A New Flux/Phase Qubit With Integrated Readout

Maria Gabriella Castellano, Fabio Chiarello, Roberto Leoni, Guido Torrioli, Pasquale Carelli, Carlo Cosmelli, Marilena Di Bucchianico, Francesco Mattioli, Stefano Poletto, and Daniela Simeone

***Abstract*—We propose a new scheme for a flux/phase qubit, based on a double-SQUID modified to achieve a direct readout of the flux state. The readout is performed by inserting a large Josephson junction in the SQUID loop; the junction is biased by an external current and switches from the zero-voltage to the running state depending on the flux state of the qubit. We report recent results concerning the theoretical behavior and the experimental characterization at 4.2 K of the device, which has been realized with Nb/AlOx/Nb trilayer technology.**

***Index Terms*—Josephson, qubit, SQUID, superconductivity.**

I. Introduction

SUPERCONDUCTING devices based on the Josephson effect are promising candidates for quantum computing applications; single Josephson qubit preparation, coherent manipulation and readout have been experimentally proven and there are first evidences concerning two qubits operations [1]–[8]. A great effort concerns the design and optimization of new systems overcoming the main limits of the first generation of Josephson qubits. In this direction, we propose a new scheme for a flux/phase qubit.

Flux qubits are based on the properties of Josephson junctions and superconducting loops [9]. The starting point is the rf-SQUID, a superconducting loop with one Josephson junction; when biased at half flux quantum, this device is described by a double well potential in the flux coordinate, with barrier height determined by the loop inductance L and the junction critical current I_0. The computational states correspond to shielding current circulating clockwise or counterclockwise. Deviation of the biasing flux from $\Phi_0/2$ produces a tilt in the potential, which at some extent can be used to manipulate the qubit. Usually the flux response of the double-SQUID to an external magnetic flux is read out by inductively coupling the SQUID loop to a magnetometer. To gain additional flexibility in the potential manipulation, the Josephson junction can be replaced with a SQUID interferometer (a loop of inductance l with two junctions, coupled to a control flux Φ_c), which, if its inductance is much smaller than that of the main rf-SQUID loop, behaves as a junction with tunable critical current; with this control it is possible to vary the barrier height from outside. This device is called double-SQUID and was proposed by J. E. Lukens [10].

A double-SQUID of this type was implemented in the last years by our group, using a full gradiometric configuration both for the outer loop and for the inner interferometer, such that uniform fields are rejected. In our design, the readout of the flux state could be accomplished by a shunted dc-SQUID used as linear amplifier or by a hysteretic dc-SQUID used as a threshold detector, both integrated on chip. The latter device is expected to be better suited to operate with qubits, since it has no additional resistors that could affect the qubit decoherence; moreover, it showed experimentally single-shot measurement capability [11].

In this paper we show the feasibility of an alternative scheme that is based on the insertion of a large Josephson junction in the main loop and that we indicate as "direct readout" in contrast with the "external, indirect readout" related to magnetic flux coupling. The direct readout scheme presents the advantages to have a very simple and compact design, to make simpler the readout operations, and to allow an extremely high efficiency in discriminating the qubit states. It can be seen as the extreme limit of strong coupling between the detector and the qubit (in this case joined together), and this opens a series of questions related, for example, to the effects of the large junction switching to the resistive state with consequent qubit heating and production of quasiparticles. Nevertheless, the direct readout scheme has been successfully applied for the first time to a different type of qubit (the so called "Quantronium" [4]), allowing a complete and effective study of the qubit coherent behavior. In our system the presence of both a standard dc-SQUID discriminator softly coupled to the qubit (small coupling limit) and of the direct readout scheme (strong coupling limit) will allow a systematic study of the discriminator effects on the qubit behavior.

II. Direct Readout of a Double-SQUID

The scheme of the device is shown in Fig. 1; the gradiometric structure of the inner interferometer has not been displayed, for simplicity. The double-SQUID has a total inductance L and a critical current I_0, determined by the inner interferometer and comprehensive of the effect of the control flux Φ_c. We suppose that the condition $L \gg l$ is satisfied and hence the inner interferometer can be considered as a tunable Josephson junction, with $I_0(\Phi_c) = I_{0\,\max}\cos(\pi\Phi_c/\Phi_0)$. A large Josephson junction, labeled LJ and with critical current I_{0L}, is inserted in the main loop and externally biased by a current I_p, leading to a superconducting phase difference δ across it. In brief, the working principle is the following. The junction is actually crossed by I_p and by the current circulating in the qubit loop, which in turn

Manuscript received October 4, 2004. This work was supported in part by Istituto Nazionale di Fisica Nucleare, Italy, under the SQC project.

M. G. Castellano, F. Chiarello, R. Leoni, and G. Torrioli are with Istituto di Fotonica e Nanotecnologie, CNR, 00156 Roma and INFN sez di Roma, Italy (e-mail: mgcastellano@ifn.cnr.it).

P. Carelli is with Dipartimento di Energia Elettrica, Università de L'Aquila, L'Aquila, and INFN, gruppo Gran Sasso, Italy.

C. Cosmelli is with Dipartimento di Fisica, Università La Sapienza, 00185 Roma, Italy, and INFN sez. di Roma, Italy.

M. Di Bucchianico is with Dipartimento di Fisica, Università La Sapienza, 00185 Roma, Italy.

F. Mattioli, S. Poletto, and D. Simeone are with Istituto di Fotonica e Nanotecnologie, CNR, 00156 Roma, and Università di Roma 3, 00146 Roma, Italy.

Digital Object Identifier 10.1109/TASC.2005.850080

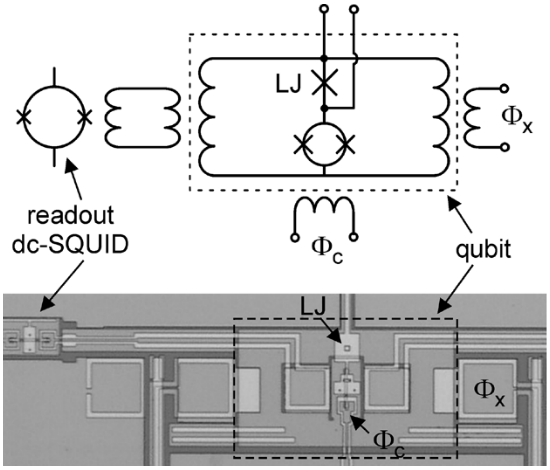

Fig. 1. Scheme of the direct readout flux qubit and picture of the realized device. The qubit has the structure of a double-SQUID, modified by the insertion of the large junction LJ. An on-chip hysteretic dc-SQUID can be used to monitor the flux in the double-SQUID. The control fluxes Φ_x and Φ_c are applied through two one-turn coils.

depends on the magnetic flux threading the loop. At the optimal working point, the qubit states produce a current $+I_q$ and $-I_q$ respectively. If the total current is well below the critical current of the large junction, the system remains in the superconducting state, otherwise there is a transition to the voltage state and consequently a voltage signal across the junction terminals. Therefore, to perform a single shot readout and discriminate the two qubit states it is sufficient to set the current pulse at a value such that $I_p - I_q < I_{0L}$ (no transition to the voltage state) while $I_p + I_q > I_{0L}$ (transition to the voltage state).

In detail, the overall potential is a function of the magnetic flux in the qubit, Φ, and of the phase difference δ across the junction; the other relevant parameters are the bias flux Φ_x of the double-SQUID, its inductance L and its critical current $I_{0,}$, and critical current and bias current of the large junction. The potential can be written as follows:

$$U(\Phi,\delta) = \frac{(\Phi-\Phi_x)^2}{2L} - \frac{I_0\Phi_0}{2\pi}\cos\left(\frac{2\pi\Phi}{\Phi_0}+\delta\right) - \frac{I_p\Phi_0}{2\pi}\delta - \frac{I_{0L}\Phi_0}{2\pi}\cos\delta. \quad (1)$$

When I_p is kept well below I_{0L}, the phase δ is essentially frozen at the value $\delta = \arcsin(I_p/I_{0L})$, provided that $I_{0L} \gg I_0$ (LJ very large) like in our case, and the SQUID behaves like a simple rf-SQUID with an additional flux bias contribution $\Phi_{\rm eff} = (\Phi_0/2\pi)\arcsin(I_p/I_{0L})$. When I_p approaches I_{0L}, a channel opens up in the potential for the phase, which starts running and produces a switch to the voltage state. Fig. 2(a) shows the contour plot of the qubit potential before the measurement procedure: the large junction is not biased and the proper flux biasing point $\Phi_x = \Phi_0/2$ produces two symmetric wells; the bottom of each well corresponds to one of the computational states. During the measurement, when the large junction is biased close to the critical current value $I_p \sim I_{0L}$, the potential is modified as shown in Fig. 2(b): the left well disappears, and if the system were initially there, it would go into a running state; the right well, instead, remains deep enough to support a static solution, although the depth of the well is decreased. As expected,

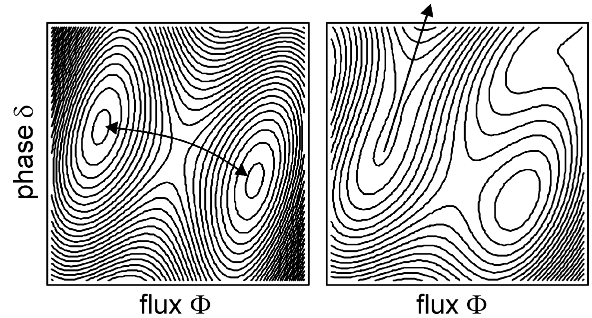

Fig. 2. Contour plot of the device potential in the plane phase-magnetic flux. Left: before the measurement, the readout junction is not current biased, the external flux is such that the potential is a double well; the system is supposed to be in the left well. Right: during the measurement, the readout junction is biased, the potential changes, the left well disappears and the system goes to a running solution, whereas the right well is still there.

then, the system is moved away from the correct operating point by the additional flux $\Phi_{\rm eff}$ due to the current bias of the large junction. To avoid the destruction of the information to be read due to this spurious bias, the barrier must be maintained high enough to prevent jumps between the states during the readout. This effect must be taken into account in the design of the qubit.

III. Device Design and Fabrication

The device has been realized with Nb/AlOx/Nb trilayer technology at IFN-CNR. On the basis of the previously developed double-SQUID, the design was modified by inserting a $10\ \mu\mathrm{m} \times 10\ \mu\mathrm{m}$ Josephson junction at the connection of the inner dc-SQUID with the outer loop. Typical values for the parameters are $L = 85$ pH, $I_{0L} = 130\ \mu$A. The junctions of the inner interferometer have smaller size (3 μm nominal side, 2.5 μm effective), with critical current of 8 μA each, and the inner loop has an inductance $l = 7$ pH. Each device is coupled, through a superconducting transformer, to a standard SQUID magnetometer and to a hysteretic dc SQUID used as a threshold detector, both fabricated on chip and used for cross checks. Two single-turn coils are used to couple from outside the control fluxes, Φ_x (coupled to the outer loop) for varying shape and tilt of the equivalent potential and Φ_c (coupled to the inner interferometer) for changing the critical current of the inner dc-SQUID.

IV. Experimental Characterization

The measurements reported here have been taken at 4.2 K and allowed us to check the main features of the device. The readout junction was used to track the device characteristics by measuring the switching current during escape measurements. While keeping the control fluxes fixed, the readout junction was swept by a current ramp at a rate of 100 mA/s and the voltage across it was sent to a threshold detector. Whenever the sum of the bias current and of the circulating current exceeds the critical current, there is a switch to the voltage state that triggers the acquisition of the corresponding bias current. This process is stochastic and depends on thermal fluctuations. For this reason, the procedure is repeated typically 1000 times and the distribution and mean value of the switching current are collected. The procedure is repeated for various values of the magnetic flux Φ_x

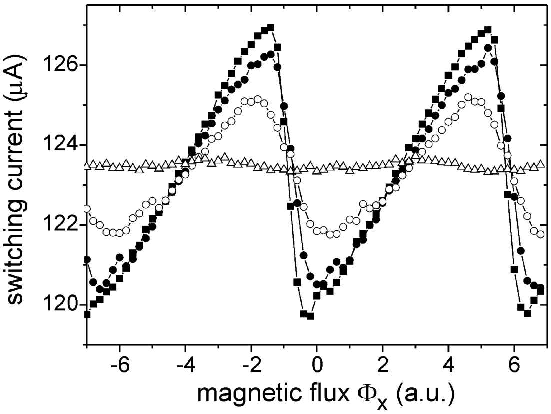

Fig. 3. Mean value of the switching current of the large junction, as a function of the magnetic flux sweeping the double-SQUID loop. Different curves, marked with different symbols, correspond to different values of the control flux Φ_c applied to the inner interferometer. It can be noticed that the curves are asymmetric, with one slope much steeper than the other, and the asymmetry is reduced as the modulation depth decreases.

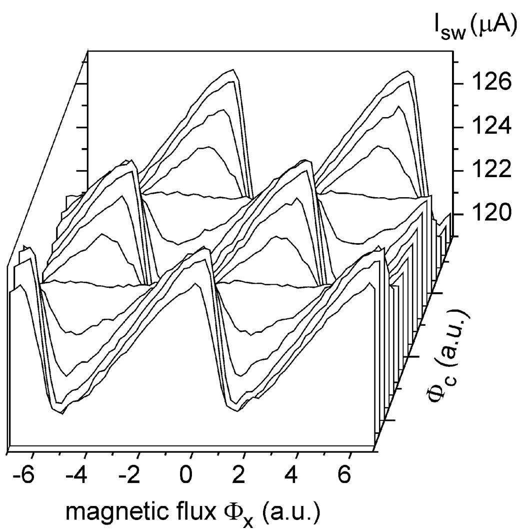

Fig. 4. Tridimensional plot of the switching current versus the two control fluxes Φ_x and Φ_c.

coupled to the large loop; the result, shown in Fig. 3, is a curve of period Φ_0 with a clear modulation of the switching current with Φ_x. The various curves of Fig. 3 correspond to different values of the control flux Φ_c, which changes the critical current of the inner interferometer and hence the hysteretic behavior of the double-SQUID through the parameter $\beta = 2\pi L I_0(\Phi_c)/\Phi_0$. The larger is β, the more asymmetric is the curve and the larger is the modulation amplitude; this situation correspond to a potential shape with well defined wells (two or more), separated by a barrier whose width and height are related to β. The steepest side of the largest curves corresponds to a jump between two distinct potential wells. As β decreases, the dependence of the switching current on the flux Φ_x gets weaker and the curves are more symmetric; this reflect the potential shape that now approaches one single well. Fig. 4 shows the switching current in a tridimensional plot versus both Φ_x and Φ_c. A further insight can be gained looking at the histograms of the switching current. Fig. 5 shows the behavior of the recorded histograms as a function of the magnetic flux Φ_x for two different values of β,

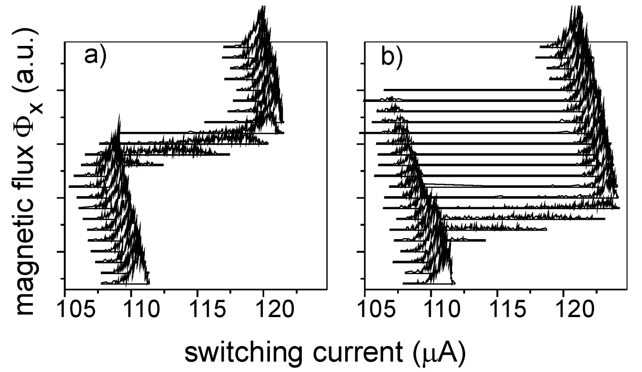

Fig. 5. Behavior of the recorded histograms as a function of the magnetic flux Φ_x for two different values of β, corresponding to small hysteresis (a) and large hysteresis (b). The inset is an enlargement of a typical histogram, with the characteristic asymmetric shape determined by the stochastic activation process.

corresponding to small hysteresis (a) and large hysteresis (b). The inset in Fig. 5(a) is an enlargement of a typical histogram, with the characteristic asymmetric shape determined by the stochastic activation process.

V. Conclusion

We proposed and tested a new flux/phase qubit having a direct readout integrated into a dc-SQUID loop. This approach should result in a simple operation with high detection efficiency. The tests performed at 4.2 K confirm the predicted behavior of the qubit characteristics as well as of the switching properties of the readout junction and show the feasibility of a direct readout approach.

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