Coupling Circuit Resonators Among Themselves and To Nitrogen Vacancy Centers in Diamond

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Abstract. We propose a scheme to couple two or more NV centers in diamond through coplanar waveguide resonators, i.e., the microwave cavity-QED systems. We first split the central conductor of the resonator into several pieces which are coupled strongly with each other through simple capacitive junctions or superconducting Josephson junctions. We then put the NV centers at the junctions. The discontinuity at the junctions induces a large local magnetic field, through which the NV centers are strongly coupled to the circuit resonator. The coupling strength g between the resonator and the NV center is of order of $g/2\pi = 1 \sim 10$ MHz.

Keywords: NV centers, Circuit-QED, Quantum Information
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INTRODUCTION

A nitrogen-vacancy (NV) center in diamond, consisting of a nitrogen atom substituting a carbon atom in diamond and a vacancy trapped adjacent to the substitutional nitrogen, has a spin triplet as its ground state, separated by optical transitions from the excited states. It has a long spin coherence time and extremely sharp optical transitions even at room temperatures, which makes the NV center an excellent candidate system for quantum information processing and quantum information storage [1]. Although the coherent manipulation of the spin within a single NV center has already been demonstrated, a reliable way to couple different NV centers is yet to be found. Here we propose a scheme to couple strongly multiple NV centers separated by hundreds micrometers through a series of coupled circuit-QED systems.

In a circuit-QED system, a local electric field associated with microwave photons in a resonator is large enough that a strong-coupling regime can be reached via an electric coupling with charge or transmon qubits [2, 3]. However, the magnetic field is only 10^{-9}-10^{-8}T, and the magnetic coupling strength with the ground state spin triplet of the NV centers is only of $g/2\pi = 0.1$-1 KHz, which is lower than the cavity decay rate. A large magnetic coupling can be achieved by separating the central conductor of the resonator by Josephson junctions, which is adopted in our scheme to couple two NV centers.

A GENERAL DESCRIPTION

We insert N Josephson junctions into the central conductor, breaking the resonator into N + 1 subresonators, and put a NV center at each junction. The adjacent subresonators are coupled via the junctions. The central conductor of the rth subresonator occupies the space $x_{2r} \leq x \leq x_{2r+1}$ with length $\ell_r = x_{2r+1} - x_{2r}$. The junctions separating the adjacent subresonators have gap $D_r = x_{2r} - x_{2r-1}$. We will assume that $\ell_r \sim 100\mu m$ and $D_r \sim 1$-$10 nm$.

The Hamiltonian of the resonator with the junctions reads

$$H_0 = \frac{1}{2}\sum_m \left(\frac{\theta_m^2}{C_\Sigma} + C_\Sigma w_m^2 \phi_m^2\right) \tag{1}$$

where C_Σ is the total capacitance of the whole system. The eigenfunctions $\psi_m(x)$ should satisfy the Schrdinger equation

$$(\partial_x^2 + k_m^2)\psi_m = 0 \tag{2}$$

for some wave number k_m from the current conservation relation

$$C_J(w_p^2 - w_m^2)\Delta_r\psi_m = C_0 v^2 \partial_x \psi_m(x_{2r}) \tag{3}$$

with $\Delta_r\psi_m \equiv \psi_m(x_{2r}) - \psi_m(x_{2r-1})$ and $w_m \equiv vk_m$, and the normalization condition

$$C_0 \sum_{r=0}^{N} \int_{x_{2r}}^{x_{2r+1}} dx \psi_m \psi_n + C_J \sum_{r=1}^{N} \Delta_r\psi_m \Delta_r\psi_n = C_\Sigma \delta_{mn} \tag{4}$$

where C_0 is the capacitance per unit length of each continuous segments of the central conductor, and C_J is the capacitance of the junction [4].

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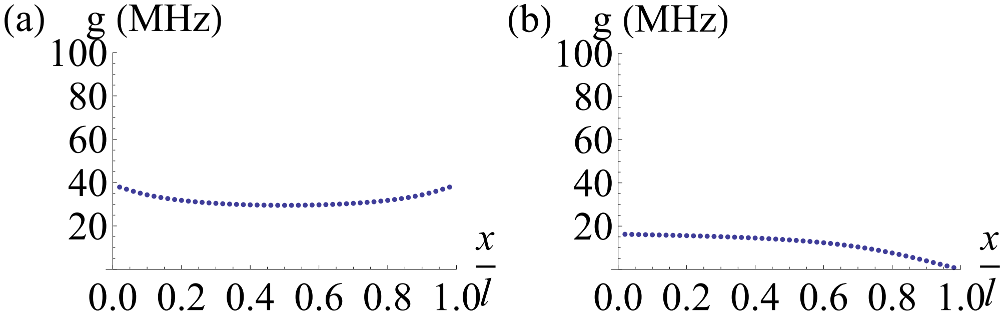

FIGURE 1. (a) The coupling strength for the even $n = 1$ solution. (b) the coupling strength for the odd $n = 1$ solution. For both of the parity solution, the coupling strength are tens of MHz which exceed the cavity decay rate of 1 MHz. This shows that the strong coupling regime is achieved. For the resonator, we take $l = 0.5cm$, $d = 10\mu m$, $v = 10^8 m/s$ and $L_0 = 600nH$. For the Josephson Junction, we take $E_J = 300$ GHz and $w_p = 9$ GHz.

The strength of the magnetic coupling of mth mode at the rth junction can be expressed as

$$g_r^m = g_e \mu_B B_r^m \tag{5}$$

where $B_r^m \equiv \Delta_r \psi_m / D_r W$ (W is the distance between the central conductor and the ground plates), g_e is the electron g-factor, and μ_B is the Bohr magneton.

COUPLING TWO NV CENTERS TO THE CIRCUIT-QED SYSTEM

Now we consider only two Josephson junctions symmetrically placed at x and $-x$ where $0 < x < \ell$ and the origin is at the center of the conductor. The NV centers are then placed at the junctions. Because of the symmetry, the eigenfunctions ψ are either even or odd functions. For the lowest mode of each parity, we calculate the eigenfunction from the schrodinger equation with appropriate boundary and normalization condition. Then, we get the coupling strength between the NV centers and the resonator. See Fig. 1.By choosing the parity and the position, we can get the coupling strength up to 40 MHz. This proves that our cavity QED system with NV center is in the strong coupling regime.

CONCLUSION

We propose a novel architecture for the quantum information processing with the NV centers in Diamond using the superconducting transmission line integrated with two Josephson Junction. We show that a strong coupling regime can be achieved.

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