressing field ($G_3 = G_4 = 0$) is normalized to 1. The intensity above and below "1" means enhancement or suppression of FWM signal intensity, respectively. When under the resonant condition $\Delta_1 = 0$, the both two dressing fields suppress the FWM signal only. The reason is that: as shown in Fig. 1(c2), the dressing fields E_3 and E_4 dress the energy level $|1\rangle$ and $|0\rangle$ into $|+\rangle$ and $|-\rangle$ respectively. Simultaneously, due to the splitting of the $|1\rangle$ and $|0\rangle$, the original ω_1 cannot be matched to the new building energy level of $|+\rangle$ and $|-\rangle$ and the intensity of the signal decreases greatly. Under the nonresonant condition ($\Delta_1 \neq 0$), however, the both two dressing fields can either suppress or enhance the FWM. Figure 2(b) presents this phenomenon. By similar analogy, although the FWM signal is small with large detuning and no dressing fields, when E_3 and E_4 are strong and Δ_3 or Δ_4 change its value to match the laser frequency ω_1 with the splitting energy level ($|+\rangle$ or $|-\rangle$) created by E_3 and E_4, resonant excitation happens and the FWM signal is enhanced. Moreover, from Fig. 2(b), we can see the enhancement effect is more dramatic in the area of $\Delta_3 < 0$ and $\Delta_4 > 0$ than other three areas, while the suppression effect is more dramatic in the area of $\Delta_3 > 0$ and $\Delta_4 < 0$ than others. It means the two dressing fields enforce each other's suppression and enhancement effect of the FWM signal with the proper detuning.

Secondly, we consider the DDFWM signal in the

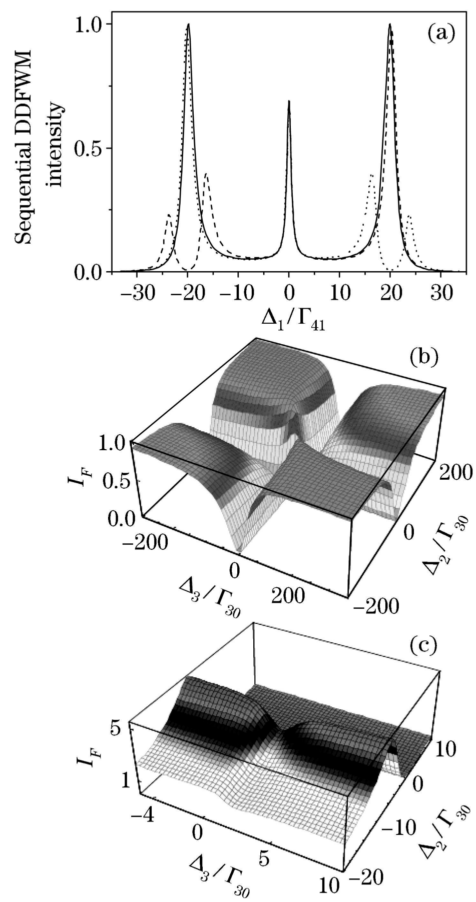

Fig. 3. Parameters are $\Delta_4 = 0$, $\Gamma_{20}/\Gamma_{30} = 1.82$, $\Gamma_{41}/\Gamma_{30} = 11.65$, $\Gamma_{10}/\Gamma_{30} = 0.5$. (a) Sequential-cascade DDFWM signal versus Δ_1/Γ_{30} when $\Delta_3/\Gamma_{30} = 1000$, $\Delta_2 = 0$ (solid line), $\Delta_3/\Gamma_{30} = 20$, $\Delta_2 = 0$ (dashed line), $\Delta_3/\Gamma_{41} = -20$, $\Delta_2 = 0$ (dotted line), $G_2/\Gamma_{30} = 20$, $G_3/\Gamma_{30} = 5$; (b) sequential-cascade DDFWM signal intensity versus Δ_2/Γ_{30} and Δ_3/Γ_{30} when $\Delta_1 = \Delta_4 = 0$, $G_2/\Gamma_{30} = 4$, $G_3/\Gamma_{30} = 4$, and (c) $\Delta_1/\Gamma_{30} = -2$, $\Delta_4 = 0$, $G_2/\Gamma_{30} = 4$, $G_3/\Gamma_{30} = 0.5$. The FWM signal intensity with no coupling field is normalized to 1.

sequential-cascade mechanism. As shown in the Fig. 1 (d2), E_3 and E_2 dress the same energy level $|1\rangle$ into two splitting levels $|+G_2G_3\rangle$ and $|-G_2G_3\rangle$. Then, Fig. 3(a) presents AT splitting in sequential mechanism when $G_2 > G_3$ under the nonresonant condition $\Delta_3 \neq 0$. As shown in Fig. 1(d3), when E_2 dress the energy level $|1\rangle$ into two splitting levels $|+\rangle$ and $|-\rangle$, as the detuning rate $\Delta_3 = \pm G_2$, the weak dressing field E_3 dress $|+\rangle$ level ($\Delta_3 > 0$) or $|-\rangle$ level ($\Delta_3 < 0$) into secondarily-dressed splitting level of $|++\rangle$ and $|+-\rangle$ or $|-+\rangle$ and $|--\rangle$, respectively. It means that the dressing field E_2 first separates the signal intensity into two splitting peaks while the dressing field E_3 devotes to the small splitting peaks on one side of established peaks. With similar devotion of two dressing fields E_2 and E_3, there is the same AT splitting phenomena under the condition of $\Delta_2 \neq 0$. Thus, different from parallel mechanism, in the sequential-cascade mechanism, the two dressing fields are likely to have the same devotion to the splitting of intensity.

The analogy of the enhancement and suppression phenomena of sequential-cascade DDFWM (ρ_{DDF2E2}) has been presented in Figs. 3(b) and (c) under resonant and nonresonant condition. In Fig. 3(b), the strong dressing fields extremely suppress the FWM signal at the resonant point; even at nonresonant point, the suppression effect cannot be neglected. Moreover, the spectra of sequential-cascade DDFWM signal versus dressing fields detuning are asymmetric. It means in sequential-cascade mechanism the two dressing fields will extremely influence each other at the nonresonant points. The controllable enhancement and suppression of the dually dressed FWM can be obtained by adjusting laser frequency and two dressing field intensities (Fig. 3(c)). In Fig. 3(c) the signal intensity versus Δ_2 is dramatically enhanced by the dressing field E_4. Especially when $\Delta_2/\Gamma_{30} = -10$ approximately, we can see the continuous enhancement of intensity versus Δ_3. However, the dressing field E_3 suppresses the intensity dramatically when $\Delta_3/\Gamma_{30} = 2$ approximately. Because the strong dressing field E_2 separate the $|1\rangle$ into $|+\rangle$ and $|-\rangle$. The dressed state $|+\rangle$ is resonant with one photon with frequency ω_1 when $\Delta_2/\Gamma_{30} = -10$, thus the intensity increases. On the other hand, when $\Delta_3/\Gamma_{30} = 2$ approximately, the weak dressing field E_3 separates $|+\rangle$ into the secondarily-dressed states ($|++\rangle$ and $|+-\rangle$) and the resonant excitation disappears, hence the intensity decreases.

Finally, we investigate the DSWM spectrum of ρ_{DS1E1} versus Δ_4/Γ_{24}. Figure 4 presents the suppression and the enhancement of the SWM signal intensity. The reason of the suppression and the enhancement in Fig. 4 are that the dressed states $|+\rangle$ and $|-\rangle$ created by the dressing field E_4 make one photon non-resonant when $\Delta_1 = 0$, while $|-\rangle$ is resonant with ω_1 when $\Delta_1/\Gamma_{24} < 0$. For field E_3 is weak ($|G_3|^2 \ll \Gamma_{20}$ and Γ_{40}), we can derive $\left|\mathrm{Re}rho^{(5)}_{\mathrm{DS1E1}}\right|^2 / \left|\mathrm{Im}rho^{(5)}_{\mathrm{DS1E1}}\right|^2 \ll 1$ under exact resonance condition which means that the contribution of the real part of $\rho^{(5)}_{\mathrm{DS1E1}}$ is negligible and most of the signal intensity comes from the contribution of the imaginary part. Thus, we have $\left|\rho^{(5)}_{\mathrm{DS1E1}}\right|^2 \approx \left|\mathrm{Im}(\rho^{(5)}_{\mathrm{S1}})\right|^2 + 2\mathrm{Im}(\rho^{(5)}_{\mathrm{S1}})\mathrm{Im}(\rho^{(7)}_{\mathrm{E1}}) + \left|\mathrm{Im}(\rho^{(7)}_{\mathrm{E1}})\right|^2$. The negative term $2\mathrm{Im}(\rho^{(5)}_{\mathrm{S1}}\rho^{(7)}_{\mathrm{E1}})$ leads to the suppression of the dressed FWM signal. There exists reductive interference as a result of competition between FWM and SWM. The suppression and enhancement of signal intensity mainly originate from the competition between absorption and dispersion of the dressed SWM. When field E_3 is weak and non-resonant parameter Δ_1/Γ_{24} increases, the simplified ratio R can be larger than 1, which means the contribution of the real part of DSWM overtakes the imaginary part.

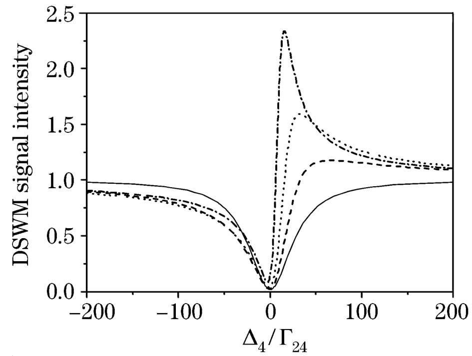

Fig. 4. Δ_4-dependence of the DSWM signal intensity with no dressing field is normalized to 1 when $\Gamma_{24}/\Gamma_{20} = 4.05$, $\Gamma_{30}/\Gamma_{20} = 0.55$, $\Gamma_{10}/\Gamma_{20} = 3.33$, $\Delta_3 = 0$, $\Delta_2 = 0$, $G_4/\Gamma_{20} = 5$, $\Delta_1 = 0$ (solid line), $\Delta_1/\Gamma_{20} = -0.5$ (dashed line), $\Delta_1/\Gamma_{20} = -1$ (dotted line), and $\Delta_1/\Gamma_{20} = -2$ (dotted-dashed line).

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