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Blockaded six- and eight-wave mixing processes tailored by electromagnetically induced transparency scissors

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Abstract
We report the first experimental observations of the blockaded six- and eight-wave mixing processes in a collective multi-level Rydberg atomic ensemble tailored by multi-channel scissors and created by three coexisting electromagnetically induced transparency (EIT) windows. The interplay between the dressed-state effect and the Rydberg blockade caused by strong van der Waals interactions is investigated when several parameters in the excitation lasers are changed. Blockaded multi-wave mixing (MWM) signals are obtained when the coupling frequency detuning is changed, which is improved to give multiple channels when the probe detuning is scanned. Such MWM signals tailored by EIT scissors produce a much narrower linewidth and therefore are suitable for application in long-distance quantum communication. The advantages of having multi-channel blockaded MWM signals also makes potential applications in demonstrating multi-channel entanglement possible and improves the performance of quantum computation with Rydberg atoms.

Keywords: electromagnetically induced transparency, Rydberg atoms, multi-wave mixing, dressing effect, Rydberg excitation blockade

(Some figures may appear in colour only in the online journal)

1. Introduction
Rydberg atoms possess large dipole moments, gigantic spatial extension and long lifetimes [1]. Such a system allows one excited Rydberg atom to block the excitations of other nearby atoms with strong van der Waals (vdW) interaction [2, 3]. Some of the promising applications of such a Rydberg excitation blockade include quantum logic gates [4, 5], atomic clocks [6], single-photon sources [7] and room-temperature quantum devices [8]. The path to achieve a reliable Rydberg-blockade effect requires effective control of the driving of the ground-state atoms into Rydberg states. Recently, nondestructively optically detected methods, such as the electromagnetically induced transparency (EIT) [9] used to probe Rydberg atoms with high resolution [10–12] and the four-wave mixing (FWM) process used to investigate the Rydberg spectrum [13], have been developed. Since the EIT window (spin coherence) can restrain the linewidth of the multi-wave mixing (MWM) spectrum, we refer to this phenomenon as tailored by EIT scissors [14].

In this paper, we use the EIT-assisted blockaded six-wave mixing (SWM) and/or eight-wave mixing (EWM) processes to study the properties of the Rydberg state in $^{85}$Rb atoms both theoretically and experimentally. Multi-channel EIT scissors resulting from multiple spin coherences can tailor the output signal with a narrower linewidth. The high-order MWM processes guarantee the necessary multiple EIT windows for
such scissors, which could have potential application in long-distance quantum communication [15]. Meanwhile, by using the blockaded MWM processes, we map the vdW interactions between the atoms onto both the probe and MWM fields, respectively. In particular, the Rydberg blockade can create saturation for a given MWM process, which can be controlled by spin coherence and improve the controllability of quantum computation. Finally, we obtain a reliable single-channel blockaded MWM process by scanning the Rydberg coupling field, whereas multi-channel blockaded MWM processes are realized by scanning the probe field.

2. Basic theory

A five-level atomic system, consisting of two hyperfine states \( F = 3(0) \) and \( F = 2(3) \) of the ground state \( 5S_{1/2} \), two low-excitation states \( 5P_{3/2}(1) \) and \( 5S_{1/2}(4) \), and a Rydberg state \( nD_{5/2}(2) \) of \( ^85\text{Rb} \) is used to generate various EIT-assisted MWM processes, in which five beams derived from four external-cavity diode lasers (ECDLs) are coupled into the corresponding transitions (see figure 1(a)). Beam \( E_1 \) (frequency \( \omega_1 \), wavevector \( \mathbf{k}_1 \)) probes the transition \( |0\rangle \leftrightarrow |1\rangle \), while beams \( E_3(\omega_3, k_3) \) and \( E'_3(\omega_3, k'_3) \) from one ECDL with a small angle between them connect \( |1\rangle \leftrightarrow |3\rangle \). A strong beam \( E_2(\omega_2, k_2) \) adding onto \( E_3 \) (in the same direction) drives the Rydberg transition \( |1\rangle \leftrightarrow |2\rangle \), and \( E_4(\omega_4, k_4) \) drives \( |1\rangle \leftrightarrow |4\rangle \) propagating symmetrically to \( E'_3 \), with respect to \( E_3, E'_3 \) propagates in the opposite direction to \( E_2, E_3/E'_3 \). By turning lights on or off selectively, one can obtain four types of MWM processes. First, by blocking \( E_2 \) and \( E_3 \), an FWM1 process satisfying the phase-matching condition \( k_{\text{FWM1}} = k_1 + k_3 - k'_3 \) occurs in \( |0\rangle \leftrightarrow |1\rangle \leftrightarrow |3\rangle \). Then, by applying \( E_2 \) (or \( E_4 \)), an EIT-assisted SWM signal \( E_{\text{SWM1}} \) (\( E_{\text{SWM2}} \)) with \( k_{\text{SWM1}} = k_1 - k_3 - k'_3 \) (\( k_{\text{SWM2}} = k_1 + k_3 - k'_3 + k_4 - k_3 \)) can be observed in \(|0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle \leftrightarrow |3\rangle \) (\(|0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle \leftrightarrow |4\rangle \)) [14]. When opening all five beams, an EWM process \( k_{\text{EWM1}} = k_1 + k_3 - k'_3 + k_4 - k_3 \) with three overlapping EIT windows can be obtained in \(|0\rangle \leftrightarrow |1\rangle \leftrightarrow |2\rangle \leftrightarrow |3\rangle \leftrightarrow |4\rangle \). These MWM signals emit along the direction opposite to that of \( E'_3 \) (see figure 1(b)), identified by their EIT windows and detected by an avalanche photodiode detector. Specifically, the generated SWM1 and EWM processes are called Rydberg signals with a blockade property.

In the Rb vapor, atoms excited to Rydberg level [2] shift the energy levels of nearby atoms, and suppress the rate of their Rydberg transitions from \(|1\rangle \) to \(|2\rangle \). Therefore, one can investigate the excitation blockade effect in a local domain (figure 1(c), green ellipse), within which only one atom is excited to the Rydberg level \(|2\rangle \) (figure 1(c), the red ball). However, the atoms (blue balls) in ground levels \(|0\rangle \) and \(|3\rangle \) can be excited to \(|1\rangle \) with \( E_1, E_3 \) and \( E'_3 \) and then to \(|4\rangle \) with \( E_4 \). We use the mean-field model to calculate the level shift \([3]\). The region where only a single excited Rydberg atom exists is considered to be a sphere, with a radius of \( R_d \), which determines the number of Rydberg atoms in the beam volume. The level \(|2\rangle \) is shifted to \( \varepsilon_2 - \varepsilon \) by other nearby \( nD \) Rydberg atoms outside the sphere, where \( \varepsilon \) is the smallest in the center of the sphere, making atoms located in the center have the largest probability \(|1\rangle \leftrightarrow |2\rangle \). The density of excited Rydberg atoms \( \rho_2 \) is assumed to be locally uniform inside and around the sphere, and \( R_d \) is the region where only one Rydberg atom exists in a sphere, namely \( \rho_2 R_d^3 \) is the volume of the given sphere. We calculate \( R_d \) and \( \varepsilon \) in dependence on the principal quantum number \( n \) and its location \( r \) within the given sphere, by solving the nonlinear equations for the excited amplitudes \( c_1 \) at \(|1\rangle \) and \( c_2 \) at \(|2\rangle \) for the continuous wave as follows [16]:

\[
\varepsilon(r) = \rho_2 \int_{V'} U(r - r') \, d^3r',
\]

\[
\text{idc}_1/\text{dt} = c_2 G_2/2,
\]

\[
\text{idc}_2/\text{dt} = -\varepsilon c_2 + c_1 G_2/2,
\]

where \( U(r - r') \) is the vdW interaction [17] for Rb atoms at \( nD \) states, \( G_1 = \mu_{ij} E_i/h \) the Rabi frequency between \(|i\rangle \leftrightarrow |j\rangle \), and \( \mu_{ij} \) the dipole moment. We consider the atomic density at \(|1\rangle \) as \( \rho_1 \propto \rho_0 |G_1|^2 \). Solving equation (1) at the steady state, \( R_d \) can be obtained, and then with \( \rho_2 V_d = 1 \) and \( V_0 \propto (R_0)^3 \) one gets [18]

\[
\rho_2 = C (\rho_0 |G_1|^2)^{0.2} (|G_2|/n^{11})^{0.4},
\]

where \( C \) is a constant resulting from numerical integration outside the given sphere and the atom excitation efficiency between \(|0\rangle \leftrightarrow |1\rangle \), and mainly determined by the coefficient of vdW interactions with its dependence on \( n \) eliminated. \( (\rho_0 |G_1|^2)^{0.2} \) and \( (|G_2|/n^{11})^{0.4} \) describe the suppressions of the contributions from the population of state \(|1\rangle \) \( \rho_1 \propto \rho_0 |G_1|^2 \) and the excitation capacity of \( E_2 \), respectively, to the Rydberg excitation, due to the blockade effect. The modified dependence of \( \rho_2 \) on \( n \) reflects the physics that the larger \( n \) is, the larger the suppression of \( E_2 \) excitation probability will be. The shift \( \varepsilon \) agrandizes rapidly with the increase of \( n \) or \( r \), and effectively enhances the Rydberg blockade (see figure 1(d)).

Generally, by the pathway \( \rho^{(0)}_0 \rightarrow E^{(1)}_1 \rightarrow \rho^{(2)}_1 \rightarrow E^{(2)}_3 \rightarrow \rho^{(3)}_2 \rightarrow \rho^{(4)}_0 \rightarrow E^{(5)}_2 \rightarrow \rho^{(5)}_1 \) and the dressing effect of \( E_2 [14] \), the fifth-order polarization \( P^{(5)}(1) \) of the SWM1 signal is

\[
P^{(5)(1)} = i \rho_0 \mu_{10} G_1 |G_2|^2 |G_1|^2 / (d_1 + |G_1|^2 / \Gamma_0 + |G_2|^2/d_3)^3 d_3 d_4),
\]

where \( d_1 = \Gamma_10 + i \Delta_1, d_2 = \Gamma_20 + i (\Delta_1 + \Delta_2), \) and \( d_3 = \Gamma_30 + i (\Delta_1 + \Delta_3) \); \( \Gamma_{ij} \) is the transverse relaxation rate for \(|i\rangle \leftrightarrow |j\rangle \). A similar method can be used for SWM2. Since SWM1 is related to the Rydberg level [2] and the excitation blockade effect of the Rydberg transition \(|1\rangle \leftrightarrow |2\rangle \) can suppress its intensity, via the transforming relationships for the Rydberg blockade (equation (2)), equation (3) can be modified to

\[
P^{(5)(1)} = i \rho_0^{0.2} \mu_{10} \tilde{C} |G_1|^2 (|G_2|^2/n^{11})^{0.4} |G_3|^2 / [(d_1 + |G_1|^2 / \Gamma_0 + (|G_2|^2/n^{11})^{0.4}/d_2)^3 d_3 d_4].
\]
The FWM2 signal (the middle curve) is generated by opening all fields except \( \varepsilon_2 \) and \( \varepsilon_{2-} \) and the ellipse background represents the region within which only one atom can be excited to the Rydberg level; the top large ball represents the single Rydberg atom, while the small balls represent atoms in lower levels; and \( \varepsilon_2 - \varepsilon \) is the shifted level. (d) The shift \( \varepsilon \) versus \( n \) and \( r \).

\[
\langle G_2 \rangle / n^{11.0.4}/d_2 \]

indicates that the dressing effect of \( E_2 \) is modified by the blockade effect.

For the EWM signal, which is also related to \( |2\rangle \), through the pathway \( \rho_{10}^{(0)} \xrightarrow{E_1} \rho_{11}^{(1)} \xrightarrow{E_3} \rho_{30}^{(2)} \xrightarrow{(E_1)^*} \rho_{10}^{(3)} \xrightarrow{E_2} \rho_{20}^{(4)} \xrightarrow{(E_2)^*} \rho_{10}^{(5)} \xrightarrow{E_4} \rho_{40}^{(6)} \xrightarrow{(E_3)^*} \rho_{10}^{(7)} \) and the dressing effects of \( E_2 \) and \( E_4 \), the corresponding seventh-order polarization \( P^{(7)} \) is

\[
P^{(7)} = -i\rho_0^{0.2} \mu_{10} \hat{C}[G_1]^{0.2} \langle G_2 \rangle / n^{11.0.4}[G_3]^2[G_4]^2/[(d_1 + G_1^2/\Gamma_0) + \langle G_2 \rangle / n^{11.0.4}/d_2 + G_4^2/d_4]\]

where \( d_4 = \Gamma_{40} + i(\Delta_1 + \Delta_4) \).

3. Experimental results and analysis

3.1. Demonstration of Rydberg MWM processes with different methods

By using a specially designed experimental scheme, the existence of Rydberg MWM processes is demonstrated. First, by opening all fields except \( E_3 \) and \( E'_3 \) and adding a new beam \( E'_4 \) (not shown in figure 1), we show the Rydberg EIT window used to tailor the MWM spectra in figure 2(a), where the probe, fluorescence and FWM2 signals are detected versus the frequency detuning \( \Delta_1 \) of the probe field \( E_1 \). The right EIT peak in the top curve is caused by \( E_4 \) at \( \Delta_1 + \Delta_4 = 0 \) and the left one by \( E_2 \) at \( \Delta_1 + \Delta_2 = 0 \). The FWM2 signal (the middle curve) is generated by \( E_1, E_4 \) and \( E'_4 \) with \( k_{FWM2} = k_1 + k_4 - k'_4 \). As \( \Delta_2 \) is tuned close to \( \Delta_4 \), an FWM2 process dressed by the Rydberg coupling field is observed. In the profile of the fluorescence spectrum emitted from \( |1\rangle \) (the bottom curve), two results modulated by \( E_2 \) and \( E_4 \) are observed. A fluorescence peak emitted from \( |4\rangle \) is located inside the dip caused by the dressing effect of \( E_4 \). However, for the case of \( E_2 \), only a dip presents due to the dressing effect, while the Rydberg fluorescence peak is too weak to be seen due to the long lifetime of the Rydberg state.

Next, an EIT-assisted Rydberg SWM1 signal versus \( \Delta_1 \) is shown in figure 2(b2), and a non-blockade SWM2 signal in figure 2(b3). When opening all fields, SWM1 and SWM2 signals coexist and the total MWM signal (\( \Delta_2 = \Delta_4 \)) in figure 2(b1) is stronger than the sum of the two individual SWM signals, which sufficiently proves the existence of the Rydberg EWM process in this system. The EWM signal intensity shown in figure 2(b4) is obtained by subtracting two SWM signals from the total signal. The theoretical predictions of total MWM, SWM1, SWM2 and EWM are shown in figures 2(b5)–(b8).

Furthermore, disturbance-free Rydberg signals can be better picked up by scanning the Rydberg coupling field \( E_2' \); i.e., the Rydberg signals stand out, while non-blockade signals descend into the background invariant versus the frequency detuning \( \Delta_2 \) of \( E_2' \). Figure 2(c) shows the measured Rydberg MWM signals versus \( \Delta_2 \) for four different \( n \). The right peak in each panel is a pure Rydberg SWM1 signal at \( \Delta_2 \neq \Delta_4 \). When \( \Delta_2 = \Delta_4 \), the relative value of the peak above the background increases clearly (left peak in each panel), which demonstrates the existence of the Rydberg EWM signal located inside three overlapping EIT windows (satisfying \( \Delta_1 + \Delta_2 = 0, \Delta_1 + \Delta_4 = 0, \) and \( \Delta_2 - \Delta_4 = 0 \), simultaneously) corresponding to the suppressions of three transitions \( |0\rangle \leftrightarrow |1\rangle, |1\rangle \leftrightarrow |2\rangle \) and \( |1\rangle \leftrightarrow |4\rangle \) with linear susceptibilities \( \chi^\text{(1)}_{10}, \chi^\text{(1)}_{21} \) and \( \chi^\text{(1)}_{41} \), respectively. When \( E_1 \) serves as the probe field and \( E_2/E_4 \) as dressing fields, we can obtain \( \chi^\text{(1)}_{10} = i\mu_1^2/\hbar\rho_0[d_1 + \langle G_2 \rangle / n^{11.0.4}/d_2 + \rangle \).
Equation (4)). Therefore, the signal intensity versus $1$ and the increasing $E$ EWM signal at is given to further demonstrate the existence of the Rydberg absorption spectrum.

The linewidth of the EIT window and as $1\omega$ EWM signal ultra-narrow linewidth ($<1$) power dependence of the SWM1 on (b1) $P_1$, (b2) $P_2$, (b3) $\rho$ and (b4) $n$. (c1)–(c4) Dependences of blockaded EWM on the corresponding parameters of the blockaded SWM1 case. The power of $E_1$ varies from 0 to 1.2 mW and $E_2$ from 0 to 120 mW. The atomic density discretely increases from $1.7 \times 10^{10}$ cm$^{-3}$ to $2.4 \times 10^{12}$ cm$^{-3}$ for each $n$ (from bottom to top). $n$ dependences (fitted dots) of blockaded MWM signals are shown in the second row with $10.0 \times 10^{12}$ cm$^{-3}$. Dots represent the original experimental data, up triangles are scaled values accounting for the dipole transition probability, and the solid curves are the theoretical predictions.

Similarly, if $E_2$ and $E_4$, respectively, serve as probes with the other two as the dressing effect, one can obtain $\chi_2^{(1)} = i|G_2|/(d_3 + |G_3|^2/d_2 + |G_4|^2/d_5)$ and $\chi_4^{(1)} = i|G_4|/(d_5 + |G_5|^2/d_4 + (|G_3|^2/n)^{1/2}d_6)$, where $d_3 = \Gamma_2 + i\Delta_2$, $d_4 = \Gamma_4 + i(\Delta_2 - \Delta_4)$, $d_5 = \Gamma_4 + i\Delta_4$, and $d_6 = \Gamma_4 + i(\Delta_4 - \Delta_2)$. Three overlapping EIT scissors give the Rydberg EWM signal ultra-narrow linewidth (<50 MHz), described as $\Delta \omega_E = \Delta \omega_{10}(\Delta \sigma_{21}/\Delta \sigma_{21}) \Delta \sigma_{41}/\Delta \sigma_{41}$, where $\Delta \omega_{ij}$ is the linewidth of the EIT window and $\Delta \sigma_{ij}$ is the linewidth of the absorption spectrum.

Finally, the $E_4$ power dependence of the SWM1 process is given to further demonstrate the existence of the Rydberg EWM signal at $\Delta_4 = -\Delta_2$ (see figure 2(d)). Initially, the signal intensity versus $\Delta_2$ corresponds to Rydberg SWM1, and the increasing $E_4$ power has little influence on it (see equation (4)). Therefore, the $E_4$ power dependence of the total intensity is mainly caused by the Rydberg EWM signal, while the non-blockaded SWM2 signal stays in the background. It is obvious that the EWM signal intensity saturates with a strong power of $E_4$, which agrees with the theoretical prediction (see equation (5)) where the dressing effect of $E_4$ can lead to such saturation.

3.2. Blockaded MWM processes

In the following, we characterize the blockaded MWM processes as functions of the atomic density $\rho$, the probe strength $P_1$, the Rydberg state coupling field strength $P_2$ and the principal quantum number $n$. Two sets of results, obtained by changing $\Delta_2$ (figure 3) and $\Delta_1$ (figure 4), respectively, are presented. For each $n$, the MWM intensity values are scaled to $n = 37$ by the factor $(n^*/37^*)^5$ accounting for the decrease.

**Figure 2.** Demonstration of the Rydberg MWM processes with different methods. (a) The top, middle and bottom curves represent the probe, FWM2 and fluorescence signals versus $\Delta_1$, respectively. Level (2) is 37D. (b1)–(b3) Total MWM signal and SWM1 and SWM2 signals versus $\Delta_1$. (b4) EWM signal by subtracting SWM1 and SWM2 from the total signal. (b5)–(b8) Corresponding theoretical curves. (c) Intensities of MWM signals versus $\Delta_2$ with $\Delta_4$; $E$ represents the EWM signal. (d) Power dependences of the total MWM (squares) and EWM signals (dots) on $\Delta_2$. Level (2) is 37D. The atomic density is $1.0 \times 10^{12}$ cm$^{-3}$. The laser powers of $E_1$, $E_2$, $E_3$, $E_4$ and $E_4'$ are 350 µW, 120 mW, 1.3 mW, 8.0 mW and 2.0 mW, respectively. In (a), (b) and (c), the power of $E_4$ is 5.0 mW.

**Figure 3.** The dependences of blockaded MWM signals on $\Delta_2$. (a) Measured total signals at various powers of $E_1$. (b) Dependences of blockaded SWM1 on (b1) $P_1$, (b2) $P_2$, (b3) $\rho$ and (b4) $n$. (c1)–(c4) Dependences of blockaded EWM on the corresponding parameters of the blockaded SWM1 case. The power of $E_1$ varies from 0 to 1.2 mW and $E_2$ from 0 to 120 mW. The atomic density discretely increases from $1.7 \times 10^{10}$ cm$^{-3}$ to $2.4 \times 10^{12}$ cm$^{-3}$ for each $n$ (from bottom to top). $n$ dependences (fitted dots) of blockaded MWM signals are shown in the second row with $1.0 \times 10^{12}$ cm$^{-3}$. Dots represent the original experimental data, up triangles are scaled values accounting for the dipole transition probability, and the solid curves are the theoretical predictions.
in $\mu_j$ with increasing $n$. Here, $n^* = n - \delta$, and $\delta = 1.35$ is the quantum defect for the $nD_{5/2}$ state [17]. The typical density of the collective atomic ensemble is $\rho_0 = 1.2 \times 10^{12}$ cm$^{-3}$ at 80°C, and then the average atom–atom distance is $R_{\text{nn}} = 0.555(\rho_0)^{-1/3} = 0.52\ \mu$m. Meanwhile, $\epsilon$ can be approximated by the polynomial of $1/R$, i.e. $\epsilon(R) \approx -C_5/R^5 - C_6/R^6 - C_7/R^7$ for nd–nd interaction [18]. Therefore, the shift induced by such nd–nd interaction is larger than gigahertz, which is larger than the linewidths of EIT windows (50 MHz) and lasers (about 1 MHz), so the blockade effect can be resolved by our measured spectra [19].

By scanning $\Delta_2$, a reliable single-channel blockaded MWM process can be obtained. Figure 3(a) shows the measured total blockaded EWM and SWM1 signals versus $\Delta_2$ at various powers of $E_1$ (from top to bottom), from which the characteristic spectral curves of MWM signals are extracted by restricting $\Delta_2$ to a narrower region. Figure 3(b) shows the dependences of the blockaded SWM1 signal on (b1) $P_1$, (b2) $P_2$, (b3) $\rho$ and (b4) $n$, respectively. Figures 3(c1)–(c4) are the dependences of the blockaded EWM signal on the corresponding parameters of the blockaded SWM1 case.

At the lowest excitation intensities, the intensities of signals for three high $n$ values fall onto the same value as the case for the isolated-atom MWM, since the Rydberg levels are not shifted, while the Rydberg atoms are sufficiently sparse that interactions between them are negligible. As $P_1$($P_2$) increases, the blockade effect on Rydberg MWM signals appears gradually and the suppression is largest for $n = 63$ at the highest intensity shown for the blockaded SWM1 process and at a lower intensity for the blockaded EWM process. For the case of $P_1$ dependence, the EWM process attains saturation more quickly than the SWM1 process and then declines due to the combined dressing effect of $E_1$ and $E_2$ (see equation (5)). Therefore, the saturation of the SWM1 process is caused by the blockade effect, while the evolution of the EWM process results from the interaction between the dressing and blockade effects.

The scaled intensities of the SWM1 (figure 3(b3)) and EWM signals (figure 3(c3)) are plotted versus increasing $\rho_0$ at four $n$ values, and the corresponding theoretical predictions are also given. It is obvious that the peak heights of the SWM1 and EWM signals both first increase and then tend to saturate with increasing $\rho_0$ whatever $n$ is. Such a saturation trend is completely derived from the blockade effect. $\rho_2$ scales as $\rho_0^{0.2}$ (see equation (2)), and therefore the intensities will gradually approach saturation when $\rho_0$ increases. Such a suppressed increase at each $n$ indicates that the SWM1 and EWM signals are blockaded. Compared with $n = 37$, the Rydberg MWM intensities at each $\rho_0$ for $n = 45$, 54, and 63 are suppressed, which indicates that the MWM carries the $n$-dependent characteristics of the Rydberg excitation blockade. The intensities of the SWM1 and EWM signals measured from the spectral curves are plotted versus four $n$ as triangles at $\rho_0 = 1.0 \times 10^{12}$ cm$^{-3}$, respectively, with the corresponding theoretical curves shown in figures 3(b4) and (c4). The tremendous difference between the scaled (squares in both panels) and the non-scaled intensities further verify that both the SWM1 and EWM signals are blockaded. With $\rho_0 = 1.0 \times 10^{12}$ cm$^{-3}$, the measured EIT-assisted SWM1 signal disappears gradually as $n$ increases. Considering the relationships between the polarizability amplitudes and the MWM signal intensities, the dependences of both the SWM1 and EWM intensities on $n$ scale as $n^{-8.8}$ (see equations (4) and (5)), which are confirmed by the theoretical curves. Eliminating the differences between the SWM1 and EWM signals in the dipole momentum and dressing effects, we can find that the blockade effect of EWM is stronger than that of SWM. This reveals that EWM is more suitable for long-distance quantum communication, because the blockade of EWM has a larger contrast.

Finally, we focus on the case of scanning $\Delta_1$. Several signals identified by their individual EIT windows can be detected

![Figure 4](image-url)
simultaneously, so multi-channel blockaded processes can be obtained. Figure 4(a) shows the total MWM signal (left column) and non-blockaded SWM2 signal (right column, used to obtain the EWM signal) versus $\Delta_1$ at increasing $\rho_0$ (from bottom to top) with $n = 37$. We pick out the interesting blockaded (b1) SWM1 ((b2) EWM) signals for four $n$ at increasing atomic densities (from bottom to top) at fixed laser powers. In the fifth panel, the scaled intensities of the SWM1 (figure 4(b1)) and EWM signals (figure 4(b2)) extracted from the spectral curves in the first four panels are plotted versus increasing $\rho_0$ at four $n$ values, and the corresponding theoretical predictions are also given. In the sixth panel of figures 4(b1) and (b2), the intensities of the SWM1 and EWM signals in the first to fourth panels are plotted versus four $n$ as triangles at $\rho_0 = 1.0 \times 10^{12}$ cm$^{-3}$, respectively, with the correspondingly theoretical curves. The power dependences of blockaded SWM1 and EWM signals on $E_2(E_1)$ for $n = 37, 45, 54, \text{ and } 63$ are measured as shown in figure 4(c) (figure 4(d)), respectively, in which the saturation of SWM due to the blockade effect, and the descent of EWM due to interaction between the dressing field and the blockade effect, are also revealed. Apparently, the signal-to-noise ratio has been greatly improved by scanning $\Delta_2$. The predictions (solid curves in the dependence curve in figures 3(c1)–(c4)) show good agreements with the experimentally measured results. With a close look at the matching between the experimental data and the theoretical predictions, the agreement by scanning the coupling field becomes obviously better than the case of scanning the probe field.

4. Conclusion

In summary, we have reported for the first time the observation of EIT-assisted blockaded SWM and/or EWM processes in a coherent atomic ensemble of rubidium ($^{85}$Rb) atoms. With multiple sets of spin coherence created by coupling fields, such MWM signals are tailored by EIT scissors and achieve ultra-narrow linewidth, and are therefore suitable for application in long-distance quantum communication. The blockade effect of the Rydberg atom is reflected in the measured blockaded MWM signals, which can provide reliable blockade controls on the adjustment of spin coherence control in multi-level atomic systems. We then characterized the resulting blockaded MWM processes as functions of the principal quantum number $n$, the atomic density of the collective atomic ensemble (therefore the inter-atomic distance), the probe strength, and the coupled field strength, respectively. In our investigation of the field-strength-dependent MWM signal, we found that the saturation of the SWM1 process is caused by the blockade effect, while the evolution of the EWM process is caused by the interaction between the dressing effect and the blockade effect. In addition, in scanning probe detuning, multi-channel blockaded MWM was obtained, and in scanning coupling detuning, blockaded MWM obtained in a single channel, but with a better fitting degree between theoretical and experimental results. The advantages of the multi-channel, ultra-narrow linewidth and blockade properties of MWM in Rydberg atoms are promising for improving the controllability of quantum computing with Rydberg atoms.

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