Observation of Angle Switching of Dressed Four-Wave Mixing Image

Volume 4, Number 5, October 2012

Suling Sang
Zhenkun Wu
Jia Sun
Huayan Lan
Yiqi Zhang
Xun Zhang
Yanpeng Zhang

DOI: 10.1109/JPHOT.2012.2217946
1943-0655/$31.00 ©2012 IEEE
Observation of Angle Switching of Dressed Four-Wave Mixing Image

Suling Sang,1,2 Zhenkun Wu,1 Jia Sun,1 Huayan Lan,1 Yiqi Zhang,1 Xun Zhang,1 and Yanpeng Zhang1

1Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Shaanxi Key Lab of Information Photonic Technique, Xi’an Jiaotong University, Xi’an 710049, China
2School of Physics and Information Technology, Ningxia Teachers University, Guyuan 756000, China

DOI: 10.1109/JPHOT.2012.2217946
1943-0655/$31.00 ©2012 IEEE

Abstract: We experimentally report that angle-control dynamics in the nonlinear propagation of the images of the probe, generated four-wave mixing (FWM) and fluorescence signals beams in FWM process in a cascade three-level, as well as a two-level atomic systems. It is shown that, by changing the angles between pumping fields and dressing fields, respectively, the characteristics of the measured signals including the spectra intensity and spatial images can be controlled to display many effects, including the electromagnetically induced transparency and absorption (EIT and EIA, respectively) and Autler–Townes splitting. In particular, we demonstrate the angle-controlled switching from EIA to EIT in probe transmission or from enhancement to suppression in FWM signal. Additionally, we also illustrate the interaction between spatial characteristics and spectra intensities of weak fields. The studies can be very useful in producing all optical-signal-processing devices, such as spatial beam splitters, routers, and switches.

Index Terms: Coherence, four-wave mixing, Kerr effect.

1. Introduction

Electromagnetically induced transparency (EIT) in multilevel atomic vapors was widely researched in last two decades [1], [2]. It has been demonstrated that the self- and cross-Kerr nonlinearities can be significantly enhanced and modified due to laser-induced atomic coherence [1], which is crucial for bringing large refractive index modulation [3]. By the refractive index modulation, laser beam self-focusing [4] and pattern formation [5] have been extensively investigated with two laser beams propagating in atomic vapors. And in recent years, we have observed spatial shift [6], spatial Autler–Townes (A–T) splitting, gap solitons, and dipole solitons of the four-wave mixing (FWM) beams with dressing effects [7], [8] generated in multilevel atomic systems [9]–[12]. In addition, we have also observed the evolution of the intensity enhancement and suppression in FWM signal spectrum by controlling additional laser fields [13]. On the other hand, fluorescence accompanying the FWM process that can be induced by spontaneous emission under EIT conditions [14], [15] was studied because of its potential applications in metrology and long-distance quantum communication and quantum correlation. It is worth mentioning that the A–T splitting in fluorescence spectrum has been also reported in lithium molecules [14].
In this paper, we first experimentally study the influence on the images and spectra intensities of probe transmission, FWM, and fluorescence signals brought by the angles between pumping fields and dressing fields in cascade three-level and two-level atomic systems. Remarkable difference in the spatial properties of signal is obtained between the cases with the dressing field and the pumping field changed. And then, we analyze the experimental results through a qualitative theory. Studies on such controlling spectra intensity and images have potential applications in all optical signal processing. The organization of the paper is as following: In Section 2, we give the experimental setup and the qualitative theory. In Section 3, we analyze the experimental results in detail, and we conclude the paper in Section 4.

2. Theoretical Model and Experimental Scheme

2.1. Experimental Scheme

A cascade three-level system \( \langle 0 | (3S_{1/2}) , | 1 | (3P_{3/2}) , | 2 | (4D_{3/2}) \rangle \) and a two-level system \( \langle 0 | (3S_{1/2}) , | 1 | (3P_{3/2}) \rangle \) from Na atom (in an 18-cm-long heat pipe oven) are shown in Fig. 1(a) and (b), respectively. Five laser beams are applied to the atomic system with the spatial configuration given in Fig. 1(c) and (d). The fields \( E_1 \) (frequency \( \omega_1 \), wave vector \( k_1 \), the Rabi frequency \( G_1 \), and frequency detuning \( \Delta_1 = \Omega_1 - \omega_1 \), where \( \Omega_1 \) is the resonant frequency of transition from \( |0\rangle \) to \( |1\rangle \)) and \( E'_1 (\omega_1, k'_1, G'_1, \Delta'_1) \) are copropagating pump fields with a small angle between them in \( x - z \) plane \( [\theta_{1x0} \approx 0.3^\circ \text{ when they are set at the point B in Fig. 1(d)}] \) and \( y - z \) plane \( (\theta_{1y} \approx 0.05^\circ) \). The probe field \( E_3 (\omega_3, k_3, G_3, \Delta_3) \) propagates in the opposite direction of \( E_1 \). These three fields \( (E_1, E'_1, \text{and} E_3) \) with.
diameter of about 0.8 mm are from the same near-transform-limited dye laser (10-Hz repetition rate, 5-ns pulsewidth, and 0.04-cm⁻¹ linewidth) connecting the transition |0⟩ → |1⟩. The Rabi frequencies of the beams here are defined as \( G_i = \mu_{mn}E_i/h \) (\( i = 1, 2, 3 \)) or \( G'_i = \mu_{mn}E'_i/h \) (\( i = 1, 2 \)) in which \( \mu_{mn} \) is the dipole moments of the transition |m⟩ → |n⟩ the field \( E_i \) (\( E'_i \)) drives and \( E_i \) (\( E'_i \)) is the electric field intensity of \( E_i \) (\( E'_i \)). Another pair of dressing fields \( E_2 \) (\( \omega_2, k_2, G_2, \Delta_2 \)) and \( E'_2 \) (\( \omega_2, k_2, G_2, \Delta_2 \)) propagates in the same direction of \( E_1 \) having a small angle between them in \( y - z \) plane (\( \theta_{2yz} \approx 0.3^\circ \)) and \( x - z \) plane (\( \theta_{2xz} \approx 0.05^\circ \)). Driving the transition |1⟩ → |2⟩ in the cascade three-level and |0⟩ → |1⟩ in two-level systems, \( E_2 \) and \( E'_2 \) with diameter of 1 mm are generated from another dye laser with same pulse parameters as the former one. A degenerate FWM (DFWM) signal \( E_{F1} \) is produced, satisfying the phase-matching condition \( k_{F1} = k_1 - k'_1 + k_3 \), as shown in Fig. 1(c) and (d). In order to optimize the beam spatial effects, the intensities of the fields \( E_1 \) and \( E'_1 \) are about 0.005 W/cm² in cascade three-level system and 0.013 W/cm² in two-level system. And those of \( E_2 \) and \( E'_2 \) are approximately 0.005 W/cm². The spectra intensity of the weak probe beam \( E_3 \) is less than 0.003 W/cm². Moreover, all the beams used in the experiment are P-polarized components after a polarization beam splitter. In this experiment, we define the reduced angle between \( E_1 \) and \( E'_1 \) as \( \Delta \theta_1 = \theta_{1x} - \theta_{1x0} \), where \( \theta_{1x} \) is the angle between \( E_1 \) and \( E'_1 \) in \( x - z \) plane. Similarly, we can define the reduced angle between \( E_2 \) and \( E'_2 \) as \( \Delta \theta_2 = \theta_{2y} - \theta_{2y0} \). In Fig. 1(d), when the intersecting points between the two pumping fields are set to move from point C (the back of the heat pipe oven) to position A (the front of the heat pipe oven), the value of \( \Delta \theta_2 \) changes from −0.15 to 0.15. The probe transmission and \( E_{F1} \) beams are split into two equal components by a 50% beam splitter before being detected. One component is captured by a CCD camera; the other detected by photomultiplier tubes (PMT1 and PMT2), and the fluorescence signal is detected by PMT3 with a fast gated integrator (gate width of 50 ns).

### 2.2. Dressed State Theory in the Cascade Three-Level Atomic System

In order to interpret the following experimental results, we perform the theoretical calculation on probe transmission, \( E_{F1} \), and fluorescence process in the cascade three-level atomic system. For DFWM signal \( E_{F1} \), its generation process can be viewed as a series of transitions steps. The first step is a rising transition from |0⟩ to |1⟩ with absorption of a pump photon \( E_1 \), the second step is a falling transition from |1⟩ to |0⟩, and the third step is another transition from |0⟩ to |1⟩ with the absorption of a probe photon \( E_3 \). Then, the last transition is from |1⟩ to |0⟩, which emits a FWM photon at frequency \( \omega_1 \). According to the Liouville pathway of the pure DFWM

\[
\rho_{00}^{(0)} \xrightarrow{G_1} \rho_{01}^{(1)} \xrightarrow{G_1'} \rho_{10}^{(2)} \xrightarrow{G_2} \rho_{10}^{(3)}
\]

we can obtain the third-order nonlinear density-matrix element \( \rho_{10}^{(3)} = g/(\Gamma_{00} \Gamma_{10}^2) \), the magnitude of which determines the spectra intensity of the DFWM signal. Here, \( g = -iG_3G_1G_1' \), \( d_1 = i(\Delta_1' + \Gamma_{10}) \), and \( \Gamma_{ij} \) is transverse relaxation rate between the states |i⟩ and |j⟩. When \( E_{F1} \) is also dressed by the fields \( E_1 \), \( E'_1 \), \( E_3 \), and \( E_2 \), \( E'_2 \), the multidressed Liouville pathway in such case is

\[
\rho_{00}^{(0)} \xrightarrow{(G_1)'} \rho_{01}^{(1)} \xrightarrow{(G_1')'} \rho_{10}^{(2)} \xrightarrow{G_2} \rho_{10}^{(3)} \]

\[
\rho_{00}^{(0)} \xrightarrow{G_1} \rho_{01}^{(1)} \xrightarrow{G_1'} \rho_{10}^{(2)} \xrightarrow{G_2} \rho_{10}^{(3)}
\]

(self-dressed by \( E_1 \), \( E'_1 \), \( E_3 \) and external-dressed by \( E_2 \), \( E'_2 \)); the expression of the density-matrix element \( \rho_{10}^{(3)} \) related to such multidressed \( E_{F1} \) can be obtained as

\[
\rho_{10}^{(3)} = g \left\{ \left( d_1 + |G_1|^2/(\Gamma_{00} + |G_1|^2/(\Gamma_{00} + A_1)) + |G_2|^2/d_2 + |G_3|^2/d_2 + |G_3|^2/(\Gamma_{00} + |G_3|^2/(\Gamma_{11} + A_1)) \right)^2 \right. \\
\left. - \left( \Gamma_{00} + (|G_1|^2 + |G_3|^2)/(d_1 + A_2) \right) \right\}
\]

(1)

where \( d_2 = \Gamma_{20} + i(\Delta_1' + \Delta_2') \), \( A_1 = |G_1|^2/(\Gamma_{10} + i\Delta_1') \) and \( A_2 = |G_2|^2/(\Gamma_{20} + i(\Delta_1' + \Delta_2')) \). On the other hand, there exist three types of fluorescence signals due to spontaneous emission of photons from the upper levels. First, the decay of atoms pumped by the beams \( E_1 \), \( E'_1 \) from |0⟩ to |1⟩ will generate a type of fluorescence signal R1, which can be described by the Liouville pathway

\[
\rho_{00}^{(0)} \xrightarrow{G_1} \rho_{01}^{(1)} \xrightarrow{G_1'} \rho_{10}^{(2)} \xrightarrow{G_2} \rho_{10}^{(3)}
\]

By solving the coupled density-matrix equations, the expression of the density-matrix element \( \rho_{10}^{(2)} \) related to the fluorescence process R1 can be obtained as
When the beams $E_2$ ($E_2^*$) are turned on, the fluorescence process $R_1$ is dressed, which can be described by the Liouville pathway $\rho^{(0)}_{00} \xrightarrow{G_1} \rho^{(1)}_{01} \xrightarrow{G_2} \rho^{(2)}_{02} \xrightarrow{G_3} \rho^{(3)}_{03} \xrightarrow{G_4} \rho^{(4)}_{04}$ (self-dressed by $E_1$ ($E_1^*$) and external-dressed by $E_2$ ($E_2^*$)). The density-matrix element $\rho^{(2)}_{11}$ can be modified as

$$\rho^{(2)}_{11} = -|G_1|^2 / \left[ (d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_2) \Gamma_{11} + |G_1|^2/d_1 + |G_2|^2/d_2 + |G_2|^2/d_3 \right]$$  \hspace{1cm}(2a)$$

where $d_3 = \Gamma_{21} + i\Delta_2^*$, and $d_4 = \Gamma_{12} - i\Delta_2$. Second, the decay of atoms pumped by the beam $E_1$ ($E_1^*$) and $E_2$ ($E_2^*$) from $|0\rangle$ to $|2\rangle$ will generate another type of fluorescence signal $R_2$, which can be described by the Liouville pathway $\rho^{(0)}_{00} \xrightarrow{G_1} \rho^{(1)}_{11} \xrightarrow{G_2} \rho^{(2)}_{22} \xrightarrow{G_3} \rho^{(3)}_{33} \xrightarrow{G_4} \rho^{(4)}_{44} \cdots$ (dressed by $E_1$, $E_1'$, $E_2$ and $E_2'$). We can also obtain the density matrix element $\rho^{(4)}_{22}$ related to the fluorescence process $R_2$ as $\rho^{(4)}_{22} = |G_1|^2|G_2|^2/(\Gamma_{22}d_1d_2d_3d_4)$. If the dressing effect is also considered, we can further obtain the density matrix element for the multirdressed fluorescence process $R_2$ as

$$\rho^{(4)}_{22} = |G_1|^2|G_2|^2 / \left[ \Gamma_{22} \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_2 \right) d_2 \left( d_3 + |G_1|^2/d_2 + |G_2|^2/\Gamma_{22} \right) \right].$$  \hspace{1cm}(2b)$$

The fluorescence signal is obviously different from the FWM signals. First, from their Liouville pathways, we can see that the FWM process follows the closed-loop path while the fluorescence process does not. This results in the second difference between them i.e., the FWM signal is of direction but the fluorescence signal is not. Third, the FWM signal is caused by the atomic coherence effect, while the fluorescence signal is induced by spontaneous decay of photons pumped to the upper levels. For the probe transmission, the Liouville pathway is $\rho^{(0)}_{00} \xrightarrow{G_3} \rho^{(1)}_{01} \rho^{(2)}_{02} \rho^{(3)}_{03} \rho^{(4)}_{04} \cdots$ (dressed by $E_1$, $E_1'$, $E_2$ and $E_2'$), and we can obtain the first-order density matrix element as

$$\rho^{(1)}_{01} = iG_3 / \left[ (d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_2 + |G_2|^2/\Gamma_{11} + A_3) \right]$$  \hspace{1cm}(3)$$

the imaginary part of which proportionally determines the absorption of probe beam in propagation. Here, $A_3 = |G_2|^2/(\Gamma_{12} - i\Delta_2)$.

### 2.3. Dressed State Theory in the Two-Level Atomic System

For the FWM processes in two-level configuration, there exist several transition paths to generate FWM signals. They can be described by Liouville pathway.

(F1) $\rho^{(0)}_{00} \xrightarrow{G_1} \rho^{(1)}_{01} \xrightarrow{G_2} \rho^{(2)}_{02} \xrightarrow{G_3} \rho^{(3)}_{03}$, respectively.

(F2) $\rho^{(0)}_{00} \xrightarrow{G_2} \rho^{(1)}_{01} \xrightarrow{G_2} \rho^{(2)}_{01} \xrightarrow{G_3} \rho^{(3)}_{02}$, respectively.

(F3) $\rho^{(0)}_{00} \xrightarrow{G_3} \rho^{(1)}_{01} \xrightarrow{G_3} \rho^{(2)}_{01} \xrightarrow{G_3} \rho^{(3)}_{02}$, respectively.

(F4) $\rho^{(0)}_{00} \xrightarrow{G_4} \rho^{(1)}_{01} \xrightarrow{G_3} \rho^{(2)}_{01} \xrightarrow{G_3} \rho^{(3)}_{01}$, respectively.

Thus, we can obtain the corresponding dressed forms of them as

(DF1) $\rho^{(0)}_{00} \xrightarrow{G_1} \rho^{(1)}_{02} \xrightarrow{G_2} \rho^{(2)}_{02} \xrightarrow{G_3} \rho^{(3)}_{02}$, respectively.

(DF2) $\rho^{(0)}_{00} \xrightarrow{G_2} \rho^{(1)}_{02} \xrightarrow{G_2} \rho^{(2)}_{02} \xrightarrow{G_3} \rho^{(3)}_{02}$, respectively.

(DF3) $\rho^{(0)}_{00} \xrightarrow{G_3} \rho^{(1)}_{02} \xrightarrow{G_3} \rho^{(2)}_{02} \xrightarrow{G_3} \rho^{(3)}_{02}$, respectively.

(DF4) $\rho^{(0)}_{00} \xrightarrow{G_4} \rho^{(1)}_{02} \xrightarrow{G_3} \rho^{(2)}_{02} \xrightarrow{G_3} \rho^{(3)}_{02}$, respectively.
The expressions of the corresponding density matrix elements related to the four FWM pathways are:

$$\rho^{(3)}_{F1} = g \left[ \left( \Gamma_{00} + |G_2|^2/d_{0} \right) \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_{0} \right) \right]^2 $$

(4a)

$$\rho^{(3)}_{F2} = -iG_3G_2(G_2^*)^*/(\Gamma_{00}d_5B_2) $$

(4b)

$$\rho^{(3)}_{F3} = -iG_3G_2(G_1^*)^*/(d_1B_3^*) $$

(4c)

$$\rho^{(3)}_{F4} = -iG_3G_2(G_2^*)^*/(d_0d_5B_1) $$

(4d)

respectively, where

$$ d_0 = \Gamma_{00} + i\Delta_1', d_5 = \Gamma_{10} + i\Delta_1', d_7 = \Gamma_{00} + i(\Delta_2' - \Delta_1'), d_9 = \Gamma_{10} + i(2\Delta_1' - \Delta_2'), d_3 = \Gamma_{00} + i(\Delta_1' - \Delta_2'), d_4 = \Gamma_{00} + i(\Delta_1' - \Delta_2'), $$

$$ A_4 = |G_2|^2/d_6, A_5 = G_2^2/\Gamma_{00}, A_6 = |G_2|^2/\Gamma_{00}, B_1 = d_1 + A_2, B_2 = d_1 + A_3, and B_3 = d_6 + A_6. $$

In the experiment, only the signals generating in the pathways DF1 and DF3 propagate oppositely to $E'_1$; thus, only they can be detected.

In the two-level type atomic system, the decay of photons pumped by the beam $E_1 (E'_1)$ and $E_2 (E'_2)$ from $|0\rangle$ to $|1\rangle$ will generate the eight types of fluorescence signal, which can be described by the Liouville pathways

(R1) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R2) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R3) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R4) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R5) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R6) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R7) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11};$

(R8) $\rho^{(0)}_{00} \rightarrow \rho^{(1)}_{01} \rightarrow \rho^{(2)}_{11}.$

By solving the coupled density-matrix equations, the expression of the density-matrix element $\rho^{(2)}_{11}$ related to the eight fluorescence processes can be obtained as

$$\rho^{(2)}_{11} = |G_1|^2/\left( \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_0 \right) \left( \Gamma_{11} + |G_2|^2/d_5 + |G_1|^2/d_1 \right) \right) $$

(5a)

$$\rho^{(2)}_{11} = |G_1||G_2|/\left( \left( d_6 + |G_2|^2/\Gamma_{00} + |G_2|^2/d_0 \right) \left( d_{10} + |G_2|^2/d_6 + |G_1|^2/d_6 \right) \right) $$

(5b)

$$\rho^{(2)}_{11} = |G_1||G_2|/\left( \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_0 \right) \left( d_{10} + |G_2|^2/d_1 + |G_1|^2/d_6 \right) \right) $$

(5c)

$$\rho^{(2)}_{11} = |G_2|^2/\left( \left( d_6 + |G_2|^2/\Gamma_{00} + |G_2|^2/d_7 \right) \left( \Gamma_{11} + |G_2|^2/d_6 + |G_1|^2/d_1 \right) \right) $$

(5d)

$$\rho^{(4)}_{11} = |G_1|^2|G_2|^2/\left( \left( d_6 + |G_2|^2/\Gamma_{00} + |G_1|^2/d_7 \right) \Gamma_{00} \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_9 \right) \times \left( \Gamma_{11} + |G_1|^2/d_1 + |G_1|^2/d_1 + |G_2|^2/d_6 + |G_2|^2/d_2 \right) \right) $$

(5e)

$$\rho^{(4)}_{11} = |G_1|^2|G_2|^2/\left( \left( d_6 + |G_2|^2/\Gamma_{00} + |G_1|^2/d_7 \right) \times d_7 \left( \Gamma_{11} + |G_1|^2/d_1 + |G_1|^2/d_1 + |G_2|^2/d_6 + |G_2|^2/d_2 \right) \right) $$

(5f)

$$\rho^{(4)}_{11} = |G_1|^2|G_2|^2/\left( \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_7 \right) \Gamma_{00} \left( d_6 + |G_2|^2/\Gamma_{00} + |G_1|^2/d_7 \right) \times \left( \Gamma_{11} + |G_1|^2/d_1 + |G_1|^2/d_1 + |G_2|^2/d_6 + |G_2|^2/d_2 \right) \right) $$

(5g)

$$\rho^{(4)}_{11} = |G_1|^2|G_2|^2/\left( \left( d_1 + |G_1|^2/\Gamma_{00} + |G_2|^2/d_6 \right) \times d_6 \left( \Gamma_{11} + |G_1|^2/d_1 + |G_1|^2/d_1 + |G_2|^2/d_6 + |G_2|^2/d_2 \right) \right) $$

(5h)

where $d_{10} = \Gamma_{11} + i(\Delta_2' - \Delta_1'), d_{11} = \Gamma_{01} - i\Delta_1', and d_{12} = \Gamma_{01} - i\Delta_2'$. 

Vol. 4, No. 5, October 2012
In addition, under the experimental condition [Fig. 1(d)], for a hot atom with velocity $v$ along the angular bisector of the pump fields, the frequency of $E_1$ (or $E_s$) shifts to $\omega_1 - k_1 \cos(\theta_{1x}/2)$ when the Doppler effect is phenomenally introduced to weak signal. In the same way, the frequency of $E_2$ (or $E_s$) shifts to $\omega_2 - k_2 \cos(\theta_{2y}/2)$. As a result, the detunings of $E_1$ (or $E_s$) and $E_2$ (or $E_s$) shift to $\Delta'_1 = \Delta_1 + k_1 \cos(\theta_{1x}/2)$ and $\Delta'_2 = \Delta_2 + k_2 \cos(\theta_{2y}/2)$, respectively.

In order to understand the interaction between spatial characteristics and above dressed spectra intensity of weak fields, the propagation equations are investigated in the following Section 2.4.

2.4. The Spatial Nonlinear Propagation Equations for the Weak Fields

To understand the beam splitting and spatial shift of the probe and FWM beams, the propagation equations which give the mathematical description of the SPM- and XPM-induced spatial interplay for the probe and FWM beams are introduced as

$$\frac{\partial u_3}{\partial Z} - i \frac{\partial^2 u_3}{\partial k^2} = \frac{i k_{10}^2 w_0 l}{n_0} \left( n_2^{s1} |u_3|^2 + 2n_2^{X1} |u_1|^2 + 2n_2^{X2} |u_2|^2 + 2n_2^{X3} |u_0|^2 + 2n_2^{X4} |u_1|^2 \right) u_3 \quad (6a)$$

$$\frac{\partial u_1}{\partial Z} - i \frac{\partial^2 u_1}{\partial k^2} = \frac{i k_{10}^2 w_0 l}{n_0} \left( n_2^{s1} |u_1|^2 + 2n_2^{X0} |u_1|^2 + 2n_2^{X6} |u_2|^2 + 2n_2^{X8} |u_0|^2 \right) u_1 \quad (6b)$$

where $Z = z/L_D$ ($L_D = k_1 w_0^2$) is the physical meaning of the diffraction length and $w_0$ is the spot size of probe beam; $z$ is the longitudinal coordinate in the beam propagation direction; $k_3 = k_{1} = \omega_1/n_0/c$; $n_0$ is the linear refractive index at $\omega_1$; $n_2^{s1-S2}$ are the self-Kerr coefficients of $E_{3,F1}$; and $n_2^{X1-X8}$ are the cross-Kerr coefficients of $E_{3,F1}$ induced by $E_1$, $E_3$, $E_2$, and $E_s$. The notations $\xi = x/w_0$ and $\eta = y/w_0$ are the two dimensionless coordinates in the dimension transverse to the propagation direction, respectively; $u_{3,F1} = A_{3,F1}/l_1^{1/2}$, $u_{1,2} = A_{1,2}/l_1^{1/2}$, and $u_{1,2}' = A_{1,2}'/l_1^{1/2}$ are the normalized amplitudes of the beams $E_{3,F1}$, $E_{1,2}$ and $E_{1,2}'$; and the intensities of strong fields are both $I$. Here, on the left-hand side of these equations, the first terms describe the beam longitudinal propagation, and the second terms give the diffraction of the beams. On the right-hand side, the first terms are for the nonlinear self-Kerr effects, and the second and third terms describe the nonlinear cross-Kerr effects. Equations (6a) and (6b) can be solved numerically by using the split-step Fourier method that is usually employed.

The Kerr nonlinear coefficient, which is given by a general expression $n_2 \approx \Re [\rho_{10}^{(3)}/(c_0 \varepsilon_0)]$, is negative for self-defocusing and positive for self-focusing. The Kerr nonlinear susceptibility is expressed as $\chi^{(3)} = D / \rho_{10}^{(3)}$, where $D = N \mu_4 / (n^2 \varepsilon_0 G_{3,F1} G_{3,F1}^{*})$ for $n_2^{s1-S2}$ and $D = N \mu_4 / (n^2 \varepsilon_0 G_{3,F1}^{*})$ for $n_2^{X1-X8}$. $N$ is the atomic density of the medium (determined by the cell temperature), and $\mu_4$ is the dipole matrix element between $|0\rangle$ and $|1\rangle$. One can solve the coupled density-matrix equations to obtain $\rho_{10}^{(3)}$.

If we neglect the diffraction, and self-Kerr terms, (6a) and (6b) can be solved to have solution as $u_{3,F1}(z, \xi) = u_{3,F1}(0, \xi) \{e^{-\xi^2/2} + e^{-(-\xi)^2/2} + e^{-(-\xi)^2/2} + e^{-(-\xi)^2/2}\} \cos \phi_{NL}$, where the XPM-induced phase shift $\phi_{NL} = 2k_{3,F1} n_2 z / [e^{-\xi^2/2} + e^{-(-\xi)^2/2} + e^{-(-\xi)^2/2} + e^{-(-\xi)^2/2}] / (n_0 l_0)$. So, we obtain the intensity of $E_{3,F1}$ as $I_{3,F1}(z, \xi) = |u_{3,F1}(z, \xi)|^2$. In a cascade three-level system, $l_0 \propto |\rho_{10}^{(3)}|^2$ for $E_{3}$, and $l_0 \propto |\rho_{10}^{(3)}|^2$ for $E_{F1}$. Moreover, the expression of the nonlinear phase shift shows that the strong spatial splitting can occur with increased $l$ and $n_2$ and decreased $l_0$; here $l$ and $l_0$ are the intensities of the strong and weak beams, respectively.

3. Experimental Results and Theoretical Analyses

3.1. Changing the Angle of the Dressing Fields in Cascade Three-Level System

First, we study spectra intensities and spatial properties of signals by changing the angle of dressing fields in cascade three-level system. The spectra intensities of probe, $E_{F1}$, and fluorescence signals when $\Delta_1$ is scanned from negative to positive with $\Delta_2 = 55$ GHz and $\Delta \theta_1 = 0$ are shown in Fig. 2(a), (c), and (e), respectively. For comparing signals with $E_2$ and $E_2'$ blocked and with no beams blocked, Fig. 2(a7), (c7), and (e7) are arranged to display the signals.
with \( E_2 \) and \( E'_2 \) blocked. For probe signal, the single-photon absorption peak arises at \( \Delta_1 = 0 \) depicted by the right dashed line in Fig. 2(a). Moreover, the EIT window arises around \( \Delta_1 = -55 \text{ GHz} \) and corresponding electromagnetically induced absorption (EIA) dip are depicted by the left dashed curve in Fig. 2(a). For \( E_{F1} \), in Fig. 2(c), the primary A–T splitting at \( \Delta_1 = 0 \) and secondary one at around \( \Delta_1 = -55 \text{ GHz} \) are obtained. For the fluorescence signals, two dips appear on the background peak. One dip is at around \( \Delta_1 = -55 \text{ GHz} \), and the other is at \( \Delta_1 = 0 \). Obviously, when \( E_2 \) and \( E'_2 \) are blocked, the EIT window of probe, secondary A–T splitting of DFWM, and the dip at around \( \Delta_1 = -55 \text{ GHz} \) of fluorescence disappear, as shown in Fig. 2(a7), (c7) and (e7). Also, when \( \Delta \nu_2 \) is changed from \(-0.15 \) to \( 0.15 \), these signals at around \( \Delta_1 = -55 \text{ GHz} \) change correspondingly with a strongest value at \( \Delta \nu_2 = 0 \).

To explain these results, we use the density matrix elements related to three signals. The Doppler effect and the power broadening effect on the weak signals are considered for the hot atom in the simulation. Determining the transmission signal of \( E_3 \), (3) includes a term \( i \Delta'_1 + \Gamma_{10} \) acting as
single-photon resonance term only when $\Delta_1$ is scanned and $|G_2|^2/(\Gamma_{20} + i(\Delta_1' + \Delta_2'))$ acting as two-photon dressing term when either $\Delta_1$ or $\Delta_2$ is scanned. Moreover, the term $|G_1|^2/\Gamma_{00}$ is constant to dress the signal. So, when $\Delta_1$ is scanned, the single-photon absorption dip arises at $\Delta_1 = 0$ due to $\Gamma_{11}' + \Gamma_{10}$ in (3) and the EIT window at $\Delta_1 = -55$ GHz where the two-photon resonance condition $\Delta_1' + \Delta_2' = 0$ determined the two-photon dressing term $|G_2|^2/(\Gamma_{20} + i(\Delta_1' + \Delta_2'))$ is satisfied, as shown in Fig. 2(b). Certainly, the appearance of the left dip is due to the satisfaction of the EIA condition $\Delta_1 + \Delta_2' + (\Delta_2'/2 + \sqrt{\Delta_2'^2 + 4G_2^2}/2) = 0$. Then, for $E_{2\parallel}$ signal, the expressions of the corresponding density matrices related to DFWM processes is (1). In the expression, the single-photon emission term $i\Delta_1' + \Gamma_{10}$. The terms $\Gamma_{00}$, $|G_1|^2/\Gamma_{00}$, and $|G_2|^2/\Gamma_{00}$ are constant to dress the DFWM signal. Also, DFWM are dressed by the terms $|G_1|^2/\Gamma_{00} + |G_1|^2/(\Gamma_{10} + i\Delta_1')$ and $|G_3|^2/\Gamma_{11} + |G_1|^2/(\Gamma_{10} + i\Delta_1')$ only when $\Delta_1$ is scanned while dressed by $|G_2|^2/(\Gamma_{20} + i(\Delta_1' + \Delta_2'))$ and $(|G_1|^2 + |G_3|^2)/(i\Delta_1' + \Gamma_{10} + \Gamma_{20} + i(\Delta_1' + \Delta_2'))$ when either $\Delta_1$ or $\Delta_2$ is scanned. As a result, as shown in Fig. 2(d), by scanning $\Delta_1$, the one-photon emission peak forms at $\Delta_1 = -55$ GHz is caused by the term $|G_2|^2/(\Gamma_{20} + i(\Delta_1' + \Delta_2'))$ in (1) due to the two-photon resonant condition $\Delta_1' + \Delta_2' = 0$. Finally, for fluorescence signal, based on the similar method, we obtained that the single-photon emission peak at $\Delta_1 = 0$ due to the term $\Gamma_{10} + i\Delta_1'$ (2a), while the suppression dip on the peak at $\Delta_1 = 0$ is caused by $E_1$ and $E_{2\parallel}$, i.e., the term $|G_1|^2/\Gamma_{10}(i\Delta_1' + \Gamma_{10})$ in (2a). The other two-photon dip at $\Delta_1 = -55$ GHz satisfied $\Delta_1' + \Delta_2' = 0$ is mainly induced by $E_2$ and $E_{2\parallel}$, i.e., the term $|G_2|^2/\Gamma_{20} + i(\Delta_1' + \Delta_2')$ in (2b). When $\Delta_2$ changes from $-0.15$ to $0.15$, the detuning of $E_2$ and $E_{2\parallel}$ changes with $\Delta_2$ due to $\Delta_2' = \Delta_2 + \kappa_2 \cos(2\theta_2/\lambda)$; thus, the dressing effect of $E_2$ ($E_{2\parallel}$) on $E_3$, DFWM, and fluorescence signals changes with $\Delta_2$, too. What’s more, the dressing effect is the strongest at $\Delta_2 = 0$.

In addition, the images of $E_3$ and $E_{1\parallel}$ beams induced by XPM are recorded at different $\Delta_2$ by $\Delta_1$ scanned from negative to positive, as shown in Fig. 2(g) and (h). Curves in Fig. 2(i) are the corresponding numerical simulations of nonlinear index $n_2$ under the dressing effect of $E_2$ and $E_{2\parallel}$ near $\Delta_1 = -55$ GHz with different $\Delta_2$.

Fig. 2(g4) can be obtained when $\Delta_2 = 0$ is fixed and $\Delta_1$ is scanned, and the images of $E_3$ show significant focusing takes up around the EIA windows [see Fig. 2(a)] in the region $\Delta_1 < 0$, in which $n_2$ is positive and arrives its maximum, as shown in Fig. 2(i4). When $|\Delta_2|$ changes from $0$ to $0.15$, the focusing and defocusing phenomena due to the crossing Kerr nonlinearity at $E_2$ and $E_{2\parallel}$ occur with the angle $\Delta_2$, can be expressed as $n_2 \propto \frac{\rho_{\phi NL}}{\rho_{\phi NL}} = \frac{g}{(|d_1| + |G_2|^2/d_2)^2d_2}$. Therefore, with angle $|$ $\Delta_2$ increasing [from Fig. 2(i1)–(i7)], we can see that $|n_2|$ decreases and reaches its maximum at $\Delta_2 = 0$. So, the focusing and defocusing effect are most significant at $\Delta_2 = 0$. Second, as discussed above, the EIA condition $\Delta_1' + \Delta_2' + (\Delta_2'/2 + \sqrt{\Delta_2'^2 + 4G_2^2}/2) = 0$ is satisfied, which leads to stronger absorption and therefore weaker intensity of $E_3$. The increasing of $n_2$ and decreasing of the intensity of $E_3$ can result in large phase shift to right direction by $E_2$ according to $\phi_{NL}$.

For $E_{1\parallel}$, the spatial splitting in x-direction is observed. In order to explain these results, we consider the relative positions of $E_{1\parallel}$ and $E_1'$. Because $E_1'$ has a small angle from $E_1$ in x-direction as shown in Fig. 1(d), $E_{1\parallel}$ overlaps in x-direction with $E_1'$ due to the phase matching condition $\kappa_{1\parallel} = \kappa_1 - \kappa_1' + \kappa_3$. So, the x-direction splitting is obviously caused due to the nonlinear cross-Kerr effect of $E_1'$. Next, we investigate the spectra intensity of the probe, DFWM, and fluorescence signals by scanning $\Delta_2$ with $\Delta_1 = -40$ GHz and $\Delta_1 = 0$ at different $\Delta_2$. The spectra intensity of probe changes when $\Delta_2$ is scanned from negative to positive, and it becomes weakest at around $\Delta_2 = 40$ GHz where the absorption is strongest i.e., an EIA appears, due to the dressing term $|G_2|^2/(\Gamma_{20} + i(\Delta_1' + \Delta_2'))$ in (3), as shown in Fig. 3(a). It is obvious that the depth of this EIA window

Vol. 4, No. 5, October 2012  Page 1980
changes with $\Delta \theta_2$ and reaches its maximum at $\Delta \theta_2 = 0$. Meanwhile, the EIA window can be also obtained when $E_1$ and $E_0$ are blocked, as shown in Fig. 3(a1) and (a2). For FWM signal dressed by $E_2(E_3)$, the switching from pure enhancement (peak higher than the baseline in each curve) to pure suppression (dip lower than the baseline in each curve) and then to pure enhancement with $\Delta \theta_2$ increased is observed, as shown in Fig. 3(c), which is induced by the term $|G_2|^2/|\Gamma_20 + i(\Delta'_1 + \Delta'_2)|$ in (1). Obviously, when $E_1$ and $E_0$ are blocked, DFWM signal disappears, as shown in Fig. 3(c1) and (c2). For fluorescence signal, the main peak is caused by the two-photon emission term $G_1^0 + i(\Delta'_1 + \Delta'_2)$, and the suppression dip on the main peak is due to the two-photon resonance caused by the terms $|G_2|^2/|\Gamma_20 + i(\Delta'_1 + \Delta'_2)|$ and $|G_1|^2/|\Gamma_20 + i(\Delta'_1 + \Delta'_2)|$ in (2b). Thus, the intensity of the suppression dip increases with $|\Delta \theta_2|$ decreasing. When $E_1$ and $E_0$ are blocked, the $E_3$ power is so weak that the two-photon emission and suppression cannot be observed and the fluorescence signal degenerates into a flat line, as shown in Fig. 3(e1)–(e2).

The images of the probe beam $E_3$ and DFWM after propagation are captured with the detuning $\Delta_2$ scanned in a large region around the two-photon resonant point $\Delta'_2 + \Delta'_1 = 0$, with different $\Delta \theta_2$ as shown in Fig. 3(g) and (h), respectively. The corresponding numerical simulations of $n_2$ are shown in Fig. 3(i1)–(i7).

First, we investigate the variation of the backgrounds in Fig. 3(g), which nearly do not change with changing $\Delta \theta_2$. For the two sides far away from two-photon resonance ($|\Delta_2 + \Delta'_1| = 0$), $|n_2|$ induced by $E_2(E_3)$ is very low and can be neglected [see Fig. 3(i1)–(i7)]. In this case, the cross Kerr nonlinearity suffered by $E_3$ is mainly due to $E_1(E'_1)$, and the refractive index is positive at $\Delta_1 = -40$ GHz, which leads to the focusing of $E_3$. This explanation can be further verified by that
fact that the spatial dispersion of $E_3$ conserves in the whole scanned region of $\Delta_2$ with $E_2$ and $E'_2$ blocked.

Second, in Fig. 3(g), it is obvious that $E_3$ spots suffer from defocusing more significantly in the region around the two-photon resonance point than in other places. This behavior can be explained by the focusing due to the cross-Kerr nonlinearity from $E_2$ ($E'_2$) for different $\Delta_2$. In Fig. 3(i1)–(i7), the coefficient $n_2$ is negative when $\Delta_2$ is scanned from $-70$ GHz to $-20$ GHz and reaches its minimum at the resonant point ($\Delta_2 = 40$ GHz), which leads to more significant defocusing. With $|\Delta\theta_2|$ increasing, the beam spots become smaller around resonant point [see Fig. 3(g1)–(g7)] due to the decreasing of $|\theta_2|$, as shown in Fig. 3(i1)–(i7). The reason is same as that in Fig. 2, which has been discussed. The other reason is that the absorption of $E_3$ is enhanced with the decreasing of $|\Delta\theta_2|$, i.e., the FWM signal increases, while the transmission of $E_3$ decreases. The two reasons will lead to the decreasing of $\phi_{NL}$ with increscent of $|\Delta\theta_2|$. Therefore, compared with the cases when $\Delta\theta_2$ set at other value, the splitting of probe beam is most obvious at $\Delta\theta_2 = 0$.

Finally, in Fig. 3(h), we concentrate on the spatial characteristics of $E_{F1}$. The spatial images display the switching from focusing to defocusing as $|\Delta\theta_2|$ increases, which is in accordance with the changing of the nonlinear coefficient $n_2$, as shown in Fig. 3(j). The phenomenon can be also explained by the reason discussed above.

### 3.2. Changing the Angle of the Pumping Fields in Cascade Three-Level System

In order to understand the difference between the results with the dressing field and the pumping field changed, the variations of the signals with the angle of pumping fields changed is also investigated in cascade three-level system. We show the spectra intensities of the probe transmission, DFWM, and fluorescence signals with different $\Delta\theta_1$ by scanning $\Delta_2$ from negative to positive, as shown in Fig. 4(a), (c), and (e). Correspondingly, the theoretical simulations in Fig. 4(b), (d), and (f) have reasonable agreement with the experimental results. In Fig. 4(a) and (b), the switching from EIA [see Fig. 4(a1)–(a3)] to EIT [see Fig. 4(a4) and (a5)] and then to EIA [see Fig. 4(a6)–(a9)] is obtained with $\Delta\theta_1$ changed. For $E_{F1}$, the switching from pure enhancement [see Fig. 4(c1) and (c2)] to pure suppression [see Fig. 4(c3)–(c5)], to partial enhancement/suppression [see Fig. 4(c6)], and then to pure enhancement [see Fig. 4(c7)–(c9)] with $\Delta\theta_1$ changed is observed.

For fluorescence, the two-photon emission peak and two-photon suppression at $\Delta_2 = 30$ GHz are all strongest at $\Delta\theta_1 = 0$. Because the detuning $\Delta_1$ changes with $\Delta\theta_1$ due to the expression $\Delta'_1 = \Delta_1 + k_1 \nu \cos(\theta_{1x}/2)$, the results by scanning $\Delta_2$ for the probe transmission, DFWM, and fluorescence are easily understood. When $|\Delta\theta_1|$ is not large sufficiently, the enhancement condition $\Delta'_1 = -[(\Delta''_2 + \sqrt{\Delta''_2^2 + 4|G_2|^2})/2 + (\Delta'_1 + \sqrt{\Delta'_1^2 + 4|G_1|^2})/2]$ is satisfied with $\Delta''_2$ being the frequency detuning of $E_2$ ($E'_2$) relative to the dressed state by $E_1$ ($E'_1$). As a result, the EIA of probe transmission [see Fig. 4(a1)–(a3) and (a6)–(a9)] and pure enhancement of DFWM [see Fig. 4(c1) and (c2) and (c7)–(c9)] are obtained. While $|\Delta\theta_1| \approx 0$, the EIT of probe transmission [see Fig. 4(a4) and (a5)] and pure suppression of DFWM [see Fig. 4(c3)–(c6)] are obtained because the suppression condition $\Delta'_1 + \Delta''_2 = 0$ is satisfied. As a result, the switching from EIA to EIT in probe transmission or from pure enhancement to pure suppression in DFWM signal is observed.

We also investigate the spatial characteristics of the probe transmission and DFWM signal when $\Delta\theta_1$ changed and $\Delta_2$ scanned from negative to positive, as shown in Fig. 4(g) and (h). As discussed above, the spots of weak beams $E_3$ and $E_{F1}$ suffer from defocusing more significantly due to the negative $n_2$ [see Fig. 4(i5)] in the region around the resonance point than those in the two sides. However, $n_2$ changes with $\Delta\theta_1$ through $n_2 \propto \phi_{10}^{(3)} = g/(|d_1| + |G_2|^2/d_2^2) d_2$, which determines that, with $|\Delta\theta_1|$ increasing, the value of $k_1 \nu \cos(\theta_{1x}/2)$ changes correspondingly, and $n_2$ varies from positive to negative, as shown in Fig. 4(i4) and (i6). Therefore, the focusing effect changes with defocusing effect, and this will lead to the defocusing of spots of $E_3$ and $E_{F1}$ [compared with Fig. 4(g5) and (h5)], as shown in Fig. 4(g4), (g6), (h4), and (h6). Moreover, the positive $n_2$ increases with the increasing of $|\Delta\theta_1|$, as shown in Fig. 4(i1)–(i3) and (i7)–(i9). It is obvious that $E_3$ and $E_{F1}$ suffer the most significant focusing effect at $|\Delta\theta_1| = 0.15$ since $n_2$ reaches its maximum value, as shown in Fig. 4(g1), (g9), (h1), and (h9), respectively.
For $E_{F1}$, the transferring between the spatial splitting in $x$- and $y$-direction is observed. It can be explained by the spatial overlapping between the weak signal $E_{F1}$ beam and the strong $E'_1$ beam. Because $E'_1$ has a small angle from $E_1$ either in $x$-direction or $y$-direction, as shown in Fig. 1(c), $E_{F1}$ overlaps in both $x$-direction and $y$-direction with $E'_1$ due to the phase matching condition $k_{F1} = k_1 - k'_1 + k_3$. With $|\Delta \theta_1| > 0.1$, the overlap of $E_{F1}$ and $E'_1$ in $x$-direction is far dominant than that in $y$-direction, so $E_{F1}$ only shows the splitting in $x$-direction, as shown in Fig. 4(h1)–(h3) and (h7)–(h9). When $|\Delta \theta_1|$ is decreases from 0.15 to 0, the $y$-direction overlap of $E_{F1}$ and $E'_1$ increase and the $x$-direction overlap decrease due to $k_{F1} = k_1 - k'_1 + k_3$. So, the $x$-direction splitting slowly disappears. Finally, with $\Delta \theta_1 = 0$, $E'_1$ overlaps with $E_{F1}$ exactly in $y$-direction. Thus, in such case, the spatial modulation of $E_{F1}$ is only in $y$-direction, as shown in Fig. 4(h4)–(h6).

From the above analyses, we can see that the two schemes of angle changing (between the dressing fields and the pumping fields) have similarities and dissimilarities. The two schemes have similar dressing effects on intensity of signals. The angle switching from EIA to EIT for probe beam or from enhancement to suppression for FWM is observed in both them. However, for spatial properties, it has more remarkable effect by changing angle of the pumping fields than changing that of the dressing fields. This is because changing the angle of pumping fields affects not only the dressing effect but also the relative position of FWM and strong fields due to the phase-matching condition $k_{F1} = k_1 - k'_1 + k_3$, while changing the angle of the dressing fields only affects the
dressing effect. So, we can conclude that changing the angle of pumping fields is more effective in control the relevant signals than changing the angle of dressing fields.

3.3. Changing the Angle of the Dressing Fields in Two-Level System

In order to research the effect of changing the angles in different system, the same process is executed in two-level systems. Based on the theoretical simulations, for FWM, by scanning $\Delta_2$, the interaction between coexisting FWMs is observed. As shown in Fig. 5(a) and (b), the left peak is the two-photon emission peak of DF3 that satisfied the two-photon resonant condition $\Delta'_3 - \Delta''_3 = 0$ due to the term $\Gamma_{00} + i (\Delta'_3 - \Delta''_3)$ in (4c). The right enhancement/suppression of DF1 near $\Delta_2 = 0$ is due to the term $|G_1|^2/|\Gamma_{00} + |G_2|^2/|\Gamma_{10} + i \Delta_2]|$ in (4a). The two-photon-like resonant condition is satisfied as $\Delta'_3 - m\Delta''_3 = 0$ by solving (4a), where $m = (G_1/G_2)$ is determined by the experiment condition. In experiment, because $m > 1$, the EIT-like condition $\Delta_2 = (\Delta_1/m)$ is equivalent to moving to the position of EIT to near $\Delta_2 = 0$. Thus, the parameter $m$ means that $E_1 (E'_1)$ can modulate the dressing effect by $E_2 (E'_2)$. Finally, in order to investigate the influence of angle on FWM and fluorescence in two-level system, $\Delta\Omega_2$ is changed from $-0.15$ to $0.15$ in the experiment. It is observed that the emission peak is highest at $\Delta\Omega_2 = 0$. For DFWM, the transformation from first suppression then enhancement, to pure suppression, and then to first suppression; then, enhancement is shown in Fig. 5(a). For fluorescence, the emission peak and suppression dip
are all strongest at $\Delta \theta_2 = 0$. Because $\Delta 2$ changes with $\Delta \theta_2$ due to the expression $\Delta \beta' = \Delta 2 + k_0 v \cos(\theta_{2f}/2)$, the results with $\Delta 2$ scanned for the DFWM and fluorescence are easily understood. When $|\Delta \theta_2|$ is not large sufficiently, first, the suppression condition and then the enhancement condition are satisfied. As a result, the first suppression then enhancement of DFWM are obtained [see Fig. 5(a1), (a2), (a6)–(c7)]. While $|\Delta \theta_2| \approx 0$, the pure suppression of DFWM [see Fig. 5(a3)–(a5)] are obtained because the suppression condition is satisfied. As a result, the switching from enhancement/suppression to pure-suppression is observed. For fluorescence and emission peak, the dressing effect and emission peak are strongest at $\Delta \theta_1 = 0$.

The images of $E_{F1}$ at $\Delta_1 = -130$ GHz and $\Delta \theta_1 = 0$ with $\Delta 2$ scanned (from top to bottom, $\Delta \theta_2$ changes from $-0.15$ to $0.15$) in the two level system are shown in Fig. 5(e). Correspondingly, the theoretical simulations of $n_2$ is shown in Fig. 5(f). When $\Delta \theta_2 = 0$, Fig. 5(e4) shows that $E_{F1}$ images evolve from focusing to defocusing with increasing $\Delta 2$ gradually, because $n_2$ varies from negative (in $\Delta 2 < 0$) to positive (in $\Delta 2 > 0$) [see Fig. 5(f4)]. As discussed above, the decreasing of $|n_2|$ due to $|\Delta \theta_2|$ will result in transforming between focusing and defocusing, as shown in Fig. 5(e5) and (e3). However, when $|\Delta \theta_2|$ increases further, $n_2$ suffered by $E_{F1}$ will be positive, i.e., $n_2 > 0$ in $\Delta 2 < 0$ and $n_2 < 0$ in $\Delta 2 > 0$, as shown in Fig. 5(f2) and (f6), respectively. Therefore, the images of $E_{F1}$ will correspondingly switch from focusing to defocusing when $\Delta 2$ is scanned, as shown in Fig. 5(e2) and (e6). Moreover, when $|\Delta \theta_2| = 0.15$, the images of $E_{F1}$ will suffer from the most significant focusing in $\Delta 2 < 0$ and defocusing in $\Delta 2 > 0$ [see Fig. 5(e1) and (e7)] since $|n_2|$ reaches its maximum, as shown in Fig. 5(f1) and (f7). The experimental results agree with the theoretical simulations very well.

4. Conclusion

To summarize, we have investigated the control of the spectra intensity and images of the probe transmission, FWM, and fluorescence signals in a three-level and two-level cascade atomic systems by changing both the angles between pumping fields and dressing fields. We have demonstrated the switch between the EIT and EIA in probe spectra intensity, enhancement, and suppression in FWM spectra intensity, and the variation of fluorescence spectra intensity by changing the relevant angles. The controlled image modulations of these signals have been also demonstrated in this way. This paper indicates that the properties of the measured signals are affected greatly by changing the angles between them. We think that the studies in this paper can have potential applications in producing all optical-signal-processing devices, such as spatial beam splitters, routers, and switches.

References


