Controllable cross-Kerr interaction between microwave photons in circuit quantum electrodynamics*

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We propose a scheme to enable a controllable cross-Kerr interaction between microwave photons in a circuit quantum electrodynamics (QED) system. In this scheme we use two transmission-line resonators (TLRs) and one superconducting quantum interference device (SQUID) type charge qubit, which acts as an artificial atom. It is shown that in the dispersive regime of the circuit-QED system, a controllable cross-Kerr interaction can be obtained by properly preparing the initial state of the qubit, and a large cross-phase shift between two microwave fields in the two TLRs can then be reached. Based on this cross-Kerr interaction, we show how to create a macroscopic entangled state between the two TLRs.

Keywords: cross-Kerr-like interaction, circuit quantum electrodynamics, macroscopic entangled state

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1. Introduction

It is well known that inter-photon cross-Kerr interaction, if available, could be very useful for macroscopic superposition and entanglement, as well as for quantum information processing. For example, the cross-Kerr interaction has been shown to have applications in quantum non-demolition measurements[1−3], quantum state preparation,[4−11] quantum teleportation[12,13] and the implementation of quantum logic gates.[14−17]

Cross-Kerr interactions in cold atom systems[18−27] and cavity quantum electrodynamics (QED) systems[28,29] have been studied widely. The cross-Kerr interaction can induce a cross-phase-modulation (XPM) between two involved fields. Schmidt and Imamoğlu[18] first proposed the XPM scheme, which exhibited giant and resonantly enhanced nonlinearity based on electromagnetically induced transparency (EIT). Hau *et al.*[20] indirectly observed giant nonlinearity in a Bose–Einstein condensate through combining EIT and cold atom technology. Kang and Zhu[21] observed EIT enhanced Kerr nonlinearity at low light intensities in coherently prepared four-level rubidium atoms. Chen *et al.*[25] experimentally demonstrated a low-light-level XPM scheme based on the light-storage technique in laser-cooled ^{87}Rb atoms. The large XPM between the two fields in a four-level tripod EIT system of Rb atoms has been observed experimentally.[23,24]

Recent advances in circuit QED[30−49] have opened new prospects in nonclassical state generation and quantum information processing in the microwave regime. In the circuit QED, superconducting circuits are made to act like artificial atoms and a one-dimensional superconducting transmission line resonator forms a microwave cavity. Such circuits typically operate at microwave frequencies. By using the quantum nature of a microwave, one can solve many problems associated with measuring quantum circuits. We can protect them from radiative decay and use single microwave photons as a means of coupling distant qubits together. Quantum circuits are fabricated on a microchip using conventional lithography techniques, which paves the way to scalable quantum circuits coupling qubits to microwave cavities. Unlike natural atoms, the properties of artificial atoms made from circuits can be designed to be tested and even manipulated *in-situ*. Because the qubit contains many atoms, the effective dipole moment can be much larger than

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those of an ordinary alkali atom and a Rydberg atom. This allows circuits to couple much more strongly to the cavity. Further, in a one-dimensional transmission line cavity, the other two dimensions of the cavity are compressed to a size much less than a wavelength, thereby increasing the energy density and further increasing the dipole coupling. This large coherent coupling allows circuits to achieve strong coupling even in the presence of a larger decoherence present in the solid state environment. One can then observe the quantum interactions of matter with single photons. Hence, circuit QED can explore new regimes of cavity QED. In fact, with the advent of circuit QED, it is now possible to take many of the concepts that have been successfully used in the field of quantum optics and transfer them to the domain of microwave photons guided along coplanar waveguides on a chip, interacting with superconducting qubits.

Recently, circuit QED systems have successfully demonstrated strong coupling between a single microwave photon and a qubit,[31] the implementation of a single microwave-photon source in an all-solid-state system,[32] as well as single artificial-atom lasing[33] and interaction between two artificial atoms.[34,35] These give rise to strong experimental support for on-chip quantum optics and quantum information processing.

Motivated by these experimental advances in circuit QED, we propose a scheme to enable a controllable cross-Kerr interaction between microwave photons entering two transmission line resonators in a circuit-QED system. This represents the limit of a single artificial atom taking the place of the nonlinear Kerr medium usually employed in optical experiments. Based on this cross-Kerr interaction, we show how to generate a macroscopic entangled state of microwave photons between two transmission line resonators.

2. Physical model

We illustrate our idea first. As shown in Fig.1, we consider a circuit-QED system in which a SQUID-type charge qubit is coupled to two transmission-line resonators, TLRA and TLRB, of lengths $L_{\rm a}$ and $L_{\rm b}$, respectively. The qubit is placed at the position of the antinode of the quantized voltage of TLRA (i.e., $x_{\rm a} = L_{\rm a}/2$) and the antinode of the quantized current of TLRB (i.e., $x_{\rm b} = L_{\rm b}/4$), respectively. It can be controlled by the gate voltage, which contains the dc part $V_{\rm g}^{\rm dc}$ and the quantum part $V_{\rm a}$ generated by the TLRA, and the biasing flux Φ, which contains the classical part $\Phi_{\rm e}$ and the quantized part $\Phi_{\rm b}$ generated by the TLRB threading the SQUID.

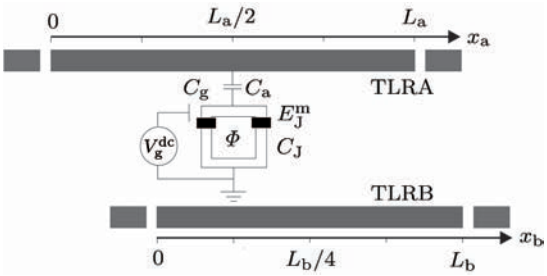


Fig. 1. Schematic setup for the proposed circuit-QED system. The SQUID-based charge qubit is coupled with two TLRs, TLRA and TLRB, of lengths $L_{\rm a}$ and $L_{\rm b}$, respectively. The SQUID is placed at the position of the antinode of the quantized voltage of TLRA (i.e., $L_{\rm a}/2$) and the antinode of the quantized current of TLRB (i.e., $L_{\rm b}/4$), respectively.

In terms of the annihilation operator $a(b)$ and creation operator $a^{\dagger}(b^{\dagger})$ of TLRA (TLRB), the Hamiltonian for this system reads as[30,31]

$$H = \hbar\omega_{\rm a}a^{\dagger}a + \hbar\omega_{\rm b}b^{\dagger}b + 2E_{\rm C}(2n_{\rm g}-1)\sigma_z - E_J\sigma_x, \quad (1)$$

where $\omega_{\rm a}$ and $\omega_{\rm b}$ are the microwave frequencies of TLRA and TLRB, respectively. The last two terms on the right-hand side of Eq. (1) represent the Hamiltonian of the charge qubit. Here $\sigma_z = |1\rangle\langle 1| - |0\rangle\langle 0|$ and $\sigma_x = |1\rangle\langle 0| + |0\rangle\langle 1|$ with 0(1) being the number of Cooper pairs on the superconducting island. $E_{\rm C} = e^2/2C_{\Sigma}$ is the charging energy with C_{Σ} being the total box capacitance. $n_{\rm g}$ is the gate charge number and $E_{\rm J}$ is the Josephson coupling energy, given by

$$n_{\rm g} = \frac{C_{\rm g}V_{\rm g}^{\rm dc} + C_{\rm a}V_{\rm a}}{2e}, \quad E_{\rm J} = E_{\rm J}^{\rm m}\cos\left(\pi\frac{\Phi}{\Phi_0}\right), \quad (2)$$

where $C_{\rm g}$ and $C_{\rm a}$ represent the gate capacitance and the coupling capacitance between TLRA and the charge qubit, respectively. $V_{\rm g}^{\rm dc}$ and $V_{\rm a}$ are the dc gate voltage and the quantum gate voltage generated by TLRA, respectively, $E_{\rm J}^{\rm m}$ is the maximum Josephson coupling energy, and Φ_0 is the flux quanta. The total magnetic flux Φ threading the dc-SQUID is a sum of two parts, i.e., $\Phi = \Phi_{\rm b} + \Phi_{\rm e}$ with $\Phi_{\rm e}$ being the external classical magnetic flux and $\Phi_{\rm b}$ the quantized magnetic flux generated by the quantized current in TLRB.

The quantum gate voltage and the quantized magnetic flux associated with TLRA and TLRB can be expressed in terms of the annihilation and creation

operators of the microwave fields in TLRA and TLRB as

$$V_{\rm a} = -\sqrt{\frac{\hbar\omega_{\rm a}}{L_{\rm a}c}}(a+a^{\dagger}),$$
$$\Phi_{\rm b} = \frac{\mu_0 S}{2\pi d}\sqrt{\frac{\hbar\omega_{\rm b}}{L_{\rm b}l}}(b+b^{\dagger}), \quad (3)$$

where c and l are the capacitance and the inductance per unit length for TLRA and TLRB, respectively, S is the area of the loop of the SQUID, d the distance between TLRB and the SQUID and μ_0 is the vacuum permeability.

Substituting Eqs. (2) and (3) into Eq. (1) we have

$$H = \hbar\omega_{\rm a}a^{\dagger}a + \hbar\omega_{\rm b}b^{\dagger}b + 2E_{\rm C}(2n_{\rm g}^{\rm dc}-1)\sigma_z \quad (4)$$
$$-\hbar g_{\rm a}(a+a^{\dagger})\sigma_z - E_{\rm J}^{\rm m}\cos[\phi_{\rm e}$$
$$+\phi_{\rm b}(b+b^{\dagger})]\sigma_x,$$

where $n_{\rm g}^{\rm dc} = C_{\rm g}V_{\rm g}^{\rm dc}/(2e)$ and we have introduced the coupling constant $g_{\rm a}$, two parameters $\phi_{\rm b}$ and $\phi_{\rm e}$. They are defined as

$$g_{\rm a} = 2E_{\rm C}C_{\rm a}\sqrt{\hbar\omega_{\rm a}/(L_{\rm a}c)}/(\hbar e),$$
$$\phi_{\rm b} = \mu_0 S\sqrt{\hbar\omega_{\rm b}/(L_{\rm b}l)}/(2d\Phi_0),$$
$$\phi_{\rm e} = \pi\Phi_{\rm e}/\Phi_0. \quad (5)$$

For simplicity, we choose the classical biasing magnetic flux $\Phi_{\rm e} = 0$ and work out the charge degeneracy point $n_{\rm g}^{\rm dc} = 1/2$. After making a rotation of $-\pi/2$ around the y axis, we obtain the following effective Hamiltonian:

$$H' = \hbar\omega_{\rm a}a^{\dagger}a + \hbar\omega_{\rm b}b^{\dagger}b - \hbar g_{\rm a}(a+a^{\dagger})\sigma_x \quad (6)$$
$$+E_{\rm J}^{\rm m}\cos[\phi_{\rm b}(b+b^{\dagger})]\sigma_z,$$

which indicates that under the condition $\phi_{\rm b} \ll 1$, we can obtain the following approximation Hamiltonian:

$$H'' = \hbar\omega_{\rm a}a^{\dagger}a + \hbar\omega_{\rm b}b^{\dagger}b + E_{\rm J}^{\rm m}[1-\phi_{\rm b}^2(1+2b^{\dagger}b)/2]\sigma_z$$
$$-\frac{E_{\rm J}^{\rm m}\phi_{\rm b}^2}{2}(b^2+b^{\dagger 2})\sigma_z - \hbar g_{\rm a}(a+a^{\dagger})\sigma_x. \quad (7)$$

In order to further simplify the above Hamiltonian, we change Hamiltonian (7) to the interaction picture with respect to the free Hamiltonian of TLRB. After discarding rapidly oscillating terms, the resulting Hamiltonian can be expressed as

$$H_I'' = \hbar\omega_{\rm a}a^{\dagger}a + \frac{\hbar\omega_q}{2}\sigma_z - \hbar g_{\rm a}(a+a^{\dagger})\sigma_x, \quad (8)$$

where the effective energy separation of the qubit is dependent on the number operator of TLRB $n_{\rm b} = b^{\dagger}b$ and is given by the following expression:

$$\omega_q = 2E_{\rm J}^{\rm m}[1-\phi_{\rm b}^2(1+2n_{\rm b})/2]/\hbar. \quad (9)$$

We consider the case of $\omega_q + \omega_{\rm a} \gg \omega_q - \omega_{\rm a}, g_{\rm a}$. Then in the rotating-wave approximation Hamiltonian (7) becomes

$$H_I'' = \hbar\omega_{\rm a}a^{\dagger}a + \frac{\hbar\omega_q}{2}\sigma_z - \hbar g_{\rm a}(a\sigma_+ + \sigma_- a^{\dagger}), \quad (10)$$

which is a generalized Jaynes–Cummings model which describes the interaction between TLRA and the charge qubit with the effective energy separation depending on the number operator of TLRB. The quantum electric circuit of Fig. 1 is therefore mapped into the problem of a two-level artificial atom inside a cavity.

We study the dispersive regime of the circuit QED, where the cavity and the qubit are out of resonance, and the qubit-cavity detuning is larger than the coupling strength, i.e., $\Delta = \omega_{\rm q} - \omega_{\rm a} \gg g_{\rm a}$. In the dispersive regime, $\omega_{\rm q}/\omega_{\rm a} < 1$ from Hamiltonian (9). Thus, we can obtain the following effective Hamiltonian:

$$H''' = \hbar\omega_{\rm a}a^{\dagger}a + \frac{\hbar\omega_{\rm q}}{2}\sigma_z - \hbar\frac{g_{\rm a}^2}{\omega_{\rm a}}\left(1+\frac{\omega_{\rm q}}{\omega_{\rm a}}\right)$$
$$\times[\sigma_z a^{\dagger}a + (\sigma_z + I)/2], \quad (11)$$

which can be expressed as the following form in the interaction picture with respect to the first two terms of the Hamiltonian:

$$H_I''' = H_0|0\rangle\langle 0| + H_1|1\rangle\langle 1|, \quad (12)$$

where H_0 and H_1 are defined as

$$H_1 = -\hbar\frac{g_{\rm a}^2}{\omega_{\rm a}}[1+2k-k\phi_{\rm b}^2(1+2b^{\dagger}b)](a^{\dagger}a+1),$$
$$H_0 = \hbar\frac{g_{\rm a}^2}{\omega_{\rm a}}[1+2k-k\phi_{\rm b}^2(1+2b^{\dagger}b)]a^{\dagger}a, \quad (13)$$

with parameter $k = E_{\rm J}^{\rm m}/(\hbar\omega_{\rm a})$ introduced. From the Hamiltonian H_I''' we can see that the state evolution of two transmission-line resonators depends on the initial state of the charge qubit. If the charge qubit is initially prepared in the state $|0\rangle$ or $|1\rangle$, it will remain confined to the state $|0\rangle$ or $|1\rangle$ due to the large detuning condition in the dispersive regime. In this situation, the dynamics of two transmission-line resonators will decouple with that of the charge qubit. The effective interaction Hamiltonian of TLRA and TLRB are cross-Kerr Hamiltonian H_0 and H_1, respectively.

From Eq. (13) we can see that apart from a phase displacement transformation of TLRA, Hamiltonian (13) describes cross-Kerr interactions between TLRA

and TLRB. The strength of the cross-Kerr coupling is given by

$$\chi = \frac{2g_{\rm a}^2\phi_{\rm b}^2 E_{\rm J}^{\rm m}}{\hbar\omega_{\rm a}^2}, \tag{14}$$

which indicates that by a careful choice of the parameters, it is possible to obtain considerable cross-Kerr nonlinearity. According to recent experimental data in Refs. [37], [50], and [51], we may consider $\phi_{\rm b} = 0.1$, $E_{\rm C}/\hbar = 5$ GHz, $E_{\rm J}^{\rm m}/\hbar = 8$ GHz, $\omega_{\rm a} = 2\pi \times 8$ GHz, $C_{\rm a} = 6$ fF and $cL_{\rm a} = 1.6$ pF. Under these conditions, we find the resulting cross-Kerr coupling strength to be $\chi = 3.6$ MHz. A large cross-phase shift of the weak signal field is critical to optical quantum communication and quantum information processing. In circuit QED, the lifetime of the charge qubit and the transmission line cavity[37] are about 2 μs and 160 ns, respectively. In the lifetime of the transmission line resonator, $\tau = 160$ ns, we can reach a cross-phase shift $\phi = \chi\tau \simeq 0.09 \times 2\pi$ for the cross-Kerr coupling in the present scheme. This means that in the lifetime of the involved subsystems, we can obtain a large cross-phase shift between two microwave fields in the two transmission-line resonators.

As is well known, the realization of controllable interaction between two subsystems is one of the major problems in solid-state quantum information processing. Fortunately, in our present scheme, a controllable interaction between TLRA and TLRB can be realized through adjusting the maximum Josephson coupling energy $E_{\rm J}^{\rm m}$ in Eq. (14). Indeed, we can replace the two Josephson junctions of the charge qubit in Fig. 1 by two SQUIDs, respectively. Then the diagram of the charge qubit can be represented as shown in Fig. 2. If we choose the external classical magnetic flux threading the two small SQUIDs such that $\Phi_1 = -\Phi_2 = \Phi_x$, then $E_{\rm J}^{\rm m}$ is replaced by $E_{\rm J}^0 \cos(\pi\Phi_x/\Phi_0)$. Therefore, we can control the interaction between TLRA and TLRB by tuning the external classical magnetic flux Φ_x. For example, if we tune Φ_x such that $\Phi_x = \Phi_0/2$, then $\chi = 0$, the interaction between the two TLRs is turned off.

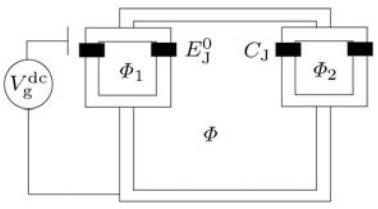


Fig. 2. Charge qubit with adjustable maximum Josephson coupling energy. Φ_1 and Φ_2 are the classical magnetic fluxes threading the two small SQUIDs, respectively.

3. A macroscopic entangled state for microwave photons

Entanglement is at the heart of quantum physics not just because of its critical role in marking the boundary between classical and quantum world but also because of its exploitability in quantum information processing. Recently, macroscopic entanglement[52−57] has attracted much attention. In this section, we show how to generate a macroscopic entangled state of microwave photons between TLRA and TLRB.

We consider the situation where the charge qubit is initially in the state $|1\rangle$, TLRA and TLRB are in the product coherent state $|\alpha,\beta\rangle_{\rm a,b} \equiv |\alpha\rangle_{\rm a} \otimes |\beta\rangle_{\rm b}$. In this case, the effective Hamiltonian of TLRA and TLRB is H_1 given by Eq. (13). It is easy to find that the evolution of the state of the TLRA-TLRB system is given by

$$\begin{aligned} |\Psi(\tau)\rangle &= {\rm e}^{-\frac{|\alpha|^2+|\beta|^2}{2}} \\ &\quad \times \sum_{n,m=0}^{\infty} {\rm e}^{{\rm i}\,\tau\theta_{n,m}} \frac{\alpha^n\beta^{\rm m}}{\sqrt{n!m!}} |n,m\rangle_{\rm a,b}, \end{aligned} \tag{15}$$

where we have used a scaled time $\tau = kg_{\rm a}^2\phi_{\rm b}^2 t/\omega_{\rm a}$ and a running frequency

$$\theta_{n,m} = [\eta + (1+2m)]\,(n+1) \tag{16}$$

with the parameter $\eta = (2k+1)/k\phi_{\rm b}^2$.

The state given by Eq. (15) is a generalized two-mode coherent state. It is generally a two-mode continuous-variable entangled state. Using the generalized coherent state approach discussed in the Refs. [26] and [27], we find that when $\tau = \pi/2$ state (15) becomes a two-state entangled state

$$\begin{aligned} \left|\Psi\left(\tau = \frac{\pi}{2}\right)\right\rangle &= \frac{\rm i}{2}(\alpha_+|\,{\rm i}\,\alpha\rangle_+|-\beta\rangle \\ &\quad + \alpha_-|\,{\rm i}\,\alpha\rangle_-|\beta\rangle)_{\rm a,b}, \end{aligned} \tag{17}$$

where $|\,{\rm i}\,\alpha\rangle_{\pm,a}$ are two normalized Schrödinger cat states defined as

$$|\,{\rm i}\,\alpha\rangle_{\pm,a} = \frac{1}{\alpha_\pm}(|\,{\rm i}\,\alpha\rangle \pm |-{\rm i}\,\alpha\rangle)_{\rm a} \tag{18}$$

with $\alpha_\pm = [2(1 \pm \exp(-2|\alpha|^2))]^{1/2}$. Obviously, Eq. (18) is a macroscopic entangled state between TLRA and TLRB. It consists of a pair of Schrödinger cat states and a pair of equal-amplitude but opposite-phase coherent states.

4. Conclusion

We have presented a scheme to create a controllable cross-Kerr interaction between microwave photons in a circuit-QED system. The scheme exploits a SQUID-type charge qubit to act as a two-level artificial atom, and two TLRs as two cavities ejected by microwave photons. We have shown that a controllable cross-Kerr interaction can be obtained in the dispersive regime of the circuit-QED system and a large cross-phase shift between two microwave fields in the two TLRs can be reached in the parameter regime of the current circuit-QED experiments. The cross-Kerr coupling strength can be controlled through adjusting the external classical flux in the SQUID. Based on this cross-Kerr interaction, we have shown how to create a macroscopic entangled state[52] between the two TLRs. The realization of the controllable cross-Kerr interaction for on-chip microwave photons is one of the most important steps for scalable quantum computing and quantum information processing by using coupled macroscopic quantum systems. It is believed that the on-chip cross-Kerr nonlinearity for microwave photons could open a way for on-chip nonlinear optics involving macroscopic objects.

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