Physica B 465 (2015) 7–12

Contents lists available at ScienceDirect

Physica B

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

Subluminal and superluminal light propagation in a superconducting quantum circuit via Josephson coupling energy

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
25 February 2015
Accepted 2 March 2015
Available online 3 March 2015

Keywords:
Superluminal light propagation
Subluminal light propagation
Transmission coefficient
Artificial molecule
Josephson coupling energy

ABSTRACT

We investigate the dispersion-group index, as well as the transmission coefficient properties of a weak probe field in a superconducting quantum circuit with a tunable V-type artificial molecule constructed by two superconducting Josephson charge qubits coupled with each other through a superconducting quantum interference device. It is realized that the slope of dispersion can be changed from negative to positive or vice versa through the ratio of the Josephson coupling energy to the capacitive coupling strength which provides an extra controlling parameter for controlling the slope of dispersion. The temporal behavior of the probe dispersion and the required switching time for switching the superluminal light propagation to the subluminal light propagation are also discussed. The results may be useful for understanding the switching feature of slow light-based systems and have potential application in optical information processing.

1. Introduction

The research on electromagnetically induced transparency (EIT) [1,2] has attracted a great deal of interest, due to its wide applications in quantum optics, such as subluminal and superluminal light propagation [3] and so on [4,5].

Over the last decade, there has been a remarkable research in creating and controlling quantum coherence in superconducting electrical circuits. The quantum electrodynamics of superconducting microwave circuits has been dubbed as circuit QED [6–11], by analogy to cavity QED in quantum optics.

Circuit QED [12] based on Josephson junctions, where transmission line resonator plays the role of cavity and superconducting qubit [13,14] behaves as artificial atom to replace the natural atom, has recently become a new test-bed for quantum optics. Circuit quantum electrodynamics (cQED) is an on-the-chip counterpart of cavity QED systems, that employs a quantized microwave mode held in a Co-Planar Waveguide resonator (CPW) (substituting the standing-wave optical cavity) and a Cooper Pair Box (CPB) (instead of two-level atom trapped in the cavity). As an on-chip realization of cavity QED, circuit QED has reproduced many quantum optical phenomena, including Kerr and cross-Kerr nonlinearities [15], the Mollow Triplet [16], Autler–Townes effect (ATS) [17], EIT [18–26], three-wave mixing [27], and photon propagation in a superconducting circuit [16,28–32]. Compared to conventional optical implementations, this solid-state architecture offers unprecedented tunability and scalability which are leading to flexible quantum optics in electronic circuits, such as offering long coherence time to implement the quantum gate operations [18], huge tunability and controllability by external electromagnetic fields [15].

In one of recent evidence of induced transparency, reported as EIT by Abdumalikov et al. [18], an experimental observation of EIT on a three-level cascade artificial atom was presented which was coupled to open 1D space of a transmission line. However, Anisimov and co-workers [19] revealed that the reported induced transparency in a superconducting circuit in Ref. [18] was ATS and not EIT. They proved that the origin of this dual interpretation is due to the appearance of a transparency window in the absorption or transmission spectrum for both EIT and ATS. The transparency window occurred in EIT is because of Fano interference among different transition pathways, while the strong field-driven interactions will lead to the splitting of energy levels in ATS. This is discussed in detail in [33]. As it is known, there are four different kinds of three-level atomic configurations: Lambda, V, upper, and lower level driven ladder cascade schemes. However, only Lambda and upper-level driven ladder systems illustrate Fano interference. More discussion on the differences and analogies between atomic and optical physics and superconducting circuits can be found in [34].

In this paper, the dispersion and transmission coefficient properties of the probe field are investigated in a three-level

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http://dx.doi.org/10.1016/j.physb.2015.03.003
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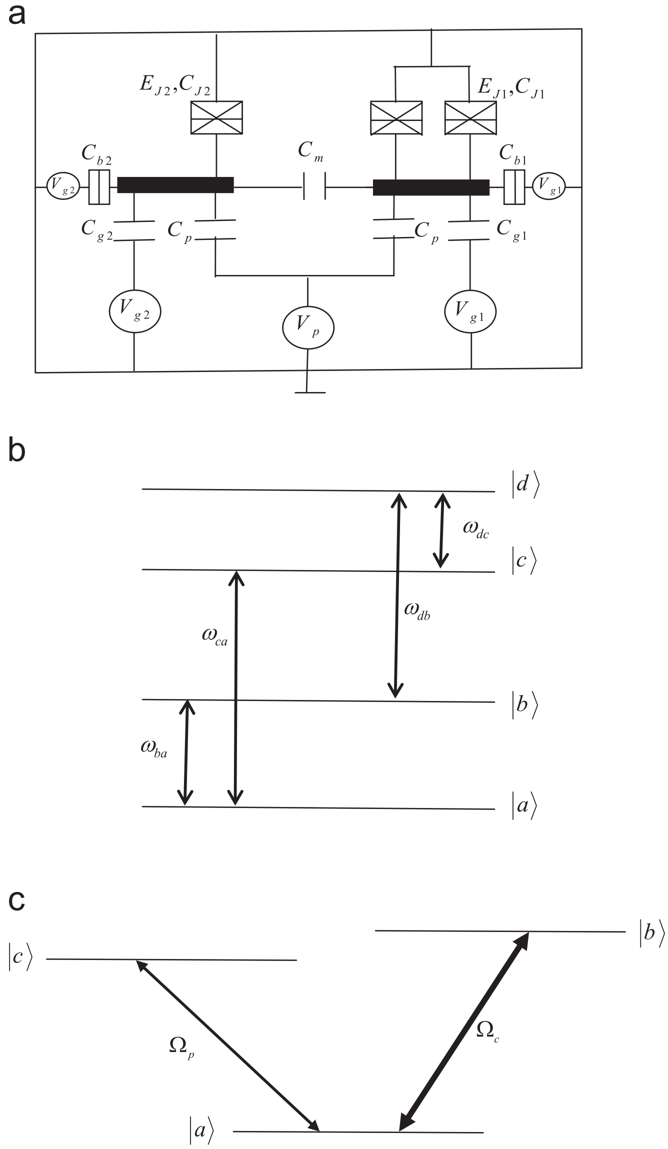

Fig. 1. (a) Schematic diagram of the two-coupled-qubit circuit. Black bars show Cooper pair boxes. (b) Schematic of the allowed transition paths of the coupled charge qubits operated at the co-resonance point. (c) Schematic of V-type three-level artificial molecule.

V-type artificial molecule constructed by two superconducting charge qubits which are coupled each other through a large capacitor. A weak probe and a strong control field couple the two upper states to the ground level, so that the V-shaped configuration is built which depends on the energy separation of Josephson coupling energy of two charge qubits. In fact, this scheme is very similar and relevant to what which is considered in Ref. [20]. However, our work is different is some respects. The system considered in Ref. [20] aims to discuss the electromagnetically induced transparency and absorption (EIT and EIA) characteristics in a three-level Lambda-type scheme of superconducting two-level system dressed by a single mode cavity field. It was shown that the Josephson coupling energy could bring a new prospective to the study of quantum optical phenomena. Due to the tunable structure of levels which depends on the variable qubit level spacing, the switching between EIT and EIA is investigated. On the other hand, in our considered scheme, we explore the propagation of light properties in a three-level V-type artificial molecule. We show that the probe dispersion and transmission are dependent to the ratio of the Josephson coupling energy to the capacitive coupling strength. This extra dependence can be introduced as a new freedom for controlling the superluminal and subluminal light propagation. In addition, the transient evolution of the probe dispersion is analyzed. By adjusting the ratio of the Josephson coupling energy to the capacitive coupling strength, the required switching time for changing the superluminal light propagation to the subluminal propagation of light or vice versa is then discussed.

The presented results could be useful for understanding the features of the next future quantum computers, detectors, and simulators [35,36].

2. Theory and model

Consider two charge qubits that are electrostatically coupled by an on-chip capacitor C_m. Both qubits have a common pulse gate but separate *dc* gates, probes and reservoirs. The pulse gate has nominally equal coupling to each box, while both reservoirs are kept grounded. External controls that we have in the circuit are the *dc* probe voltages V_{b1} and V_{b2}, *dc* gate voltages V_{g1} and V_{g2}, and pulse gate voltage V_p. The information on the final states of the qubits after manipulation comes from the pulse-induced currents measured in the probes.

Each charge qubit has a superconducting quantum interference device (SQUID) ring geometry biased by an external flux. The Hamiltonian of coupled qubits reads [24,37]

$$H = E_{c1}(n_1 - n_{g1})^2 - E_{J1}\cos\Theta_1 + E_{c2}(n_2 - n_{g2})^2 - E_{J2}\cos\Theta_2 + E_m(n_1 - n_{g1})(n_2 - n_{g2}) \tag{1}$$

Here the first four terms describe two independent qubits, whereas the last term shows the interaction between the qubits due to the electrostatical coupling of the capacitor. In this equation, E_{J1} and E_{J2} represent the effective Josephson coupling energy for the corresponding SQUID, where Θ_1 and Θ_2 are the phases of the SQUID. Moreover, $E_{c1,2} = 4e^2C_{\sum 2,1}/2(C_{\sum 1}C_{\sum 2} - C_m^2)$ are defined as the effective Cooper-pair charging energies for the qubits, $C_{\sum i} = C_{gi} + C_{Ji} + C_m$, $(i = 1, 2)$ are the sum of all capacitances connected to the corresponding island, while n_i and $n_{gi} = C_{gi}V_{gi}/2e$, $(i = 1, 2)$ are the number operator of excess Cooper-pairs on the island and the normalized gate induced charge. Also, $E_m = 4e^2C_m/2(C_{\sum 1}C_{\sum 2} - C_m^2)$ is the capacitive coupling energy between the charge qubits.

The Hamiltonian of the superconducting system in the eigenbasis of the qubits and in the vicinity of one degeneracy point ($n_{gi} \in [0, 1]$) can be written as

$$H = \frac{1}{2}E_{J1}\sigma_{z1} + \frac{1}{2}E_{J2}\sigma_{z2} + \frac{1}{2}E_m\sigma_{x1}\sigma_{x2} \tag{2}$$

where σ are a set of Pauli matrices acting on the eigenstates of qubits.

Without loss of generality, one can consider a special case that the two superconducting charge qubits are identical (i.e., $E_{J1} = E_{J2} = E_J$, $E_{c1} = E_{c2} = E_c$, $C_{J1} = C_{J2} = C_J$, $C_{\sum 1} = C_{\sum 2} = C_{\sum}$). In this situation, one may introduces E_J and E_m as

$$E_m = \varpi \sin 2\varphi, \tag{3.a}$$

$$E_J = \frac{\varpi}{4}\cos 2\varphi, \tag{3.b}$$

where

$$\varpi = (E_m^2 + (4E_J)^2), \tag{4}$$

Therefore, from these equations, one can define parameter φ as