Low-noise RSFQ Circuits for a Josephson Qubit Control

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Abstract. We address the problem of reducing the noise of an RSFQ circuit, which may significantly decohere a Josephson qubit in the case of integration of these circuits. The main sources of such noise in traditional RSFQ circuits are low-ohmic shunting resistors ensuring sufficiently high damping. We developed the toggle flip-flop (TFF) cells with weakly-damped individual junctions due to high-ohmic shunts. The dominant part of necessary damping in this circuit was realized by applying an additional, so-called “perpendicular”, low-ohmic resistor connecting the centre of the storing TFF inductance to ground. The TFF circuits with junctions shunted by 50 $\Omega$ resistors and perpendicular resistor of 1.5 $\Omega$, ensuring suppression of noise by more than one order, have been fabricated and demonstrated an operation range of $\pm 20\%$. In order to make the circuit compact and, therefore, less sensitive to external noise, the passive frozen-flux-based phase shifting elements, replacing large quantizing inductances, were also included. The circuits were fabricated using PTB Nb trilayer process with critical current density $j_c = 100$ A/cm$^2$.

1. Introduction
The qubits based on the Josephson junctions are promising elements for a reliable and scalable quantum computer being developed worldwide [1-2]. The Josephson qubits integrated with the control and readout circuits must operate at sufficiently low temperature and in an environment with low dissipation in order to preserve the coherent behaviour. The natural and viable solution for manipulation of Josephson qubits, is the use of rapid single flux quantum (RSFQ) logic [3] based on processing of magnetic flux quanta. RSFQ circuits suit for integrating with superconducting qubits because of speed, scalability, low dissipation, compatibility with the qubit fabrication process and their operation in a low temperature environment. These circuits allow efficient and simple control of several types of Josephson qubits [4-6]. However, integration of RSFQ logic circuits with the qubits presents some problems. In particular, RSFQ circuits designed to work with the qubits require significant modification of its parameters due to necessity of the operation at very low temperature (in 10-100 mK range) and small signals. Moreover, the rapidity of SFQ transitions can induce non-adiabatic escapes outside the computational-basis states. Therefore, the shape of driving dc pulses should be smoothed, so the high frequency components of its spectrum should be filtered out. The shunting resistances, necessary for the RSFQ logic operation, can introduce intolerable decoherence of the qubits, therefore the noise generated by the shunting resistors should be sufficiently reduced and/or effectively decoupled from the qubit.

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In this paper we developed non-standard RSFQ circuit including a toggle-flip-flop (TFF), and demonstrated its functionality. The sample has been fabricated at PTB with a critical current density of 100 A/cm$^2$, i.e. a factor of ten lower than the standard one applied for traditional RSFQ circuits. The value of the critical current of the smallest Josephson junctions is 12.5 µA and shunting resistor value ensuring the Stewart-McCumber parameter value of $\beta_c = 1$ is about 7 $\Omega$. The characteristic voltage $V_c$ is therefore about 85 µV, that defines the highest operation frequency of about 40 GHz. The sheet resistance of the Pt metallic layer used for resistors is 2 $\Omega$/square.

2. Fabrication technology
The technological process is based on the PTB production line for the fabrication of externally shunted Josephson junctions (JJs) in 4-µm Nb/Al-Al$\text{O}_x$/Nb trilayer technology [7]. Thermally oxidized three-inch silicon wafers are used as substrates.

First, an Nb film (170 nm thick) is deposited and patterned for structuring a ground plane of the circuits. The electrical isolation of the ground plane is provided by wet anodization of the Nb film followed by sputtering of a dielectric SiO$_2$ (80 nm) layer on top of it. To form the bias and shunt resistors, we deposit a Cr/Pt/Cr (10 nm/40 nm/10 nm) sandwich patterned by an Ar-milling etch process. Thereafter, a further SiO$_2$ (140 nm) ground plane isolation layer is sputtered. In order to connect the groundplane and resistors to other metal layers, holes are etched in the dielectric layer. The Nb/Al-Al$_x$O$_y$/Nb (170 nm/10 nm/80 nm) trilayer is deposited in a UHV system with a base pressure lower than 10$^{-6}$ Pa. The oxidation process is performed in a load-lock with a base pressure lower than 10$^{-5}$ Pa. The tunnel areas of the JJs are formed by etching of the Nb counter electrode of the trilayer. Then, the wet anodization process is applied again followed by the patterning of the Nb base electrode. In order to realize the galvanic connections between Nb base electrode and Nb wiring electrode an additional etching process of the Nb counter electrode, removing the parasitic JJs from the connections places, is applied once more. An SiO$_2$ (300 nm) layer is sputtered onto the sample for isolating the edges of the base electrode and strengthening of the anodic oxide. The process is completed by sputtering and structuring of an Nb (400 nm) wiring layer.

3. TFF circuit, design and functionality
In this paper we address the problem of reducing the noise of RSFQ circuits, which may significantly decohere the qubit. The main source of such noise in traditional RSFQ circuits is low-ohmic shunting resistors ensuring sufficiently high damping and, hence, enabling manipulation of single flux quanta. We focus on TFF circuit generating short rectangular control pulses. The design of the TFF-cells

![Figure 1](image-url)  
*Figure 1* The T-flip-flop circuit: a) electrical scheme; b) microphotograph. Electrical parameters are $L=110$ pH, $R=1.5$ $\Omega$, $J_1=J_2=18$ µA, $J_3=J_4=24$ µA, the junctions are shunted with resistors of value $R = 50$ $\Omega$. 

\[ L = 110 \text{ pH}, \quad R = 1.5 \text{ $\Omega$}, \quad J_1 = J_2 = 18 \text{ µA}, \quad J_3 = J_4 = 24 \text{ µA}, \quad \text{the junctions are shunted with resistors of value } R = 50 \text{ $\Omega$}. \]
included a weak damping of the junctions due their shunting by high-ohmic resistors $R$, while the dominant part of damping in this circuit was realized by an additional, so-called “perpendicular”, low-ohmic resistor $R'$ connecting the centre of the storing TFF inductance $L$ to ground. Such configuration of the damping elements ensured minimum output flux noise. The TFF consists of two interferometer loops, one acting as a signal splitter (junctions $J_1$ and $J_2$), the other acting as a memory of the TFF state (junctions $J_3$ and $J_4$). The input of the TFF circuit is connected to the dc/SFQ converter circuit and its outputs to the SFQ/dc converter circuits. The TFF toggles between its two states under the application of a single flux quantum pulse. This SFQ pulse is generated by a dc/SFQ converter and is transferred to TFF through a Josephson transmission line (JTL). Figure 2 shows the time traces of the signals confirming correct operation of the TFF circuit. The applied to dc/SFQ signal (trace $I_{in}$) creates one SFQ pulse per period. The first SFQ pulse from dc/SFQ converter switches $J_3$, the second one switches $J_4$. These SFQ pulses via individual JTLs transferred to SFQ/dc converter circuits and converted into the voltage signals (traces $V_{out1}$, $V_{out2}$). The TFF states differ by direction of the circulating current in its loops. This current makes the self-inductances of the junctions unequal that leads to imperfect compensation of noise in the output flux even in the fully symmetric TFF circuit. By simulating our circuit we found that the net noise contribution is about 5\% of the Johnson current noise $P_R$ generated by resistor $R'$, i.e. of the order of the uncorrelated noise contributions of the shunting resistors $R$. The circuit optimization shows that for the shunt resistor value of $R = 100 \, \Omega$ and value of the “perpendicular” resistor $R' = 1.25 \, \Omega$, operating range of the TFF circuit is quite acceptable, i.e. about ±30\%. Note, that the Stewart-McCumber parameter $\beta_C$ of individual junctions is as high as 100.

Due to the large value of the characteristic time constant $L/R'$, this circuit ensures a smoothing of the sharp switching in TFF. This is a desirable feature preventing non-adiabatic transitions to the higher energy eigenstates (above the qubit basis levels).

For correct matching of the signal magnitudes in the RSFQ circuit and the qubit, low values of the critical currents are required. Therefore, the nominal value of the critical current density of the Josephson junctions was set to $j_c = 100 \, \text{A/cm}^2$. Since the storage and flow of information are realized

![Figure 2](image-url)
in RSFQ circuitry by means of single flux quanta, the product of the critical current and inductance of the circuit cells should be about $\Phi_0$. For the given values of $I_c$ the values of all inductances were proportionally (by factor 10) increased and the value of the TFF storage inductance was chosen close to 110 pH. To reduce local overheating on the chip, the resistor network serving for the bias-current distribution was placed far from (is about 4 mm) the active elements (Josephson junctions) of the RSFQ circuit. The physical volumes of the bias and shunt resistors were realized relatively large (about $4.5 \times 10^{-15}$ m$^3$ and $0.9 \times 10^{-16}$ m$^3$ respectively). The estimated total power dissipation, determined mostly by the bias resistors, was about 0.23 µW. Note that the power dissipated on the TFF cell is only about 25 nW. Moreover, usual working frequencies of the Josephson qubits is much lower in comparison with characteristic frequency of the junctions $f_c = V_c / \Phi_0$ of the RSFQ circuit. This make possible further decrease of the biasing voltage (about 5 times), which should result in proportional decrease of the power dissipation in the RSFQ circuit.

The RSFQ circuit has been optimized using PSCAN (Personal Superconductor Circuit ANalyzer) software [8]. Operation ranges were found to be about ±30% for the bias currents, greater than ± 40% for the inductances and greater than ± 25% for the critical current density. The optimum values of inductances were calculated using Lmeter software [9]. The measured operation range of the correct functionality of the circuit defined by the SFQ/dc converter is ±20%.

4. TFF with integrated phase shifter element

We have designed and fabricated a TFF circuit in which the large quantizing inductance has been replaced by an appropriate passive $\pi$-phase shifting element (see Figure 3(a)). These phase shifters are based on miniature superconducting loops containing small numbers of frozen flux quantum [10]. Topologically, the $\pi$-shifter used in this circuit is identical to that described in [11]. The parameters of this TFF circuit have been optimized for fabrication in conventional Nb/Al trilayer technology with $j_c = 100$ A/cm$^2$. Figure 3 (a) shows the block diagram of the realized TFF circuit with incorporated $\pi$-shifter loop, and Figure 3 (b) a microphotograph of its central part. The circuit operates in the following way: Single Flux Quantum (SFQ) pulses are generated by a dc/SFQ converter circuit at the rising ramps of the input current $I_{in}$ having triangular waveform. The amplitude of the input current $I_{in}$ has been chosen for the generation of one SFQ pulse per period of the incoming signal. The generated SFQ pulses propagate via the Josephson Transmission Line (JTL) to the input of the TFF

Figure 3. The TFF circuit with the integrated phase shifter element: a) block diagram; b) microphotograph of its central part.
and change its state creating singly the SFQ pulses in the TFF outputs. Both complimentary outputs of the TFF are connected to different SFQ/dc converters via individual JTLs. These SFQ/dc converters include TFF circuits of conventional design and are used to provide back conversion of the SFQ pulses into DC voltage signals at their outputs. The optimum value of the current $I_{\text{bias}}$ has been determined experimentally to be 350 $\mu$A, rather close to the designed value. When one flux quantum is trapped in the loop of the phase shifter, the phase shift took a value of $\pi$ and correct operation of the TFF circuit is observed. The time traces of the signals in this regime are shown in Figure 4. Each of the output traces $V_{\text{out}1}$ and $V_{\text{out}2}$ has a period four times longer than the one of the input signal $I_{\text{in}}$. This behavior originates from the pulse rate division by two sequentially connected TFFs. The first one is the TFF of the novel design with integrated $\pi$-shifter, and the second one is the TFF of conventional design in the respective SFQ/dc converter. The mutual shift of the output signals $V_{\text{out}1}$ and $V_{\text{out}2}$ corresponds to exactly one period of the input signal $I_{\text{in}}$. This confirms the correct toggling function of the flip-flop circuit with integrated $\pi$-shifter.

5. Conclusion

We proposed and experimentally demonstrated functionality of the TFF circuit ensuring minimum output flux noise. The design of the TFF-cells included a weak damping of the junctions due to high-ohmic shunts, while the dominant part of damping in this circuit was realized by an additional, so-called “perpendicular”, low-ohmic resistor connecting the centre of the storing TFF inductance to ground. The obtained operating range is about ±20% (defined by SFQ/dc converter circuits) for the TFF circuit with the shunts value of $R = 50 \Omega$ of the junctions and value of the low-ohmic resistor $R^* = 1.5 \Omega$. The simulations show correct functionality of the circuit with the shunts resistance value of $R = 100 \Omega$ for the Josephson junctions and the value of $R^* = 1.25 \Omega$ of the perpendicular resistor.

We realized and experimentally verified the TFF circuit with the passive phase shifting elements replacing large quantizing inductances, which make the circuit compact and, therefore, less sensitive to external noise. These phase shifters are based on miniature superconducting loops containing small numbers of frozen flux quantum. The measured circuits have been fabricated with a critical current density of 100 A/cm$^2$. The value of the critical current of the smallest Josephson junctions is 12.5 $\mu$A.

Figure 4. Time traces of the signals in the TFF circuit including passive $\pi$-shifter which loop traps one flux quantum. The frequency of the output signals $V_{\text{out}1}$ and $V_{\text{out}2}$ is four times lower compared with the frequency of the input signal $I_{\text{in}}$. The observed division of the frequency of the pulses indicates the correct operation of the TFF.
and shunting resistor value is about 7 Ω for the $\beta_c = 1$, the characteristic voltage $V_c$ is 85 µV defining highest operation frequency is about 40 GHz.

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