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Observation of 65 GHz Coherent Oscillation in a Superconducting Flux Qubit Manipulated by Pulses

Chiarello F ¹, Carelli P ², Castellano M G ¹, Cosmelli C ³, Torrioli G ¹

¹ IFN-CNR, via Cineto Romano 42, 00156 Rome, Italy.

² DSFC, Università dell'Aquila, via Vetoio 1, 67100 L'Aquila, Italy

³ Dep. Physics, "Sapienza" Università di Roma, P.le A. Moro 5, 00185 Rome, Italy

fabio.chiarello@cnr.it

Abstract. A superconducting flux qubit can be manipulated by a fast modification of its potential, with a rapid transition from a double well to a single well shape, and coming back to the initial condition. This mechanism is based on a non-trivial quantum phenomenon, involving "partial" Landau-Zener transitions, coherent evolution in an harmonic potential and quantum interference. The study of this system enables a deep insight in decoherence mechanisms typical of superconducting qubits. Moreover, this procedure allows quantum operations with extreme high speeds, not possible with other standard manipulations. We present the experimental observation of coherent oscillations showing tunable frequencies with a 65 GHz top value.

1. Introduction

Superconducting devices based on Josephson effect are important candidates for the study of macroscopic quantum effects [1] and for the implementation of quantum computing [2]. They allow the realization of "artificial atoms" [3] that can be used as qubits, manipulated by microwave trains or by non-adiabatic pulses, and integrated in complex structures by using microelectronics techniques. The main problem in their use as qubits and quantum logic gates concerns the number of achievable coherent operations. This number must be well above $10^3 - 10^4$ in order to ensure the feasibility of real quantum algorithms. Great efforts are done in order to improve the coherence time by studying and removing the main causes of decoherence, and recent results show typical values of microseconds up to tens of microseconds [4–6]. On the other hand one can try to improve the operating rate. In previous works we showed the possibility to reach operation rates up to 21 GHz by using non adiabatic pulses in a double SQUID system [7–9]. In this paper we present an improved system that allowed the observation of operations up to 65 GHz. We present and discuss the system and the experimental results.

2. Double SQUID and pulse manipulation

The basic element for the manipulation with fast pulses is the double SQUID, a superconducting loop of inductance L interrupted by a second SQUID (a dc SQUID) consisting on a smaller loop of inductance l interrupted by a couple of nominally identical Josephson junctions of critical current i_0 and capacitance c_0 (Fig.1a).



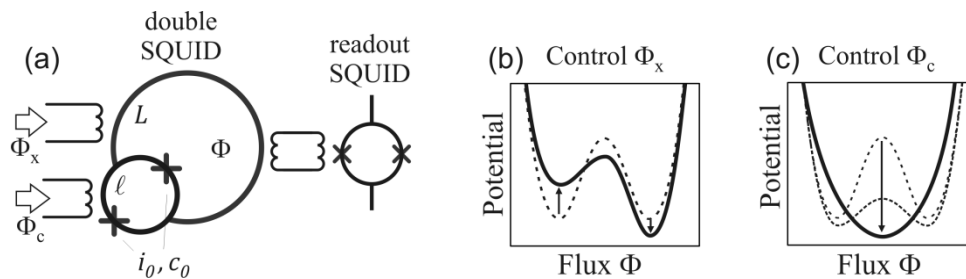


Figure 1. (a) Scheme of the double SQUID. (b) Modification of its potential by using magnetic fluxes applied respectively to the large (b) and to the small loops (c).

In the limit $l \ll \Phi_0 / i_0$ (where $\Phi_0 = h / (2e)$ is the flux quantum) the dc SQUID behaves approximately as a single Josephson junction with total capacitance $C = 2c_0$ and modifiable critical current $I_0 = 2i_0 \cos(\pi \Phi_c / \Phi_0)$, controlled by the magnetic flux applied to the small loop Φ_c . In the small loop limit the double SQUID can be described by a mechanical equivalent, with a particle of effective mass C moving along the “coordinate” Φ (the flux response in the large loop) in a potential $U = (\Phi - \Phi_x)^2 / (2L) - I_0 \Phi_b \cos(\Phi / \Phi_b)$ [10], where Φ_x is the magnetic flux applied to the large loop and $\Phi_b = \hbar / (2e)$ is the reduced flux quantum. In the π -junction case, for $2\pi L I_0 / \Phi_0 < -1$, the potential can present a double well shape, with two minima separated by a central barrier.

For $\Phi_x = 0$ the potential is symmetric, and the flux states in the two wells are degenerate. Applied magnetic fluxes modify the potential shape and can be used to manipulate the SQUID state (Fig.1b and Fig.1c). In particular it is possible to prepare the flux state in one of the two wells by strongly unbalancing the potential (acting on Φ_x) and waiting for the complete relaxation in the minima. An oscillation between the flux states can be obtained by using an interferometric technique [8]. First of all the barrier is completely and abruptly removed by changing the flux Φ_c in order to arrive to a single well potential condition. This turns the system away from the degeneracy point with the effect of a half Landau Zener transition (“half” just because starting from the degeneracy point). Thanks to the particular energy levels structure, it is possible to have transitions that are completely non-adiabatic from the first two levels, but adiabatic for all the upper states. The effect of this fast transition is an equal population of the first two energy levels with a relative phase given by the initial flux state. Far from the degeneracy point (single well condition) there will be the accumulation of a phase difference between the two energy states. A fast return to the degenerate case (double well condition) stops the phase accumulation and causes a second half Landau Zener transition that projects energy states in flux states. The final state, a superposition of left and right flux states, will depend on the accumulated phase and on the pulse duration and depth too. The final flux state can be read out by means of an unshunted SQUID magnetometer, inductively coupled to the qubit large loop by means of a superconducting transformer (Fig.1a).

The oscillation frequency is given by the gap between energy levels and can be significantly higher than that obtainable with a manipulation based on Rabi oscillations with microwave pulses. This gap, expressed as a frequency, is approximately given by $f = f_0 \sqrt{1 + \beta_0 \cos(\pi \Phi_c / \Phi_0)}$, where $f_0 = 1 / (2\pi \sqrt{LC})$ and $\beta_0 = 2i_0 L / \Phi_b$.

3. Experimental setup and results

In a previous work we obtained oscillation frequencies up to 21 GHz [9]. In this work we present a system that allows oscillation frequencies up to 65 GHz. This has been possible thanks to an advanced fabrication technology, the deep submicron (DSM) with fully-planarized Nb-(Al-AlOx)-Nb trilayer process available at the MIT Lincoln Laboratory facility (current density of 500 A/cm²), which allowed the realization of high quality Josephson junctions with small dimensions (1 μm side) and reduced capacitance (ten times smaller than in the previous setup). In the new design the Josephson

junctions have nominal critical currents $i_0 \cong 6 \mu A$ and capacitances $c_0 \cong 30 fF$, and the SQUID has large and small loops with nominal inductances $L = 120 pH$ and $l = 10 pH$ respectively, with gradiometric configurations (“8-shape” loops). The device has been first tested at 4.2 K, and then cooled down to 30 mK in a dilution refrigerator equipped for ultra low-noise qubits measurements, with concentric metal, μ -metal and superconducting shields. The dc lines are filtered by means of passive filters and thermocoax cables at different stages, while the fast lines (used for pulses) pass through attenuators at three different temperature stages. The fast pulses are generated by an Agilent 81130A pulse generator, characterized by a (measured) rise-time of 0.8 ns. For fixed amplitude and duration of the fast pulse, a sequence of operation is repeated: first of all a flux pulse (a Gaussian pulse of width 5 μs) is applied to Φ_x in order to unbalance the potential and prepare the initial state (the left state). Then (at 30 μs from the beginning of the sequence) a fast pulse is applied on Φ_c to perform the rotation between the flux states. After some time (at 40 μs) a current ramp is applied to the readout dc SQUID. The measured transition to the voltage state is used to trigger the acquisition of the critical current, and the double SQUID flux state is determined from this value. This sequence is repeated many times (from 1000 to 10 000, according to the required accuracy) with a repetition rate of 20 kHz in order to evaluate the mean flux state, and so the probability to find the left well occupied. By repeating this procedure for different pulse durations Δt it is possible to plot the oscillation curve, showing the rotation between the flux states. By using pulses with different heights $\Delta\Phi_c$ the frequency of oscillations changes. A series of curves corresponding to different oscillation frequencies are plotted in (Fig.2a) by using a waterfall graph.

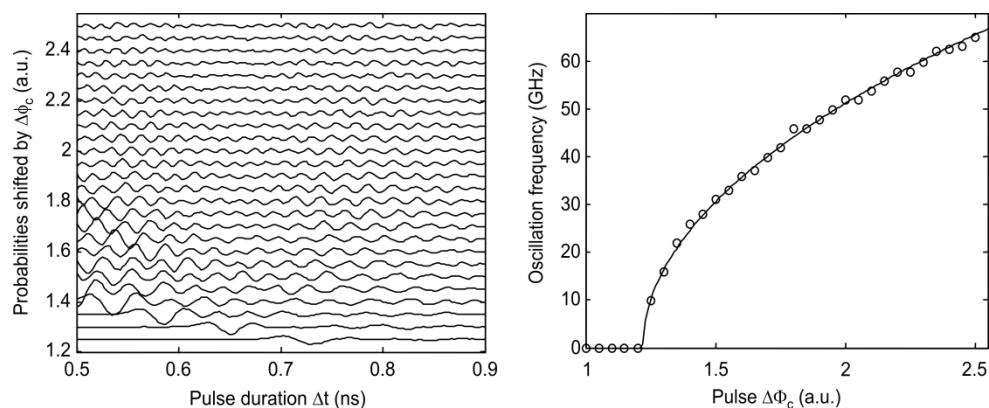


Figure 2. (a) Waterfall plot of the experimental oscillation curves obtained for different pulse heights $\Delta\Phi_c$ (the different curves are vertically shifted by the relative $\Delta\Phi_c$). (b) Measured oscillation frequencies (circles) compared with the expected values (line).

These curves presents an unwanted modulation in frequency and amplitude that can be explained by considering a small spurious fixed resonance at about 10 GHz, probably related to our setup. From these curves it is possible to extract a plot of the oscillation frequencies vs. pulse heights (Fig.2b), which is in good agreement with the theoretical expectation. The higher measured point in Fig.2a corresponds to a frequency of 65 GHz.

4. Discussions

This result is particularly interesting and promising, but emphasizes technological difficulties and limits reached with this kind of manipulation. First of all, in order to perform a single manipulation it is necessary to have pulses shorter than those of operation period. For a 65 GHz frequency this corresponds to use pulses shorter than 15 ps with rise times much shorter. Our setup allows only rise/fall times of 800 ps, so that we are not able to observe a single oscillation and also our shorter pulse contains a lot of rotations. Moreover, in order to have a slew-rate suitable for the Landau Zener

transition and because of our “small” rise times, we have to use pulses with amplitude higher than necessary. Such large pulses have harmful effects on the oscillations stability and coherence because of overshoots, unwanted resonances and spurious couplings with other lines. The use of a faster pulse generator would mitigate this problem, but it would not be the final solution. In any case the control pulses must be large enough to ensure the modification of the potential from the double well to the single well shape (larger than in the case of manipulation with microwaves, where such a strong modification of the potential is not required). These pulses must be very well formed since small distortions strongly modify the dynamics. Therefore, well-shaped picosecond large pulses that could be transmitted with small distortions and reflections from room temperature to 30 mK stage would be needed. This is an hard technological challenge that must be addressed in order to make really advantageous the use of SQUID qubits manipulated by fast pulses.

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