Shaping Temporal Correlation of Biphotons in a Hot Atomic Ensemble

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The biphon states have served as one of the candidates for most quantum-enabled technologies. Moreover, with the benefit of photon–atom interactions, biphotons with controllable wave functions are particularly interesting in quantum information processes. Herein, an experimental realization of the shaping temporal correlation of biphotons from the four-wave mixing process in a hot Rb atomic ensemble is presented. Based on the slow-light effect and electromagnetically induced transparency in the group delay region, the precursor-like propagation is observed and separated from the rising edge of the delayed wave packets of biphotons temporal correlation. In addition, the application of an additional dressing field enriches the features of the biphotons temporal correlation such as the manipulation of the dispersion experienced by the generated photons and controllable coherent time. Furthermore, with a higher optical depth and stronger dressing coupling effect, the temporal correlation of biphotons is shaped from the group delay region to the Rabi oscillation region and even superposed of them.

1. Introduction

Biphoton generations through nonlinear processes have attracted much attention in the basic research of quantum optics as well as the potential applications in quantum-enabled technologies.[1–4] Although biphotons produced from the spontaneous parametric down-conversion are dominant in the quantum business,[5,6] recent development of narrowband biphotons generation from atomic ensembles provides an alternative source to this avenue.[7–20] Such narrowband biphotons are interested in long-distance quantum communication due to long temporal coherence time.[11,13,17] Generally, the optical responses in atomic ensemble, linear, and nonlinear susceptibilities of the photon–atom interactions, are significant to determine the biphoton temporal correlation.[7–20] Therefore, with the benefit of multiparameter controlling features in an atomic ensemble, the temporal waveforms of biphotons can be shaped in group delay region or Rabi oscillations region, or in between.[17–20] Previous studies were mostly done with cold atoms and hot atomic gas was less researched.

The optical precursor propagation always travels at vacuum light velocity in any dispersive medium and showed theoretically by Sommerfeld and Brillouin.[21,22] Following, many studies have been carried out to precisely predict the precursor and main pulse with its group velocity.[23–26] Recently, optical precursor propagation has been proved to exist at the photon level.[13–16] In a cold atomic system, the sharp front-edge spike of the biphoton temporal wave packet is characterized as precursor propagation in the group delay region.[16] Here, the precursor originates from the central component of the frequency spectrum experience a vanishing dispersion inside the atomic ensemble.[27] In this case, the precursor propagation is weak and can be easily switched to an ordinary wave packet with dispersion due to it away from the resonance region in the linear and nonlinear optical responses. Therefore, it is necessary to delay the main wave packet of biphotons using the slow-light effect in group delay region for the observation of the precursor propagation.[13–16] By increasing the nonlinearity of biphotons generation in an atomic ensemble, the temporal correlation of biphotons can be shaped from the group delay region to the Rabi oscillation region.[10–12] Rabi oscillation has been demonstrated in many systems that produce under the dressed state picture.[8,10–12,17–20,28,29] In the Rabi oscillation region, the biphoton temporal correlation is shaping to multiperiod Rabi oscillation and proposing to 3D energy-time-entangled qubits using the external dressing field in hot atomic vapor.[20] Such quibts can enhance the information capacity of the quantum information unit by increasing the superposed states.[18,20]

In this article, we experimentally study the observation of shaping temporal correlation of biphotons by a spontaneously four-wave mixing process (FWMP) in a hot atomic vapor. With a hot atomic system, photon pairs were generated at lower costs and showed interesting features in the manipulation of biphoton temporal correlation in the hot atomic ensemble are observed that have not been discovered in the previous work. Applying the electromagnetically induced transparency (EIT) and slow-light
effect of generated photons, a sharp front-edge spike in precursor propagation is observed from the wave packet of biphoton temporal correlation. In addition, by adding a dressing field, the group delay of the main packet can be manipulated. Moreover, with a higher optical depth (OD), the temporal correlation of biphoton is shaped with a longer coherent time. Further, the competition and coexistence of linearity and nonlinearity are observed in biphoton waveforms by changing with a stronger dressing coupling effect. These coherent manipulations of biphotons state, such as precursor propagation with nearly lossless nature and multiperiod Rabi oscillation with high information capacity, are interested and useful in quantum information processes.

2. Experimental Scheme of Biphotons Generation

In a four-level atomic system, as shown in Figure 1a, the pump laser field $E_1$ (wave length $\lambda_1 = 795$ nm, frequency $\omega_1$, wave vector $k_1$, Rabi frequency $\Omega_1$) and coupling field $E_2$ ($\lambda_2 = 780$ nm, $\omega_2$, $k_2$, $\Omega_2$) in the counter-propagation geometry are applied to generate photon pairs from the spontaneously FWMP. Two photons $E_S$ ($\lambda_S = 795$ nm, $\omega_S$, $k_S$) and $E_{AS}$ ($\lambda_{AS} = 780$ nm, $\omega_{AS}$, $k_{AS}$) are spontaneously emitted and frequency-correlated due to energy conservation ($\omega_1 + \omega_2 = \omega_S + \omega_{AS}$) and phase matching condition ($k_1 + k_2 = k_S + k_{AS}$). As a result, the generated photons $E_S$ and $E_{AS}$ exhibit genuine time-energy entanglement of biphoton state. Thus, the detection of the frequency of the photon $E_S$ requires the detection of the another at $\omega_{AS} = \omega_1 + \omega_2 - \omega_S$. Therefore, the properties of biphoton temporal correlation can be experimentally measured by two-photon coincidence counts. For forcing the atomic population to stay in the ground state and largely suppressing quantum atomic noise, the pump beam $E_1$ is weak powered and puts a large detuning by $\Delta_1 = -1.8$ GHz of from $^{85}$Rb transition $|S5/2\rangle \rightarrow |P1/2\rangle$. $\Delta_1$ is the detuning of $E_1$ and defined as $\Delta_1 = \omega_1 - \omega_c$. The coupling laser $E_2$ makes the transition $|S5/2\rangle \rightarrow |P3/2\rangle$, $\Delta_2 > 2$ with the near-resonance condition, in which, it also assists a $\Lambda$-type EIT window regarding photons $E_{AS}$ with the slow-light effect. Moreover, an external dressing field $E_3$ ($\omega_3$, $k_3$, $\Omega_3$) driving $|1\rangle \rightarrow |4\rangle$ with $\lambda_3 = 780$ nm is used to manipulate the temporal correlation of generated photons. This third strong field also serves as a repumping field to make most of the atomic population in the lower ground state.\[9,20\]

With the lasers $E_1$ (vertical polarization), $E_2$ (horizontal polarization), and $E_3$ (horizontal polarization) injecting into a hot Rubidium vapor, two output photons $E_S$ and $E_{AS}$ are obtained, as shown in Figure 1b. Here, these lasers from external cavity diode lasers are coupled into the center of atomic vapor by optical lenses. $E_1$ and $E_2$ are counter-propagation geometry, whereas $E_3$ is in the same direction as $E_1$. The rubidium vapor cells with a longitudinal length $L = 7$ cm are magnetic shielded in a metal cover and used by a temperature of 75°C. The powers of $E_1$, $E_2$, and $E_3$ are $P_1 = 4$ mW, $P_2 = 6$ mW, $P_3 = 6$ mW, respectively. Based on the phase-matching condition of FWMP, the opposite photons $E_S$ and $E_{AS}$ emitted along the $Z$-axis with an angle of 4°. Two fiber-coupled single-photon counting modules (SPCMs) are used to record the counts of $E_S$ and $E_{AS}$, respectively. And, the coupling efficiency of the fibers and the detection efficiency of the SPCMs is 70% and 40%, respectively. Due to the large detuning of photon $E_S$, the group velocity of $E_S$ approaches $c$, whereas $E_{AS}$ is generated with EIT slow-light effect. In this case, the detected $E_S$ and $E_{AS}$ serve as the start triggering photon and stop triggering photon, respectively. Therefore, the two-photon coincidence counts can be recorded with the largest correlations. Before recording, it is necessary to use the filters, narrowband etalon Fabry–Perot cavity to filter most of the noises of uncorrelated single photons and dark counts. Here, the noises are generated from several weaker FWMPs ($2k_1 = k_S + k_{AS2}$, $2k_2 = k_{AS} + k_{S2}$, $2k_3 = k_{S3} + k_{AS3}$, $k_1 + k_2 = k_S + k_{AS}$, $k_2 + k_3 = k_{AS} + k_{S3}$). The bandwidth, transmission efficiency, and extinction ratio of the filters are nearly 350 MHz, 80%, and 60 dB, respectively. The bandwidth of the Fabry–Perot cavity is near 500 MHz. Some residual will remain to constitute the background of waveforms of biphotons. With a temporal bin width of 0.0244 ns, electronic pulses from SPCMs of photons are inputting into the time-to-digit converter. Therefore, the two-photon coincidence count is recorded, so that the temporal correlation of biphoton is obtained. To further understand the temporal correlation of biphotons in different optical response regions, we use the effective interaction Hamiltonian to calculate the second-order correlation function $G^{(2)}$ of biphotons.

3. Shaping Temporal Correlation of Biphotons

Generally, the optical responses including the linear and nonlinear responses of the coherent light-matter interaction, play an

Figure 1. a) Energy-level diagram for FWMP; b) Experiment set up of biphotons generation. PBS: polarization beam splitter; ECLD: external cavity diode laser; F: filter; FP: Fabry–Perot cavity; SF: Single-mode polarization-maintaining fiber; SPCM: single-photon counting module.
By comparing the natural width of the phase

\( \Phi \) is the nonlinear coupling coefficient and longitudinal detuning function, respectively; \( \Delta k = k_S + k_{AS} - (k_1 + k_2) \) is the phase mismatch along the z-axis in Figure 1b that relates to the linearities of generated photons; HC is the Hermitian conjugate.

In the group delay region, the linear susceptibility plays a major role in determining the spectral width of biphoton, which results in the nonlinear coupling coefficient \( \kappa \approx 1 \). In this case, the biphoton state \( |\Psi> \) has two parts that arise from different components in the frequency spectrum, which can be written as \( |\Psi> = |\Psi_0(\tau)\rangle + |\Psi_{SB}(\tau)\rangle \). \( |\Psi_0(\tau)\rangle \) represents the precursor-like propagation term that has been studied in the studies by Wei et al. and Du et al.\(^{[14,16]} \). Here, the precursor originates from the central component of the frequency spectrum experience a vanishing dispersion inside the atomic ensemble.\(^{[27]} \) \( |\Psi_0(\tau)\rangle \) represents the main wave packet of biphotons and can be expressed through the first-order perturbation in the interaction picture as

\[
\psi_0(\tau) = \frac{L}{2\pi} \int d\omega_{AS} \kappa(\omega_{AS}) |\Phi(\omega_{AS})\rangle e^{-i\omega_{AS} \tau} \tag{2}
\]

where \( \tau = t_{AS} - t_3 \) is the relative time delay that represents the temporal correlation of biphoton state. Usually, the Glauber correlation function of biphotons can be expressed as the second-order intensity correlation function of \( C^{(2)}(\tau) = |\langle \Psi |\langle \tau)\rangle|^2 \) + \( R_S R_{AS} \); where \( R_S R_{AS} \) represent the background from uncorrelated photons. Therefore, by measuring the two-photon coincidence counting, we can obtain the temporal correlation of the biphoton state.

The natural spectral width of biphoton is determined by the linear optical response. In Figure 1a, \( E_1 \) is weak powered and puts a large detuning by \( \Delta_1 \approx 1.8 \text{GHz} \) of from transition \( |2> \rightarrow |1> \). Therefore, by considering \( |\Omega_2|^2 \ll \Delta_1 \) and \( |\Omega_1|^2 \ll \Delta_1 \), the linear susceptibilities of \( E_S \) can be approximated by \( \chi_{AS} \approx 0 \), which means the group velocity of \( E_S \) approaches \( c \). Consequently, the linear susceptibility of \( E_{AS} \) can be written as

\[
\chi_{AS} = \frac{N \mu_f^2 f(\nu)}{\epsilon_0 \hbar} \left[ \frac{W_{D_4} \delta + \Delta_{2D} - i\gamma_{41} - |\Omega_2|^2 / (W_{D_4} \delta - i\gamma_{21})}{-i} \right]
\]

where \( \mu_f \) is the electric dipole matrix elements, \( \epsilon_0 \) is the permittivity of vacuum, \( \hbar \) is the Planck constant, \( \gamma_{ij} \) are the dephasing rates, \( |\Omega_1|^2 \) and \( |\Omega_2|^2 \) are the Doppler-broadening coefficients, \( W_{D_4} = (1 + \nu / \epsilon) \). \( \Delta_{2D} \) is the detuning of \( E_1 \) and is defined as \( \Delta_{1D} = \omega_{AS} - \omega_{D_1} \), \( \Delta_{2D} \) is the detuning of \( E_3 \) and is defined as \( \Delta_{2D} = \omega_{AS} - \omega_{D_2} \), \( \delta = \omega_{AS} - \delta \) is small quantum deviation window around the central frequency \( \Delta_\text{AS} \) of photon \( E_{AS} \), and automatically have \( \omega_5 = \omega_3 - \delta \) due to the frequency correlation between \( E_3 \) and \( E_{AS} \). The atomic density is \( N = 8.4 \times 10^{11} \text{cm}^{-3} \) under the temperature of atomic vapor and the Doppler width is \( \Delta \Omega_0 = 550 \text{MHz} \); in this case, the optical depth OD = \( N \sigma_{14} \) results its value of 46, where \( \sigma_{14} \) is the non-resonance absorption cross-section.

When \( E_1 \) is applied with a detuning of \( \Delta_{1D} = \omega_{AS} - \omega_{D_1} \), the linear susceptibility of \( E_{AS} \) photon in Equation (3) can be rewritten as

\[
\chi_{AS} = \frac{N \mu_f^2 f(\nu)}{\epsilon_0 \hbar} \left[ \frac{W_{D_4} \delta + \Delta_{2D} - i\gamma_{41} - |\Omega_2|^2 / (W_{D_4} \delta - i\gamma_{21})}{-i} \right]
\]

where \( \delta = \omega_{AS} - \omega_{D_1} \), the mismatching bandwidth can express as \( \delta / \omega_{AS} \). Therefore, ignoring the loss in Equation (2), it can be rewritten as

\[
\psi_0(\tau) = \frac{L}{2\pi} \int d\omega_{AS} \kappa(\omega_{AS}) |\Phi(\omega_{AS})\rangle e^{-i\omega_{AS} \tau} \tag{2}
\]

Here, we assume that the cell temperature \( T \) with a very minute deviation and can be viewed as a constant value.\(^{[20]} \) Using the slow-light effect, the group velocity of \( E_{AS} \) can approximately be written as

\[
\nu_{AS} = \frac{c}{1 + \frac{\Delta \Omega_{AS} \nu_{AS} \Omega_{T_{AS}}}{\kappa(\omega_{AS})}}
\]

where it can be defined by the function of \( c |n + \delta(nf/\delta_0)| \); \( n = (1 + \text{Re}(\chi_{AS}))^{1/2} \) is the refractive index; \( k_{AS} \) represents the complex wavenumber of the resonant transition. The group velocity controls the transmission spectrum and dispersion profile of the generated photons. The complex wavenumber of \( E_{AS} \) is written as \( k_{AS} \approx k_{AS0} - \delta / \nu_{AS} + i\alpha_{AS} \), where the real part is Raman gain and the imaginary part is EIT loss; \( k_{AS0} \) is the central wavenumber of \( E_{AS} \). Therefore, the phase mismatch is written as

\[
\Delta k(\delta) = k_S - k_{AS} - k_1 + k_2 \approx \frac{\delta}{k_{AS}} + i\alpha_{AS}
\]

In the group delay region, the biphoton wave function can be approximated by \( \psi_0(\tau) = \psi_0(0) |\Phi(\omega_{AS})\rangle \). Here, \( \psi_0(0) \) is the nonlinear resonance constant. The EIT bandwidth is determined by the imaginary parts of \( \chi_{AS} \), and can be written as \( \Delta \omega_{EIT} \propto (|\Omega_2|^2 + |\Omega_1|^2 / \Omega_{T_{AS}}) / (\delta / \Omega_{T_{AS}})^{1/2} \). When the mismatching bandwidth is smaller than EIT bandwidth, the anti-Stokes loss can be ignored and the biphoton temporal correlation approaches a square-type shape. Conversely, the biphoton temporal correlation follows a sharp decaying profile. Therefore, ignoring the loss in Equation (2), it can be rewritten as
\[ \psi_0(\tau) = \kappa_0 L \Phi(\tau) = \kappa_0 V_{AS} \Pi(\tau; 0, L/V_{AS}) e^{-i\omega_{AS} \tau} \]  \hspace{1cm} (7)

where rectangular function, ranging from 0 to \( L/V_{AS} \), shows that the correlation time of biphoton is determined by the group delay \( \tau_g = L/V_{AS} \). When the mismatching bandwidth is smaller than EIT bandwidth, the EIT loss is considered and suppose \( e^{-\omega_{AS}^2 L} \ll 1 \). The wave function of biphotons becomes

\[ \psi_0(\tau) = \kappa_0 V_{AS} e^{-\omega_{AS}^2 V_{AS}^2 \tau} e^{-i\omega_{AS} \tau} \]  \hspace{1cm} (8)

In this case, the biphoton wave function has a decaying profile with a decay time of \( 1/2 \Omega_{AS}^2 \). Moreover, considering the whole EIT loss, the biphoton wave function is calculated in Equation (9). Where \( \text{erf} \) is error function; \( u \) is unit step function; \( A \) and \( B \) are two constants, \( A \propto 1/\left(\Omega_2^2 + |\Omega_3|^2 + 4\gamma_2\gamma_3\right)^3 \), \( B \propto 1/\left(\Omega_2^2 + |\Omega_3|^2 + 4\gamma_2\gamma_3\right) \). Thus, the biphoton temporal correlation is shown as the interaction of rectangular function and weak damping oscillation.

\[
\psi_0(\tau) = e^{\left(-\frac{\sqrt{4AB\tau^2 + 1}}{2V_{AS}^2}\right)} \cdot u(\tau) \\
-\sqrt{\frac{\pi}{AL}} e^{-\sqrt{\frac{\pi}{4\omega_{AS}^2}}} \frac{1}{\sqrt{\pi L AL}} e^{-\frac{\tau^2}{4\omega_{AS}^2}} e^{-\sqrt{\frac{\pi}{2\omega_{AS}^2}}} \cdot BL \\
\times \left[ \sqrt{\pi AL} + \text{erf}\left(\frac{\tau + 2L}{\sqrt{2\omega_{AS}^2}} - \frac{L}{\sqrt{2\omega_{AS}^2}} \sqrt{1 + 4AB\tau^2} \right) \right] \]  \hspace{1cm} (9)

4. Two-Photon Coincidence Counting Measurements

Based on the generated photon pairs through FWMP in Figure 1b, the properties of biphoton temporal correlation are investigated by two-photon coincidence counting measurements in Figure 2–5. In Figure 2a, the clear coincidence peaks of biphotons that locate at \( \tau = 0-4 \) ns are obtained, in which, these peaks represent the strong correlation between \( E_0 \) and \( E_{AS} \). The main wave packet approaches a rectangular shape \( \Pi(\tau; 0, 4) \) in Equation (7), which shows the main part of the wave package of biphoton temporal correlation travels at a lower velocity in the group delay region with the slow-light effect. The generation rate of such biphoton is 4000 ± 300 per second, and the correlation time resulting from EIT loss is near 4 ns. Due to the strong nonlinear susceptibility in the hot atomic system, there have backgrounds consist of dark counts and uncorrelated single-photon in biphoton temporal correlation. Therefore, after 4 ns in Figure 2a, it still has some accidental coincidence counts. In the top of the rectangular shape of the biphoton wave packet, there have weak damping oscillations, which is mainly resulting from the two parts of reasons; one is EIT loss in Equation (9); another one is the weak nonlinear Rabi oscillation. In this case, the main wave packet includes two parts of precursor propagation function \( \Psi_{SB}(\tau) \) and wave function \( \Psi_0(\tau) \). However, in the condition of the detuning of pump field \( E_1 \) (\( \Delta_1 = -1 \) GHz), the nonlinear reaction of FWMP is stronger whereas the precursor propagation term is weaker. Therefore, in Figure 2a, it is not easy to observe the optical precursor. From Figure 2a–e, the detuning of \( E_1 \) increased from \(-1 \) to \(-1.8 \) GHz. In this case, the pump field is further from the resonance. Therefore, the nonlinear reaction of FWMP becomes weaker gradually, and the generation rate and background of biphoton also decreased from Figure 2a–e. Moreover, due to the weaker term of \( \Psi_0(\tau) \) and stronger term \( \Psi_{SB}(\tau) \), the sharp front-edge spikes characterized as precursor-like propagation are shown in Figure 2b–e. Here, the precursor propagation term \( \Psi_{SB}(\tau) \) is produced from the spectral tails of the third-order optical response which also is away from the resonance region in the linear optical response. Therefore, the strength of \( \Psi_{SB}(\tau) \) is weak and can be easily switched to an ordinary wave packet with dispersion under strong third-order nonlinearity. Further, it means a large detuning of pump field and enough value of optical depth in group delay region are the requirements for the appearance of the optical precursor in an atomic system.

Based on the observations of optical precursor propagation in Figure 2e, the property of biphoton temporal correlation also can be manipulated by the parameters of the dressing field. In Figure 3a, the power of coupling field \( E_2 \) is increased to 8 mW, in which, the optical precursor propagation also can be observed. However, the group delay \( \tau_g \) becomes smaller than Figure 2e due to the stronger dressing effect of \( E_2 \) in Equation (3). Therefore, the correlation time in Figure 3a is shorter than 4 ns. Moreover, compared with Figure 2e, the wave packet changed from rectangular shape to sharp decaying profile because of stronger loss. In Figure 3b, the power of \( E_2 \) is increased to 10 mW. In this case, the generation rate of the biphoton state is higher than it in Figure 3a. In addition, the group delay \( \tau_g \) becomes smaller because of the stronger dressing effect of \( E_2 \), and wave function \( \Psi_0(\tau) \) becomes larger than precursor propagation function \( \Psi_{SB}(\tau) \). Therefore, the optical precursor is not obvious in Figure 3b, which proves the approximate strength of wave
function and precursor propagation function is a requirement for the appearance of the optical precursor.

Applying the external dressing field, the properties of biphoton temporal correlation are investigated in Figure 4 and 5. Based on the temporal correlation of photon pairs in Figure 3a, an external dressing field \( E_3 \) with the power of 6 mW and detuning of \( \Delta_2 = -100 \) MHz is applied in Figure 4. In this case, it needs to consider the double dressing effect in linear susceptibility in Equation (4). Therefore, the group delay \( \tau_g \) becomes smaller and the corresponding correlation time is about 2.5 ns in Figure 4a. Moreover, due to the slow-light effect with the external dressing field, the optical precursor propagation is separated from the triangular main wave packet. In Figure 4b, the detuning of \( E_3 \) is changed to \(-200\) MHz, in which, the dressing effect of \( E_3 \) in linear susceptibility in Equation (4) becomes smaller than it in Figure 4a. In this case, compared with Figure 4a, the main wave packet has a larger group delay \( \tau_g \) and longer correlation time. Therefore, adding the external dressing field is an efficient method for manipulating and shaping the biphoton temporal waveforms.

In the group delay region, a very important parameter is optical depth, which can manipulate the group velocity and group delay efficiently. In Figure 5, a higher OD is used by increasing the temperature of the vapor cell to 115 °C. In this case, the OD obtains the value of 640 with \( \Delta \omega_2 = 582 \) MHz and \( N = 1.29 \times 10^{13} \) cm\(^{-3} \). Compared with Figure 4b, the group delay \( \tau_g \) with a higher value of OD becomes larger in Figure 5a. Also, the wave packet of biphoton temporal correlation with exponential decay shape in Equation (8) has a longer correlation time of nearly 70 ns. A higher value of OD not only can increase the group delay of the wave packet but also can enhance the nonlinear reaction of FWMP. Therefore, the wave function \( \Psi_0(\tau) \) becomes very larger than precursor propagation function \( \Psi_{SB}(\tau) \), and the optical precursor is switching in the main wave packet with dispersion. From Figure 5b–d, the power of \( E_3 \) is increased to 15, 20, and 30 mW, respectively. Therefore, the dressing effect of \( E_3 \) and the nonlinear reaction become stronger in FWMP. And the temporal correlation of biphoton is shaped from the group delay region to the Rabi oscillation region and even superposed of them. In Figure 5b, the wave packet mainly contributes from the group delay region and weaker nonlinear Rabi oscillation, and the exponential decay is resulting from the EIT loss. In Figure 5c, the wave packet mainly contributes

![Figure 3. Two-photon coincidence counting measurements. a) Collected over 100 s; \( P_1 = 4 \) mW, \( P_2 = 8 \) mW, \( \Delta_1 = -1.8 \) GHz, \( \Delta_2 = -100 \) MHz; b) same with (a), but changed the power of coupling field \( E_1 \) as 10 mW.](image)

![Figure 4. Two-photon coincidence counting measurements. Same with Figure 3a, but applied \( E_3 \) with power of 6 mW; a) set the detuning of \( E_3 \) as \(-100\) MHz; b) changed the detuning of \( E_3 \) as \(-200\) MHz.](image)
from the nonlinear Rabi oscillation and weaker slow-light effect, and the decay is resulting from the nonlinear loss. In Figure 5, the temporal correlation of biphoton is changed to Rabi oscillation region and behaved as periodic Rabi oscillation. In this case, Rabi oscillation is resulting from the interference among different channels of biphotons generation.\cite{8,10–12,17–20,28,29} The oscillation period and correlation time are about 7 and 49 ns in Figure 5d. And the calculated oscillation period and damping rate can be obtained in the study by Li et al.\cite{20} Therefore, waveshaping of the photon pair state provides powerful methods for the observation of different properties of biphoton temporal correlation.

5. Conclusion

In conclusion, we studied the dressing manipulated biphoton temporal correlation in a hot atomic ensemble. Based on the slow-light and single or double dressing effects, the optical precursor-like propagations, with the almost square-type temporal waveforms, sharp decaying profile, and triangular wave packets, are observed in the group delay region. In addition, a large detuning of pump field and appropriate value of optical depth are requirements for the appearance of the optical precursor in a hot atomic system. Moreover, with a higher optical depth, a longer correlation time is observed, which has the advantage to encode quantum information. By increasing the dressing coupling effect, the temporal correlation of biphoton is shaped from the group delay region to the Rabi oscillation region and even superposed of them. Therefore, waveshaping of the biphoton state has the potential for applications in quantum information processes and quantum memory.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data available on request from the authors.
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