Verification of stable operation of rapid single flux quantum devices with frequency-dependent dissipation

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Abstract. It has been suggested that rapid single flux quantum (RSFQ) devices could be used as the classical interface of superconducting qubit systems. One problem is that the interface acts as a dissipative environment for a qubit. Recently, ways to modify the RSFQ damping to reduce the dissipation have been introduced. One of the solutions is to damp the Josephson junctions by a frequency-dependent linear circuit instead of the plain resistor. The approach has previously been experimentally tested with a simple SFQ comparator. In this paper we perform experiments with a full RSFQ circuit, and thus conclude that in terms of stable operation the approach is applicable to scalable RSFQ circuits. Realization and optimization issues are also discussed.

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1. Introduction

There is an ongoing effort to integrate rapid single flux quantum (RSFQ) technology [1] as the classical interface of qubit systems [2]–[4]. Despite the potential compatibility of the fabrication technology and the operating environment, it has been found that certain issues need to be resolved before functional RSFQ/qubit systems are feasible. The basic question is to develop devices with sufficient functionality, which also preserve quantum coherence. The generic issues that have been addressed from the RSFQ side include fabrication [5, 6] and design [7, 8] solutions to decrease self-heating [9] as well as the control of the level of dissipation. The latter is important since the classical interface acts as a dissipative environment for a qubit. In an RSFQ circuit the dynamics is based on ‘classical’ $2\pi$ rotations of the phase differences across the Josephson junctions (JJs). Stable operation requires that such rotations are performed individually in a controlled manner. Therefore the energy released by the rotations needs to be dissipated somewhere, typically in the shunt resistor of the junction. Insufficient or missing dissipation leads to continuous rotation of the phase, i.e. to permanent switching into the finite voltage state. The level of dissipation experienced by the qubit can be reduced by choosing a low enough level of coupling between the RSFQ circuit and the qubits. This may degrade the functionality by limiting the signal levels seen by the qubit or by degrading the readout resolution. There are realizations of particular RSFQ components, which by design are less dissipative than the conventional ones [3, 4, 10]. Furthermore, unconventional damping schemes have been proposed which enable the design of generic RSFQ circuits with reduced dissipation. One such scheme is based on nonlinear shunts [11]. Another scheme is based on linear frequency dependent shunts, for which the damping resistor has been high-pass filtered by an appropriate circuit [12]. In the simplest form the filtering circuit consists of a capacitor $C_s$ in series with the shunt resistor $R_s$, a configuration previously considered for SQUIDs used as magnetometers [13] or flux qubit readout elements in the escape detector mode [14]. For stable RSFQ operation the $R_sC_s$ cutoff is to be chosen sufficiently below the plasma frequency $\omega_p$ of the JJ. The principle of $RC$ damping is illustrated in figure 1 together with a microscope photograph of a realization using a Nb trilayer process [6].

To our knowledge, the experimental verification of the unconventional damping schemes has up to now been limited to single JJs [11, 15] or SFQ comparators [12], though the functionality of complete RSFQ circuits has been verified by network simulations [12, 16]. In this paper we verify experimentally that complete $RC$ shunted RSFQ devices function in a stable manner.

2. The device

The circuit diagram and a microscope photograph of the device under study are shown in figure 2. The device is a toggle flip-flop (TFF) driven by a dc/SFQ converter through a short section of Josephson transmission line (JTL). Apart from the damping arrangement the design of the circuit elements has been adopted from [1] and [17]. The dynamical sequence of the device is described as follows. As the input current $I_{in}$ of the dc/SFQ converter is ramped up, at a certain threshold value the phase of junction J3 rotates by $2\pi$ (J3 flips), which causes a flux quantum to propagate through the JTL to the TFF. The second effect of this is that a persistent current flowing in loop LP1 changes causing junctions J1 and J2 to flip instead of J3 during the ramp-down. The ramp-down thus restores the original persistent current configuration in LP1, but has no other effect completing the dc/SFQ cycle. As a flux quantum enters the TFF either junctions in pair J8 and
J10, or pair J9 and J11 flip depending on the value of the persistent currents in the TFF (loops LP2 and LP3). These events also change the value of the persistent current in LP2 and LP3 in such a way that subsequent events alternate the persistent current between two values corresponding to zero and one flux quanta through the loops. The above description thus confirms that the device utilises all the basic elements of RSFQ dynamics, namely the selection process as well as the propagation and the storage of flux quanta. The resulting simulated time-trace of the flux in LP2 is shown in figure 3(a). The simulation was performed by a resistively shunted junction (RSJ) based model similar to that described in [12].

The loop of the TFF is coupled to the loop of a readout dc SQUID (RD SQ) by a weak inductive coupling used to sense the state of the TFF. By replacing the RD SQ by a flux qubit, this type of an arrangement could be utilized for qubit manipulation though our device as such is not yet optimized for this purpose. Here we are using the TFF–RD SQ arrangement as a SFQ/dc converter to be able to verify the proper operation of the circuit.

The device is fabricated by a Nb trilayer process, the VTT RSFQ/qubit process [6] which fixes the critical current density $J_c = 30 \text{ A cm}^{-2}$ for the JJs. The junction size is set to about 7 $\mu$m varying slightly depending on the design of the elements (see caption of figure 2 for details). All the junctions in the RSFQ circuit are damped with $RC$ shunts. The hysteresis parameter of the JJs is $\beta_c = 2\pi I_c R_s^2 C/\Phi_0 \approx 0.4$, and the ratio of the $R_s C_s$ cutoff and the JJ plasma frequency is $\gamma = 1/R_s C_s \omega_p \approx 0.1$ [12]. This leads to typical physical values $I_c \approx 12 \mu\text{A}$, $C \approx 1.9 \text{ pF}$, $R_s \approx 2.4 \Omega$ and $C_s \approx 35 \text{ pF}$. The inductances are of the order of 100 $\text{pH}$.

3. The experiment

The experiments were performed at liquid He temperature using a conventional cryoprobe. The SFQ input signal and the bias currents (the SFQ bias and the RD SQ current and flux bias) were
low-pass filtered by room temperature RC filters (cutoffs ranging from 8 kHz to 30 kHz), and fed to the 4.2 K stage through twisted pairs of constantan wire. The RD SQ voltage output was amplified by a commercial room temperature preamplifier. An experimental plot is shown in figure 3(b). The similarity in comparison with the simulated data of figure 3(a) confirms that the device works in the desired mode described above. The difference in the time-scales is not important here from the point of view of comparison of experimental and computational data, since between the SFQ events the device is in the quiescent state (i.e. in the state between the flipping events where the voltage is zero across all the JJs). The shorter time-scale is chosen in the simulation to minimize the computational effort. The only requirement in this respect is that the frequency of the dc/SFQ input signal $I_{in}$ is much smaller than the inverse of the time scales of the SFQ events (here of the order of 100 ps).
Figure 3. (a) Simulated and (b) measured characteristics of the device. The thick line (left axis) is the input current of the dc/SFQ converter \( I_{in} \). The thin line in (a) (right axis) is the flux \( \Phi_{TF} \) through loop LP2 of the TFF. The corresponding plot in (b) is the output voltage \( V_{RD} \) of the readout SQUID, which is proportional to \( \Phi_{TF} \). The bias point is here \( I_{b1} \approx 7 \, \mu A \). The threshold values of the input current are indicated by dotted lines.

The only discrepancy between the simulation and the experiment is that the threshold value of the input current is slightly smaller (about 30 \( \mu A \)) in the experiment than in the simulation (about 50 \( \mu A \)). This may be partially explained by the difference in the designed and realized inductance values, but more likely the cause is partial flux trapping. The threshold value for a given device varied somewhat between different cooldowns, which supports this hypothesis. This variation was also reproduced in simulations by applying flux to the loops of the dc/SFQ converter. The noise at the output voltage \( V_{RD} \) is well explained by the preamplifier voltage noise (about 4 nV Hz\(^{-1/2}\)).

4. Discussion

Since our main aim is to verify here that the high-frequency damping alone suffices to stabilize the devices, we briefly discuss the excess damping mechanisms present in our system. The current
bias of the device is based on on-chip bias resistors of $R_b \geq 40 \Omega$ performing the required voltage-to-current conversion. The voltage is fed over an off-chip resistor (0.5 $\Omega$) located near the chip at 4 K. Thus the bias resistor and the off-chip resistor form a loop of about 40 $\Omega$ in series with a bonding wire inductance of order 1 nH, i.e. the excess damping ranges roughly from dc to 5–10 GHz. As the worst-case the hysteresis parameter from bias resistors corresponds to $\beta_c \sim 100$, which is not enough to stabilize the system. The RD SQ, which is R-shunted, potentially causes some excess dissipation as well, which couples, however, to the RSFQ circuit only at high-frequencies (\(\geq\)10 GHz in our circuit). To ensure that the excess dissipation mechanisms do not stabilize our system, we removed the $RC$ shunts and added the damping from the RD SQ and the bias resistors in the simulation. The result was that no stable operating point was found. This provides very strong evidence that the stabilisation of our system is in practice completely due to the $RC$ shunts.

The bandwidth was limited in our experiment in order to record the SFQ operation with low frequency room temperature electronics. One should note that such limitations are by no means fundamental in RSFQ/qubit experiments, where the full plasma frequency limited speed of the RSFQ technology is available. For example, the device described here could readily be driven at frequencies up to about 10 GHz. However, to utilise the full potential of integrated control one could eventually apply integrated clock sources [18] instead of an external clock signal such as $I_{\text{in}}$ here.

One issue in $RC$ damped circuits is the parasitic resonance of the shunt capacitor. A sufficient criterion for avoiding this is that the capacitor dimension should be at maximum $\lambda_p/8$, where $\lambda_p$ is the wavelength in the capacitor dielectric at the plasma frequency. This is given as $\lambda_p = 2 \pi c / \omega_p \sqrt{\varepsilon_r (1 + 2 \lambda_L / d)}$, where $c$ is the speed of light, $\varepsilon_r$ is the dielectric constant, $\lambda_L$ is the London penetration depth of the electrodes, and $d$ is the insulator thickness. In our case $\omega_p / 2 \pi = \sqrt{(1 / 2 \pi \Phi_0) (I_c / C)} \approx 22 \text{ GHz}$, $\varepsilon_r \approx 45$ (Nb$_2$O$_5$ dielectric), $\lambda_L \approx 85$ nm (Nb electrodes) and $d \approx 140$ nm. It follows that $\lambda_p / 8 \approx 0.170 \mu m$, which is also the maximum dimension we have used in the capacitors. However, in our geometry the lowest frequency resonance that could be excited is a $\lambda / 2$ resonance corresponding to the long edge of the capacitor, so elements somewhat larger than this could be safely realized. In more general terms, parasitic resonances limit the maximum value of realizable capacitance. Since capacitance of a square with side $w$ is $C_s = \varepsilon_r \varepsilon_0 w^2 / d$, it follows $C_s \lesssim (\pi c)^2 \varepsilon_0 / 16 \omega_p^2 d (1 + 2 \lambda_L / d)$ from the requirement $w \lesssim \lambda_p / 8$. In other words, realizability requires that

$$\gamma \gtrsim \frac{16 \omega_p d (1 + 2 \lambda_L / d)}{\pi^2 R_c \varepsilon_0^2 \varepsilon_r} = \frac{32 \sqrt{2} d (1 + 2 \lambda_L / d)}{\pi \Phi_0 \varepsilon_0 c^2} I_c, \quad (1)$$

where we have used the definition of $\gamma$. In the last form we have also used the definitions of $\omega_p$ and $\beta_c$, and furthermore set $\beta_c = 1/2$, which is a typical value. Realizability thus gives the minimum $\gamma$.

From equation (1) we see that the minimum $\gamma$ depends only on $\lambda_L$, $d$ and $I_c$. The maximum is determined from the stability requirement, which typically leads to $\gamma \lesssim 0.3$ [12]. The thickness $d$ can be varied to some extent within fabrication tolerances. The dependence on $I_c$ is, however, more important in terms of the optimization of the RSFQ/qubit systems. The realizability and stability together set an upper limit for $I_c$. Low $I_c$ is favourable also in terms of minimal self-heating of RSFQ components [7]–[9]. In qubit applications the effect of the dissipation from the $RC$ shunts

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on the decoherence should be taken into account [14]. It was previously analysed that in the case of a qubit inductively coupled to an RSFQ circuit the minimization of the dissipation together with RSFQ stability criteria favours an RSFQ circuit with large $J_c$ [12]. Therefore it appears that at least in this coupling scheme the optimum solution would be a large-$J_c$ process with small area junctions, e.g. sub-$\mu$m Nb junctions [19]. However, there may be other ways around this as well. It may be possible to relax the realizability restrictions by different implementations of the damping circuit. It also depends very much on the particular design whether the self-heating is a problem. For example, the device measured in this paper spends most of its time in the quiescent state, whence it should not heat very much above the bath temperature.

5. Conclusion

In conclusion we have successfully verified the stability of a RSFQ device based on selective damping realized by $RC$ shunts. The device under study utilises all aspects of RSFQ dynamics. Our measurement scheme also gives direct evidence of SFQ events instead of the earlier measurement based on the statistical properties of a balanced comparator [12]. We therefore conclude that it is now experimentally verified that generic RSFQ devices can be realized by this damping scheme.

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