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Invited Paper

Tunable electromagnetically induced transparency in a composite superconducting system

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ABSTRACT

We theoretically propose an efficient method to realize electromagnetically induced transparency (EIT) in the microwave regime through a coupled system consisting of a flux qubit and a superconducting *LC* resonator. Driven by two appropriate microwave fields, the system will be trapped in the dark states. In our proposal, the control field of EIT is played by a second-order transfer rather than by a direct strong-pump field. In particular, we obtained conditions for electromagnetically induced transparency and Autler–Townes splitting in this composite system. Both theoretical and numerical results show that this EIT system benefits from the relatively long coherent time of the resonator. Since this whole system is artificial and tunable, our scheme may have potential applications in various domains.

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1. Introduction

Electromagnetically induced transparency (EIT), which manifests spectroscopically in quantized three-level structures of an atomic medium through its interaction with two semiclassical fields, was first observed in atomic gases [1]. The destructive interference between two dressed states results in a transparent window for the probe field [2,3]. As a powerful technique that can be used to eliminate the effect of a medium on a propagating beam of electromagnetic radiation, it has application potential in non-linear optics and quantum information. In recent years, EIT in artificial systems [4] such as optomechanical systems [5,6], photonic crystals [7], and superconducting systems [8–10] has also been demonstrated.

Recent developments on superconducting quantum devices provide versatile artificial quantum systems. Since they can be designed and fabricated on demand, superconducting circuits (SCs) are employed in wide range of areas, for instance, being the basic qubits in quantum information process [11] and serving as quantum simulators [12–14]. Working as artificial atoms, SCs can be used to demonstrate many phenomena (vacuum Rabi Oscillations [15], generation of Fock states [16,17], simultaneous cooling [18], etc.) in atomic physics and quantum optics [19]. SCs can also be combined with other quantum systems, such as atoms, spins and resonators, to form new quantum structures. These hybrid systems [20] inherit advantages of each component and thus have more application potential in experiments.

EIT in SCs has been extensively studied in recent years. The tunability of SCs can be used to prepare the artificial atoms into approximate arbitrary dark states, and as a result, EIT for a strong probe field can also be realized, which is an important advantage over natural atoms [19]. In Refs. [21,22], based on the setup in superconducting circuits, the authors employed the EIT method to check the imperfect preparation of the desired states and work as sensitive probe of decoherence of superconducting qubits. Moreover EIT in SCs has been used in quantum information processes, such as storing microwave photons [23] and demonstrating single-photon router devices [24].

However, due to relatively short coherence times, EIT in superconducting systems is more fragile than in atomic systems [25,26]. Usually, the dip of susceptibility in superconducting circuit-based setups is not as sharp as that in atoms, and as a result, some research might confuse EIT in SCs with another similar coherent interaction effect known as Autler–Townes Splitting (ATS) [27,28]. The similarities between EIT and ATS have led to many discussions. For example, in Ref. [29] the authors claimed that they had realized EIT, but according to Ref. [30] they demonstrated ATS rather than EIT. Although EIT and ATS are similar in many aspects, they originate from completely different physical mechanisms [26,31]: in EIT implementations, strong Fano interference between different pathways leads to no absorption of the probe fields; in ATS implementations, a strong-coupling field leads to dynamical Stark splitting and the transparency is just due to no direct transition energy level for the resonant probe field. In Ref. [30], a rigorous method named Akaike's information criterion was established to discern EIT from ATS objectively both for theoretical results and experimental data.

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Tunable EIT and its related quantum interference processes can also be produced in hybrid systems consisting of superconducting units [8,32]. In this work we will show the possibilities to demonstrate EIT via a flux qubit coupling to a superconducting LC resonator. Differences between our study of EIT with those in Refs. [8–10] are as follows: (i) The coupling between the qubit and the resonator is of diagonal form (σ_z-coupling), rather than Jaynes–Cummings coupling. As discussed in the following sections, σ_z-coupling makes it possible to overcome problems due to rapid decoherence in superconducting artificial atomic systems. Moreover, the corresponding parameters are tunable via controlling the resonator and the qubit independently. (ii) Employing effective Hamiltonian methods, we find that the second-order coherent transfer between dressed states acts as the coupling field, rather than a direct coherent driving. (iii) The time-dependent driving fields are applied to the 1D transmission line, and the electromagnetic response is characterized by a reflection rate. Being periodically spaced in linear array, the setup in our proposal can also work as an efficient optical device to control slow light and fast light in the microwave regime, which has been discussed in detail in Refs. [23,33,34].

To distinguish EIT from ATS, we employ methods provided in Refs. [10,26,30,31], and obtain conditions for these two coherent effects. In our proposal, EIT and ATS phenomena can be demonstrated continuously by controlling the pump field. The setup of our proposal is composed of superconducting quantum units, so it can be integrated on chips, and may have potential applications in microwave photonics, nonlinear optics and optical communication in the microwave regime.

The organization of this paper is as follows: we propose the theoretical model in Section 2. The semiclassical results for the reflection rate are shown in Section 3. In Section 4, we interpret the transparency via dark-state theory and give conditions for EIT and ATS in our proposal, respectively. In Section 5, we discuss distinctive features of this composite EIT system. The last section presents the conclusions.

2. Model

Our proposal is illustrated in Fig. 1. The quantum device consists of a superconducting flux qubit [18,35,36] and a superconducting LC resonator made by a capacitor C and an inductor L

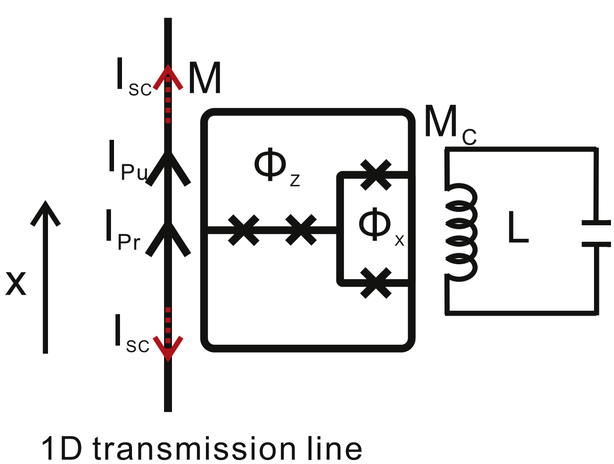

Fig. 1. Schematic of the system composed by a flux qubit and a superconducting LC resonator. The microwave currents with frequencies ω_{pu} and ω_{pr} are applied through the qubit loop. I_{sc} (red dot line) is the scattered current of the probe field. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

[20,37]. The Hamiltonian of the gap-tunable flux qubit composed of a qubit loop and a superconducting quantum interference device (SQUID) has the form $H_q = \left[\frac{1}{2}\epsilon(\Phi_z)\bar{\sigma}_z + \Omega(\Phi_x)\bar{\sigma}_x\right]$ in the basis of persistent current states $\{|+\rangle, |-\rangle\}$, where $\bar{\sigma}_z = |+\rangle\langle+| - |-\rangle\langle-|$ and $\bar{\sigma}_x = |+\rangle\langle-| + |-\rangle\langle+|$ are Pauli operators in the basis of clockwise $|+\rangle$ and anticlockwise $|-\rangle$ of the persistent currents. Here ϵ and Ω can be controlled via the external flux Φ_z and Φ_x, respectively.

For the first term of H_q, $\epsilon(\Phi_z) = 2I_p(\Phi_z - \Phi_0/2)$ describes the energy bias between the clockwise $|+\rangle$ and anticlockwise $|-\rangle$ of the persistent current I_p in the qubit loop, $\Phi_0 = \hbar/2e$ is the flux quantum, and Φ_z is the external flux though the qubit loop that can be induced by the flux driving through the qubit loop. In our proposal the qubit loop is inductively coupled to an 1D transmission line (along the x direction) via a mutual kinetic inductance M [38,39]. To minimize the flux noise, we apply a magnetic flux threading through the qubit loop $\Phi_{ext} = \Phi_0$. In the following discussions we adopt the dipole approximation: since the characteristic size of qubit loop ($\sim 10\ \mu m$) is negligible compared with the wave-length of microwaves in transmission line (of centimeters), the driving is assumed to be independent of position. Under the driving of the time dependence current $I(t)$ in the transmission line, the first term of H_q is a driving term and can be expressed as $H_q = \mu I(t)\bar{\sigma}_z$, where $\mu = MI_p$ is the dipole moment matrix element [29,39].

For the second term of H_q, $\Omega(\Phi_x)$ is the qubit gap and depends on the flux driving Φ_x of the SQUID loop. Here we consider the SQUID loop coupled with a superconducting LC micrometer resonator [20,40,41], which can be described by a simple harmonic oscillator Hamiltonian $H_R = \hbar\omega(b^\dagger b + 1/2)$, where $b^\dagger(b)$ are the creation (annihilation) operators of the resonator. The resonance frequency of the resonator is given by $\omega = 1/\sqrt{LC}$, and the value of the frequency is in the range of hundreds of MHz to several GHz with a relatively high quality factor $Q \sim 10^3$–10^6 [37]. The LC resonator interacts with the SQUID loop of the flux qubit via the mutual inductance M_c. With a static part $\hbar\upsilon/2$ we can express the qubit gap as $\Omega(\Phi_x) = \hbar\upsilon/2 + \hbar R(M_c\sqrt{\omega/2\hbar L})(b^\dagger + b)$, where R is the sensitivity of the SQUID loop to the flux [31], and $\sqrt{\hbar\omega/2L}$ is the amplitude of the vacuum fluctuation of the current in the LC oscillator. Assuming $g = R(M_c\sqrt{\omega/2\hbar L})$, we rewrite H_q as

$$H_q = \mu I(t)\bar{\sigma}_z + \frac{1}{2}\hbar\upsilon\bar{\sigma}_x + \hbar g(b^\dagger + b)\bar{\sigma}_x. \tag{1}$$

In the new basis of the eigenstates of the qubit $\{|e\rangle = (|+\rangle + |-\rangle)/\sqrt{2}, |g\rangle = (|+\rangle - |-\rangle)/\sqrt{2}\}$, the Hamiltonian of the system can be expressed as

$$H_{sys} = H_q + H_R = \frac{1}{2}\hbar\upsilon\sigma_z + \hbar\omega b^\dagger b + \hbar g(b^\dagger + b)\sigma_z + \mu I(t)(\sigma^+ + \sigma^-), \tag{2}$$

where $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$, $\sigma^+ = |e\rangle\langle g|$, $\sigma^- = |g\rangle\langle e|$, $[\sigma_z, \sigma^\pm] = \pm 2\sigma^\pm$, $[\sigma^+, \sigma^-] = \sigma_z$. We consider two driving currents being set in a 1D transmission line: pump (control) and probe (signal) currents with amplitude ε_{pu} and ε_{pr} at frequency ω_{pu} and ω_{pr}, respectively; that is, $\mathrm{Re}[I_{pu}(x,t)] = -2\cos(\omega_{pu}t - k_{pu}x)\varepsilon_{pu}$ and $\mathrm{Re}[I_{pr}(x,t)] = -2\cos(\omega_{pr}t - k_{pr}x)\varepsilon_{pr}$, where k_{pu} and k_{pr} are the associated wave numbers, respectively. Not loss any generalities, we assume that the qubit is at $x=0$. Applying a frame rotating at frequency ω_{pu} and adopting the rotating wave approximation, we can rewrite the Hamiltonian of the system as ($\hbar = 1$)

$$H_{sys} = \frac{1}{2}\Delta\sigma_z + \omega b^\dagger b + g(b^\dagger + b)\sigma_z - \Omega_{pu}(\sigma_+ + \sigma_-) - \Omega_{pr}(\sigma_+ e^{-i\delta t} + \sigma_- e^{i\delta t}), \tag{3}$$

where $\Delta = \upsilon - \omega_{pu}$ is the pump-exciton detuning, $\Omega_{pu} = \mu\varepsilon_{pu}/\hbar$ ($\Omega_{pr} = \mu\varepsilon_{pr}/\hbar$) is the Rabi frequency of pump current (probe current), and $\delta = \omega_{pr} - \omega_{pu}$ is the probe–pump detuning.

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