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Coherence-protected operations in hybrid superconducting circuit-magnon system

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Hybrid systems consisting of superconducting circuits and magnon systems are a promising platform for quantum technology. However, realizing high-fidelity magnon state preparation and manipulation remains an outstanding challenge due to the complexity of interactions and noise sources in hybrid systems. Here, we propose a coherence-preserving magnon state manipulation scheme. By engineering a superconducting-magnon coupling pulse and combining it with dynamical decoupling pulses, we design a composite pulse sequence. We demonstrate the manipulation and preparation of non-classical states of magnons with a fidelity of up to 98% under realistic conditions. These designs significantly improve the fidelity of manipulation and robustness to noise in hybrid systems compared to existing schemes. These results pave the way for practical applications of quantum magnonics platforms.

Keywords: circuit QED, quantum information with hybrid systems, entanglement production

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1. Introduction

Magnon states are collective spin excitations in magnetically ordered materials. Manipulation of them can provide promising candidates for applications in quantum information processing and quantum sensing.[1–4] The large number of collective spins leads to a large strength of magnetic dipolar interactions. Using this interaction, a strong coupling between magnon modes in a magnet and photon modes in a cavity can be realized, which gives rise to an interesting direction, cavity magnonics.[5–10]

Further, a three-component hybrid system consisting of superconducting qubits, photons, and magnons has attracted wide interest. In this setup, the effective coherent coupling between superconducting qubits and magnons is achieved by utilizing virtual photons in the cavity as a mediator. On this basis, the field of quantum magnonics has been intensively investigated.[11–18] In exploring exotic phenomena, for example, strong interactions between qubits and magnons can prevent the simultaneous excitation of multiple magnons such that the correlation function of the magnons exhibits a non-classical anti-bunching effect, indicating the occurrence of magnon blockade.[15] Moreover, the interference between coherent and dissipative couplings can lead to a dependence of the statistics of the magnons on the propagation direction of the driving field, which can be used to construct non-reciprocal magnon devices.[16] In aspects of quantum state preparation, tripartite entangled states can be prepared by utilizing higher-order processes, such as annihilating an atomic excitation to simultaneously excite a photon and a magnon.[17] Alternatively, stable tripartite entangled states can be generated by exploiting dissipative couplings, such as cooperative jump processes between qubits, photons and magnons.[18] In aspects of applications, using auxiliary superconducting qubits, single shot readout of a magnon can be achieved, demonstrating a prototype single magnon detector similar to a single photon detector.[13] These exciting advances pave the way for a wide range of applications based on versatile quantum magnonics.

Despite these advances, the preparation and manipulation of magnon states with high fidelity remains an outstanding challenge. For example, in a recent study,[13] entanglement between superconducting qubits and magnon modes was utilized to enhance the performance of quantum sensing, but the corresponding fidelity was only 71%. High-fidelity control of magnon states is a highly desirable but challenging goal under current experimental conditions. These challenges include: First, a hybrid platform for quantum magnonics usually includes multiple subsystems, such as superconducting qubits, superconducting microwave cavities, and magnon systems. Such a large number of degrees of freedom have various noise sources and decoherence channels, which will in-

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troduce corresponding errors during the manipulation of the hybrid system. Second, some methods have been developed to address the effects of noise and fluctuations, such as dynamical decoupling (DD) pulses. However, current DD pulses are mainly designed for individual two-level systems.[19–27] In contrast, hybrid systems usually have multiple degrees of freedom and complex energy level structures and interactions. Further, DD pulses decouple a quantum system from its environment and other quantum systems simultaneously, so DD pulses conflict with the interactions between different quantum systems. Thus it is difficult to combine DD pulses with gate operations in a hybrid system.

Here, we present a scheme for high-fidelity manipulation of magnon states in a hybrid superconducting circuit–magnon system. We tune the coupling strength between superconducting qubits and magnons by adjusting the frequency of superconducting qubits. Then, we design the amplitude and time interval of the coupling pulse and match it with the DD pulse. This composite pulse sequence protects the coherence of the hybrid system as well as effectively manipulates the magnon states. Using this coherence-protected gate operation, we demonstrate that the Fock and superposition states of magnons can be prepared with a fidelity of up to 98% under realistic parameter conditions, which is a significant improvement over previously reported results on the fidelity of magnon states. In addition, we also show the robustness of this method to various noises and fluctuations and the ability to faithfully encode quantum information into the magnon states. These results provide a powerful and convenient toolbox for the development of the field of quantum magnonics.

We note an important recent work in magnon state manipulation.[14] By applying a continuous driving field, a superconducting qubit is dressed into Autler–Townes doublet states. This enables a frequency tunable qubit by varying the amplitude of the driving field. When the hybrid system is tuned to the resonant coupling regime, rapid preparation and manipulation of single magnon states can be implemented. Compared to this study,[14] our scheme is different in two ways: first, we apply discrete DD control pulses instead of a continuous driving field. Second, we utilize alternately switching on and off the resonant coupling rather than being in the resonant coupling regime all the time, which is the way to match the DD control pulse. Since DD pulse is an intensively studied quantum control method, it has excellent flexibility and tunability. By changing the control parameters such as amplitude and time of the DD pulse, better resistance to noise and higher operation fidelity can be achieved, which is an advantage of our scheme.

2. Setup and models

As shown in Fig. 1, the hybrid system we consider consists of three components: a superconducting qubit, a superconducting microwave resonator cavity, and a ferrinagnetic crystal of yttrium iron garnet (YIG). The superconducting qubit is of the typical transmon type, consisting of a single island capacitor and two parallel Josephson junctions. The Hamiltonian of the superconducting system can be written as[28–30]

$$H_{\rm s}^{0} = 4E_{\rm c}(\hat{n}-\hat{n}_{\rm g})^2 - E_{\rm J}\cos\hat{\varphi}, \tag{1}$$

where $\hat{n}$ and $\hat{\varphi}$ denote the charge number operator on the junction and the phase difference operator across the junction, and $E_{\rm c}$ and $E_{\rm J}$ are the charging energy and Josephson tunneling energy of the junction. We diagonalize this Hamiltonian and consider only the two lowest energy levels $|g\rangle$ and $|e\rangle$. Since the energy level structure has a large anharmonicity, we can neglect the other higher energy levels. In this way we obtain the Hamiltonian of the superconducting qubit

$$H_{\rm s} = \frac{1}{2}\omega_{\rm s}\sigma_z, \tag{2}$$

where $\omega_{\rm s}$ is the transition frequency of the qubit and σ_z is the Pauli operator. We note that by controlling the magnetic flux in the superconducting loop, the transition frequency of the superconducting qubits can be easily adjusted to bring the hybrid system into the corresponding operating regime.

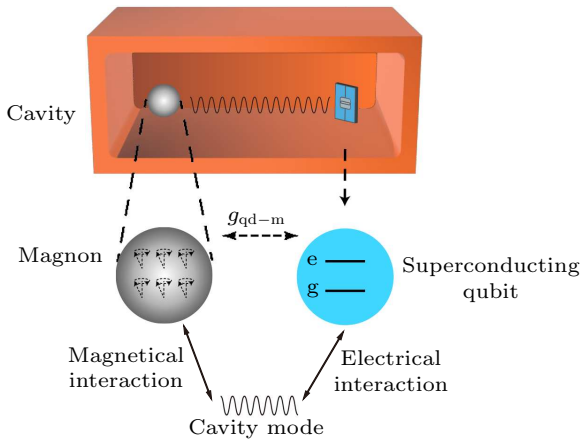


Fig. 1. Schematic diagram of the superconducting–magnon hybrid architecture. The hybrid system integrates three different quantum systems: a superconducting qubit and a micromagnet, which are coupled to a common microwave cavity.

For a superconducting microwave resonator cavity, the Hamiltonian can be written as

$$H_{\rm c} = \omega_{\rm c} a^{\dagger} a, \tag{3}$$

where $a^{\dagger}$ and a are the creation and annilation operators of the photon modes in the cavity, and $\omega_{\rm c}$ is their frequency. For a YIG magnet, the Hamiltonian can be similarly written as

$$H_{\rm m} = \omega_{\rm m} c^{\dagger} c, \tag{4}$$

where $c^\dagger$ and c are the creation and annihilation operators of the magnon modes and $\omega_{\rm m}$ is their frequency.

In this hybrid system, the microwave cavity plays the role of an intermediate interface. The superconducting qubit and the cavity are coupled through an electric-dipole interaction and their interaction Hamiltonian can be described as[13]

$$H_{\rm s-c} = g_{\rm s-c}(\sigma^- a^\dagger + \sigma^+ a), \tag{5}$$

where $g_{\rm s-c}$ is the coupling strength. On the other hand, the magnon and photon modes are coupled through a magnetic-dipole interaction and the interaction Hamiltonian is described as[13]

$$H_{\rm m-c} = g_{\rm m-c}(ca^\dagger + c^\dagger a), \tag{6}$$

where $g_{\rm m-c}$ is the corresponding coupling strength.

Putting things together, we get the total Hamiltonian of the hybrid system as

$$\begin{aligned} H_{\rm t} =& \frac{1}{2}\omega_{\rm s}\sigma_z + \omega_{\rm c}a^\dagger a + g_{\rm s-c}(\sigma^- a^\dagger + \sigma^+ a) \\ &+ \omega_{\rm m}c^\dagger c + g_{\rm m-c}(ca^\dagger + c^\dagger a). \end{aligned} \tag{7}$$

When both the qubit and magnon frequencies are substantially detuned from the frequency of the cavity, an effective interaction between the qubit and the magnon can be produced by exchanging virtual photons.

In order to obtain the effective Hamiltonian explicitly, we use the Schrieffer–Wolff transformation technique.[13,16] First we write the total Hamiltonian as the sum of the free and perturbation parts

$$\begin{aligned} H_{\rm t} =& H_0 + H_{\rm int}, \\ H_0 =& \frac{1}{2}\omega_{\rm s}\sigma_z + \omega_{\rm c}a^\dagger a + \omega_{\rm m}c^\dagger c, \\ H_{\rm int} =& g_{\rm s-c}(\sigma^- a^\dagger + \sigma^+ a) + g_{\rm m-c}(ca^\dagger + c^\dagger a). \end{aligned} \tag{8}$$

Then we apply a unitary transformation $U = \exp(S)$, which gives

$$H_{\rm eff} = U^\dagger H_{\rm t} U = H_0 + \frac{1}{2}[H_{\rm int}, S] + \cdots. \tag{9}$$

In order to eliminate the cavity field term, we choose the unitary transformation as

$$S = \frac{g_{\rm s-c}}{\Delta_{\rm s-c}}(\sigma^- a^\dagger - \sigma^+ a) + \frac{g_{\rm m-c}}{\Delta_{\rm m-c}}(ca^\dagger - c^\dagger a), \tag{10}$$

where $\Delta_{\rm s-c} = \omega_{\rm s} - \omega_{\rm c}$, $\Delta_{\rm m-c} = \omega_{\rm m} - \omega_{\rm c}$ are the frequency detuning between the qubit, the magnon, and the cavity field, respectively.

Since S satisfies the condition $H_{\rm int} + [H_0, S] = 0$, up to the second order of the perturbation theory, we obtain an approximate expression for the effective Hamiltonian

$$\begin{aligned} H_{\rm eff} \approx& H_0 + \frac{1}{2}[H_{\rm int}, S] \\ =& \frac{1}{2}\omega_{\rm s}^{(0)}\sigma_z + \omega_{\rm m}^{(0)}c^\dagger c + g(\sigma^- c^\dagger + \sigma^+ c) \\ &+ \left(\omega_{\rm c} - \frac{g_{\rm m-c}^2}{\Delta_{\rm m-c}} + \frac{g_{\rm s-c}^2}{\Delta_{\rm s-c}}\sigma_z\right)a^\dagger a. \end{aligned} \tag{11}$$

Here

$$g = \frac{1}{2}g_{\rm s-c}g_{\rm m-c}\left(\frac{1}{\Delta_{\rm s-c}} + \frac{1}{\Delta_{\rm m-c}}\right)$$

is the effective coupling strength between the qubit and magnon, $\omega_{\rm s}^{(0)} = \omega_{\rm s} + g_{\rm s-c}^2/\Delta_{\rm s-c}$ is the dressed qubit frequency and $\omega_{\rm m}^{(0)} = \omega_{\rm m} + g_{\rm m-c}^2/\Delta_{\rm m-c}$ is the dressed magnon frequency. Further, because the cavity field is large detuned from both the qubit and the magnon, the cavity field is always in a ground state with zero average photon number, $\langle a^\dagger a\rangle \approx 0$. Therefore, we obtain the effective Hamiltonian of the hybrid system as

$$H_{\rm eff} = \frac{1}{2}\Delta\sigma_z + g(\sigma^- c^\dagger + \sigma^+ c), \tag{12}$$

here $\Delta = \omega_{\rm s}^{(0)} - \omega_{\rm m}^{(0)}$ is the frequency detuning between the superconducting qubit and magnon.

3. Combining dynamical decoupling with magnon manipulations

Since the hybrid superconducting–magnon system includes multiple quantum systems, it is subject to a variety of noises and fluctuations. For example, superconducting qubits are subject to decoherence processes due to charge noise and flux noise in the environment, photon modes are subject to leakage due to imperfections of the cavity, and magnon modes are subject to decay due to coupling to a bath of two-level systems in the magnet. Additional noises and fluctuations are introduced when control pulses are applied to the hybrid system. For example, when tuning the superconducting qubit frequency, it can be sensitive to external flux noise, leading to significant errors.[14] In particular, since the manipulation time and decoherence time of each component in the hybrid system varies greatly, this creates new challenges for the design of the corresponding manipulation scheme.

Dynamical decoupling (DD) pulses have been developed to compensate for the effects of noises and fluctuations. This technique has been widely used in single quantum systems such as single ions,[22] single superconducting qubits,[23] single quantum dot systems,[24,25] and single electron spins of NV centers in diamond.[26] Compared with individual quantum systems, hybrid systems usually have complex interactions and energy level structures. In particular, if DD pulses are applied to one of the subsystems, this subsystem decouples from the environment and other subsystems simultaneously. Thus, it is difficult to combine DD pulses that protect the coherence of the hybrid system with control pulses that implement gate operations on the system. Here we designed a composite pulse sequence to address this issue. The key idea of this scheme is that the dynamics of the manipulation pulse

sequence can be adjusted to match the dynamics of the DD pulse sequence. In this way, it is possible to manipulate the hybrid system while preserving its coherence.

As shown in Fig. 2, we design a three-stage composite pulse sequence. In the first and third stages, we turn on the coupling $g(t)$ between the superconducting qubit and magnons for a duration of τ_1 and τ_3; while in the second stage, we turn off the coupling $g(t)$ between the qubit and magnons for a duration of τ_2. Between each stage, we apply a DD π pulse to the superconducting qubit. Such a composite pulse process is called the "couple–decouple–recouple" sequence. We note that the coupling strength and time interval of such a sequence can be conveniently set by adjusting the frequency of the superconducting qubit. Moreover, this composite pulse sequence can be repeated more times to obtain better coherence protection.

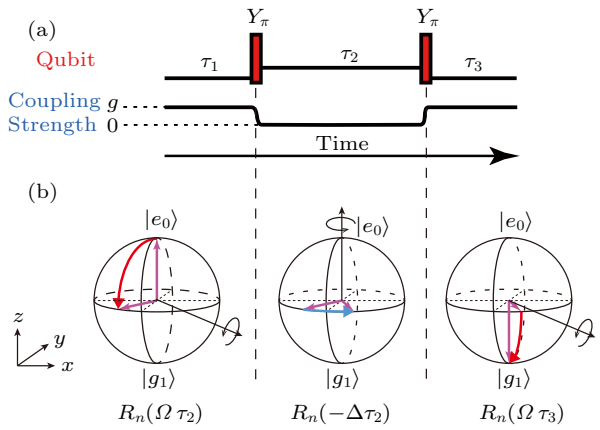


Fig. 2. (a) Designed composite pulse sequence, consisting of a three-stage sequence of tunable coupling pulses, and dynamical decoupling pulses between each two stages. (b) Bloch spheres shows the evolution during the three stages.

To better understand this composite pulse sequence, we utilize the toggling frame to describe the dynamics of the system. The control Hamiltonian for the whole hybrid system can be written as

$$H(t) = H_{\text{eff}}(t) + H_{\text{DD}}(t), \tag{13}$$

where $H_{\text{eff}}(t)$ is the time-dependent Hamiltonian of the hybrid system and $H_{\text{DD}}(t)$ is the applied DD pulse. In the toggling frame, the control Hamiltonian of the system can be re-written as

$$H(t) = U_{\text{DD}}^{+} H_{\text{eff}}(t) U_{\text{DD}}, \tag{14}$$

where $U_{\text{DD}} = \exp(-\mathrm{i}\int H_{\text{DD}}(t)\,\mathrm{d}t)$ is the evolution operator of the DD pulse. During the three stages of the composite pulse sequence, the dynamical Hamiltonian of the system can be expressed as

$$H(t) = \frac{1}{2}\Delta\sigma_z + g(t)(\sigma^- c^\dagger + \sigma^+ c), \tag{15}$$

for the first and third stages, and

$$H(t) = -\frac{1}{2}\Delta\sigma_z + g(t)(\sigma^- c + \sigma^+ c^\dagger), \tag{16}$$

for the second stage.

Further, we can establish the computational subspace with $|e_0\rangle$ and $|g_1\rangle$ and the corresponding Bloch sphere representation. As shown in Fig. 2, in the first stage the state vector of the system is rotated around the x-axis by an angle $g\tau_1/2$, then in the second stage the state vector is rotated around the z-axis, and in the third stage the state vector continues to be rotated around the x-axis by an angle $g\tau_3/2$. Thus, after these three stages, the total evolution operator of the system is

$$U = U_x(g\tau_1)U_z(\Delta\tau_2)U_x(g\tau_3). \tag{17}$$

This is a rotating operation of the superconducting–magnon hybrid system. When the rotation angle θ is chosen to be π, this realizes an SWAP operation between superconducting qubits and magnon modes. In particular, such a manipulation process also incorporates DD pulses, thus eliminating the effect of noise and preserving the coherence of the hybrid system during the gate operation.

4. Noise effects and master equation of the hybrid system

To evaluate the performance of this composite pulse sequence, we use the master equation to simulate the dynamics of the system:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\mathrm{i}[H_{\text{eff}} + \delta H, \rho] + \sum_i \gamma_i \mathcal{D}[O_i]\rho, \tag{18}$$

where ρ is the density matrix of the system, H_{eff} is the Hamiltonian of the system, and the Lindblad operator $\mathcal{D}[O]\rho = O\rho O^\dagger - (O^\dagger O\rho + \rho O^\dagger O)/2$ describes the decoherence processes due to the environment: the relaxation process $\frac{1}{T_1}\mathcal{D}[\sigma_-]\rho$ of the superconducting qubit, and the decay process $\frac{1}{T_m}\mathcal{D}[a]\rho$ of the magnon modes. In addition, during the manipulation process, the superconducting qubit is sensitive to external noises and fluctuations, which we characterize in terms of the following fluctuating Hamiltonian:

$$\delta H = \delta\Delta\sigma_z + \delta\varepsilon\sigma_x, \tag{19}$$

where the noise parameters $\delta\Delta$, $\delta\varepsilon$ are random quantities denoting longitudinal and transverse fluctuations, respectively. These two fluctuations are the main noise sources in superconducting circuits.[23,29] In realistic systems, the time scale of the fluctuations is much longer than that of the operation and thus can be approximated as quasi-static noise. We model the noise parameters $\delta\Delta$, $\delta\varepsilon$ with two Gaussian distributions, which have a mean value of zero and deviations of σ_Δ, σ_ε. In the numerical simulation of the master equation, we sample random noise parameters from the Gaussian distributions, and then repeat such calculations many times, and finally average

to obtain the results. We note that similar simulation methods have been used in various quantum dot and superconducting circuit setups.[23,29] In order to obtain a scheme that is instructive for the experiments, we use experimentally feasible control parameters and noise parameters in our simulations:[13,14] $T_1 = 0.8$ μs, $T_m = 0.3$ μs, $\sigma_\Delta = 14$ MHz, $\sigma_\varepsilon = 28$ MHz, and we adjust the control parameters $\Delta_{s-c}/2\pi = \Delta_{m-c}/2\pi = 360$ MHz, $g_{s-c}/2\pi = 120$ MHz, and $g_{m-c}/2\pi = 15$ MHz to turn on the effective coupling $g(t)/2\pi = 5$ MHz.

5. Coherence-protected manipualtion of magnon states

First we utilize this composite pulse sequence to prepare non-classical states of magnons. Starting from the excited state of the superconducting qubit and then applying a swap-type pulse sequency, the magnon Fock state $|1\rangle$ can be prepared. Repeating this operation several times, higher order Fock states $|n\rangle$ can be prepared. As shown in Fig. 3(a), we use the Wigner function of magnon states in phase space to represent the prepared states.[31,32] We also show the dynamics of the preparation process in Fig. 3(b). Currently proposed schemes for the preparation of magnon states are mainly based on the heralded measurement process, which is a probabilistic approach with low efficiency.[33,34] Our scheme, on the other hand, is a deterministic scheme that allows the preparation of magnon states on demand.

Next, we utilize this composite pulse sequence to encode quantum information into the magnon state. As shown in Fig. 3(c), starting from the initial state of the superconducting qubit $(|g\rangle - \mathrm{i}\,|e\rangle)/\sqrt{2}$, the application of a swap-type operation can prepare a superposition state of magnons $(|0\rangle - \mathrm{i}\,|1\rangle)/\sqrt{2}$. This type of superposition state is a useful resource in both phase-sensitive quantum sensing and bosonic fault-tolerant codes.[35]

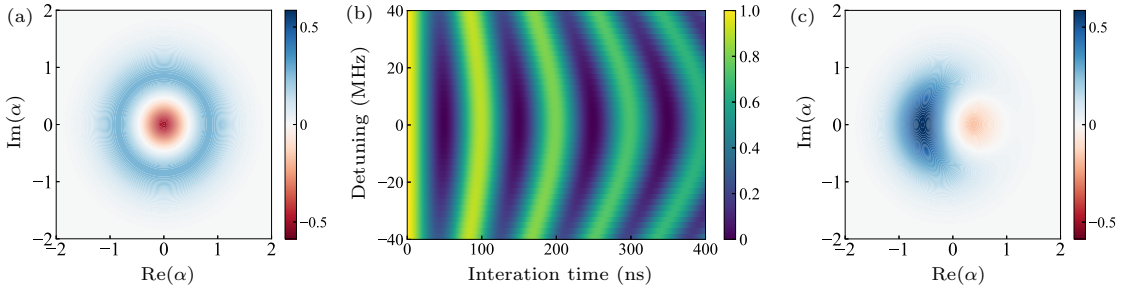


Fig. 3. (a) Wigner function shows the prepared magnon Fock state. (b) Probability of magnon states as a function of pulse time and detuning during a swapping process. (c) Wigner function shows the prepared magnon superposition state.

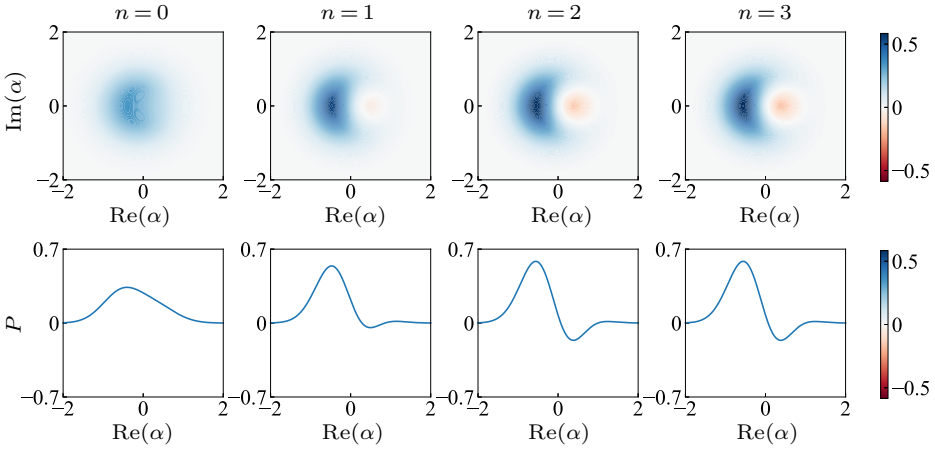


Fig. 4. The Wigner function (top row) and the cuts along the imaginary axis illustrate that the coherence of the prepared magnon superposition states is preserved as the number of pulses increases.

Now we demonstrate the protection of this composite pulse sequence on the coherence of the hybrid system. As shown in Fig. 4, we investigate the results of the application of different numbers of composite pulse sequences. When there are no DD pulses, the coherence of the system decays rapidly, leading to blurrier interference fringes in the magnon superposition state. As the operation sequence increases, the effect of noise is compensated and the coherence of the system is preserved, so that the interference fringes in the magnon superposition state are gradually clear. This is strong evidence that the coherence of the hybrid system is protected.

In order to quantitatively characterize the effect of the composite pulse sequence, we calculated the fidelity of the magnon state preparation process $F = \sqrt{\langle\Psi_1|\rho_r|\Psi_1\rangle}$.[36] Here Ψ_1 is the target state in the ideal case without noise and ρ_r is the density matrix in the realistic case with noise. As shown

in Fig. 5(a), the fidelity increases significantly from 70% to 98% as the pulse sequence increases. As the number of pulses increases, the fidelity approaches a saturation value. Further analysis shows that the state fidelity is limited by the decay time of magnon modes.

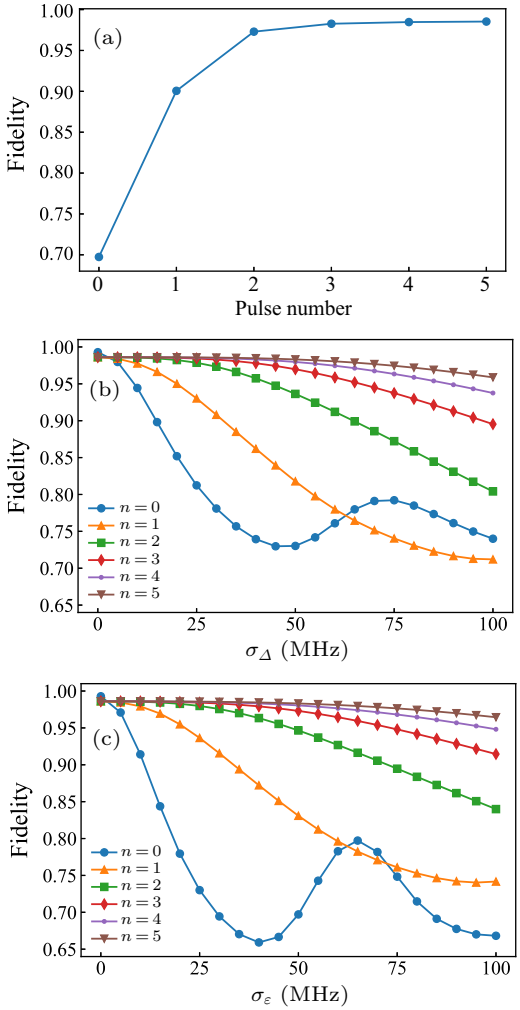


Fig. 5. (a) Magnon state preparation fidelity as a function of the number of composite pulse sequences. State preparation fidelity as a function of longitudinal noise width (b) and transverse noise width (c) for different pulse sequences.

In addition, we investigate the robustness of the composite pulse sequence to different noises. In this hybrid system, there are two main types of noise sources: longitudinal fluctuations and transverse fluctuations. Our simulations find that the pulse has a similar compensatory behavior for both types of noise. As shown in Figs. 5(b) and 5(c), even in the presence of strong fluctuations, the application of a certain number of pulse sequences suppresses their effects, thus significantly improving the fidelity.

In practical setting, the rising time of the switch coupling pulse, as well as the duration of the dynamical decoupling pulse, can have an important impact on our scheme. First, we consider switching the coupling g on/off for a certain rising time t_r. As shown in Fig. 6(a), the fidelity of the state preparation slowly decreases as the pulse rise time t_r increases. This result is understandable because there exists a small finite value of the coupling constant g during the pulse rise time, which can introduce some unwanted small errors in the evolution of the system. From the simulation results, it can be noticed that the fidelity remains at a large value 96% when t_r is large and when multiple pulses are applied.

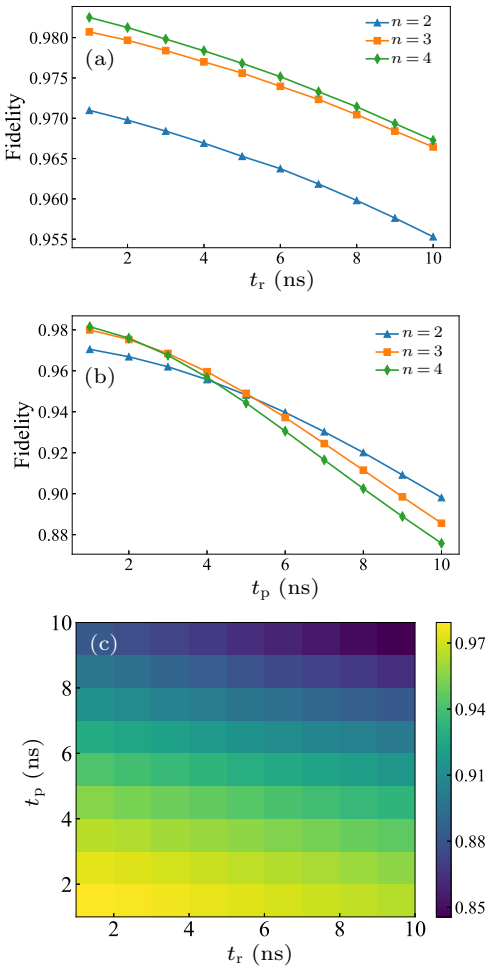


Fig. 6. (a) Magnon state preparation fidelity as a function of coupling pulse rise time t_r for different pulse sequences. (b) Magnon state preparation fidelity as a function of π pulse duration t_p for different pulse sequences. (c) State fidelity versus control parameters t_r and t_p when three pulse sequences are applied.

Further, we numerically evaluate the effect of π pulse duration t_p. As shown in Fig. 6(b), the fidelity of the state preparation decreases significantly as the π pulse duration t_p increases and more pulse sequences are applied. This result suggests that decoherence effect accumulates more and more errors over the time that the π pulse sequences are applied. Despite the limitations imposed by the duration of the π pulse, combining the results of the two aspects discussed above, as shown in Fig. 6(c), our scheme still achieves a high level of fidelity over a large parameter range.

6. Conclusion

Here we present a scheme for high-fidelity magnon state manipulation in a hybrid system consisting of superconducting

circuits and magnons. The scheme combines tunable coupling pulses and dynamical decoupling pulses. This enables gate manipulation of the hybrid system while maintaining its coherence at the same time. We show that various non-classical states of magnons can be prepared with a fidelity of up to 98% under realistic parameter conditions.

Our study opens up several interesting new directions. First, the time intervals of the composite pulse sequence are freely adjustable parameters, and we use the same time intervals in this work. Thus exploring different forms of the sequence can further optimize the fidelity of the operation. Second, this scheme can be easily generalized to various application scenarios in quantum magnonics, such as quantum transducers or nodes based on coherent magnon manipulations and quantum sensors based on magnon superposition states.[37–49]

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