

Construction of quantum bisource based on dressed-state-assisted photon blockade effect

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A simple scheme that could contribute to the construction of quantum double sources effectively is proposed and numerically verified. The scheme could be constructed by a four-wave-mixing system under a weak driving, in which the same-frequency single-photon and two-photon blockade effects could be realized simultaneously based on a blockade mechanism referred to as dressed-state-assisted photon blockade. The advantages of this mechanism over conventional and unconventional photon blockades are revealed, which could contribute to improve the purity and brightness of quantum bisources effectively. All of these make the construction of quantum bisource possible and would open a route to design simple and efficient quantum sources.

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I. INTRODUCTION

With the rapid development of quantum technologies, the study of photon sources has become a conspicuous focus in quantum optics and quantum information science [1–5]. The photon blockade effect, which is one of the effective ways to construct stable photon sources, was first proposed in 1997 [6]. It describes a phenomenon that the presence of photons inside the cavity blocks the entry of subsequent photons. Up to now, this effect has been investigated extensively and different kinds of schemes have been proposed to create and manipulate it [7–24]. In most studies, the realization of this effect is based on two main mechanisms: conventional photon blockade and unconventional photon blockade. The former mechanism arises from the anharmonic energy ladders of the system [25–31] and the latter one is enabled by the destructive interference between different paths [32–39].

In recent studies, results show that different kinds of blockades, such as single-photon, two-photon, or multiphoton blockades, could be achieved in one scheme by adjusting the parameters of the system, for example, changing the driving objects [40], changing the driving types [41], changing the relative coupling strength [42], and so on. In order to improve the effectiveness of the scheme, we focus on how to realize different kinds of blockades in one scheme simultaneously, which would contribute to the construction of quantum double or multiple sources and have wider applications in experiments and applications. We propose a simple and effective scheme that could realize same-frequency single-photon and two-photon blockade effects simultaneously and contribute to the construction of same-frequency quantum bisources. The realization of this effect results from the

superposition of dressed states of the system. We refer to this mechanism as dressed-state-assisted photon blockade. This mechanism shows significant advantages over conventional and unconventional photon blockades, which could contribute to enhance the purity and brightness of quantum bisources effectively.

Besides, based on this mechanism, the same-frequency single-photon and two-photon blockade effects in this scheme could persist over an extensive range of frequencies of classical driving, which could reduce the requirements for the monochromaticity and linewidth of the driving laser greatly. In addition to the same-frequency single-photon and two-photon sources, other different kinds of quantum bisources or multisources could also be constructed based on this mechanism.

II. MODEL

The scheme could be constructed by a four-wave-mixing system [43–46] under a weak driving, for example, a double-cavity structure, as shown in Fig. 1(a). In a rotating frame at driving frequency ω_l , the effective Hamiltonian of the system could be given as

$$\begin{aligned} \hat{H}_{\text{eff}} = & \Delta_a \hat{a}^\dagger \hat{a} + \Delta_b \hat{b}^\dagger \hat{b} + \Delta_c \hat{c}^\dagger \hat{c} + J(\hat{a}^{\dagger 2} \hat{b} \hat{c} + \hat{a}^2 \hat{b}^\dagger \hat{c}^\dagger) \\ & + \varepsilon_a (\hat{a}^\dagger + \hat{a}), \end{aligned} \quad (1)$$

where $\hat{a}^\dagger(\hat{a})$, $\hat{b}^\dagger(\hat{b})$, and $\hat{c}^\dagger(\hat{c})$ represent the creation (annihilation) operators of modes a , b , and c , respectively. J describes four-wave-mixing interaction. $\Delta_a = \omega_a - \omega_l$, $\Delta_b = \omega_b - \omega_l$, and $\Delta_c = \omega_c - \omega_l$ denote the detunings between the cavity modes and the driving field, and $2\Delta_a = \Delta_b + \Delta_c$. ε_a is the driving strength of the pump field. Under the weak driving limit, by diagonalization of the effective Hamiltonian we could get the eigenfrequencies and eigenstates of the system for the ground state and the first-, second-, third-, and fourth-excited states as

$$\omega^{(0)} = 0, \quad |\psi^{(0)}\rangle = |000\rangle, \quad (2)$$

$$\omega_0^{(1)} = \Delta_a, \quad |\psi^{(1)}\rangle = |100\rangle, \quad (3)$$

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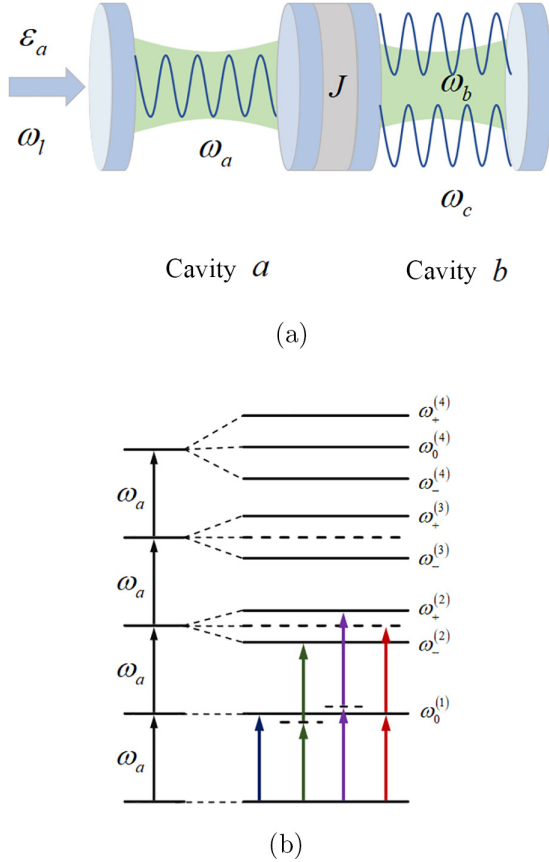


FIG. 1. (a) Sketch of the four-wave-mixing system under a weak driving setup. (b) Schematic energy-level diagram of this system.

$$\omega_{\pm}^{(2)} = 2\Delta_a \pm \sqrt{2}J, \quad |\psi_{\pm}^{(2)}\rangle = \frac{1}{\sqrt{2}}(|200\rangle \pm |011\rangle), \quad (4)$$

$$\omega_{\pm}^{(3)} = 3\Delta_a \pm \sqrt{6}J, \quad |\psi_{\pm}^{(3)}\rangle = \frac{1}{\sqrt{2}}(|300\rangle \pm |111\rangle), \quad (5)$$

$$\omega_0^{(4)} = 4\Delta_a, \quad |\psi_0^{(4)}\rangle = \frac{1}{\sqrt{5}}(-\sqrt{2}|400\rangle + \sqrt{3}|022\rangle), \quad (6)$$

$$\omega_{\pm}^{(4)} = 4\Delta_a \pm 2\sqrt{5}J, \quad |\psi_{\pm}^{(4)}\rangle = \pm \frac{\sqrt{3}}{\sqrt{10}}|400\rangle + \frac{1}{\sqrt{2}}|211\rangle \pm \frac{1}{\sqrt{5}}|022\rangle, \quad (7)$$

where $|n_a, n_b, n_c\rangle$ denote the Fock basis with n_a, n_b, n_c the photon numbers of the cavity modes.

III. ANALYTICAL CALCULATIONS

Usually, the zero-delay-time correlation functions are used to characterize the quantum statistics of photons. The single-photon blockade in cavity a happens when the two-order correlation function $g_a^{(2)}(0) = \langle \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} \rangle / \langle \hat{a}^\dagger \hat{a} \rangle^2 < 1$, while the two-photon blockade in cavity b occurs when the autocorrelated function of the photon pair [47–51] $g_{bc}^{(2)}(0) = \langle \hat{b}^\dagger \hat{c}^\dagger \hat{b}^\dagger \hat{c}^\dagger \hat{b} \hat{c} \rangle / \langle \hat{b}^\dagger \hat{c}^\dagger \hat{b} \hat{c} \rangle^2 < 1$. Under the weak-driving limit, the wave function of the system can be

approximately written as

$$|\psi\rangle = C_{000}|000\rangle + C_{100}|100\rangle + C_{200}|200\rangle + C_{011}|011\rangle + C_{300}|300\rangle + C_{111}|111\rangle + C_{400}|400\rangle + C_{211}|211\rangle + C_{022}|022\rangle, \quad (8)$$

where the bare-state basis has been truncated to the fourth-excitation states [52,53]. Adopting dressed-state representation, the wave function could be rewritten as

$$|\psi\rangle = D_0|\psi^{(0)}\rangle + D_1|\psi^{(1)}\rangle + D_2^+|\psi_+^{(2)}\rangle + D_2^-|\psi_-^{(2)}\rangle + D_3^+|\psi_+^{(3)}\rangle + D_3^-|\psi_-^{(3)}\rangle + D_4^0|\psi_0^{(4)}\rangle + D_4^+|\psi_+^{(4)}\rangle + D_4^-|\psi_-^{(4)}\rangle. \quad (9)$$

Considering the damping of the system, the non-Hermitian Hamilton of the system could be written as $\tilde{H} = \hat{H}_{\text{eff}} - (i\kappa_a/2)\hat{a}^\dagger\hat{a} - (i\kappa_b/2)\hat{b}^\dagger\hat{b} - (i\kappa_c/2)\hat{c}^\dagger\hat{c}$. By solving the Schrödinger equation $i\partial_t|\psi\rangle = \tilde{H}|\psi\rangle$, we could get the expressions of all the coefficients in the wave function (see the Supplemental Material [54]). Then, the photon-number distributions and the zero-time-delay correlation functions could be expressed as

$$P_{100} = |C_{100}|^2 = |D_1|^2, \quad (10)$$

$$P_{200} = |C_{200}|^2 = \frac{1}{2}|D_2^+|^2 + \frac{1}{2}|D_2^-|^2 + \text{Re}(D_2^+ D_2^{-*}), \quad (11)$$

$$P_{011} = |C_{011}|^2 = \frac{1}{2}|D_2^+|^2 + \frac{1}{2}|D_2^-|^2 - \text{Re}(D_2^+ D_2^{-*}), \quad (12)$$

$$P_{022} = |C_{022}|^2 = \frac{1}{5}|D_4^+|^2 + \frac{3}{5}|D_4^0|^2 - \frac{2\sqrt{3}}{5}\text{Re}(D_4^+ D_4^{0*}) + \frac{1}{5}|D_4^-|^2 - \frac{2}{5}\text{Re}(D_4^+ D_4^{-*}) + \frac{2\sqrt{3}}{5}\text{Re}(D_4^0 D_4^{-*}), \quad (13)$$

$$g_a^{(2)}(0) = \frac{\langle \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2} \approx \frac{2P_{200}}{P_{100}^2}, \quad (14)$$

$$g_{bc}^{(2)}(0) = \frac{\langle \hat{b}^\dagger \hat{c}^\dagger \hat{b}^\dagger \hat{c}^\dagger \hat{b} \hat{c} \rangle}{\langle \hat{b}^\dagger \hat{c}^\dagger \hat{b} \hat{c} \rangle^2} \approx \frac{4P_{022}}{P_{011}^2}. \quad (15)$$

IV. CONVENTIONAL PHOTON BLOCKADE

For the single-photon blockade effect in cavity a , as shown in Fig. 1(b), if the transition of $0 \rightarrow \omega_0^{(1)}$ is resonant, the transition of $\omega_0^{(1)} \rightarrow \omega_{\pm}^{(2)}$ is detuned. Thus, the conventional single-photon blockade could be realized in cavity a with the optimal condition $\Delta_a = 0$.

For the two-photon or photon-pair blockade effect in cavity b , as shown in Fig. 1(b), if the two-photon transition of $0 \rightarrow \omega_{\pm}^{(2)}$ is resonant, the transition of $\omega_{\pm}^{(2)} \rightarrow \omega_0^{(4)}, \omega_{\pm}^{(4)}$ is detuned. Thus, the conventional two-photon or photon-pair blockade could be realized in cavity b with the optimal condition $\Delta_a = \pm J/\sqrt{2}$.

In order to confirm the above analytical calculation and the corresponding analysis, we study the photon blockade effect in the system numerically. In numerical simulation, the expectation value of any operator $\hat{O}$ could be obtained by $\langle \hat{O} \rangle = \text{Tr}(\hat{O}\hat{\rho}_{ss})$ with $\hat{\rho}_{ss}$ the steady-state solution of the

master equation, that is,

$$\begin{aligned} \frac{d\hat{\rho}}{dt} = & -i[\hat{H}_{\text{eff}}, \hat{\rho}] + \frac{\kappa_a}{2}[2\hat{a}\hat{\rho}\hat{a}^\dagger - \hat{\rho}\hat{a}^\dagger\hat{a} - \hat{a}^\dagger\hat{a}\hat{\rho}] \\ & + \frac{\kappa_b}{2}[2\hat{b}\hat{\rho}\hat{b}^\dagger - \hat{\rho}\hat{b}^\dagger\hat{b} - \hat{b}^\dagger\hat{b}\hat{\rho}] \\ & + \frac{\kappa_c}{2}[2\hat{c}\hat{\rho}\hat{c}^\dagger - \hat{\rho}\hat{c}^\dagger\hat{c} - \hat{c}^\dagger\hat{c}\hat{\rho}]. \end{aligned} \quad (16)$$

Figures 2(a) and 2(b) give the plots of $g_a^{(2)}(0)$ and $g_{bc}^{(2)}(0)$ as a function of Δ_a/κ , respectively. All the parameters have been rescaled with respect to the decay rate κ . Both the numerical and analytical results are given in these figures, denoted by the blue dashed line and the red solid line, respectively. The results show that they agree with each other. Figure 2(c) displays the numerical results of photon-number distributions P_{100} (the blue dotted line), P_{200} (the green dashed line), and P_{011} (the red solid line) as a function of Δ_a/κ , under the same parameters adopted in Figs. 2(a) and 2(b). For the single-photon blockade effect in cavity a , as shown in Fig. 2(a), the blockade effect could occur when the optimal condition satisfies $\Delta_a = 0$. Besides, as shown in Fig. 2(c), the probability of single-photon excitation P_{100} would reach its local maximum value under this optimal condition. These results indicate the occurrence of conventional single-photon blockade at $\Delta_a = 0$ in cavity a [55]. For the two-photon or photon-pair blockade effect in cavity b , as shown in Fig. 2(b), the blockade effect could appear under optimal condition $\Delta_a = \pm J/\sqrt{2}$. Besides, as shown in Fig. 2(c), the probability of two-photon or photon-pair excitation P_{011} would reach its local maximum value under this optimal condition. These results indicate the appearance of conventional two-photon or photon-pair blockade at $\Delta_a = \pm J/\sqrt{2}$ in cavity b .

V. DRESSED-STATE-ASSISTED PHOTON BLOCKADE

For the two-photon or photon-pair blockade effect in cavity b , as shown in Fig. 2(b), the blockade effect could also appear under optimal condition $\Delta_a = 0$. Different from conventional photon blockade, the blockade effect under this condition results from the superposition of the dressed states, that is, the dressed-state-assisted quantum interference effect. This effect not only determines the two-photon or photon-pair blockade in cavity b under optimal condition $\Delta_a = 0$, but also contributes to the single-photon blockade in cavity a under the same condition. Specifically, the photon-number distributions and the correlation functions illustrate the role of quantum interference between the probability amplitudes of the dressed states. For example, as given in Eqs. (11) and (12), the terms $\pm \text{Re}(D_2^+ D_2^{-*})$ reveal the influences of the quantum interference between the probability amplitudes of the two-photon dressed states $|\psi_+^{(2)}\rangle$ and $|\psi_-^{(2)}\rangle$ on the photon-number distributions P_{200} and P_{011} . Under optimal condition $\Delta_a = 0$, as shown in Fig. 2(c), the probability of P_{200} is lower than P_{011} , which indicates that the dressed-state-assisted interference is destructive and constructive for the probabilities P_{200} and P_{011} , respectively. For the photon blockade effect in cavity a , under optimal condition $\Delta_a = 0$, the destructive quantum interference suppresses the two-photon excitation, so the single-photon blockade effect is enhanced by the dressed-state-assisted interference. For the photon blockade effect

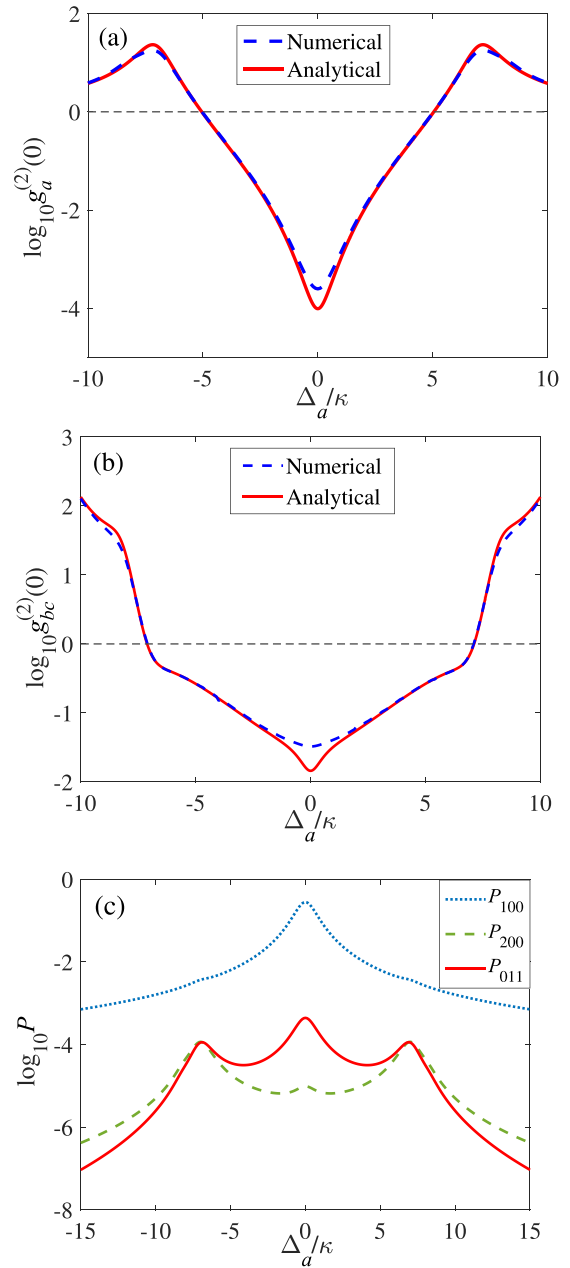


FIG. 2. (a) The second-order correlation function $g_a^{(2)}(0)$ as a function of Δ_a/κ . (b) The autocorrelation function $g_{bc}^{(2)}(0)$ as a function of Δ_a/κ . The red solid line and the blue dashed line denote the analytical and numerical results, respectively. (c) The photon-number distributions P_{100} (the blue dotted line), P_{200} (the green dashed line), and P_{011} (the red solid line) as a function of Δ_a/κ . The shared parameters are $J/\kappa = 10$, $2\Delta_a = \Delta_b + \Delta_c$, $2\kappa_a = \kappa_b = \kappa_c = 2\kappa$, and $\varepsilon_a/\kappa = 0.4$.

in cavity b , the interference assisted by the dressed states contributes to the two-photon absorption and the two-photon excitation is enhanced by the constructive quantum interference, so the two-photon or photon-pair blockade could occur under optimal condition $\Delta_a = 0$. It is evident that this blockade mechanism is attributed to the superposition of the dressed states, so we refer to it as dressed-state-assisted photon blockade.

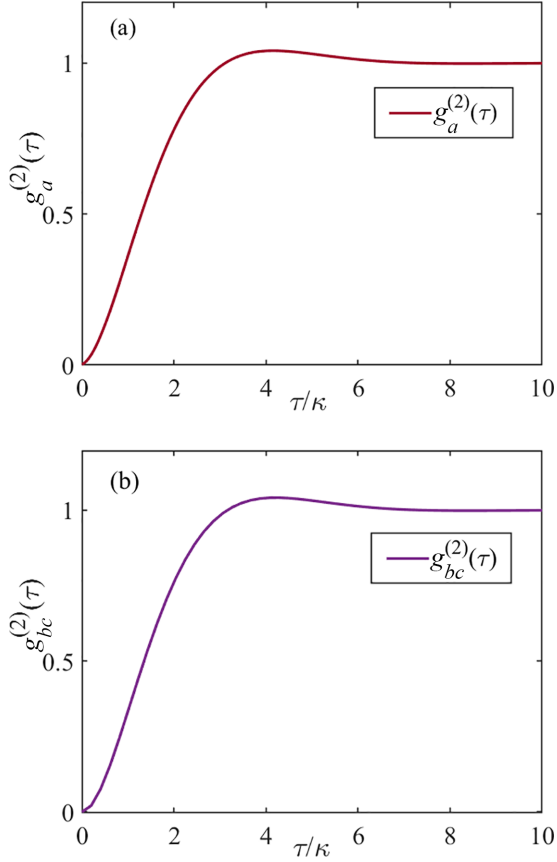


FIG. 3. (a) The time-delay correlation function $g_a^{(2)}(\tau)$ as a function of τ/κ . (b) The time-delay autocorrelation function $g_{bc}^{(2)}(\tau)$ as a function of τ/κ . The shared parameters are $J/\kappa = 6$, $\Delta_a = \Delta_b = \Delta_c = 0$, $2\kappa_a = \kappa_b = \kappa_c = 2\kappa$, and $\varepsilon_a/\kappa = 0.4$.

Based on this blockade mechanism, the single-photon blockade effect in cavity a and two-photon or photon-pair blockade effect in cavity b could be realized simultaneously under optimal condition $\Delta_a = 0$. Figures 3(a) and 3(b) give the plots of delay-time correlation functions $g_a^{(2)}(\tau)$ and $g_{bc}^{(2)}(\tau)$ as a function of τ/κ at $\Delta_a = 0$, respectively. The results further indicate the occurrence of the single-photon and two-photon blockades in this scheme at $\Delta_a = 0$. Evidently, under this condition, the frequencies of blocked single-photon and two-photon could be the same, which could contribute to the construction of same-frequency bisources effectively. Besides, under this condition, the frequency of classical driving needed is equal to the cavity resonant frequency and is independent of the four-wave-mixing coupling strength, which would be much easier to control in experiments and applications.

The conventional photon blockade comes from increasing the excitation of single-photon state, so the single-photon sources generated by it usually have high brightness but with relatively poor purity. The unconventional photon blockade effect results from inhibiting the excitation of two-photon state by destructive quantum interference and its ability to excite the single-photon state is weak, so the single-photon sources generated by it usually have high purity but with relatively poor brightness. However, different from conventional

and unconventional photon blockades, the dressed-state-assisted photon-pair blockade at $\Delta_a = 0$ in cavity b results from the increase of single-photon-pair excitation by the constructive quantum interference, which combines the advantages of both conventional and unconventional photon blockades and could contribute to construct the photon-pair sources with high purity and high brightness simultaneously. As shown in Figs. 2(b) and 2(c), the value of the two-order correlation function $g_{bc}^{(2)}(0)$ at $\Delta_a = 0$ is much lower than that at $\Delta_a = \pm J/\sqrt{2}$, and the value of the probability of single-photon-pair excitation P_{011} at $\Delta_a = 0$ is much larger than that at $\Delta_a = \pm J/\sqrt{2}$, which indicates the superiority of this mechanism over conventional and unconventional photon blockades. That is, it could contribute to the construction of quantum bisources with much higher purity and much higher brightness.

Similarly, as shown in Fig. 2(b), due to the dressed-state-assisted photon blockade effect, the two-photon or photon-pair blockade could also occur over the detuning range from $\Delta_a = -J/\sqrt{2}$ to $\Delta_a = J/\sqrt{2}$ in cavity b . Combining the conventional and dressed-state-assisted photon blockade effects, the same-frequency single-photon and two-photon blockade could persist over an extensive detuning range between the driving frequency and the cavity resonant frequency in this scheme, as shown in Figs. 2(a) and 2(b). That is, this scheme could realize same-frequency single-photon and two-photon blockades over an extensive range of frequencies of classical driving, or even under continuously tunable driving. This could reduce the requirements for the monochromaticity and linewidth of the driving laser greatly.

Besides, based on this mechanism, other different kinds of quantum bisources or multisources could also be constructed, for example, the two single-photon sources, in which one source is a simple single-photon source and the other one is a second-harmonic single-photon source [54]. This is also an example of the application of this mechanism in single-photon blockade. The dressed-state-assisted single-photon blockade of the second-harmonic mode results from increasing the excitation of single-photon state by constructive quantum interference, which combines the advantages of both conventional and unconventional photon blockades and could also overcome their shortcomings. This mechanism provides a way of improving the purity and brightness of single-photon sources effectively.

VI. CONCLUSIONS

We have proposed a simple and effective theoretical scheme to construct same-frequency quantum bisources based on photon blockade effect. The blockade mechanism arises from superposition of dressed states and is referred to as dressed-state-assisted photon blockade effect. It has been analytically and numerically demonstrated that the same-frequency single-photon and two-photon blockade effects could be realized simultaneously in this scheme. The superiority of this mechanism over conventional and unconventional photon blockades has also been revealed, which could contribute to the effective enhancement of the purity and brightness of quantum bisources. Besides, it has been found that the blockade effect could persist over a wide range of

frequencies of classical driving in this scheme, which could lower the demand of the monochromaticity and linewidth of the driving laser greatly. In addition to the same-frequency single-photon and two-photon sources, this mechanism could also be applied to construct other different kinds of quantum bisources or multisources. These findings would have wide applications and be highly significant in the development of quantum sources.

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DATA AVAILABILITY

The data supporting this study's findings are available within the article.

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