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Rydberg six-wave mixing process

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Abstract – We experimentally and theoretically investigate the Rydberg six-wave mixing (SWM) process in \(^{85}\)Rb atomic vapor. Through comparing the center frequency positions of resonant Rydberg SWM signals with different atomic densities, atomic levels induced by van der Waals interaction are observed. Meanwhile, such SWM process which is sensitive to blockade can be modulated by the self-dressing effect and/or external dressing effect. In addition, the Rydberg eight-wave mixing process can be obtained if the power of the external dressing field is low. Such blockaded multi-wave mixing process has potential applications in multi-channel quantum information.

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One of the most important consequences of strong interaction among Rydberg atoms is the excitation blockade effect \([1,2]\), which can be used to realize room temperature quantum devices \([3]\), quantum computation \([4]\), single-photon sources \([5]\), atomic clocks \([6]\), and so on. To achieve the quantum application with Rydberg atoms, an effective control of the interaction is required. Recently, an optical detecting method is developed, which utilizes electromagnetically induced transparency \([7,8]\) (EIT) of Rydberg atoms in a mesoscopic ensemble with high resolution \([9–11]\) and four-wave mixing (FWM) processes to investigate the Rydberg spectrum \([12,13]\). Especially, the generated FWM signal could be used to produce a directional single-photon on-demand source or for fast quantum-state detection or transmission \([14]\). Motivated by these developments, we study the EIT-assisted six-wave mixing (SWM) process and also the related phenomena.

In this paper, we present a new viewpoint on Rydberg research via SWM process, a fifth-order nonlinearity effect, which can be mediated by spin coherence \([7]\) and Rydberg excitation blockade of the collective atomic ensemble of \(^{85}\)Rb. We map the strong van der Waals (vdW) interactions of Rydberg atoms onto the EIT-assisted SWM signal \([7,14]\). The contribution of the blockade to SWM process is characterized as a function of the density of collective atom ensemble, principle quantum number, probe strength and coupled field strength. Center frequencies of the maximum Rydberg SWM signals at different atomic densities are measured and used to obtain the level shift induced by the vdW interaction. Next, such SWM process with the blockade property not only can be modulated by the self-dressing effect and/or external dressing effect \([14,15]\) (consisting of ac-Stark and quantum interference) but also used to study the interaction between the Rydberg SWM signal and the non-Rydberg SWM signal. Finally, by setting the power of the external dressing field to be low, a Rydberg eight-wave mixing (EWM) process can be obtained.

To implement the current experiment, a five-level atomic system, consisting of two hyperfine states \(F = 3\) (\(0\)) and \(F = 2\) (\(3\)) of the ground state \(5S_{1/2}\), a first excited state \(5P_{3/2}\) (\(1\)), a lower-lying excited state \(5D_{3/2}\) (\(4\)), and a highly excited Rydberg state \(nD_{3/2}\) (\(2\)) of \(^{85}\)Rb, is used to generate EIT-assisted multi-wave mixing (MWM) processes. Five laser beams, derived from four commercial external cavity diode lasers (DLs) with frequency-stabilized devices, are coupled into the corresponding transitions as shown in fig. 1(a). A diagram of the experimental setup is shown in fig. 1(b). The laser beam \(E_1\) (780.24 nm with a diameter 0.8 mm, frequency \(\omega_1\), wave vector \(k_1\)) from DL1 probes the lower

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transition \( |0\rangle \) to \( |1\rangle \), while a pair of coupling beams \( E_3 \) (780.23 nm, \( \omega_3, k_3 \)) and \( E_4'(\omega_3, k_4') \), derived from the same DL3 with a small angle and both diameters 1 mm, connect another lower transition \( |3\rangle \) to \( |1\rangle \). To excite rubidium atoms from level \( |1\rangle \) to Rydberg states \( |2\rangle \), we get the needed 480 nm laser \( E_2(\omega_2, k_2) \) by means of frequency doubling DL2 at \( \sim 960 \) nm with a periodically poled KTP crystal in an external ring resonator to generate the second harmonic wave. The strong beam \( E_3 \) (diameter 1 mm), is added onto the beam \( E_3 \) in the same direction, which counterpropagates with beam \( E_1 \). Beam \( E_4 \) (775.98 nm with a diameter 1 mm, \( \omega_4, k_4 \)) from DL4 drives the transition \( |1\rangle \) to \( |4\rangle \), which propagates with \( E_3 \) symmetrically. All beams are focused by two equal lenses (L1 and L2, respectively) with focal length 500 mm between the cell and intersect at one point inside the cell. The 5 cm long rubidium cell is wrapped by \( \mu \)-metal and heated by the heater tape.

By turning the incident beams on and/or off selectively, four types of MWM processes can be obtained. Firstly, by blocking beams \( E_2 \) and \( E_4 \), a FWM process with the phase-matching condition \( k_{\text{FWM}} = k_1 + k_3 - k_2 \) occurs in the \( ^2 \)S\( e \)-type three-level subsystem \( |0\rangle \leftrightarrow |1\rangle \leftrightarrow |3\rangle \). Secondly, by applying the beam \( E_2 \) (or \( E_4 \)), an EIT-assisted SWM [14] signal \( E_{\text{SWM1}} \) (or \( E_{\text{SWM2}} \)) satisfying the phase-matching condition \( k_{\text{SWM}} = k_1 + k_2 - k_3 + k_4 \) can be observed in \( |0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle \leftrightarrow |3\rangle \). Finally, when all beams are open, an EIT-assisted EWM process \( E_{\text{EWM}} \) will be generated with \( k_{\text{EWM}} = k_1 + k_2 - k_3 + k_4 - k_5 \). These MWM signals have the same emitting direction (opposite to the direction of \( E_4 \), as shown in fig. 1(b)), which can be identified by tuning the frequency detunings of the corresponding incident beams, and are detected by an avalanche photodiode detector (APD). Specifically, the MWM process, related to the Rydberg state \( |2\rangle \), is called Rydberg signal with blockade property.

Generally, the excitation blockade effect can be investigated in a spherical domain \([1]\), where only one atom is excited to the Rydberg level \( |2\rangle \). Therefore, the mean-field model can be used to calculate the energy level shift. The entire sample is divided into many domains with the same radius \( R_d \), blockade radius, which determines the number of Rydberg atoms in the cell. The Rydberg level \( |2\rangle \) is shifted to be \( \varepsilon_2 - \varepsilon \) (\( \varepsilon_2 \) is the eigenenergy and \( \varepsilon \) is the shifted value of level \( |2\rangle \), respectively) by other nearby Rydberg atoms outside the sphere. So, the level shift \( \varepsilon \) is the smallest in the center of the sphere, and then the largest probability to be excited to level \( |2\rangle \) can occur in such position. We assume that the density of excited Rydberg atoms \( (\rho_2) \) is locally uniform inside and around the sphere, and only one Rydberg atom is excited, so \( \rho_2 V_d = 1 \) with \( V_d \) being the volume of the given sphere. The radius \( R_d \) of the sphere and the level shift \( \varepsilon \) (with the dependence of principal quantum number \( n \) and the location \( r \) within the given sphere) are calculated by solving the optical Bloch equations for the excited amplitude \( c_2 \) at \( |1\rangle \) and Rydberg-state amplitude \( c_2 \) at \( |2\rangle \) [1]. Considering the interaction of Rydberg atoms, the energy shift is given by

\[
\varepsilon(r) = \rho_2 \int U(r - r') d^3 r',
\]

where \( U(r - r') \) is vdW interaction for \( nD \) approximate \( -C_6/r^6 \) [16]. Considering two EIT windows generated by the optical field \( (E_2 \) and \( E_4 \)) and optical pumping effect \( (E_3 \)), the atom density at \( |1\rangle \) is given by

\[
\rho_1 = \frac{1}{2} \rho_0 \left( \frac{\Omega_2^2}{R_e d_1^2 + |\Omega_2|^2/d_2} + \frac{\Omega_2^2}{R_e |d_3|} \right),
\]

where \( d_1 = \Gamma_{10} + i\Delta_1, d_2 = \Gamma_{20} + i(\Delta_1 + \Delta_2), d_3 = \Gamma_{13} + i\Delta_3, d_4 = \Gamma_{40} + i(\Delta_1 + \Delta_4); \rho_1 = (\Gamma_i + \Gamma_j)/2 \) is the decoherence rate between \( |i\rangle \) and \( |j\rangle \); \( \Gamma_i \) is the transverse relaxation rate determined by the longitudinal relaxation time and the reversible transverse relaxation time; \( \Delta_1 = \omega_i - \omega_j \) is the detuning \( \omega_i \) denotes the laser frequency of \( E_4 \), \( \omega_j \) denotes the resonant transition frequency between \( |i\rangle \) and \( |j\rangle \); \( \Omega_i = \mu_i E_i / h \) is the Rabi frequency corresponding to the optical field \( E_i \). Solving eq. (1) with steady-state approximation and taking \( \rho_2 V_d = 1 \) and \( V_d \propto (R_d)^3 \) into account, the density of excited Rydberg atoms \( \rho_2 \) can be written as

\[
\rho_2 = C \rho_1^{0.2} \left( |\Omega_2|/n^{11}\right)^{0.4},
\]

where \( C \) is a constant, mainly determined by the coefficient of vdW interaction, resulting from numerical integration outside the given sphere and the atom excitation efficiency between \( |0\rangle \) and \( |1\rangle \). Substituting eq. (2) into eq. (3), one can obtain the atom density of the Rydberg state \( |2\rangle \) in detail. The terms \( \rho_1^{0.2} \) and \( (|\Omega_2|/n^{11})^{0.4} \) respectively, describe the suppressions of the contributions of the population \( (\rho_1) \) in level \( |1\rangle \) and excitation capacity of \( E_2 \) to the Rydberg excitation, due to the excitation blockade effect.

The modified dependence of \( \rho_2 \) on \( n \) reflects the important physics in such Rydberg system, i.e., the bigger the
principal quantum number $n$, the larger the suppression of $E_2$ excitation probability. The mean-field energy shift $\varepsilon$ aggrandizes rapidly with increasing $n$ or $r$, and effectively enhances the Rydberg blockade. For instance, taking $n = 37$ and the Rabi frequencies (shown below) into account, the typical atomic density in current experiment of the collective atomic ensemble is $\rho_0 = 2.4 \times 10^{12} \text{ cm}^{-3}$ with about 40% pumping into level 1, so the average space between atoms is $R = 0.555(\rho_0)^{-1/3} = 0.5 \mu m$. The density is calculated (by eq. (3)) to be $\rho_2 = 9.2 \times 10^{16} \text{ cm}^{-3}$, giving a domain (sphere) radius of $R = 1.37 \mu m$ with 11 ground-state atoms and 1 Rydberg atom inside.

In this region, the vdW interaction has an attractive potential dominated by $\varepsilon \propto -C_6/R^6$ for the nd-nd interaction. Thus, considering the residual Doppler effect and the Rydberg ionization effect, $\varepsilon$ depends on the particular location, i.e., $\varepsilon \sim -19 \text{ MHz}$ at the center of the domain and $\varepsilon \sim -10^7 \text{ MHz}$ at the edge. A similar spatial dependence is true for the excitation probability $|c_2|^2$. To simplify the discussion, we make modifications on the corresponding parameters as $\rho_0 \rightarrow \rho_0^{(0)}$, $\Omega_1 \rightarrow \Omega_1^{(0)}$, $\Omega_2 \rightarrow (\Omega_2/n^{11})^{0.2}$, and $\Omega_3 \rightarrow \Omega_3^{0.2}$.

In addition, the intensity of the output SWM signal is proportional to the density matrix element $\rho_1^{(5)}$. Via a Liouville pathway, and taking the dressing effects of $E_1$ and $E_2$ into account, $\rho_1^{(5)}$ can be obtained [14]. Since $\rho_1^{(5)}$ is related to the Rydberg level [2], the collective Rydberg ensemble can be ionized due to the collision between atoms. For precision depiction, we introduce the collision ionization rate [17] $\Gamma_\varepsilon = A v_{rel} \sigma_\beta \rho_2$, where $A$ is a constant, $\rho_2 = N_R/\pi \ell_0^2$ with $N_R$ the number of Rydberg atoms, $\ell_0$ the length and radius of interaction region, respectively, $v_{rel}$ the relative velocity, and $\sigma_\beta = \pi (a_0 n^2)^2$, the transit time ($\Gamma = 2\pi/\tau$, where $\tau = D/u$ with $D$ the diameter of $E_1$ and $u = \sqrt{2k/\mu_0}$ the most probable speed), and the Doppler effect ($ke$). Therefore, one can get

$$\rho_1^{(5)} = \frac{iC[\Omega_1^{(0)}]^{0.4}[(\Omega_2/n^{11})^{0.4}]^{0.4}[(\Omega_1^{(0)})^{0.4}]}{[d_1' + [\Omega_1^{0.4}]/\Gamma_1 + (\Omega_2/[n^{11}]^{0.4})]d_2'd_3d_30} + \rho_0^{(5)} \mu_0 C[\Omega_1^{(0)}]^{0.4}[(\Omega_2/n^{11})^{0.4}]^{0.4}d_2d_3d_30,$$

where the term $(\Omega_2/n^{11})^{0.4}$ is caused by the Rydberg dressing field $E_2$ with the modification of the blockade effect, $d_1' = (\Gamma_{10} + \Gamma_1 + i(\Delta_1 + k_1 v)$, $d_2' = (\Gamma_0 + \Gamma_1 + \Gamma_1 + i(\Delta_1 + \Delta_2) + i(k_1 + k_2 v)$, and $d_3' = (\Gamma_{30} + \Gamma_3 + i(\Delta_3 - \Delta_3) + i(k_1 + k_3 v)$. Furthermore, besides the above self-dressing effects, such blocked SWM process can be modulated by an external field $E_4$. Therefore, the intensity of polarization of output SWM is given by

$$P_1^{(5)} = \int_{-\infty}^{+\infty} N(v) \rho_1^{(5)} \mu_0 C[\Omega_1^{(0)}]^{0.4}[(\Omega_2/n^{11})^{0.4}]^{0.4}d_2d_3d_30$$

where $N(v) = N e^{-v^2/2u^2}u/\sqrt{\pi}$ is the particle number density in terms of speed distribution function.

Meanwhile, another SWM $E_{SWM2}$ occurs in such system [14].

To observe the blockade in thermal vapor, several key requirements must be fulfilled. Especially, the atomic cloud should be sufficiently dense such that the blockade condition $\varepsilon \geq \gamma_{EIT/MWM}$ is fulfilled [18], where $\gamma_{EIT/MWM}$ is the linewidth of measured Rydberg EIT/MWM spectra. The measured linewidth of Rydberg EIT is $\gamma_{EIT} \sim 30 \text{ MHz}$ in our experiment as shown in fig. 2(a), attributed to the long lifetime of Rydberg state [2] (or small decay rate $\gamma_2$). (Lowerer excitation efficiency is determined by the lower Rydberg atomic density.) Thus, it provides a higher resolution which will relax the excitation blockade condition of such two-photon excitation process of EIT. Consequently, two Rydberg polaritons cannot propagate simultaneously when they are closer than the blockade radius $R_{EIT} = (2\hbar/\gamma_{EIT})^{1/6}$, which is set by $V(\text{REIT}) = \hbar v^{EIT}/2$, where $\gamma_{EIT} = (\Omega_2)^2/\Gamma_2$ is the single-atom EIT linewidth and related with the decoherence rate $\Gamma_2 = (\gamma_2 + \gamma_1)/2 \approx \gamma_1/2$ between states 1 and 2. Take the $3\Delta_{D_{12}}$ state for example, the vdW coefficient $C_6 \sim 10^{11}$ and $\gamma_{EIT}/2\pi = 4.8 \text{ MHz}$ give a critical blockade radius $R_{EIT} = 2.18 \mu m$, corresponding to the Rydberg atom density $N_{EIT} = 9.65 \times 10^{10} \text{ cm}^{-3}$ ($N_0 = 1.1 \times 10^{12} \text{ cm}^{-3}$).

Similarly, we introduce another critical blockade radius $R_{MWM} = (C_6/\gamma_{MWM})^{1/6}$ that is related with the MWM signal width $\gamma_{MWM}/2\pi = 3.2 \text{ MHz}$ as shown in fig. 2(b). Apparently, one can see that $\gamma_{MWM} < \gamma_{EIT}$. In contrast to the Rydberg EIT, the Rydberg SWM spectrum provides higher resolution due to its narrower linewidth, which indicates that the SWM is more sensitive to the Rydberg blockade. Since such SWM is generated by five photons $|0\rangle \rightarrow |1\rangle \rightarrow |3\rangle \rightarrow |1\rangle \rightarrow |2\rangle \rightarrow |1\rangle$ and assisted by one EIT window, which make the linewidth of the Rydberg SWM signals narrow, are described as $\Delta \omega_{ij} = \Delta \omega_{00} (\Delta \omega_{21}/\Delta \omega_{21})$, where $\Delta \omega_{ij}$ is the linewidth of the EIT windows and $\Delta \omega_{ij}$ is the linewidth of the absorption spectrum. It seems that the advantage of Rydberg SWM is not so obvious, but a
new research perspective is open and its merit will become more prominent with increasing $n$.

Note that SWM signals can coexist by scanning the probe field $\mathbf{E}_1$, so multi-channel processes can be obtained. Next, a disturbance-free Rydberg SWM signal can be better picked up by scanning the frequency of the coupling field $\mathbf{E}_2(\Delta_2)$. In this case, only the Rydberg SWM signal stands inside the unique $\mathbf{E}_2$ EIT window, while the other non-Rydberg signals hide in the background. Thus, a reliable single-channel Rydberg SWM process can be obtained.

First, we focus on the Rydberg SWM process mediated by the vdW interactions. By measuring the central frequency positions of the SWM signals vs. $\Delta_2$, picked up by its EIT window for different densities, one can directly observe the SWM signal shifts as shown in fig. 3(a) for the Rydberg states $37D$ and $45D$, respectively. We concern the change in frequency position of the SWM signal, so all measured signals use the same coordinate system where the zero point of horizontal axis is calibrated at the unperturbed atomic energy level of $nD_{5/2}$. Generally, the maximum intensity of the EIT-assisted SWM process occurs at the resonant transition. To analyze this case, we use the level shift $\varepsilon$ instead of the blockade term $\rho_2$. Thus, with the modification from $d_2$, we get (19) $\rho_{10}^{(5)} = i\Omega_1|\Omega_2|^2|\Omega_3|^2/\{d_1 + \Omega_1|\Omega_2|^2/\Gamma_{11} + |\Omega_2|^2/d_1^2|d_1^2|d_1d_2\}$, where $d_1^2 = \Gamma_{20} + i(\Delta_1 + \Delta_2 + \varepsilon(r))$. Therefore, as changing the atomic density, the resonant frequency between $|1\rangle$ and $|2\rangle$ is changed due to the vdW interactions of Rydberg atoms, and then the position $(\Delta_1 = \Delta_3 = -\Delta_2 + \varepsilon)$ of the maximum intensity of the SWM signal is changed correspondingly. Figure 3(b) shows the dependence of the measured frequency shift on the principal quantum number $n$. For each $n$, since the energy shift of the nonlinear SWM signal is $|\Omega_2|^{0.4} \propto n^{0.6} (\mu_{21} \propto n^{-3/2})$, the SWM maximum shift is scaled to $n = 37$ by the factor $(n^* / 37^{0.6})$ in order to account for the decrease in transition strength (i.e., the transition dipole moment) with increasing $n$. Here $n^* = n - \delta$ and $\delta = 1.35$ in the quantum defect for $nD_{5/2}$ state [16]. From fig. 3(b), we can obtain that the energy shift $\varepsilon$ increases with $n$, because of stronger interactions between Rydberg atoms. For example, the shift changes from 19.0 MHz to 21.1 MHz when $|2\rangle$ changes from $37D$ to $63D$, which is verified by computation resorting to eqs. (1) and (3). In our theory, the density matrix element $\rho_{10}^{(5)}$ determines the intensity of SWM signals, and the maximum value appears when the condition $\Delta_1 + \Delta_2 + \varepsilon = 0$ is satisfied. For different density and principal quantum number of Rydberg atoms, $\varepsilon$ is different, so the peak location $\Delta_2 = -\Delta_1 - \varepsilon$ of each SWM signal will vary with $\varepsilon$ when $\Delta_1$ is fixed. In addition, another way to represent the blockade effect is to measure the level shift at different density by scanning the frequency of probing laser as shown in fig. 3(c). The measurement of the level shift $\varepsilon$, induced by changing the atomic density, is represented as the difference between two resonant SWM signals at two atomic density values $2.4 \times 10^{12} \text{cm}^{-3}$ (labeled as $\rho$) and $1.7 \times 10^{11} \text{cm}^{-3}$ (labeled as $\rho'$), respectively. Here, the zero point of the horizontal axis is calibrated by the resonant frequency without the blockade effect. One can find that the maximum (resonant) points at the two values are separated.

Finally, such Rydberg SWM process $\mathbf{E}_{\text{SWM1}}$ can also be affected by the laser powers, and this was discussed in ref. [20]. Now, by applying an external field $\mathbf{E}_4(\omega_4, k_4)$ (see fig. 4a), we focus on modulated SWM and eight-wave mixing when the powers of $\mathbf{E}_4$ is high and low, respectively. Figure 4(a1) shows the modulated Rydberg SWM signal at $\rho_0 = 2.4 \times 10^{12} \text{cm}^{-3}$ by scanning the detuning $\Delta_1$ with fixed $\Delta_2$ and $\Delta_3$, and different $\Delta_4$. The peak labeled by S2 is another SWM process $\mathbf{E}_{\text{SWM2}}$ and is used to monitor the frequency detuning $\Delta_1$. Apparently, the Rydberg SWM signal $\mathbf{E}_{\text{SWM1}}$ is suppressed dramatically at $\Delta_2 = \Delta_4$ as shown in fig. 4(a2). This because the dressing effect of $\mathbf{E}_4$ becomes the strongest when $\Delta_2 = \Delta_4$, according to the dressing term (\langle |\Omega_4|^2/d_4\rangle) on state $|1\rangle$.

When the power of $\mathbf{E}_4$ is low, the dressing effect is not the dominant factor, and then an enhancement Rydberg SWM signals can be obtained due to generation of EWM. Via the Liouville pathway and take the dressing effects of $\mathbf{E}_1, E_2$ and $\mathbf{E}_4$ into account, the intensity of polarization of output EWM is given (after using Rydberg state modification) by

$$P_1^{(7)} = \int_{-\infty}^{+\infty} iN(v)$$

$$\times \rho_1^{(0)2}\mu_{10}C[\Omega_1^{0.4}(|\Omega_2^{0.4}|/n^{1.1})^{0.4}\Omega_4^{0.4}|\Omega_4^{0.4}|/d_4]d_4^{d_4}d_4^{0}d_4^{F},$$

where $d_4' = \Gamma_{40} + i(\Delta_1 + \Delta_4) + i(k_1 + k_4)v$. 

33001-p4
Fig. 4: (Color online) Modulated results of the Rydberg SWM process $E_{\text{SWM1}}$ by applying an external field $E_4 (\omega_4, k_4)$ at (a) higher power or (b) lower power. (a) Interaction between two SWM processes $E_{\text{SWM1}}$ and $E_{\text{SWM2}}$ vs. $\Delta_1$, in which $\Delta_2$ is fixed and $\Delta_4$ is changed. Level $|2\rangle$ is $37D$. (b) Demonstration of the EWM signal. Intensities of the total signals are measured by scanning $\Delta_2$ with fixed $\Delta_1$ and $\Delta_3$ at different detuning $\Delta_4$. The atomic density is $2 \times 10^{12} \text{cm}^{-3}$. Laser powers of $E_1$, $E_2$, $E_3$, $E_3'$ and $E_4$ are 350 $\mu$W, 120 mW, 1.3 mW, 8.0 mW and 2.0 mW, respectively.

Figures 4(b1) and 4(b2) show the measured signals by scanning $\Delta_2$ with fixed $\Delta_1$ and $\Delta_4$ at different detuning $\Delta_4$ for $n = 37$ and 45, respectively. The profile consisting of the baseline of each signal (shown in fig. 4(b)) represents $E_{\text{SWM2}}$ vs. the detuning $\Delta_1$. If $\Delta_1$ is away from the resonance region, one can get a pure EWM signal $E_{\text{SWM1}}$. However, at $\Delta_2 = \Delta_4 = 0$, one can find that the measured peak height is bigger than the sum of intensities of two individual SWM signals, which can be attributed to the generation of the EWM process, i.e., the region enclosed by the dotted curve and the top dashed curve as shown in fig. 4(b).

In summary, we have investigated the contribution of the blockade to the Rydberg SWM process in $^{85}\text{Rb}$ atoms both theoretically and experimentally, which is a novel nondestructively optical detection method. The blockade information induced by the strong vdW interaction of Rydberg atoms is mapped onto the EIT-assisted SWM field. The level shift can be observed via the difference between the center frequencies positions of two resonant SWM signals with two different atomic density values. In addition, the blocked SWM process can be modulated by the self-dressing effect and/or external dressing effect. What is more, an EWM process can be obtained by applying a new weak field. The unique nature of such blockaded MWM process provides a potential application in quantum computation and information.

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