Implementation of Cross-Resonance System for Universal Quantum Computing

1215047 S. Shirai

Department of Physics, Tokyo University of Science.   Center of Emergent Matter Science, RIKEN.

Introduction

Universal quantum computing

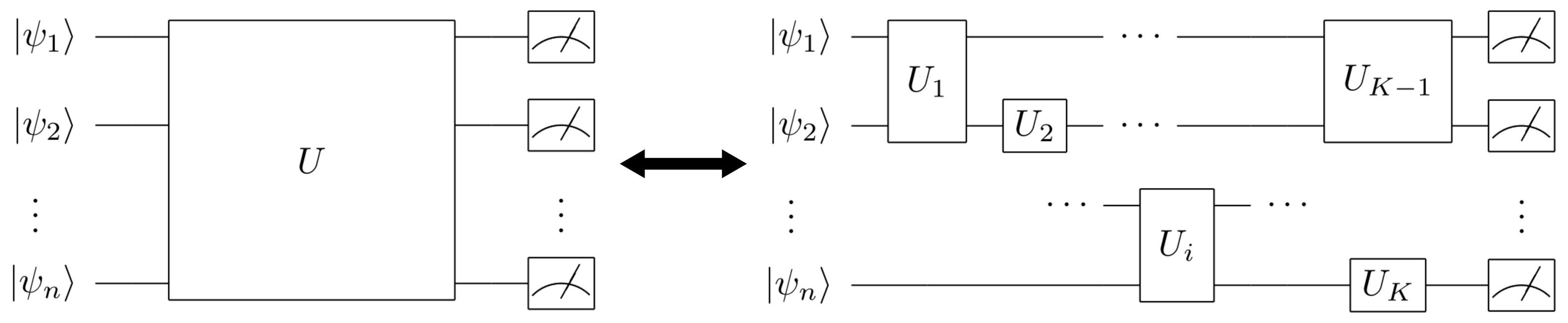
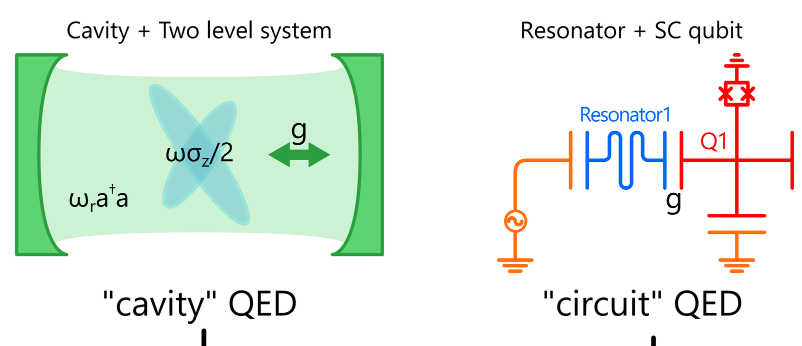


fig.1 example of quantum circuit

According to **the Solovay-Kitaev theorem**, arbitrary N-qubit unitary operators can be approximated with "universal gate set".{S, H, T, CNOT} is one of universal set.
CNOT gate is so-called two-qubit entangling gate. It is difficult to realize two-qubit gates compared to one-qubit gates. So, implementing a precise 2-qubit gate is one of the big challenges.

Theory of circuit QED



Cavity Quantum electrodynamics (cavity QED) is the study of the interaction between light and atom. The case of a single 2-level atom in the cavity is mathematically described by the Jaynes-Cummings model. On the other hand, by using the macroscopic quantum effect appearing in the superconductor, it is possible to construct a system of cavity QED by the solid element. Such a system is called a "**circuit QED**" system.

Jaynes-Cummings Hamiltonian :

$$H = \sum_j \omega_j |j\rangle\langle j| + \omega_r a^\dagger a + \left(\sum_i g_{i,i+1} |i\rangle\langle i+1| a^\dagger + H.c.\right)$$

Superconducting Qubit

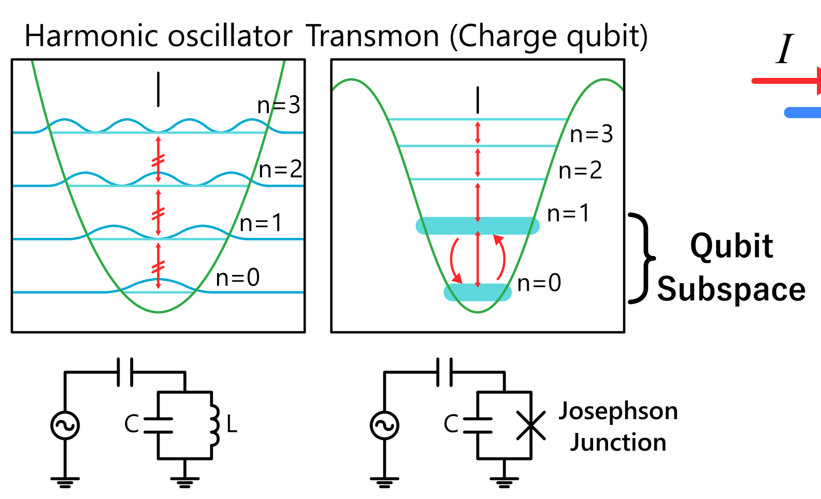


fig. Potential energy and circuit

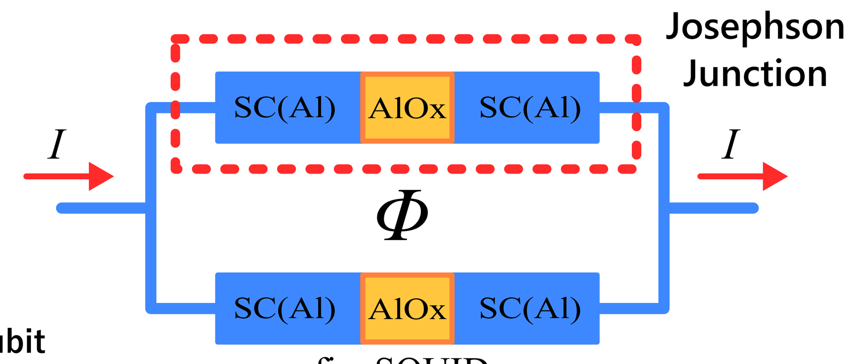


fig. SQUID

$$I = I_C \left| \frac{\sin\left(\frac{\pi\Phi}{\Phi_0}\right)}{\frac{\pi\Phi}{\Phi_0}} \right|$$

- Tunability
- Noise sorce

Cross-Resonance Gate

Cross-Resonance interaction

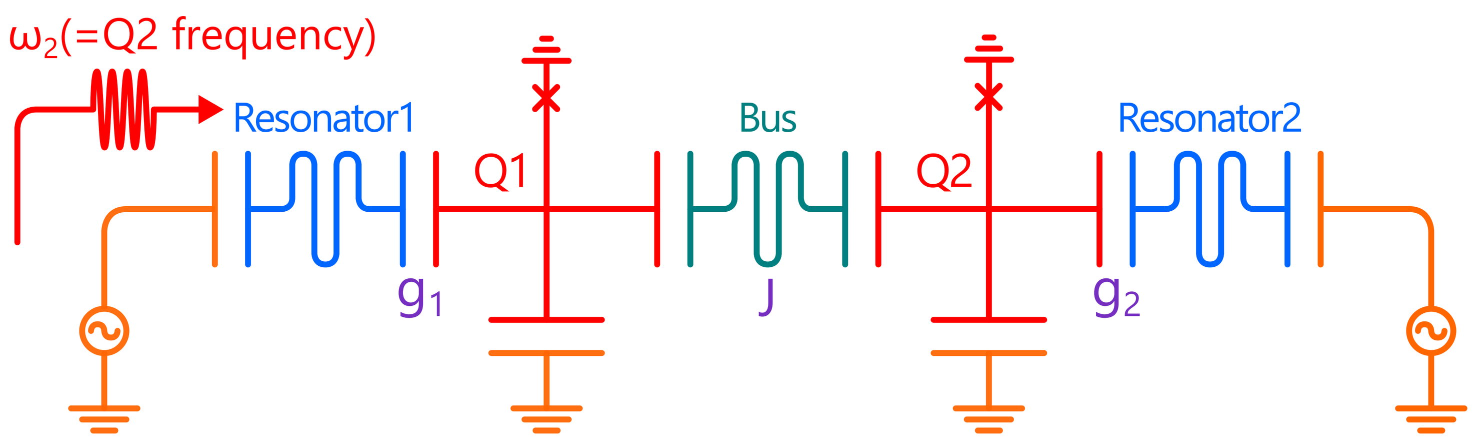


fig. Cross-Resonance system

Resonator + SC qubit are smallest set of cQED system.
The above system Hamiltonian can be written as bellow.

$$H_5 = \sum_{l=1,2,b} \omega_l^r a_l^\dagger a_l + \sum_{q=1,2} \sum_{k_q=0}^{N-1} \omega_k^q |k_q\rangle\langle k_q| + \sum_{l=1,b} g_l^{01}(a_l^\dagger c_1 + a_l c_1^\dagger) + \sum_{l=2,b} g_l^{01}(a_l^\dagger c_2 + a_l c_2^\dagger)$$

After performing the two-level approximation, unitary transformation and perturbative expantion are performed and the following interaction Hamiltonian is obtained while irradiating microwaves from the outside under the condition of {| *J / ω1-ω2* | << *1*}.

$$\tilde{H}_{rot2} = \underbrace{\frac{\Omega(t)}{2}\left(\sigma_x^1 \cos\left(\frac{\tilde\omega_1 - \tilde\omega_2}{2}t\right) - \sigma_y^1 \sin\left(\frac{\omega_1 - \tilde\omega_2}{2}t\right)\right)}_{\text{fast oscillating term}} - \underbrace{\frac{J\Omega(t)}{2\Delta_{12}}}_{=A(t)} \sigma_z^1 \sigma_x^2$$

When the time evolution by microwave irradiation of the system is sufficiently long, the effect of the vibration term is reduced.

Time evolution for CNOT

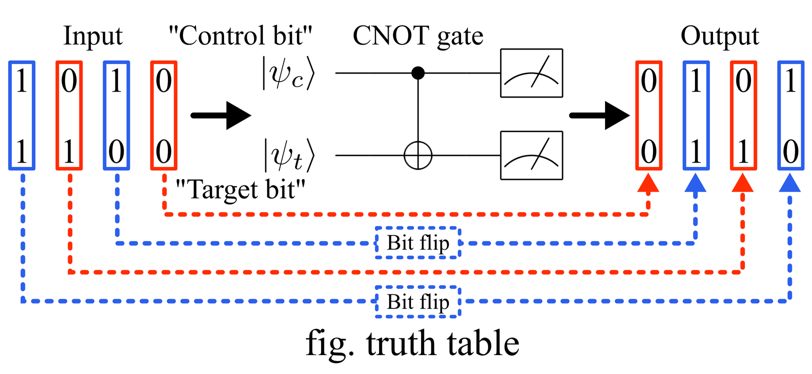


fig. truth table

When the value of the control bit is 1, the gate that inverts the value of the target bit is called "**Controled-NOT gate**" (Simply, CNOT).

Time evolution by *H(t)* :

$$|\psi(0)\rangle \to |\psi(t)\rangle = e^{-i\int_0^t H(\tau)d\tau}|\psi(0)\rangle$$

$$\frac{\pi}{2} = \int_0^{T_{gate}} A(\tau)d\tau$$

$$[ZX]^{1/2} = e^{-i\frac{\pi}{4}\sigma_z^1\sigma_x^2}$$

We get CNOT by combining with one qubit gates.

CNOT=$[ZI]^{-1/2}[ZX]^{1/2}[IX]^{-1/2}$

ref. 10.1103/PhysRevB.81.134507

Fabricated Sample

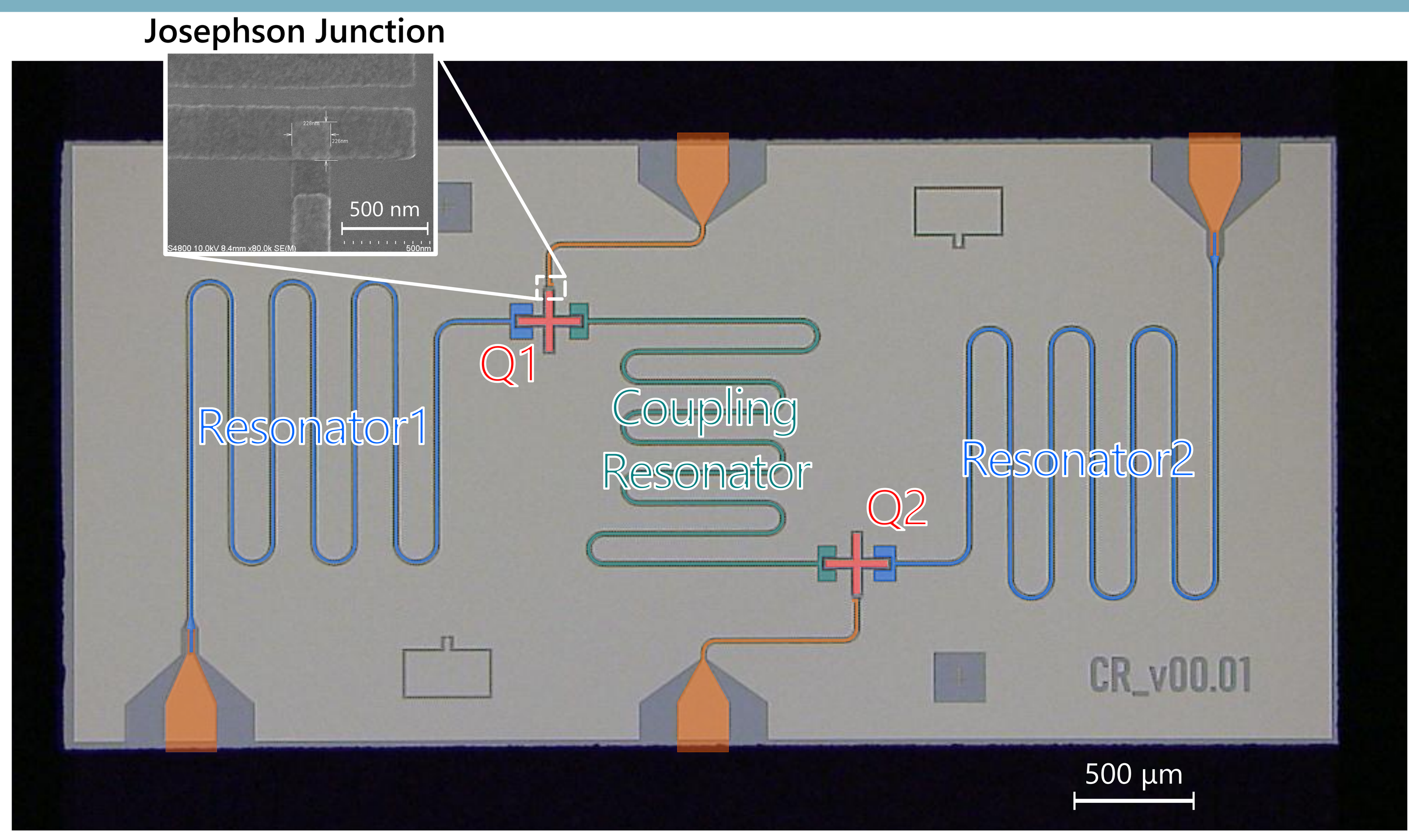


fig. Two qubits(red) coupled circuit via a central resonator(green).

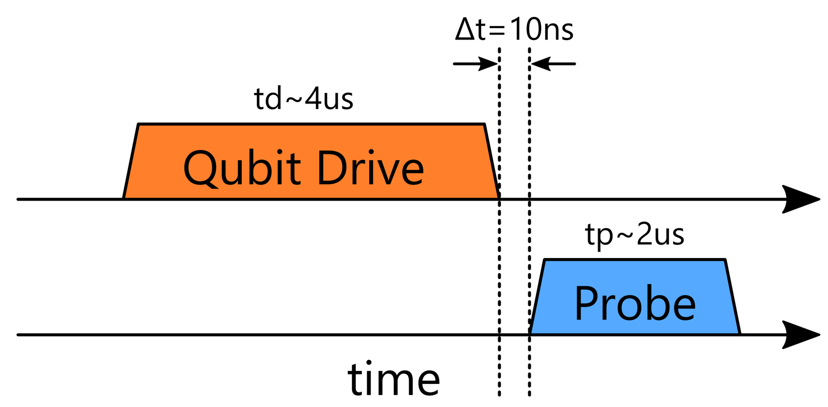
Experimental Result

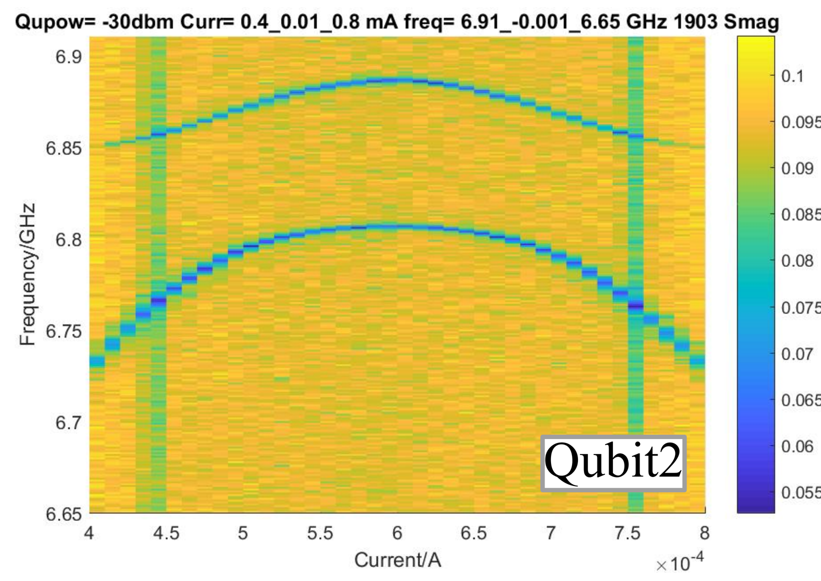
Pulsed spectroscopy

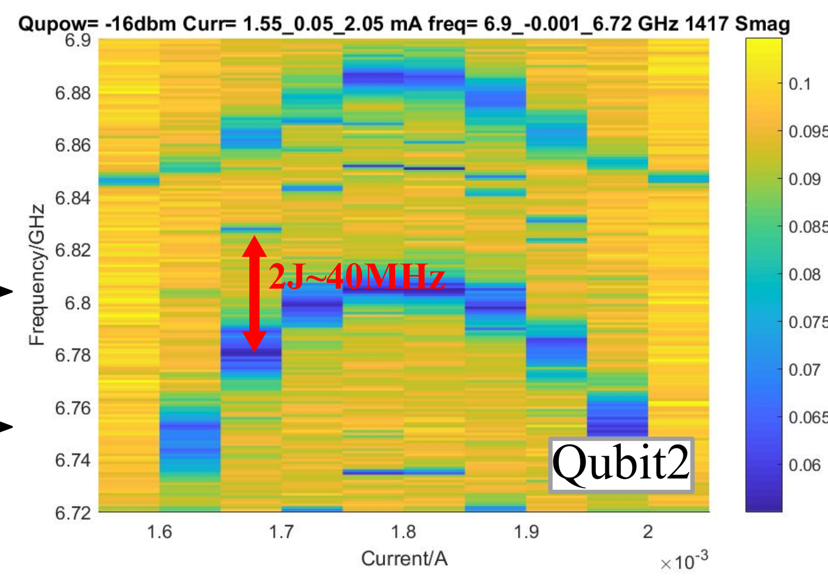
Procedure :

1. Irradiate the microwave for a long time.
2. The state of the qubit becomes classical mixed state by the microwave.
3. The resonance frequency of the resonator varies according to the state of the qubit.
4. The change in the reflection signal of the resonator due to the change of the resonance frequency is read by VNA.

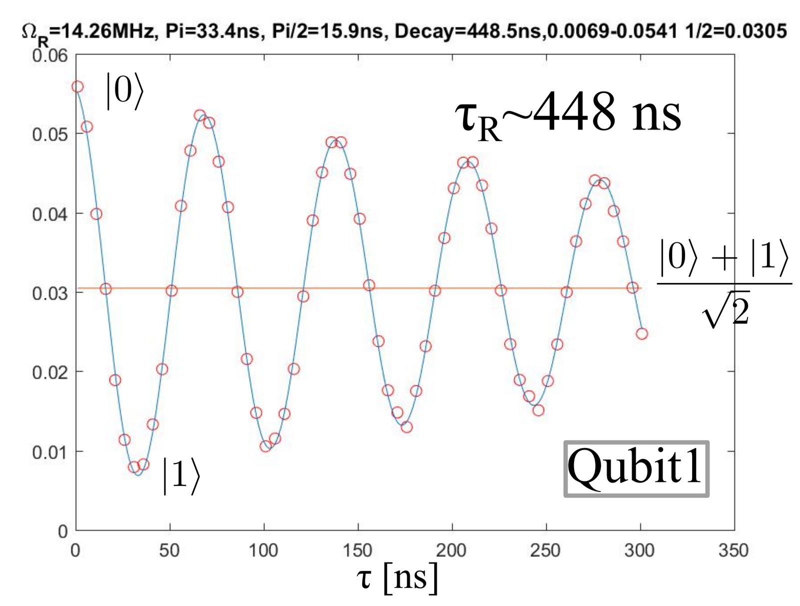
f_{q1}~6.866, f_{q2}~6.886 GHz
J~20MHz

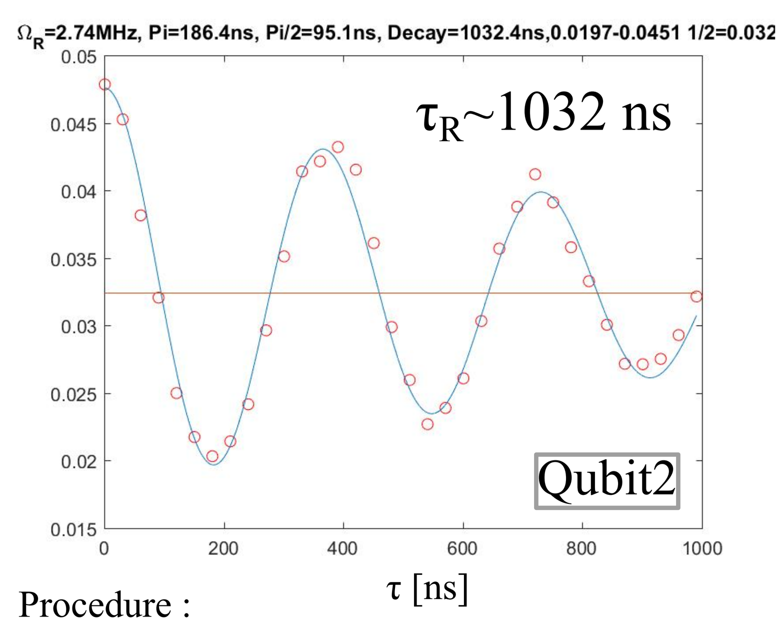


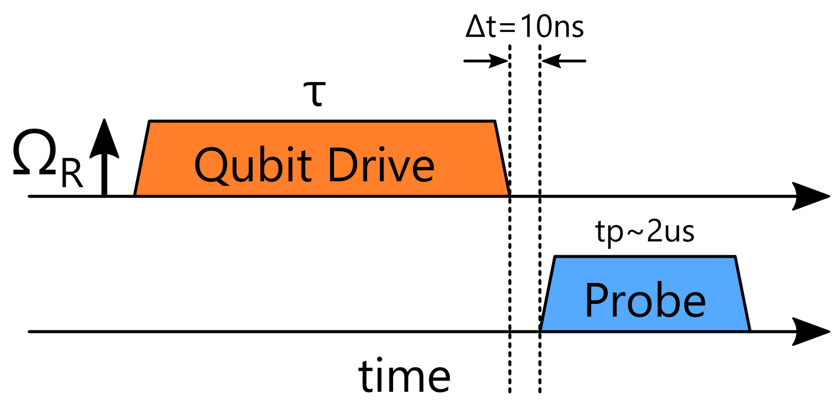




Rabi oscillation







Procedure :

1. Irradiate the microwave pulse to the qubit.
2. Read the state of the qubit through the resonator.
3. Repeat steps 1 and 2 while changing irradiation time of microwave pulse.

Fitting function :

$$p_e(\tau) \simeq \frac{1}{2} - \frac{1}{2}e^{-\tau/\tau_R}\cos\left(\frac{\Omega_R \tau}{2}\right)$$

Conclusion and Future Work

The sample could not work in the regime of CR gate. However, I could confirm the existence of coupling between qubits.

Next time, I would like to fabricate the qubits with better coherence time in CR gate regime.

Acknowledgment

This work supported by JST CREST Grant Number JPMJCR1676, Japan.