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ANALYZING THE SWITCHING ERRORS OF RSFQ-CIRCUITS

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ABSTRACT

The Rapid Single Flux Quantum electronics is a superconducting, naturally digital circuit family which is currently close to getting commercially applied. RSFQ is outstanding by its very low switching energy resulting in a very low power consumption which is the reason for a significant influence on thermal noise. For industrial applications a certain noise immunity is required which is still a challenge especially for circuits of higher complexity. In superconducting electronics resistors are the only on-chip noise sources.

We analyzed the influence of each individual resistor in a toggle Flip-Flop circuit to the overall bit-error rate. The shunt resistors of comparator structures are the dominant noise sources and bias resistors have almost no influence.

We analyzed in detail the types of thermal introduced switching errors of an toggle Flip-Flop which was optimized with respect to the fabrication yield. Simulation studies were accomplished to investigate the influence of circuit parameters on quality and on quantity of switching errors.

By identifying and manipulating the parameters with the most significant influence on the noise susceptibility an enhanced noise immunity of the device can be achieved. The goal is to improve the robustness of RSFQ circuits against the influence of thermal noise for an specific topology by changing the circuit parameters of the device.

***Index Terms*—** RSFQ, circuit design, thermal noise, BER, bit-error rate, sensitivity

1. INTRODUCTION

The Rapid Single Flux Quantum (RSFQ) electronics is a pulse driven naturally ultra fast electronic family where the information is represented by the magnetic flux quantum $\Phi_0 = h/2e$ with the Planck's constant h and the elementary charge e [1]. It consists of superconducting loops disrupted by a well designed barrier called Josephson junction [2]. The Josephson junction is the active element acting like a kind of gate allowing the controlled exchange of flux quanta between adjoining loops. During this data transfer the junction switches into a voltage state for the very short time period of some pico seconds. RSFQ circuits are typically composed of three components namely: inductors, current sources and Josephson junctions. Based on them, three basic structures for transfer, storage and decision can be constructed [3].

The energy consumption of a single switching event of a Josephson junction is extremely low, less than 10^{-18} Joule. The circuit behavior shows a significant influence on thermal noise, because of this low switching energy. RSFQ is a superconducting electronics, nevertheless on-chip resistors are essential and are used. Noise is generated by those resistors according to Johnson and Nyquist [**?**]. The created noise depends on the resistance and operation temperature. The circuits are operating in liquid helium with a temperature of $T = 4.2K$. However, the operation temperature is extremely low the thermal noise is influencing the circuit behaviour like illustrated in Fig.1.

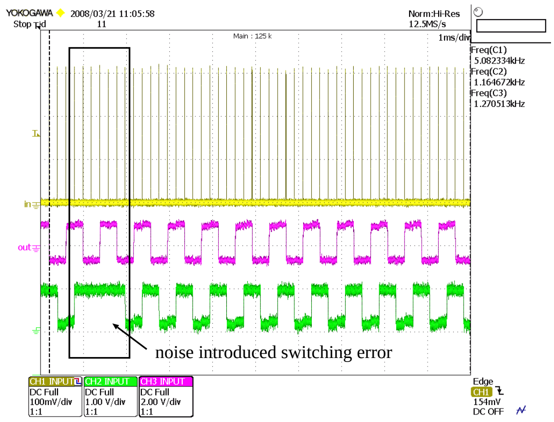

Fig. 1. The result of an experimental investigation of a RSFQ-circuit. A noise introduced switching error can be recognized.

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2. THE NOISE INFLUENCE ON RSFQ-CIRCUITS

The power supply of each electronic device can be variated inside a specific region without influencing the functionality. If the circuit operation is not influenced by thermal noise a sudden vanishing of the correct operation can be observed at the border of the operation region. By the influence of thermal noise a transition regions occurs beside the operation region (Fig.2a). Within the transition region there is for each value of the bias supply a certain probability for a switching error. The width of the transition region is distinguished by the noise power and the circuit susceptibility to the influence of thermal noise. That means the operation region of the device becomes smaller under the influence of noise. One criteria for circuit optimization could be the

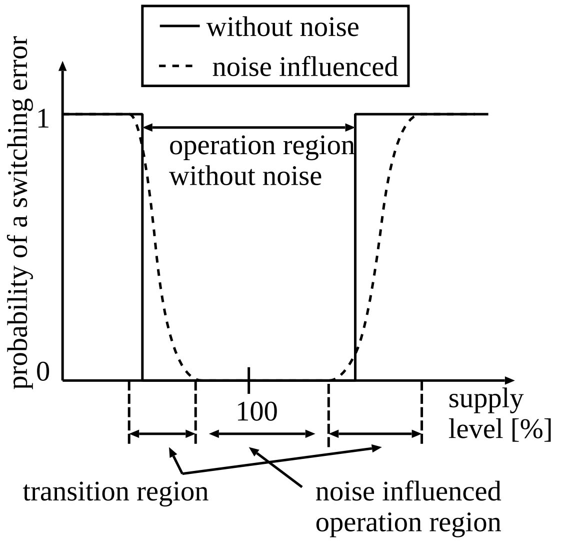

Fig. 2. A sketch of the principle influence of thermal noise on behavior of RSFQ circuits. The probability of switching errors as a function of the bias current.

minimization of the transition region width for a specific temperature to ensure the best available noise immunity. A realistic circuit optimization should furthermore take the parameter variation caused by the fabrication process into account. Thus it is not enough to find a sharp transition into the operation region, it should also be robust against parameter variations. Such an optimization method is associated with a huge computation effort and is not applicable at the time. More practicable is just to analyze the circuit behaviour by simulation or+ experiments.

3. THE TOGGLE FLIP-FLOP

The Toggle-Flip-Flop (TFF) is a well known logic cell of RSFQ-electronics and it has often been the subject of studies. It was, for example, one of the first mentioned RSFQ basic cells [4] and it is today the device with highest measured clock frequency of 770GHz ever [5]. We going to analyze alternative topologies at first. Then we going to investigate the influence of the on-chip noise sources.

The equivalent network of different TFF versions is illustrated in Fig.3. The core of the TFF is composed of two comparators (J4,J2) and (J5,J3) coupled by an in-

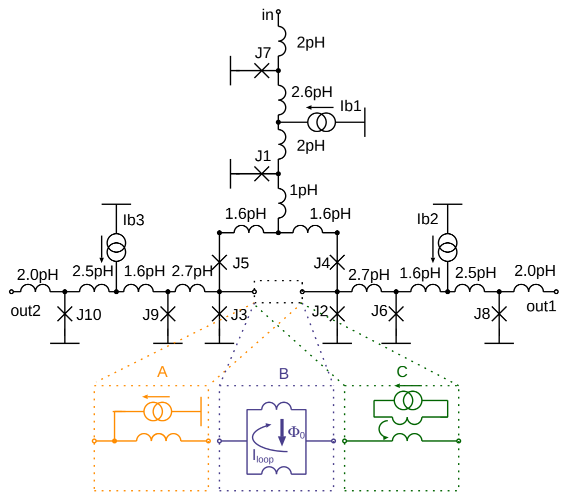

Fig. 3. The schematic diagram of the TFF with different kinds of phase shifting elements creating the storing capability. The critical current of the junctions are 200μA:J6/J9; 250μA:J7/J8/J10 those are identical in all realized types. In versions B and C all junctions are identical resulting in a symmetric circuit (225μA:J1; 150μA:J4/J5; 125μA: J2/J3). In version A the asymmetric critical currents of the junctions are necessary to create a correct bistable operation (175μA:J1/J5; 200μA:J4; 325μA:J2; 300μA:J3).

ductor. If a flux quantum enters the TFF input by J1, the junctions of the core will switch in pairs J2 and J3 or J4 and J5 depending on the direction of the current flowing in the couple inductor. This circulating current represents the internal logical state of the Flip-Flop. For each input pulse the state toggles between ”0” and ”1”. This behavior is illustrated in Fig.4.

? A TFF has two storing loops which are close coupled by sharing one inductance. Each storing loop consists of two junctions and an inductor. Such a structure is naturally tristable. In standard RSFQ a bias current source like in version A (Fig 3) is used to restrict one of the stable states. In this why the bistable behaviour is artificially created. An alternative approach is to utilize a phase shifting element. An overview about that approach is given in [6]. For a single storing loop a significant improve of the stability against parameter variations by implementing phase shifting elements was shown in [7].

We going to analyze the influence of different topologies of the circuit on the noise susceptibility. Therefore we implement a phase shifting element into the core

of a TFF. In version B a π-Phaseshifter is used. This element consist of a superconducting loop in which a single flux quantum is trapped [8]. In version C the bistable behavior is created by an inductively coupled current source.
All of this versions were optimized concerning the expected fabrication yield [9].

4. SIMULATIONS OF THE BIT-ERROR RATE

We accomplished simulation studies by utilizing the circuit simulator program JSIM [10] with the noise model implemented by J. Satchell [11]. The equivalent circuit of the TFF is more extensive than shown in Fig. 3 since the parasitic inductances are not illustrated. Furthermore there is no model for a phase source implemented in JSIM, thus an equivalent circuit for the π-phaseshifter has been used which can be found in [6]. The current sources are implemented by resistors and a 2.5 mV voltage source. This source is assumed to be noiseless, but the Johnson noise generated by the resistors was considered.
To get an estimation about the noise susceptibility the bit-error rate as the function of the bias supply was evaluated by simulations. The values for critical currents ?and inductances were assumed to be nominal values, while the bias current ITFF was varied (Fig 5). The increment was chosen in a way to have at least 30 steps within the transition region between function and no-function. Ten thousands clock cycles with a clock frequency of 5 GHz were simulated per step. The BER illustrated in Fig. 6 is calculated by dividing the number of clock cycles and the number of switching errors.
The BER as a function of the bias current I_b is well described by the error function according to:

$$\mathrm{BER} = \frac{1}{2} + \frac{1}{2} \cdot \mathrm{erf}\left(\sqrt{R/8k_{\mathrm{B}}TB}(I_b - I_m)\right). \quad (1)$$

The parameter I_m is the bias current corresponding to BER=0.5. The slope of this function depends on the factor $\sqrt{\frac{R}{8k_{\mathrm{B}}TB}}$, with the bandwidth B of the system, the resistance R, the Boltzmann constant k_{B} and the temperature T. It is not possible to assign the resistance to a certain element in the circuit. It is an equivalent value for a resistor, which would generate the same noise power like that noise power created by all resistors of the circuit. This slope is an indicator for the susceptibility of the circuit to noise. The larger the factor is, the higher is the slew rate of the curve and the lower is the noise influence. In Fig. 6 the noise temperature $T = 4.2$ K was assumed. Thus the different slopes are a result of different circuit characteristics. In the following, the transition from no-function to function of the circuit for increasing values of the bias current I_b is called falling slope (f.s), the opposite transition is called rising slope (r.s). The parameter value for

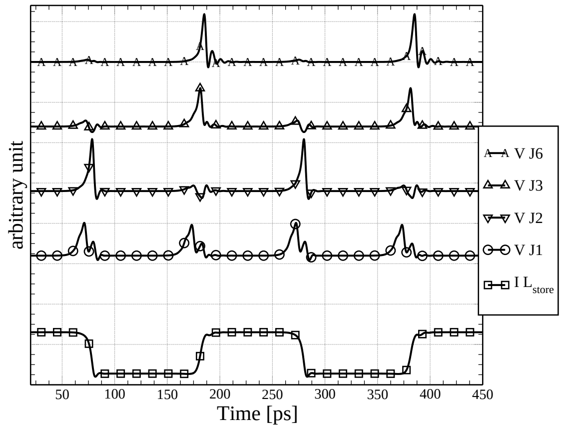

Fig. 4. The switching characteristic of a toggle flip-flop. The state of the device is distinguished by the current IL_{store} flowing in the inductor.

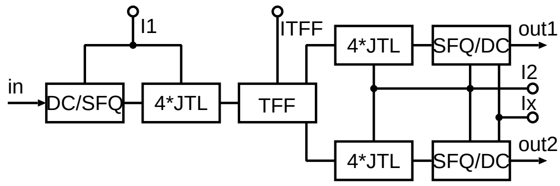

Fig. 5. Block diagram of the setup used to analyze the TFF.

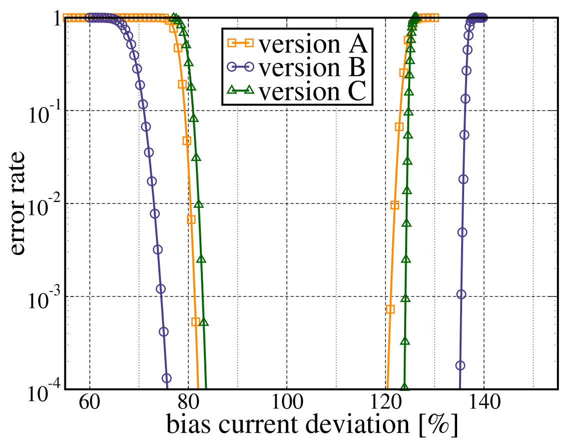

Fig. 6. The bit-error rate versus TFF bias current evaluated by simulations, of different TFF configurations illustrated in Fig.3. The noise temperature for all resistors was $T = 4.2$ K.

Version	$\sqrt{\frac{R}{8k_{\text{B}}TB}}$		ITFF Margin	
	f.s.	r.s.	BER=10^{-4}	BER=10^{-12}
A	62.9	66.2	-18/+20.3%	-14/+16.7%
B	40.1	165.7	-25/+35%	-18/+33.7%
C	65.3	200	-16.6/+23.8%	-13/+22.7%

Table 1. Overview of significant values extracted from the simulated BER.

$\sqrt{\frac{R}{8k_{\text{B}}TB}}$ of both slopes and the bias current margin are listed in Tab. 1.

The rising slope is clearly sharper in TFF version B/C than in version A. In version B are the slopes very different concerning their noise susceptibility. The overall margin of the bias current for the BER=10^{-4} and BER=10^{-12} is decreased by 20% for version A, 14% for version B and 11.6% for version C. However version A and C have for high BER nearly the same bias margin, but for values below BER=10^{-4} the margin of version C is higher. That shows an improved robustness against the influence of thermal noise by implementing a phase shifting element.

5. SENSITIVITY ANALYSIS

It was shown that it is possible to improve the noise immunity by using new elements. Now we going to investigate possible improvements for a certain topology. It would be a great advantage to improve the existing circuits without using new elements or technologies. To detect the component with the strongest influence on the circuit behavior a sensitivity analysis was done for each on-chip noise source. These are the resistors for shunting the junctions and for bias current distribution. It can be expected that a certain noise power will influence the circuit behavior in different ways depending where the noise power is considered in the circuit. For example, it is well known that a comparator is especially susceptible to noise. To gain a quantitative information about that sensitivity, the number of switching errors for a specific operation point was analyzed. According to Fig. 7 the bias current value I_b was set to obtain approximately BER=1%. The total number of switching errors was calculated for 10^5 clock cycles with $T = 4.2$ K for each resistor. In the second step the noise temperature of one resistor was artificially tenfold increased to 42 K. Again 10^5 clock cycles were simulated and the increase of BER was calculated. This method was applied to all resistors. The results are displayed in Fig. 8. For the resistors of the current sources Ib1-Ib3 and the shunt resistors of J7/J8/J10 we found no change of the BER like for J1, thus they are not shown. It is a new result, that the BER is mainly influenced by the shunt resistors of comparator structures. The on-chip resistors of the bias current sources have almost no influence. An important finding is, that in the standard TFF (version A) obviously the compara-

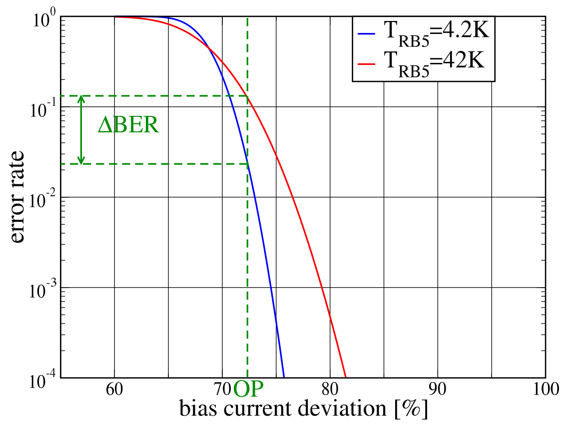

Fig. 7. Two different simulation results for the falling slope of BER to demonstrate the strategy of the sensitivity analysis.

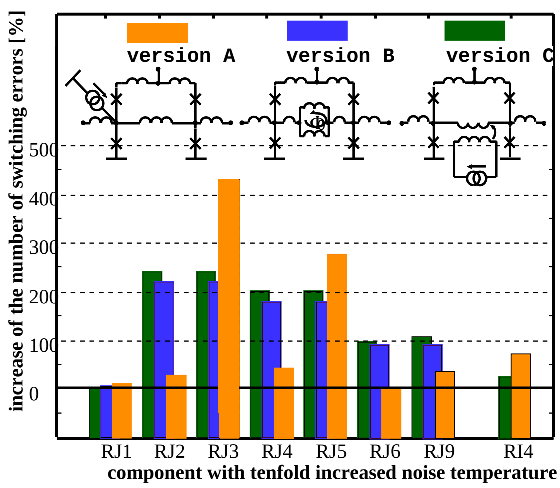

Fig. 8. Increasing of the BER in an certain point of operation by artificially tenfold increased noise temperature of a single resistor. RJ* are the shunt resistors of the junctions according to the identifier in Fig. 3. RI4 is the resistor utilized to establish bias current Ib4.

tor made of junctions J3, J5 has more influence on the cell behavior than that one composed of the junctions J2, J4. Because both comparators are strong coupled, it should be possible to change the shunt resistance of J3 and J5 without jeopardizing the functionality of the cell. So we propose according to Eq.(1) to increase shunt resistances of them.

6. FURTHER INVESTIGATIONS OF TFF VERSION A

The previous investigations was done exclusive for the falling slope. In Figure 9 the switching errors of a TFF version A are illustrated for both slopes. It can be recognized that different kind of switching errors appear at both slopes. At the falling slope junction J5 and J4 are switching together and now output signal is generated. That means one of the comparators makes a wrong decision. The nature of the switching error at the raising slope is different. At this ramp the circuit is nearly overbiased. Both comparators are working correctly. The make the right decision, the TFF is changing the state and a SFQ leaves the circuit. By this switching events an additional switching of J9 is triggered, because this junction is nearly overbiased. Thus one flux quantum leaves the output 1, one leaves output 2 and a one leaves the input of the TFF.
So it is worth to investigate the sensitivity at the raising slope as well. The results are compared in Fig. 10. If the increase of the BER was higher than factor 10 the value was artificially restricted to be 10. According to

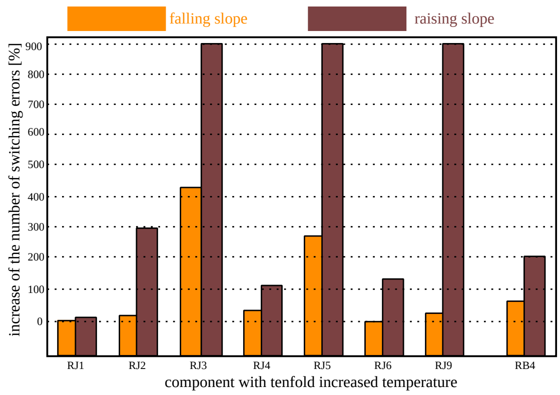

Fig. 10. Increasing of the BER in an certain point of operation by artificially tenfold increased noise temperature of a single resistor. The investigation were done at raising and falling slope of the operation regin of TFF version A.

Fig. 6 the increase of the raising slope is much higher than the falling slope. So an increase of the noise power in the system results in a stronger change of the bit-error rate at the raising slope. Furthermore, the base value were different in both investigations. Thus it is not possible to compare the sensitivity to one specific resistor at both slopes. But again the most influential resistors can be identified. This investigation confirms the results that the circuit behaviour is only influenced by the shunt resistors. Also the most influential resistors were confirmed. In addition the resistor R9 get important. The reason is well understood because of the already mentioned nature of the switching error at the raising slope (Fig. 9). Junction J9 is creating the switching error thus the circuit is especially sensitive to noise generated by RJ9.

7. CONCLUSIONS

We designed and analyzed by simulations different types of a bistable device, namely a TFF. We found that the realization with the π-phaseshifter was the best one concerning the robustness against the influence of noise. A lower probability of malfunction due to noise was observed compared to the standard TFF for both versions containing a phase shifting element.
Furthermore we simulated the sensitivity of the TFF types on each on-chip noise sources. We identified the resistors with the main influence on the bit-error rate and we showed that the on-chip resistor of the current sources have a weak influence. The conventional TFF realization is mainly affected by one specific comparator and we propose to optimize them concerning their generated noise.
Finally we found different types of switching errors for the falling and raising slope.

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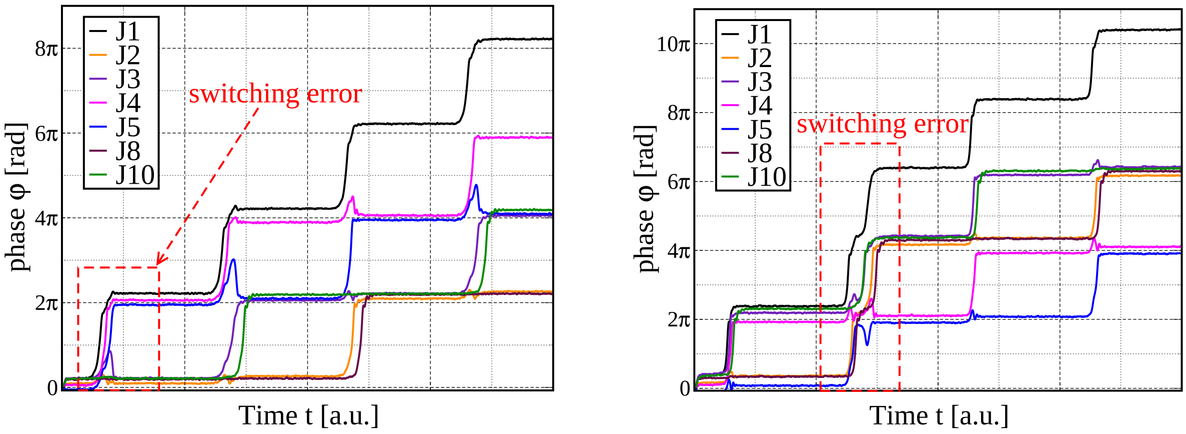

(a) (b)

Fig. 9. The typical switching errors which were identified by simulation for TFF version A. (a) The switching error appearing at the falling slope. (b) The switching error appearing at the raising slope.

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