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Dressed spontaneous parametric the four-wave mixing process in Pr$^{3+}$:YSO crystal

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Abstract
We investigate fluorescence (FL) and spontaneous parametric four-wave mixing (SP-FWM) signals in V-, A- and N-type energy level systems by changing the frequency detuning or power of the dressing field in Pr$^{3+}$ doped Y$_2$SiO$_5$ at 77 K. The lifetime of the two kinds of signals has been calculated, and the desired experimental results have been obtained. We successfully control the intensity and lifetime of fluorescence and SP-FWM signals by changing the power or frequency detuning of the dressing field. The research has potential applications in optical switches and all optical communication.

Keywords: spontaneous parametric process, four-wave mixing, SP-FWM, fluorescence, lifetime

1. Introduction

It is demonstrated that parametric processes in atomic vapors such as parametric self-oscillation have applications in quantum communications [1–4]. Using alkali atomic vapor with a ‘double-Λ’ configuration, the four-wave mixing (FWM) process occurs where Stokes and anti-Stokes photons are parametrically generated, which can be quantum-mechanically correlated both theoretically [5] and experimentally [1]. Currently, most experimental researches on atomic coherence are reported in hot or cold atomic gas systems. Compared with atomic gases, atomic coherence-induced effects in solid materials are parametrically generated, which can be quantum-mechanically correlated both theoretically [5] and experimentally [1]. Currently, most experimental researches on atomic coherence are reported in hot or cold atomic gas systems. Compared with atomic gases, atomic coherence-induced effects in solid materials are parametrically generated, which can be quantum-mechanically correlated both theoretically [5] and experimentally [1].

Progress related to atomic coherence in solid-state materials, including enhanced four-wave mixing (FWM) based on atomic coherence [6], optical quantum computing [7, 8], light velocity reduction and coherent storage [9–12], and electromagnetically induced transparency in solid materials [13–16], have provided the basis for potential applications. Recently, we have reported the seeded parametric amplification (PA-FWM) process. Various possible amplification processes are discussed by selectively seeding various multi-wave mixing (MWM) signals [17], and the competition between the SP-FWM and second- or fourth-order FL signal in the same channel in YSO crystal is observed [18]. The principal motivation of this work is to understand how the intensity and lifetime of the SP-FWM process are controlled by the dressing effect in V-type, A-type and N-type energy systems in a Pr:YSO crystal. Such results can find potential applications in all-optical information processing and quantum communication technologies for on a photonic chip.

In this paper, we investigate, both theoretically and experimentally, the SP-FWM and fluorescence as well as their lifetimes in three systems: V-type, A-type and N-type energy systems in Pr$^{3+}$ doped Y$_2$SiO$_5$ (Pr:YSO) crystal. This allows a comparison to be made between the two energy systems and allows a discussion of the intensities and lifetimes of fluorescences and SP-FWM signals, which can be controlled by the dressing effects of self-dressing fields and external fields with the frequency detuning and the power of the involved field.

2. Experiment setup

Figure 1(a) shows the N-type level energy diagram of 0.05% rare-earth Pr$^{3+}$ doped Y$_2$SiO$_5$ crystal. A detail analysis of
acts on the anti-Stokes channel.

For the perturbation chain to the phase-matching condition \(k\) phase-conjugated FWM (PC-FWM) process occurs according to the chain denote the initial, intermediary and final states of the energy-level system, respectively. (d), (e) V- and \(\Lambda\)-type three-level subsystems, respectively. (d), (e) V- and \(\Lambda\)-type three-level subsystems, respectively. Under the action of crystal field of YSO, the terms in \(\tilde{H}_0\) are neglected in the current work since it is easy to identify them reliably by investigating the optical spectrum of the Pr\(^{3+}\) ions. Under the action of crystal field of YSO, the terms in \(\tilde{H}_0\) are neglected in the current work since it is easy to identify them reliably by investigating the optical spectrum of the Pr\(^{3+}\) ions.

The sample (a 3 mm Pr:YSO crystal) is held in a cryostat (CFM-102) with a temperature of 77 K. Three tunable dye lasers (narrow scan with a 0.04 cm\(^{-1}\) linewidth) pumped by an injection locked single-mode Nd:YAG laser (Continuum Powerlite DLS 9010, 10 Hz repetition rate, 5 ns pulse width) are used to generate the pumping fields \(E_1(\omega_1, \Delta_1), E_2 & E_3^*(\omega_2, \Delta_2)\), and \(E_3(\omega_3, \Delta_3)\) with the frequency detuning of \(\Delta = \omega_m - \omega_i (i = 1, 2, 3)\), respectively, where \(\omega_m\) denotes the corresponding atomic transition frequency. For convenience, we use FL1 and FL2 to represent the fluorescence signals radiated from levels 1) and (2), which are pumped by fields \(E_1\) and \(E_2\), respectively. The emitted signals \(E_3\) and \(E_{3S}\) form a spatial conical alignment, as shown in figure 1(f). But the FL is a non-coherent signal. Therefore, the pair pure SP-FWMs \((E_{3S} \text{ and } E_3)\) are only detected by two photomultiplier tubes (D3 and D2) along the direction of \(E_{3S}(E_{3S} \upsilon E_3)\) and \(E_{3S}\), and a composite signal (including FL and SP-FWMs) is monitored by another detector D1, as shown in figure 1(f). The lifetime and intensity of SP-FWM and FL signals are detected with a digitizing oscilloscope and are averaged with a fast gated integrator (gate width of 10 \(\mu s\)).

The triplet energy-level \(^{3}H_4\) and singlet energy-level \(^{1}D_2\) is neglected in the current work since it is easy to identify them reliably by investigating the optical spectrum of the Pr\(^{3+}\) ions. Under the action of crystal field of YSO, the terms in \(\tilde{H}_0\) are neglected in the current work since it is easy to identify them reliably by investigating the optical spectrum of the Pr\(^{3+}\) ions. Under the action of crystal field of YSO, the terms in \(\tilde{H}_0\) are neglected in the current work since it is easy to identify them reliably by investigating the optical spectrum of the Pr\(^{3+}\) ions.

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### 3. Theoretical model

We adopt the perturbation theory to investigate the SP-FWM and FL signals. When the \(E_1\) and \(E_2\) are open, the SP-FWM signals are generated in the V-type level system of Pr\(^{3+}\):YSO, which is a heteronuclear-like molecule system. A pair of SP-FWM signals \((E_{3S1} \text{ and } E_{3S1})\) is generated in a spontaneous parametric process. The Hamiltonian can be written as

\[
H = \hbar \nu (\hat{a}^{+} \hat{b}^{+} + \hat{a} \hat{b})
\]

where \(\hat{a}^{+}(\hat{a})\) is the boson-creation (annihilation) operator acting on the electromagnetic excitation of the Stokes channel, whereas \(\hat{b}^{+}(\hat{b})\) acts on the anti-Stokes channel. \(\nu\) is the group velocity of light in the nonlinear media. The pumping parameter of the amplifier \(g = \chi^{(3)}E_0E_2 = |h\phi_{10020_{51}}^{S1}/h\phi_{10}G_{51}S_{1/2}|\) depends on the nonlinear susceptibility \(\chi^{(3)}\) and the pump-field amplitudes, \(\chi^{(3)}\) is a function of high-order density-matrix elements. According to the description above, the Hamiltonian of the V energy system can be written as

\[
H_{int} = -\hbar |\Delta_1| |1 > |1+\Delta_2| 2 > |2|
\]

\[
-\hbar |G| 1 > |0+0| G 2 > |0+h.c.|
\]

Then the density-matrix equations can be obtained:

\[
\frac{d}{dt} \rho = -\frac{i}{\hbar} [\hat{H}, \rho] - \Gamma \rho
\]

For the perturbation chain method, although such an approach makes significant approximations, it shows a simple but clear picture of which give leading contributions in the complicated nonlinear optical processes. Considering an V energy system, there is a simple SP-FWM expressed as the perturbation chain \(\rho_{00}^{(0)} \rightarrow \rho_{10}^{(1)} \rightarrow \rho_{10}^{(2)} \rightarrow \rho_{20}^{(3)} \rightarrow \rho_{20}^{(2)} \rightarrow \rho_{10}^{(3)}\) and \(\rho_{00}^{(0)} \rightarrow \rho_{10}^{(1)} \rightarrow \rho_{10}^{(2)} \rightarrow \rho_{10}^{(3)}\). Density-matrix elements in the chain denote the initial, intermediary and final states of the transition process of generating SP-FWM. Consequently, simplified density-matrix equations about \(\rho_{00}^{(1)}, \rho_{00}^{(2)}\) and \(\rho_{20}^{(3)}\) are:

\[
\rho_{10}^{(1)} = iG_1 e^{i\theta_1} \frac{\rho_{00}^{(0)}}{i\theta_1} (2a)
\]
where $d_{1} = \Gamma_{10} + i\Delta_{1}$, $d_{2} = \Gamma_{20} + i\Delta_{2}$. $G_{i} = -\mu_{i}E_{i}/h$ is the Rabi frequency of $E_{i}$ with $\mu_{i}$ the electric dipole moment between levels $|i\rangle$ and $|j\rangle$, and $\Gamma_{ij}$ is the decoherence rate.

Substitute equation (2a) into equation (2b), and then the results substitute to equation (2c), under the ground state approximation $\rho_{00}^{(0)} \approx 1$, we get:

$$\rho_{20(3)}^{(0)} = -iG_{20}G_{10}e^{i(k_{1} + k_{2} - k_{3})}r_{00}/2d_{2}$$

Similarly, we can obtain:

$$\rho_{01(3)}^{(0)} = -iG_{20}G_{10}e^{i(k_{1} + k_{2} - k_{3})}r_{00}/2d_{2}$$

Here, taking the dressing effects of $E_{1}$ and $E_{2}$ into account, one can obtain the modified formations as:

$$\rho_{20(3)}^{(0)} = -iG_{20}G_{10}^{*}G_{12}^{*}[d_{1} + G_{20}^{2}T_{01} + G_{12}^{2}d_{2}]
\Gamma_{00} + iG_{12}^{2}/d_{2} + G_{12}^{2}/d_{2}]
\rho_{10(3)}^{(0)} = -iG_{20}G_{10}^{*}G_{12}^{*}[d_{2} + G_{20}^{2}/d_{2} + G_{12}^{2}/d_{2}]
\Gamma_{00} + iG_{12}^{2}/d_{2} + G_{12}^{2}/d_{2}]$$

So, the intensities of output signals of $E_{1}$ and $E_{2}$, $E_{3}$ are

$$\langle \hat{a}_{out}^{+}\hat{a}_{out} \rangle = \frac{1}{2} \left[ \cos \left( 2\sqrt{AB} \sin \frac{q_{1} + q_{2}}{2} \right) + \cosh \left( 2\sqrt{AB} \cos \frac{q_{1} + q_{2}}{2} \right) \right] \frac{A}{B}$$

$$\langle \hat{b}_{out}^{+}\hat{b}_{out} \rangle = \frac{1}{2} \left[ \cos \left( 2\sqrt{AB} \sin \frac{q_{1} + q_{2}}{2} \right) + \cosh \left( 2\sqrt{AB} \cos \frac{q_{1} + q_{2}}{2} \right) \right] \frac{B}{A}$$

where, for convenience, we set $\rho_{20(3)}^{(0)} = A e^{\varphi_{1}}$, and $\rho_{10(3)}^{(0)} = B e^{\varphi_{2}}$: with $A$, $B$, $q_{1}$, and $q_{2}$ being the modulus and phase angles of $\rho_{20(3)}^{(0)}$ and $\rho_{10(3)}^{(0)}$ respectively.

Similarly, we can obtain the intensity of the FL signal according to the perturbation chains

$$\rho_{20}^{(0)} \rightarrow \rho_{20}^{(1)} \rightarrow \rho_{20}^{(2)} \rightarrow \rho_{20}^{(3)} \rightarrow \rho_{1}^{(4)}$$

The intensity of the FL signal can be described by the diagonal density matrix element $\rho_{1}^{(4)}$ which is given by

$$\rho_{1}^{(4)} = \frac{|G_{12}^{2}|^{2}}{d_{1} + G_{12}^{2}d_{2} + G_{12}^{2}d_{3} + G_{12}^{2}d_{4}}$$

where $d_{12} = \Gamma_{12} + i(\Delta_{1} - \Delta_{2})$, $d_{21} = \Gamma_{21} + i(\Delta_{2} - \Delta_{1})$.

With $E_{1}$ and $E_{3}$ on ($\Lambda$-type energy level system), according to the aforementioned method, the perturbation chains of the FL2 and SF-FWM are expressed by

$$\rho_{1}^{(4)} = \frac{\Gamma_{1}^{2}}{d_{1} + G_{12}^{2}d_{2} + G_{12}^{2}d_{3} + G_{12}^{2}d_{4}}$$

$$\rho_{1}^{(4)} = \frac{\Gamma_{1}^{2}}{d_{1} + G_{12}^{2}d_{2} + G_{12}^{2}d_{3} + G_{12}^{2}d_{4}}$$

$$\rho_{1}^{(4)} = \frac{\Gamma_{1}^{2}}{d_{1} + G_{12}^{2}d_{2} + G_{12}^{2}d_{3} + G_{12}^{2}d_{4}}$$

4. Results and discussions

Firstly, the FL1, Stokes and anti-Stokes of SP-FWM signal processes are investigated in the $\Lambda$-type level system in
Pr$^{3+}$:YSO. Figures 2(a1)–(a3) show the signals of FL1, Stokes and anti-Stokes of SP-FWM signal processes versus $\Delta_1$ by increasing the power of $E_2$ from 0.5 to 7 mW. For the FL1 signal, the background first increases then decreases (the profile indicated by the dashed line in figure 2(a1)) when $E_2$ power increases. The scanning curves vary from Autler–Towns (AT) splitting to pure suppression dip, because the FL1 only suffers the dressing effect of $E_1$ when $P_2$ is low, the suppression effect comes into play gradually due to the dressing state $|G_1\pm\rangle$. The reason is that particles are excited to $|1\rangle$ which is split into $|G_1\pm\rangle$ caused by field $E_1$. If we set $1\rangle$ as the frequency reference point, the Hamiltonian can be written as: $H = -\hbar \begin{bmatrix} 0 & G_1 \\ G_1^* & (-1)^i \Delta_2 \end{bmatrix}$. From the equation $H|G_1\pm\rangle = \lambda_{\pm}|G_1\pm\rangle$, we can obtain $\lambda_{\pm} = \left[-(-1)^i \Delta_2 \pm \sqrt{\Delta_2^2 + 4|G_1|^2}\right]/2$. The AT-splitting distance corresponding to the dressed states $|G_1\pm\rangle$ can be written as $\Delta_0 = \lambda_+ - \lambda_- = \sqrt{\Delta_2^2 + 4|G_1|^2}$. However, the suppression dip becomes small due to the total signal suppression being too weak and the dressing effect reaches maximum as $P_2 = 7$ mW is fixed. At last, the spectra of the FL1 signal show pure suppression due to the dressing effect of $E_2$. The intensities of Stokes and anti-Stokes SP-FWM signals increase when $P_2$ increases, as shown in figures 2(a2) and (a3), respectively. The increased background signal is SP-FWM which is generated by $E_2$ and the reflected beam. Each peak is another SP-FWM generated by $E_1$ and $E_2$ in V-type level system $|0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle$, which is described by equations (5) and (6). But the emission peaks of Stokes and anti-Stokes decrease due to the dressing effect of $E_2$ (the term $|G_2|^2|d_2\rangle$ and $|G_2|^2|d_2\rangle$ in equations (3) and (4)) increase more quickly than the production. The simulations of FL1 and Stokes signal processes in figures 2(f) and (g) correspond to the experimental conditions in figures 2(a1) and (a2), respectively.

Next, we consider controlling the intensities of FL1, Stokes and anti-Stokes by changing detuning of $E_2$. Figures 2(b1)–(b3) show the FL1, Stokes and anti-Stokes signals with different $\Delta_2$ and fixed $P_2 = 7$ mW. When $\Delta_2 = 0$, the FL1 signal dip is similar to the last curve in figure 2(a1) due to the same reason that is explained in figure 2(a1). As $\Delta_2$ moves away from the resonant point, the background (two-order FL of $E_2$) indicated by the dashed line in figure 2(b1) increases due to the dressing effect of $E_2$ ($|G_2|^2|d_2\rangle$). The scanning curves evolve from suppression dip to AT-splitting due to the weakened dressing effect of $E_2$ (i.e. $|G_2|^2|d_2\rangle$ and $|G_2|^2|d_2\rangle$ in equation (7)) when $\Delta_2$ changes from resonance to large detuning. It is obvious that the profile (the short-dashed line in figure 2(b1)) of $\rho_1^{(4)}$ at the resonant point is similar to the background of $\rho_1^{(2)}$ caused by $E_2$ because of the same reason. The Stokes and anti-Stokes processes are shown in figures 2(b2) and (b3), respectively. The background signal is the SP-FWM of $E_2$ and it is the reflected beam, which exhibits a Lorentzian shape because the excitation at $\Delta_2 = 0$ is larger than that far away from the resonant point. At the same time, the dressing effect of $E_2$ is enhanced in the resonance region, which is determined by terms $|G_2|^2|d_2\rangle$ and $|G_2|^2|d_2\rangle$ in equations (3) and (4). So, the SP-FWM generated by $E_1$ and $E_2$ is supposed to be smaller near $\Delta_2 = 0$ than that in the resonant-off region. Figure 2(b) shows the dressing picture of the V-type level system because the dressing field $E_2$ splits the ground level $|0\rangle$ into two levels $|G_2^+\rangle$ and $|G_2^-\rangle$. The simulations of FL1 and Stokes signals (figures 1(b) and (i)), which are obtained according to equations (7) and (3), agree with the experiments very well.
Finally, let us focus on the modulated lifetime of FL1, Stokes and anti-Stokes processes. Such a lifetime, represented by the slope value, is obtained by the logarithmic transformation \[ I_{\text{FL}}(t) = I_{0,\text{FL}} \exp[-\Gamma_1 t], \] \[ I_3(t) = I_{0,\text{SS}} \exp[-\Gamma_3 t], \] \[ I_{\text{SS}}(t) = I_{0,\text{SS}} \exp[-\Gamma_{\text{SS}} t], \] where \( I_{0,\text{FL}} \), \( I_{0,\text{SS}} \), \( I_{0,\text{SS}} \) and \( \Gamma_1, \Gamma_3 \) and \( \Gamma_{\text{SS}} \) is the decay rate. Here, \( \Gamma_{\text{FL}} = (\Gamma_{10}) + (\Gamma_{01}) + (\Gamma_{11}), \) \( \Gamma_{\text{SS}} = (\Gamma_{00})/2 + (\Gamma_{01})/2 + (\Gamma_{11})/2 + (\Gamma_{12}), \) \( \Gamma_3 = (\Gamma_{00}) + (\Gamma_{01}) + (\Gamma_{02}) + (\Gamma_{10}) \), where \( \Gamma_i = (2\pi T_1)^{-1} + (2\pi T_2)^{-1}, i = 0, 1, 2, 3 \) on behalf of the level, but \( (2\pi T_1)^{-1} = (2\pi T_2)^{-1} = 0 \) due to \( \Delta_1 = 0 \) and \( \Delta_3 = 0 \) are ground level.

\[
(2\pi T_1)^{-1} = 16\pi(v_i + \Delta v_i)\beta^2\eta^2/\hbar c^3, \tag{17a}
\]
\[
(2\pi T_2)^{-1} = (2\pi T_3)^{-1} = (2\pi T_4)^{-1} = (2\pi T_5)^{-1} = P(t)_{0,3}, \tag{17b}
\]
\[
(2\pi T_6)^{-1} = (2\pi T_7)^{-1} = P(t)_{1,2} + \gamma_0. \tag{17c}
\]

\[
P(t)_{0,3} = \exp \left[ -c_{H_0} \sum_{n=6,8,10} (A_{nH}/R_n^H) \right], \tag{18a}
\]
\[
P(t)_{1} = \exp \left[ -c_D \sum_{n=5,6,8} (A_{nD}/R_n^D) \right], \tag{18b}
\]
\[
P(t)_{2} = \exp \left[ -c_D^* \sum_{n=5,6,8} (A_{nD}/R_n^D) \right]. \tag{18c}
\]

The term \((v_i + \Delta v_i)\) in equation (17a) represents the dressing of the energy-level which can be dressed by the location of the dressing field. In equations (18a) and (18b), \( c_{H_0} \) and \( c_D \) \( (c_D^*) \) are controlled by the power of pump field and determine the population densities at \( |H_2 \rangle \) and \( |D_2 \rangle \). The two terms \( \sum(A_{nH}/R_n^H) \) and \( \sum(A_{nD}/R_n^D) \) \((\sum(A_{nD}/R_n^D)^*) \) are the induced dipole–dipole interactions [13, 15] of states \( H-H \) and \( D-D \), respectively.

Figure 2(c) shows the decay rate of FL and Stokes at the resonant point \( \Delta_1 = \Delta_2 = 0 \) as \( P_2 \) increases. The decay rate \( \Gamma_{\text{FL1}} \) (square) decreases due to the enhancement of the dressing effect of \( E_2 \). Thus, the decay rate (equation (15a)), as well as the induced dipole–dipole interactions \((C\alpha R^4)\) in equation (16a), decease because of the splitting of energy level \( \Delta_1 \), as shown in figure 1(b). But for the Stokes decay rate (circles), it increases due to the strengthened induced dipole–dipole interactions in equations (18a)–(18b) caused by the increasing total intensity of Stokes when \( P_2 \) increases. Figure 2(d) shows the similar decay rates at \( \Delta_1 = 0 \) when \( \Delta_2 \) is changed from negative to positive. The decay rate of FL1 (squares) is smaller than that in the region of non-resonance, which corresponds to the signal at \( \Delta_1 = 0 \) in figure 2(b1). The reason is that the level \( |0 \rangle \) is strongly dressed by \( E_2 \), and the dressing effect is the strongest when \( \Delta_1 = 0 \). So, the lifetime of FL1 becomes large near the resonant point due to the increased decay rate. For the Stokes, particles are mostly excited to the excited state when \( E_2 \) is resonant between \( |0 \rangle \) and \( |2 \rangle \), and the induced dipole–dipole interaction in level \( 2 \) will be strengthened, so the decay rate increases (circles) in figure 2(d) that leads to the lifetime decrease.

Next, let us consider controlling the intensities and lifetimes of FL2 and SP-FWM signals in the \( \Lambda \)-type system. Figure 3 describes the FL2 and SP-FWM signals as well as their decay rates by opening \( E_1 \) and \( E_3 \) and scanning \( E_1 \) with increasing the power of \( E_3 \) (figure 3(a)) or varying \( \Delta_1 \) from negative to positive (figure 3(b)). When the power increases, the background of the FL2 first increases then decreases, at last it is suppressed almost to zero (dashed line in figure 3(a1)). The scanning signal of FL2 (fourth-order) varies from an emission peak to AT-splitting, then to a suppression dip, and at last to a line (the intensity near to zero). The reason is that the background is consisted of second-order FL generated by \( E_3 \). The background signal increases due to the generation of is domain, and then decreases because the dressing effect of \( E_3 \) (the terms \( |G_3|^2/d_{31}, |G_3|^2/d_{30}, \) and \( |G_3|^2/T_{13} \) in equation (8)) is enhanced when the \( P_3 \) increases continuously. The AT-splitting and the suppression dip of fourth-order FL2 are caused by the dressing effect of \( E_3 \) determined (the terms \( |G_3|^2/d_{31} \) and \( |G_3|^2/d_{30} \) in equation (8)). Then the FL2 is suppressed to a line due to the dressing term \( |G_3|^2/T_{13} \) in equation (8). For the
SP-FWM signals, the intensities of Stokes and anti-Stokes increase as \( P_1 \) changes from 1 mW to 7 mW, as shown in figures 3(a2) and 3(a3), respectively. The background intensities of Stokes and anti-Stokes of SP-FWM signal processes (the dashed line in figures 3(a2) and 3(a3)) increase gradually because the enhanced SP-FWM signal generated by \( E_1 \) and the reflected beam. The background trend of SP-FWM in figure 3(a) is similar to that in figure 2(a), but the emission peaks of Stokes and anti-Stokes processes also increase because the generation of the SP-FWM signal produced by \( E_3 \) and \( E_1 \) is dominant but the dressing effect is weak as \( P_1 \) increases.

Figure 3(d) shows the decay rates of FL2 (squares) and Stokes (circles) processes with \( \Delta_1 = \Delta_3 = 0 \) and the same power in figure 3(a). The decay rate of FL2 decreases when \( P_1 \) increases. It is because the dressing effect from \( E_3 \) (dresses level 11) is dominant (the splitting gap is determined by the term \( \Delta_1 \) in equation (17a)).

But the decay rate of the Stokes signal shows an opposite trend as in figure 3(d), because induced dipole–dipole interaction increases when the intensity of the Stokes signal increases due to a larger \( P_3 \).

Figures 3(b1)–(b3) exhibit FL2, Stokes and anti-Stokes signals versus \( \Delta_1 \) with \( \Delta_3 = -150 \text{ GHz}, -100 \text{ GHz}, -50 \text{ GHz}, 0, 50 \text{ GHz}, 100 \text{ GHz} \) and 150 GHz, respectively. For the FL2 signal, indicated by a dashed curve, it shows a Lorentz lineshape when \( \Delta_3 \) is scanned from negative to positive. The emission peak of fourth-order FL alters from AT-splitting to pure emission peak when \( \Delta_3 \) is close to the resonance from larger frequency detuning, because of the net dressing effect term in equation (15). For the signals \( E_{a2} \) and \( E_{a22} \), the background profile also has a Lorentz lineshape and the emission peak becomes small when \( \Delta_3 \) approaches the resonant point gradually, as shown in figures 3(b2) and (b3). It is because the background is the SP-FWM generated from \( E_3 \). But the emission peak of SP-FWM which is generated by \( E_1 \) and \( E_3 \) is suppressed because the dressing effect of \( E_3 \) (terms \( |G_3|^2/d_{31} \) and \( |G_3|^2/d_{30} \) in equation (7)) becomes strong when \( \Delta_3 \sim 0 \). Corresponding to the spectral of FL2 and \( E_{a2} \) signals, figure 3(e) shows the decay rates of FL2 (squares) and \( E_{a2} \) (circles) when \( \Delta_3 \) is set at renounce and \( \Delta_3 \) is changed from negative to positive. The decay rate of FL2 as well as that of \( E_2 \) shows a Lorentz lineshape because the induced dipole–dipole interaction of state \( D-D \) increases when the total signal intensity becomes strong.

The atomic coherence associated with the two ground states in a \( \Lambda \) system is largely free from the influence of the quantum fluctuations due to spontaneous emission. In a \( V \)-type system, the atomic coherence is generated between the two excited states and is therefore fully subject to the quantum fluctuations from spontaneous emission. This may explain why the intensity and decay rate of FL and SP-FWM signals increase linearly as the pump field increases, and the intensity and decay rate of FL and SP-FWM signals remain the same at lower power of pump field. In addition, the dipole moment \( u_{32} \) is larger than \( u_{31} \), so the Rabi frequency in (0) ↔ (12) is larger than that in (3) ↔ (1) with the same power \( P_2 \) and \( P_3 \), which can lead to larger suppression of the FL signal and enhancement of SP-FWM signals, as shown in figures 2 and 3.

Finally, to verify different dressing effects between \( V \)- and \( \Lambda \)-type systems, we also consider SP-FWM that is generated by \( E_1 \) and \( E_2 \) (\( E_3 \)) with the external dressing field \( E_1 \) (\( E_2 \)) in the N-type energy system. Figure 4 describes FL and SP-FWM signals as well as the decay rate of FL and Stokes by opening \( E_1 \), \( E_2 \) and \( E_3 \) and scanning \( E_1 \) with increasing \( P_3 \) (figures 4(a) and (c)) or increasing \( P_2 \) (figures 4(b) and (d)). As \( P_3 \) increases, the background of the sixth-order FL gradually increases, as shown in figure 4(a1), due to the contribution from the second-order FL of \( E_3 \). The emission peak varies from AT-splitting to pure suppression dip due to the increasing dressing effect of \( E_3 \) described by the terms \( \langle G_3 \rangle^2/d_{31} \) and \( \langle G_3 \rangle^2/d_{30} \) in equation (14). The backgrounds of Stokes and anti-Stokes in figures 4(a2) and (a3) are similar to that of FL, which are caused by the increasing SP-FWM, the same as that in figures 3(a2) and (a3). The emission peaks of Stokes and anti-Stokes increase because the SP-FWM signal is generated by \( E_1 \) and \( E_3 \). Here we should note that the variation of other group SP-FWM is not observed. The decay rates of sixth-order FL and Stokes signals at \( \Delta_1 = \Delta_2 = \Delta_3 = 0 \) are calculated, as shown in figure 4(c). The trends are similar to that in figure 3(c). Comparing figure 4(a) with figure 4(b), one can find that the dressing effect of \( E_2 \) is bigger than that of \( E_3 \), even though the power of the two fields are equivalent. This would lead to larger suppression of the FL signal and enhancement of SP-FWM signals.
Then, we change $P_2$ from small to large, the sixth-order FL, Stokes and anti-Stokes signals are shown in figures 4(b1)–(b3), respectively. For the sixth-order FL, the background and the suppression dip profiles are similar to that in figure 2(a1). But the peak changes from a larger AT-splitting to a suppression dip, and then the depth of the dip becomes small. The reason is that a stronger dressing effect appears in sixth-order FL caused by the combination of $E_2$ and $E_3$. However, the variation of sixth-order FL comes from the dressing effects of $E_2$. For SP-FWM, the backgrounds of Stokes and anti-Stokes of SP-FWM signals in figures 4(b2) and (b3) are similar to those in figures 4(a2) and (a3). But the emission peaks of them become small because SP-FWM resulted from $E_1$ and $E_3$ suffers the external dressing effect of $E_1$ which are expressed by $|G_2|^2/d_23$ in equations (11)–(14). Figure 4(d) shows the decay rate of FL (square) and Stokes (circles) at $\Delta_1 = \Delta_2 = \Delta_3 = 0$ with increasing $P_3$. The evolution of the decay rate of Stokes is similar to the profile indicated by circles in figure 4(c). However, the decay rate of sixth-order FL stayd invariant because the FL signal is suppressed to zero at the resonant point.

5. Conclusion

In summary, we have presented the dressed SP-FWM processes and florescence as well as their life time in V-, A- and N-type energy level systems of Pr$^{3+}$:YSO both in theory and experiment. Due to the influence of the quantum fluctuations and dipole momenta, the dressing effects in V- and A-type energy systems are different. Such a difference can lead to larger suppression of the FL signals and enhancement of SP-FWM signals. By changing the frequency detunings and powers of the controlling fields, SP-FWM signal processes and florescence can be modulated by self- or external-dressing effect. Meanwhile, the lifetime of SP-FWM and FL are controlled through competition between the dressing effect and the induced dipole–dipole interaction. In addition, the Autler–Townes-like (or Autler–Townes) splitting effect of the fluorescence spectrum induced by itself and/or the external field, as well as the mutual interaction between two fluorescence signals are investigated. Such results can find potential applications in all-optical on-chip information processing and quantum communications technologies.

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References