Vertical Josephson Interferometer for Tunable Flux Qubit

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Abstract. We present a niobium-based Josephson device as prototype for quantum computation with flux qubits. The most interesting feature of this device is the use of a Josephson vertical interferometer to tune the flux qubit allowing the control of the off-diagonal Hamiltonian terms of the system. In the vertical interferometer, the Josephson current is precisely modulated from a maximum to zero with fine control by a small transversal magnetic field parallel to the rf superconducting loop plane.

1. Introduction

A large variety of solid state systems as strong candidates to be unit elements for a quantum computer[1], have been recently published. Actually phase-[2], and charge-[3] devices have been proposed for operations with single qubit, or two coupled qubits [4,5]. In a final design, quantum gates require qubit-qubit coupling that preserves quantum coherence, and conventional superconducting devices can couple the flux between two qubits but it may be difficult to switch or to control the qubit [6-9]. A tunable coupling of multiple qubits can be a central step towards the realization of a quantum computer[10]. In this paper, we present a niobium-based Josephson device as prototype for applications to quantum computation using tunable flux qubits. In particular we have designed, fabricated and characterized rf SQUID based-devices including a vertical two Josephson junctions interferometer as a controllable element of the rf SQUID.

2. Theoretical background

A rf SQUID, namely a superconducting loop of inductance $L$ closed by a Josephson junction of critical current $I_c$, and with a reduced inductance $\beta = \frac{2\pi L}{\Phi_0}$, in the presence of an external flux $\phi$, is described by a double well potential[1,6]. The external magnetic flux $\phi$ controls the energy difference between the minima, the symmetric situation being for $\phi = 0$. Each logical state is represented by a wave-function localized in a distinct potential well, and corresponds to distinguishable flux states trapped in the ring with current flowing in opposite directions, say $|0\rangle$. 

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clockwise and $|1\rangle$ anticlockwise. The coupling of the states can be described by the tunneling amplitude $\Delta$, and the Hamiltonian of the flux qubit reduces to the regular two-state form in the basis of these logical states:[1]:

$$H = \frac{1}{2} \left[ \varepsilon \left( |0\rangle\langle 0| - |1\rangle\langle 1| \right) - \Delta \left( |0\rangle\langle 1| + |1\rangle\langle 0| \right) \right] = \frac{1}{2} \left( \varepsilon \sigma_z - \Delta \sigma_x \right)$$

being the Pauli matrices. The diagonal elements of $H$ can be easily controlled by an external magnetic field $B_z$ in the z-direction generating an external flux $\Phi$, while the off-diagonal elements are related to the tunneling amplitude which strongly depends on the Josephson energy $U = U_0 \varepsilon$ ($U_0$ is the barrier height), and this parameter is difficult to be independently controlled with enough precision. An external magnetic field $B_x$ in the x-direction generates an external flux $\Phi_{dC}$, independently applied to the Josephson element, modulates the Josephson energy $U$, and, as a consequence, the tunneling rate. To be effective in controlling the Hamiltonian we need a wide modulation of $I_c$ (possibly to zero) as well as a magnetic field generating $\Phi_{dC}$ orthogonal to the one generating $\Phi$, in order to reduce the interference between the two control signals. Here we present a way to realize this control via a Vertical Josephson Interferometer (VJI)[9]. In fact, such device can be used to control the inductance parameter of the rf SQUID and to realise a switchable and tunable flux qubit. The Josephson junction of the rf SQUID, in fact, replaced by a double-junction interferometer, where the critical current is precisely controlled by a small transversal magnetic field parallel to superconducting loop plane and modulates from a maximum to zero with fine control and precision. In such configuration, in the rf SQUID including a VJI, the total flux as a function of the external flux $\Phi$, is:

$$\Phi = \Phi_0 - \frac{\beta(B_x) \Phi_0}{2\pi} \sin \frac{2\pi \Phi}{\Phi_0}$$

where the dependence of $\beta$ on the magnetic field $B_x$, is given by $I_c(B_x)$[9].

3. Experiments

The fabrication process, is based on all-refractory Niobium technology and it is reported elsewhere[11]. The device fabricated is shown in Fig. 1.

**Figure 1** Picture of the device including a vertical Josephson interferometer for a fine control of the rf SQUID.

The single junction of the rf-SQUID is here given by a vertical interferometer consisting in two square Josephson junction ($A_j = s^2 = 4 \times 4 \mu m^2$) separated by a distance $l = 20 \mu m$. The interferometer loop
area perpendicular to the x-axis is $A_l = (0.34 \times 20) \ \mu \text{m}^2 = 6.8 \ \mu \text{m}^2$, while the magnetic penetration depth is $d = t + 2 \lambda_L = 0.34 \ \mu \text{m}$, with $t = 0.22 \ \mu \text{m}$ and $\lambda_L = 0.06 \ \mu \text{m}$. A relevant parameter of the interferometer is $\beta_{dc} = 2\pi L_{dc} I_c(0)/\Phi_0$, where $L_{dc}$ is the superconducting loop inductance and $I_c(0)$ is the total critical current at zero magnetic field. For our sample, resulting an inductance $L_{dc} = 2.13 \ \text{pH}$, and a critical current $I_c(0) = 20 \ \mu \text{A}$, we have $\beta_{dc} = 0.01$. In order to verify the full magnetic modulation depth down to zero, we have also measured the $I_c(B_x)$ on a test interferometer integrated on the same device verifying the expected zero modulation at $B_x = 0$. Such a field is provided either by an integrated vertical coil magnetically coupled to the vertical interferometer or by an external coil (solenoid assembled around the sample). The integrated coil consists of two overlapped niobium striplines (9 $\mu \text{m}$ wide, and 5 $\mu \text{m}$ far from the vertical interferometer) separated by the double oxide layers (400 nm thick). The rf SQUID was inductively coupled to a dc SQUID readout by a superconducting flux transformer in a gradiometric configuration. The reduced inductance of the rf-SQUID at zero transversal magnetic field was: $\beta(0) = 4.9$. The dc SQUID consists of a parallel double-washer forming a first order planar gradiometer with respect to background magnetic field. The external flux $\Phi_e$ is provided by an external current into a niobium single coil located inside the rf SQUID hole. Furthermore the compensation and feedback coils for flux locked loop operation[12], have been integrated on the device.

The measurements were performed at $T = 4.2 \ \text{K}$ in a pumped liquid $^4\text{He}$ cryostat with three $\mu$-metal shields and two copper layers to reduce electromagnetic noise. The SQUID device was also shielded by a coaxial lead/cryoperm double can. All the electrical connections to room temperature were radio frequency filtered. A readout electronics with a direct coupled scheme has been used, where the dc SQUID is directly coupled to a low voltage noise preamplifier. The whole pre-amplification stage was carefully shielded by copper boxes[11].

We measured the transitions between adjacent flux states of the rf SQUID as a function of the external flux, $\Phi_{out} vs \Phi_e$, at different transversal magnetic fields $B_x$ (Fig.2). Due to the relative high current required in the integrated coil (about 10 mA) to modulate the vertical interferometer, we observe a slight degradation of the dc SQUID readout performances resulting in 20% noise added.

![Figure 2](image-url)  

**Figure 2** Flux output signal as function of the external magnetic flux, $\Phi_{out} - \Phi_e$, of a rf SQUID device including VJII at $T = 4.2 \ \text{K}$. The variation of the reduced inductive parameter $\beta$, at different transversal magnetic fields $B_x$, is shown. The curves are slightly shifted to show the details of the different hysteresis.

This problem can be easily eliminated by reducing the separating distance between the excitation coil and the vertical interferometer. In any case all the measurements have been performed using both integrated coil and an external coil, obtaining the same results. As it is shown in figure we are able to control the reduced inductive parameter $\beta$ in the range (0-4.9), by varying $B_x$. It is worth noting that
the fitting $\beta$ values are consistent with the evaluation of $\beta$ as obtained measuring the critical current $I_c$ in the test vertical interferometer, at the same value of the external magnetic field $B_x$. Comparing the experimental hysteresis widths with theoretical predictions (Eq. 2), it is possible to observe a reduction of experimental values due to additional thermal noise.

In conclusion, we have presented a niobium-based device including vertical Josephson interferometer which can be proposed as new complex system for quantum computing. The possibility to control the Josephson properties of the vertical interferometer by a transversal magnetic field can be used to vary the off-diagonal elements of a flux qubit.

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