Entanglement concentration and purification of two-mode squeezed microwave photons in circuit QED

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We present a theoretical proposal for a physical implementation of entanglement concentration and purification protocols for two-mode squeezed microwave photons in circuit quantum electrodynamics (QED). First, we give the description of the cross-Kerr effect induced between two resonators in circuit QED. Then we use the cross-Kerr media to design the effective quantum nondemolition (QND) measurement on microwave-photon number. By using the QND measurement, the parties in quantum communication can accomplish the entanglement concentration and purification of nonlocal two-mode squeezed microwave photons. We discuss the feasibility of our schemes by giving the detailed parameters which can be realized with current experimental technology. Our work can improve some practical applications in continuous-variable microwave-based quantum information processing.

Keywords: entanglement concentration; entanglement purification; two-mode squeezed microwave photons; quantum nondemolition measurement; circuit quantum electrodynamics

I. INTRODUCTION

Nowadays, quantum entanglement plays an indispensable role in quantum communication, such as quantum teleportation 1, quantum dense coding 2,3, quantum key distribution 4,5, quantum secure direct communication 6,7, and quantum secret sharing 8. To realize quantum communication, the legitimate parties should first construct a quantum channel. This critical step usually requires nonlocally maximally entangled states between two remote parties to promise an high-efficiency quantum communication. However, it is hard for the parties to keep a nonlocally maximally entangled state due to the decoherence from the environment in the process of the transmission and storage of the states in practice. To overcome this problem, some effective approaches have been proposed, such as the error-rejecting coding with decoherence free subspaces 11, entanglement concentration 14,22, and entanglement purification 23-40.

As another important form of quantum entanglement, continuous variable systems have been used for quantum information processing (QIP) 41, such as continuous variable teleportation 42,43, continuous variable quantum computation 44, error correction 45,46, and continuous variable quantum cryptography 47. Continuous-variable quantum systems have the advantages of cheap resources and easy generation and control in QIP. Similar to the discrete variable, continuous variable systems also suffer from the decoherence inevitably. Therefore, some interesting methods are proposed to overcome this problem, such as continuous-variable entanglement concentration 48,52, purification and distillation 48,49,54,63. For example, in 2000, Duan et al. 48 proposed an efficient entanglement concentration and purification protocol for continuous-variable quantum systems. In 2012, Datta et al. 51 proposed the scheme for a compact continuous-variable entanglement distillation. In 2007, Ourjoumtsev et al. 60 experimentally increased the entanglement between Gaussian entangled states by non-Gaussian operations. In 2008, Hage et al. 61 prepared the distilled and purified continuous-variable entangled states in experiment. In the same year, Dong et al. 62 experimentally realized the entanglement distillation of mesoscopic quantum states. In 2010, Takahashi et al. 63 realized the entanglement distillation from Gaussian input states.

Circuit quantum electrodynamics (QED), which couples the superconducting qubit to transmission line resonators 64, is a very good platform for operating the interaction between a superconducting qubit and a microwave photon. With the advantages of good tunability and scalability, circuit QED has already been studied widely for QIP 65-81. The realization of 9-qubit state preservation 81 and 10-qubit 81 entanglement in experiment indicates that the superconducting qubit has a big potential in quantum computation. On the other hand, the manipulation of a microwave quantum state is also a meaningful research area in circuit QED. Cross-Kerr effect, a typical nonlinear effect, has been studied both theoretically 82,84 and experimentally 85,86 in recent years. In 2011, Hu et al. 82...
proposed the cross-Kerr effect induced by coupling resonators to a superconducting molecule in circuit QED. In 2015, Holland et al. [86] demonstrated this cross-Kerr effect between two resonators in experiment. Due to the strong anti-interference and low loss in the process of transmission, microwave photon becomes a very important flying bit in both classical and quantum communication. However, microwave photons also cannot avoid the decoherence in quantum communication and will change from a maximally quantum entangled state to a partially entangled pure state or a mixed one. Therefore, the entanglement concentration and purification of microwave quantum state are indispensable for promising an effective microwave-based quantum communication. For continuous-variable microwave quantum systems, there is no research in this area.

In this paper, we propose the first physical implementation scheme for the entanglement concentration and purification of two-mode squeezed microwaves, one kind of continuous-variable systems, in circuit QED. Using our scheme, the parties in quantum communication can effectively concentrate and purify the pure and mixed two-mode squeezed microwaves in long distance microwave quantum communication, respectively. Superconducting circuit is easy to operate the microwave-based QIP with current experimental technology due to its good tunability. Our scheme will improve the applications in nonlocal microwave-based quantum communication with continuous-variable quantum states.

This paper is organized as follows: In Sec. II, we introduce the physical implementation of cross-Kerr effect and QND measurement of photon number of microwave photon in two cascade resonators in circuit QED. In Sec. III and Sec. IV, we perform the physical implementation for the entanglement concentration and purification of two-mode squeezed state of microwave, respectively. A discussion and a summary are given in Sec. V.

II. QUANTUM NONDEMOLITION MEASUREMENT BASED ON KERR EFFECT IN CIRCUIT QED

The cross-Kerr effect can be induced by coupling two resonators to a four-level superconducting molecule in circuit QED. The schematic diagram is shown in Fig. 1(a). A and B are two resonators, and the middle box is a four-level superconducting molecule constructed by two transmon qubits [87] shown in Fig. 1(b). The level structure and corresponding couplings are described in Fig. 1(c). The resonators A and B couple to $|1\rangle$ and $|2\rangle$, respectively. The corresponding coupling strengths are $g_1$ and $g_2$, respectively. The detunings are $\delta$ and $\Delta$, respectively. The classical field with the strength $\Omega$ is resonant with level $|2\rangle - |3\rangle$. In the interaction picture, the Hamiltonian is given by [83] (with $\hbar = 1$)

\[ \hat{H} = \delta \hat{\sigma}_{33} + \Delta \hat{\sigma}_{44} + i g_1 (\hat{\sigma}_{13} \hat{a}^\dagger - \hat{\sigma}_{31} \hat{a}) + i g_2 (\hat{\sigma}_{24} \hat{b}^\dagger - \hat{\sigma}_{42} \hat{b}) + i \Omega (\hat{\sigma}_{23} - \hat{\sigma}_{32}) . \] (1)

Here the detunings $\delta = E_{31} - \omega_a$ and $\Delta = E_{42} - \omega_b$. The level spacing $E_{ij}$ is defined with $E_{ij} = E_i - E_j$. $\omega_a$ and $\omega_b$ are the frequencies of resonators A and B, respectively. $\hat{a}$ ($\hat{a}^\dagger$) and $\hat{b}$ ($\hat{b}^\dagger$) are the annihilation (creation) operators for resonators A and B, respectively. The operator $\hat{\sigma}_{ij}$ is defined with $\hat{\sigma}_{ij} = |i\rangle\langle j|$. When the parameters satisfy the conditions with $|g_1/\Omega_c|^2 \ll 1$ and $|g_2| \ll |\Delta|$ [88], one can obtain the effective cross-Kerr Hamiltonian [83]

\[ \hat{H}_{Kerr} = \chi \hat{a}^\dagger \hat{b}^\dagger \hat{b}, \]

where $\chi = -g_1^2 g_2^2 / (\Delta \Omega_c^2)$ is the cross-Kerr coefficient.

![FIG. 1: (Color online) Schematic diagram for the cross-Kerr effect in circuit QED. (a) Cross-Kerr effect induced by coupling two resonators to a superconducting molecule. (b) The detailed structure of superconducting circuit in the dashed box above. The symbols of cross represent the Josephson junctions. (c) The level structure of the molecule and the corresponding interactions [83].](image-url)
The four-level artificial molecule used before (dashed box in Fig. (a)) can be constructed with two transmon qubits and a superconducting quantum interference device (SQUID). The detailed structure is shown in Fig. (b). The top loop represents SQUID and the two bottom loops are transmon qubits. The crosses in each loop are Josephson junctions. The two transmon qubits can couple to each other via the SQUID. By using the two level language, the coupling system is translated to a superconducting molecule with four levels shown in Fig. (c).

In the schemes of entanglement concentration and purification, the QND measurement system is usually a crucial part. Here, we use the two same cross-Kerr media induced by circuit QED to realize the QND measurement shown in Fig. (2). We choose the storage and readout resonators with low and high decay rates, respectively. When the probe light is resonant with readout resonators, the Heisenberg-Langevin equations for two same cross-Kerr media are given by

$$\frac{d\hat{a}_i}{dt} = -i\chi \hat{n}_i\hat{a}_i - \frac{\kappa_1}{2}\hat{a}_i - \sqrt{\kappa_1}\hat{a}_i^{in}, \quad (i = 1, 2).$$

Here, the input of the first resonator is $\hat{a}_1^{in} = g\sqrt{\kappa_1}$ (without noise), where $g\sqrt{\kappa_1}$ is a constant driving field. As a cascade system, the input of the second resonator equals the output of the first resonator with the formula $\hat{a}_2^{in} = \hat{a}_1^{out}$. We assume the decay rates of readout resonators are very large and satisfy $\kappa_1 \gg \chi$, after adiabatically eliminating the cavity modes ($\hat{a}_i = 0$), we can get the output field of the second resonator as

$$\hat{a}_2^{out} \approx -\frac{4ig\chi}{\sqrt{\kappa_1}}(\hat{n}_1 + \hat{n}_2) + g\sqrt{\kappa_1}.$$

Here we use the standard input-output equation $\hat{a}_{out} = \hat{a}_{in} + \sqrt{\kappa_1} \hat{a}$ in calculation.

When we make a homodyne measurement on the $X$ component of the quadrature phase amplitudes of the output field of the second readout resonator $\hat{a}_2^{out}$, the measuring operator is $\hat{X}(\tau) = \frac{1}{\sqrt{2}} \int_0^\tau \sqrt{2} \left[\hat{a}_2^{out}(t) + \hat{a}_2^{out}(t)\right] dt$. Here, $\tau$ is the measuring time. Substituting the result of $\hat{a}_2^{out}$ into the measuring operator and choosing $g = i|g|$, we can get the result as

$$\hat{X}(\tau) = \frac{4\sqrt{2}g|\chi|}{\sqrt{\kappa_1}}(n_1 + n_2).$$

The signal is proportional to the total photon number $n_1 + n_2$. One can infer the total photon number according to the signal.

### III. The Entanglement Concentration of Two-Mode Squeezed Microwave States

Here, we perform the physical implementation for entanglement concentration protocol of two-mode squeezed microwaves. We choose the theoretic entanglement concentration protocol proposed by Duan et al. The detailed schematic diagram is shown in Fig. (3). Here, we consider Alice and Bob hold the resonators $A_1A_2$ and $B_1B_2$, respectively. $A_iB_i$ ($i = 1, 2$) are prepared in two-mode squeezed microwave states $|\psi\rangle_{AB} = \exp[i(\hat{a}_A^\dagger\hat{a}_B - \hat{a}_A\hat{a}_B)]|0\rangle$ with the form expanded in Fock state basis

$$|\psi\rangle_{AB} = \sqrt{1 - \lambda^2} \sum_{n=0}^\infty \lambda^n |n, n\rangle_{AB},$$
where $\lambda = \tanh(r)$ and $r$ is the squeezing parameter. The magnitude of entanglement of this pure squeezed state is given by

$$E(|\psi\rangle_{AB}) = \cosh^2(r) \ln[\cosh^2(r)] - \sinh^2(r) \ln[\sinh^2(r)].$$

(7)

So, the state of this composite system composed of two pairs of squeezed states can be written as

$$|\psi\rangle_1 = |\psi\rangle_{A_1B_1} \otimes |\psi\rangle_{A_2B_2}$$

$$= (1 - \lambda^2) \sum_{m=0}^{\infty} \lambda^m \sqrt{1 + m} |m\rangle_{A_1A_2B_1B_2},$$

(8)

where the state $|m\rangle_{A_1A_2B_1B_2}$ is

$$|m\rangle_{A_1A_2B_1B_2} = \frac{1}{\sqrt{1 + m!}} \sum_{n=0}^{m} |n, m-n\rangle_{A_1A_2} |n, m-n\rangle_{B_1B_2}.$$  

(9)

Now, Bob makes a local QND measurement on the total photon number of the cavities $B_1$ and $B_2$. When Bob gets the result with $m$, the state $|\psi\rangle_1$ will collapse to $|m\rangle_{A_1A_2B_1B_2}$ with the probability $p_m = [(1 - \lambda^2)\lambda^m]^2(1 + m)$. The magnitude of entanglement of $|m\rangle_{A_1A_2B_1B_2}$ is

$$E(|m\rangle_{A_1A_2B_1B_2}) = \ln(1 + m).$$

(10)

If $E(|m\rangle_{A_1A_2B_1B_2}) > E(|\psi\rangle_{AB})$, Alice and Bob get the state with more entanglement. According this inequality, one can see that $m$ should satisfy the requirement

$$m > [\cosh^2(r)]^{\cosh^2(r) \ln[\sinh^2(r)] \sinh^2(r) - 1}. $$

(11)

Therefore, if the result of the QND measurement satisfies the above inequality, Alice and Bob can keep the corresponding maximally entangled microwave state.

![Schematic diagram for the entanglement concentration of two-mode squeezed microwave photons](image)

**FIG. 3**: (Color online) Schematic diagram for the entanglement concentration of two-mode squeezed microwave photons. The two remote parties, say Alice and Bob, hold the resonators $A_1A_2$ and $B_1B_2$, respectively. The same two-mode squeezed states are prepared between superconducting resonators on two sides. Bob holds the QND measurement system composed of two same cross-Kerr media. The probe light input from resonator $B_{R1}$ and will be detected via a homodyne detection after it leaves $B_{R2}$. The circle with an arrow is a circulator.

IV. THE ENTANGLEMENT PURIFICATION OF TWO-MODE SQUEEZED MICROWAVE STATES

In practice, one cannot avoid the noise in the process of the state preparation. It may appear the mixed state due to the influence of noise. Therefore, we need purify the mixed entangled state for high-fidelity quantum communication. The detailed schematic diagram of entanglement purification is shown in Fig. 3. Compared with the concentration process, the difference here is that both Alice and Bob hold the QND measurement systems. The classical channel is used to compare the measurement results. Now, we consider the situation with a very small noise. According to the quantum trajectory theory, the state of two pairs can approximatively be expressed in two situations. If there are no jumps, the state is

$$|\psi\rangle_{no} = \frac{1 - \lambda^2}{\sqrt{P_{no}}} \sum_{m=0}^{\infty} \lambda^m e^{-\eta m^2/2} \sqrt{1 + m} |m\rangle_{A_1A_2B_1B_2}. $$

(12)
Here, the probability is \( p_{\Delta \eta} = \frac{(1-\chi^2)^{2}}{1-\chi^2} - \frac{1}{\eta} \). The total loss rate \( \eta = \eta_A + \eta_B \) and \( \tau \) is the transmission time. When the jump occurs, the state becomes \[ |\psi\rangle_{\text{jump}} = \sqrt{\frac{\eta T}{p_{\Delta \eta}} a_x} |\psi\rangle_{A1B1} \otimes |\psi\rangle_{A2B2}, \] where \( x = A, B \) and \( i = 1, 2 \). The probability is \( p_{\Delta \eta} = \tilde{n} \eta T \tau \) with the mean photon number of single mode \( \tilde{n} = \sinh^2(r) \). Here, we consider that the quantum jump only occurs on one side of Alice and Bob. Both Alice and Bob should make a QND measurement on their two resonators. When they get the same result with \( m_A = m_B = m \) compared by classical channel, they keep this maximally entangled state with entanglement \( ln(1 + m) \). If the result of photon number is different, they should discard this situation.

![Schematic diagram for the entanglement purification of two-mode squeezed microwave photons](image)

**FIG. 4:** (Color online) Schematic diagram for the entanglement purification of two-mode squeezed microwave photons. Alice and Bob hold the \( A_1A_2 \) and \( B_1B_2 \), respectively. Both Alice and Bob have QND measurement systems. The Kerr-1 (Kerr-3) and Kerr-2 (Kerr-4) are the same ones. The classical communication channel is used to compare the measuring results from Alice and Bob. The circle with an arrow is a circulator.

### V. DISCUSSION AND SUMMARY

The cross-Kerr effect in circuit QED should be realized with reasonable parameters. According to the previous work \cite{83}, we can choose the parameters as follows. To satisfy the conditions \( |g_1/\Omega_c|^2 \ll 1 \), \( |g_2| \ll |\Delta| \), the coupling strengths are chosen as \( g_1/2\pi \sim g_2/2\pi \sim 300 \text{ MHz} \). The detuning and the strength of classical pump field are chosen with \( \Delta/2\pi \sim \Omega_c/2\pi \sim 1.5 \text{ GHz} \). With the above parameters, the strength of cross-Kerr effect in our scheme is \( |\chi|/2\pi \sim 2.4 \text{ MHz} \). In the recent circuit QED experiment \cite{86}, the first single-photon-resolved cavity-cavity cross-Kerr interaction has been observed with a state dependent shift \( \chi_{sc}/2\pi = 2.59 \pm 0.06 \text{ MHz} \). For two-mode squeezed states, we choose the squeezed parameter with \( r \sim 0.9 \) and the mean photon number \( \langle \tilde{n} \rangle = \sinh(r) \sim 1.1 \). We choose \( |g| \sim 50 \). To keep an effective QND measurement, the condition \( \kappa_1 \gg \chi \) should be met. The decay rates of readout and storage resonator are set with \( \kappa_1/2\pi \sim 100 \text{ MHz} \) and \( \kappa_2/2\pi \sim 20 \text{ kHz} \), respectively.

In practice, the QND system will be influenced with the noise from environment. When we consider the standard vacuum white noise, we rewrite the input field with \( \hat{a}^m_i = g\sqrt{\kappa_1} + \hat{a}^{in}_i \), where the noise term \( \hat{a}^{in}_i \) satisfies the relations \( \langle \hat{a}^{in}_i(t)\hat{a}^{in}_i(t') \rangle = 0 \) and \( \langle \hat{a}^{in}_i(t)\hat{a}^{in}_i(t') \rangle = \delta (t - t') \). Then the noise term will make a contribution to the measurement result. According to previous work \cite{49}, promising an effective QND measurement should satisfy the requirement \( \kappa_1/(64|g|^2\chi^2) < \tau < 1/\kappa_2 \). With the parameters given above, the measuring time should be 0.02 ns < \( \tau < 8 \mu s \) in our system. The imperfections in the QND measurement also influence the protocol. Here, to make an effective measurement, we show the requirements for some parameters given in the previous work \cite{49}. When the phase of driving field is unstable, i.e., \( g = i|g|e^{i\theta} \). The phase instability should satisfy \( \delta < 4\chi/\kappa_1 \). If the decay rates and the Kerr coefficients for the resonators are not identical, we denote the decay rates for readout resonators \( B_{R1} \) and \( B_{R2} \) with \( \kappa_{R1} \) and \( \kappa_{R2} \), respectively. The Kerr coefficients for Kerr-1 and Kerr-2 are labeled with \( \chi_1 \) and \( \chi_2 \). At this point, one should keep them with \( \chi_{R1} \chi_{R2} = 1 \). Actually, there exist the absorption and leakage of the probe light in some devices, such as circulators and resonators. We use \( \gamma_i (i = 1, 2) \) to represent all the loss and the \( \gamma_i \) should follow the requirement \( \gamma_i < \kappa_1/(n_{Bi})^2 \).

In summary, we have presented the first physical implementation of entanglement concentration and purification protocol for two-mode squeezed microwave photons in circuit QED. The protocol can be extended to multiple entangled pairs with adding more cascade QND measurement systems. Our scheme has the advantage that it can be realized easily in practice with current experimental technology. Our work will improve the feasibility of nonlocal microwave-based quantum communication with continuous-variable quantum states.
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