Optics Communications 364 (2016) 185–190

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Electromagnetically induced transparency using a superconducting artificial atom with optimized level anharmonicity

Zhu-Lei Shao [a], Zhi-Bo Feng [a,b]

[a] School of Electric and Information Engineering, Xuchang University, Xuchang 461000, China
[b] State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form
22 November 2015
Accepted 24 November 2015
Available online 6 December 2015

Keywords:
Electromagnetically induced transparency
Superconducting artificial atom
Optimized level anharmonicity

ABSTRACT

We propose a theoretical scheme to implement electromagnetically induced transparency (EIT) using an artificial atom of superconducting circuit. Allowed by the selection rule, two kinds of interactions between the atom and driving fields can be obtained, in which we focus on the leakage effect. In terms of dark-state mechanism in generating EIT, the leakage could destroy the EIT considerably. By removing the leakage effect in an optimized three-level atom, we consider a realization of EIT through the technique of density matrix. Furthermore, another effective way to optimize the level anharmonicity is analyzed in a dressing-state method. The scheme could provide a promising approach for experimentally improving EIT with the artificial atoms.

1. Introduction

Serving as artificial atoms, superconducting quantum circuits have some distinctive advantages, such as flexible design, convenient control, potential scalability and precise measurement, and thus provide the appealing testbeds for exploring the fundamental laws of quantum mechanics and realizing quantum state engineering [1,2]. By adjusting the external parameters including gate voltages and bias fluxes (or currents), the desired level structures can be obtained effectively [3–5]. In the artificial atoms driven by external microwave fields, some interesting dynamical behaviors have been considered, consisting of Landau–Zener interference [6,7], Stark shift [8], dynamical parity recovery [9] and optical bistability [10]. In particular, the analogical investigations of EIT [11,12] with superconducting artificial atoms have increasingly captured the attentions during the past few years [13–17].

The optical EIT has been widely explored since its inception [11] and become one of the most important subjects in quantum optics [12]. As a non-linear optical phenomenon, EIT makes the probe light travel through a medium without being absorbed when applying a strong control light to the medium simultaneously, which results from the quantum interference between the atomic level states. By taking advantages of the effect of EIT, the optical properties of the medium can be changed considerably. And thus many promising applications associated with EIT have been investigated extensively, including coherent population trapping [18,19], lasing without inversion [20], and non-linear optics [21]. As an attractive research field, EIT also provides a potential avenue towards studying the controlled slow and fast light [22,23] and implementing optical information storage [24,25].

Based on single Josephson artificial atom [26,27], coupled-atom system [28,29] as well as resonator-assisted composite system [30,31], many novel phenomena associated with EITs have been studied both theoretically and experimentally. Compared with the natural atoms, the artificial atoms of superconducting quantum circuits act as solid-state systems and then are more easily affected by environmental noises, which make them possess the shorter coherence times generally [32,33]. To obtain the ideal EITs, these artificial atoms should be protected to have the sufficiently long coherence times during the processes of the quantum interference [13,14]. Besides, allowed by the selection rule, the cyclic Δ-type interactions of the artificial atoms with external fields occur at some appropriate working points [34–36], which do not exist in the natural atoms due to dipolar-forbidden transition. Physically, the cyclic transition can produce the significant effect of quantum leakage on the dynamical population [37]. Since the leakage is mainly determined by the level harmonicity, choosing the optimized level structure becomes an alternative way to improve EIT with Josephson artificial atoms.

In this paper, we theoretically investigate the EIT using an artificial atom of Cooper-pair box (CPB). For the considered three-level atom, Λ- (Δ-) type interaction between the atom and two driving fields can be achieved in the absence (presence) of quantum leakage. In terms of the dark-state mechanism, quantum leakage has a significant impact on the generation of EIT. After

E-mail address: zbfeng010@163.com (Z.-B. Feng).

http://dx.doi.org/10.1016/j.optcom.2015.11.057
0030-4018/

choosing the preferable characteristic parameters, the leakage error can be nearly removed in an optimized atom with the sufficient level anharmonicity. Based on the optimized atom, we present the realization of EIT by the technique of density matrix. As another effective way to optimize level anharmonicity, cavity-field dressing an artificial atom is considered within a circuit QED. So, the proposed scheme could offer a potential approach for experimentally optimizing EIT with the superconducting artificial atoms.

This paper is organized as follows. Section 2 describes a three-level atom and its interactions with driving fields. Section 3 addresses the impact of quantum leakage on EIT and the dependence of leakage on level harmonicity. Based on an optimized level structure, we derive a performance of EIT in Section 4. Another approach to optimize level anharmonicity is explored in Section 5. Finally, a brief conclusion is drawn in Section 6.

2. An artificial atom and its interactions with driving fields

The quantum circuit under consideration contains a superconducting loop interrupted by a box with excess Cooper-pairs n and two identical Josephson junctions characterized by coupling energy E_{J0}, as schematically shown in Fig. 1. A static gate voltage V_g applied to the gate capacitance C_g induces offset charges. A magnetic flux Φ_e threading the loop is used to modulate the effective Josephson coupling, $E_J = 2E_{J0}\cos(\pi\Phi_e/\Phi_0)$, with $\Phi_0 = h/2e$ being the flux quantum. In the charge-phase regime, E_J has the same order of the charging energy E_c [38,39], and satisfies $\Delta \gg E_J \sim E_c \gg k_B T$, where Δ is superconducting energy gap, $k_B T$ denotes the energy of thermal excitation. Within the charge state basis $\{|n\rangle, |n+1\rangle\}$, the static Hamiltonian of the system reads

$$H_0 = \sum_n [E_c(n-n_g)^2|n\rangle\langle n| - \frac{E_J}{2}(|n\rangle\langle n+1| + H.c.)]. \tag{1}$$

Here the first term is charging energy with scale $E_c = (2e)^2/2C_t$, where C_t is the total capacitance of the box, and $n_g = C_g V_g/2e$ indicates the induced gate charges. Ac gate voltages $\tilde{V}_p$ and $\tilde{V}_c$ are applied to the box through gate capacitances C_p and C_c, respectively, inducing the transitions between the eigenlevels of the system [40], as mentioned below.

According to Eq. (1), the first three levels E_k versus the gate charge n_g for $E_J = 1.5E_c$ are plotted in Fig. 2, with k=g, e and a. At bias point $n_g = 0.35$, we select the level states $|g\rangle$, $|e\rangle$ and $|a\rangle$, which can be expanded in terms of Cooper-pair states $|n\rangle$, namely, $|k\rangle = \sum_n c_{kn}|n\rangle$, with c_{kn} being superposition coefficients. Such a quantum circuit has the well-separated level structure and then can be considered as an effective artificial atom. Although the quantum states at magic point ($n_g = 0.5$) are to first-order decoupled from $1/f$ noise of the gate charges and then are helpful to combat the dephasing effects [38], the selection rule of level states impedes the desired driving-induced transition between $|g\rangle$ and $|a\rangle$ [41]. For this reason, we choose these three states at the present working point of $n_g = 0.35$.

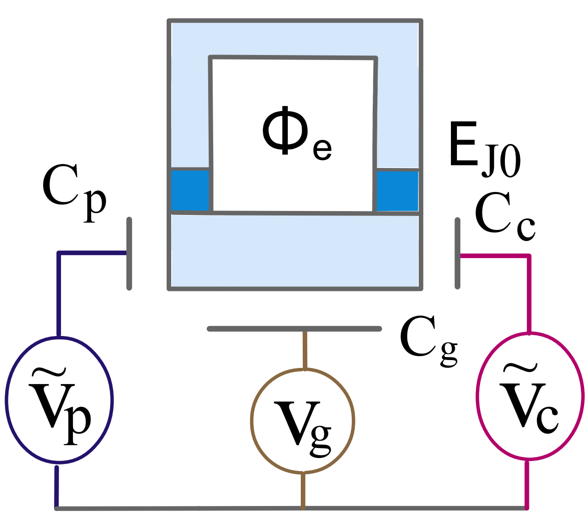

Fig. 1. Schematic diagram of the considered artificial atom driven by a control microwave field $\tilde{V}_c$ and a probe field $\tilde{V}_p$.

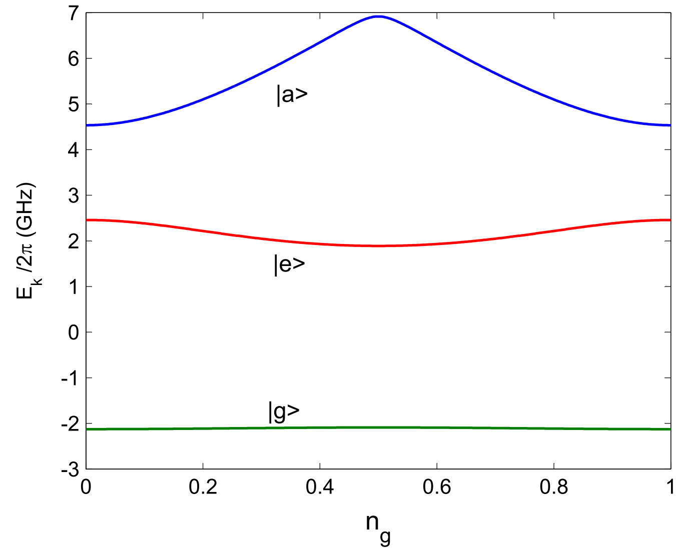

Fig. 2. The three lowest eigenlevels E_k of the quantum circuit versus the gate charge n_g, with k=g, e and a. Here the system characteristic parameters satisfy $E_J = 1.5E_c$, with $E_c/2\pi = 3.0$ GHz. The level states $|g\rangle$, $|e\rangle$ and $|a\rangle$ are chosen at the biased point $n_g = 0.35$.

Two classical microwave pulses $\tilde{V}_p = V_p\cos(\omega_p t)$ and $\tilde{V}_c = V_c\cos(\omega_c t)$ are applied to the atom, leading to the respective level transitions $|g\rangle \leftrightarrow |a\rangle$ and $|e\rangle \leftrightarrow |a\rangle$, here ω_p and ω_c are nearly resonant with the corresponding transition frequencies ω_{ag} and ω_{ea}. The interaction Hamiltonian between the microwave pulse $\tilde{V}_p$ (serving as a pump driving) and the CPB system takes the form of diagonal coupling [41]

$$H_{ps} = -2E_c\tilde{n}_p\sum_n (n-n_g)|n\rangle\langle n|,$$

where $\tilde{n}_p = n_p\cos(\omega_p t)$, with $n_p = C_g V_p/(2e)$. The $\tilde{V}_p$-induced transition matrix element between $|g\rangle$ and $|a\rangle$ is $t_{ga} = \langle g|H_{ps}|a\rangle$. According to $|g\rangle = \sum_n c_{gn}|n\rangle$ and $|a\rangle = \sum_n c_{an}|n\rangle$, we have

$$t_{ga} = -2E_c\tilde{n}_p\sum_n (n-n_g)c_{gn}^*c_{an} = \Omega_{ga}\cos(\omega_p t),$$

where $\Omega_{ga} = -2E_c O_{ga} n_p$, with $O_{ga} = \sum_n (n-n_g)c_{gn}^*c_{an}$ being the overlap between $|g\rangle$ and $|a\rangle$ at the bias point n_g.

Similarly, the interaction Hamiltonian between the control pulse $\tilde{V}_c$ and the atom can be expressed as

$$H_{cs} = -2E_c\tilde{n}_c\sum_n (n-n_g)|n\rangle\langle n|,$$

where $\tilde{n}_c = n_c\cos(\omega_c t)$, with $n_c = C_g V_c/(2e)$. The pulse $\tilde{V}_c$-induced transition matrix element is

$$t_{ea} = \Omega_{ea}\cos(\omega_c t),$$

in which $\Omega_{ea} = -2E_c O_{ea} n_c$, with $O_{ea} = \sum_n (n-n_g)c_{en}^*c_{an}$.

For the artificial atom, the selection rule determined by the parity symmetries of the level states at the present working point ($n_g = 0.35$) allows the transition between $|g\rangle$ and $|e\rangle$ as well, which is significantly different from the dipolar-forbidden transition in