

IARPA SuperTools Deliverable

# **ColdFlux Logic Cell Library for MIT-LL SFQ Process**

*Submitted by*

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Version 2.1

# Version History

- **Version 2.1:** This version updates the AQFP and RSFQ logic cell libraries for SuperTools phase 2, and combines both libraries in a single document.
- **Version 1.5:** Previous release of AQFP Logic cell library document.
- **Version 1.1:** Previous release of RSFQ Logic cell library document.

# Acknowledgment

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# **Part I**

## **AQFP Logic**

## **Part II**

# **RSFQ Logic**

# 1. Introduction and Setup

## 1.1 Introduction

This RSFQ cell library is developed under the IARPA SuperTools/ColdFlux contract via the U.S. Army Research Office grant W911NF-17-1-0120. The aim is to create a generic and open-source cell library with RSFQ logic [1] as part of the IARPA SuperTools Program [2], [3]. The cell library is continually updated and the latest version of the library can always be found at: <https://github.com/sunmagnetics/RSFQlib>.

The free and open-source tools *XIC* [4], *JoSIM* [5], [6], *JoSIM-tools* [7], *KLayout* and *TimEx* [8], [9] are used to develop and test the RSFQ cells. The circuit schematics are drawn using *XIC*. *JoSIM* is used as the SPICE engine for simulating the cells, while *JoSIM-tools* is used for operating margin analysis as well as cell parameter optimization. *KLayout* is used to construct the cell layouts. *TimEx* is used to extract the characteristics of the cell to generate the Mealy Finite State Machine diagram and Verilog files. Icarus *Verilog* [10] and *GTKWave* [11] can be used to simulate and view the verilog files for each cell. Additionally, *InductEx* [12], [13] is used for impedance extraction during cell layout design. A free version of *InductEx* is available, but has limited capacity.

Version 2.1 of the RSFQ cell library includes two versions of each cell: one with standard connections designed to be connected directly with other cells, and a version designed to be connected to Passive Transmission Lines (PTLs). The version of the cell designed to be connected to PTLs include integrated PTL transmitter and receiver cells. To indicate the integration of PTL transmitters and receivers within a cell, the letter ‘T’ is added at the end of a cell name, for example the DFF with integrated PTL transmitters and receivers will be referred to as DF<sup>T</sup>.

The following core cells are included in the RSFQ cell library:

- Interconnects: JTL, JTLT, SPLIT, SPLITT, MERGE, MERGET, PTLLTX, PTLLRX, Always0 (synchronous and asynchronous) and Always0T (synchronous and asynchronous).
- Logic cells: AND2, AND2T, OR2, OR2T, XOR, XORT, NOT, NOTT, XNOR, XNORT.
- Buffers: DFF, DF<sup>T</sup>, NDRO, NDROT, BUFF and BUFFT.
- Interfacing cells: DCSFQ, DCSFQ-PTLLTX, PTLLRX-SFQDC and SFQDC.

More complex functions can be constructed through connecting several core cells. The cells are currently optimized to run at a maximum clock frequency of 50 GHz. Each delivered cell is documented in 5 parts:

1. **Schematic:** The schematic of a cell is constructed using *Xic* and is delivered in the native *Xic* format.
2. **Layout:**
  - (a) The physical layout of the cells can be constructed using *Xic* or *KLayout* and is delivered in standard GDSII format.
3. **Analog model:**
  - (a) **Netlist:** The netlist presents the device-level construction of a circuit. Each cell is delivered with both a “base” and “optimized” circuit netlist files. The base netlist shows how the cell is designed from first principles using phase-based equations. The cells are then optimized before the physical layout is done. The optimized circuit netlists provides the back-annotated netlist extracted through *InductEx*.
  - (b) **Pin list:** The pin labels and function of each pin is listed.
  - (c) **Simulation results:** JoSIM is used for all circuit simulations.
4. **Digital model:**
  - (a) **Verilog model:** The behavior-level model of a cell with timing specifications included within the model. All verilog models are extracted using *TimEx* and is delivered in standard HDL Verilog format.
  - (b) **Simulation results:** The digital simulation testbench is generated through *TimEx* and is run using *Icarus Verilog* and wave viewer *GTKWave*. Each edge event indicates an SFQ pulse.
  - (c) **Mealy finite state machine diagram:** The state machine diagram is extracted using *TimEx* and is delivered in standard PDF format.
5. **Power consumption:** The power consumption of each cell is calculated in terms of static and dynamic power consumption. Following [14], dynamic power consumption can be calculated as  $P_d = f\Phi_0 I_c$  and static power consumption can be calculated as  $P_s = I_b V_b$ .

## 1.2 Setup

The latest version of the RSFQ cell library can be found at: <https://github.com/sunmagnetics/RSFQlib>. The RSFQ cell library is simulated and tested using several free and/or open-source tools:

- *Xic* is part of *XicTools* and can be found at <http://www.wrcad.com/xic.html>.
- *JoSIM* can be found at <https://github.com/JoeyDelp/JoSIM/>.
- *JoSIM-tools* can be found at <https://github.com/pleroux0/josim-tools>.
- *TimEx* can be found at <https://github.com/sunmagnetics/TimEx>.
- *KLayout* can be found at <https://www.klayout.de/>.
- *InductEx* can be found at <https://www.inductex.info>.
- *Icarus Verilog* can be found at <http://iverilog.icarus.com/>.
- *GTKWave* can be found at <http://gtkwave.sourceforge.net/>.

No additional setup is required to use the RSFQ cell library.

## 1.3 License

The generic RSFQ cell library is free to distribute and/or modify under the terms of the MIT license.

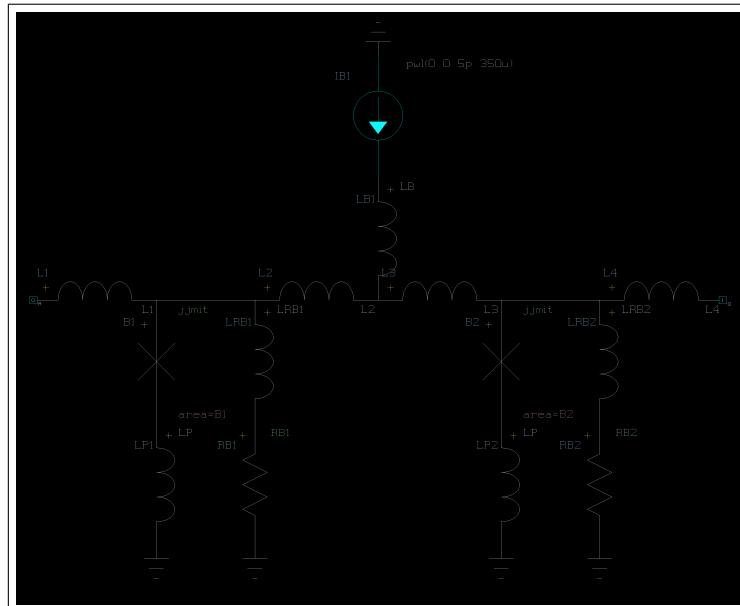
## 2. RSFQ Cell Library: Standard Connections

### 2.1 Interconnects

#### 2.1.1 JTL

The JTL, Josephson transmission line, cell is commonly used to re-establish and propagate SFQ pulses. The cell is not designed to be directly connected to a PTL.

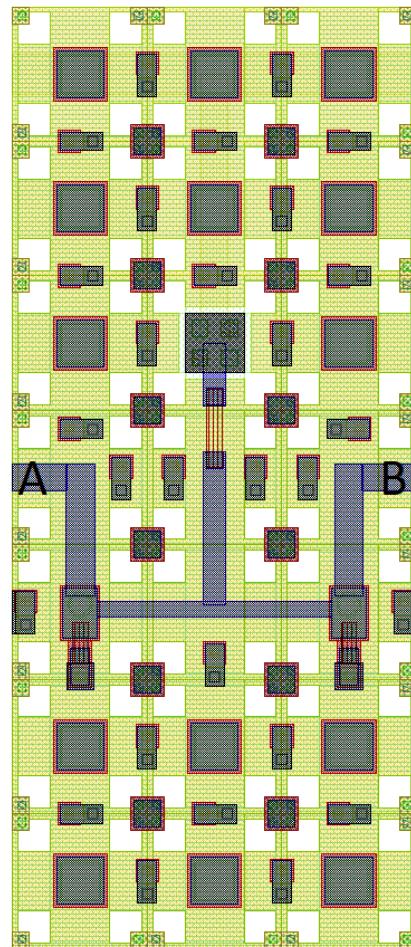
##### Schematic



**Figure 2.1:** Schematic of RSFQ JTL.

## Layout

The physical layout for the RSFQ JTL is shown in Fig. 2.2. The layout height is  $70 \mu m$  and the width is  $30 \mu m$ . The cell includes an integrated bias line on M0 within the top row of track blocks. A bias pillar from M0 to M6 connects the circuit to the integrated bias line.



**Figure 2.2:** RSFQ JTL Layout

**Table 2.1:** RSFQ JTL pin list.

Pin	Description
a	Data input
q	Data output

## Analog model

```

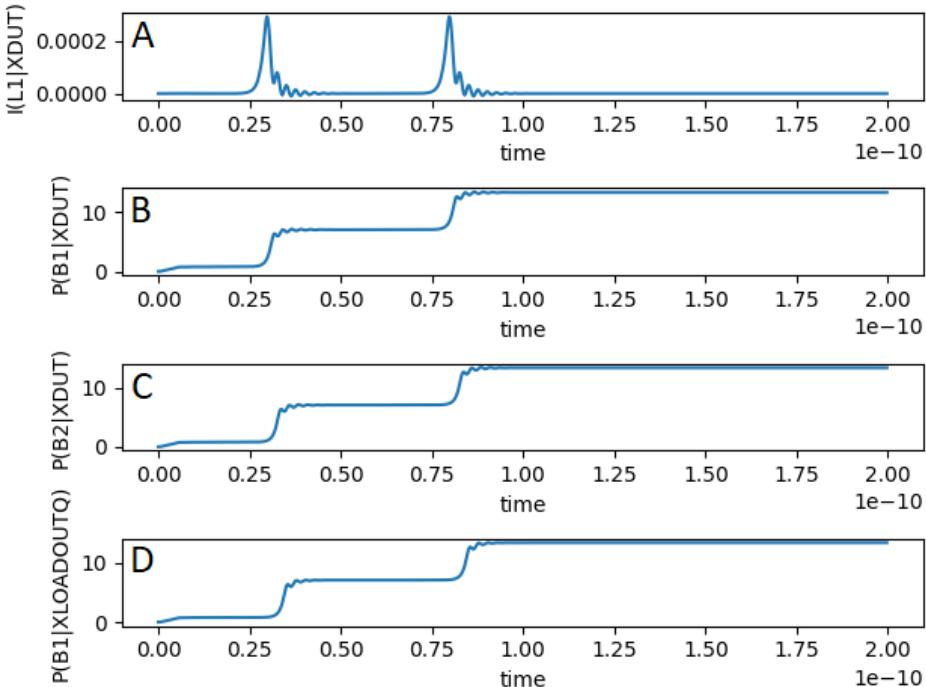
1 * Back-annotated simulation file written by InductEx v.6.0.4 on 10-3-21.
2 * Author: L. Schindler
3 * Version: 2.1
4 * Last modification date: 12 January 2021
5 * Last modification by: L. Schindler
6
7 *$Ports a q
8 .subckt LSMITLL_JTL a q
9 .model jjmit jj(rtype=1, vg=2.8mV, cap=0.07pF, r0=160, rn=16, icrit=0.1mA)
10 .param Phi0=2.067833848E-15
11 .param B0=1
12 .param Ic0=0.0001
13 .param IcRs=100u*6.859904418
14 .param B0Rs=IcRs/Ic0*B0
15 .param Rsheet=2
16 .param Lsheet=1.13e-12
17 .param LP=0.2p
18 .param IC=2.5
19 .param Lptl=2p
20 .param LB=2p
21 .param BiasCoef=0.7
22
23 .param B1=IC
24 .param B2=IC
25 .param IB1=(B1+B2)*Ic0*BiasCoef
26 .param LB1=LB
27 .param L1=Phi0/(4*B1*Ic0)
28 .param L2=Phi0/(4*B1*Ic0)
29 .param L3=Phi0/(4*B1*Ic0)
30 .param L4=Phi0/(4*B2*Ic0)
31 .param RB1=B0Rs/B1
32 .param RB2=B0Rs/B2
33 .param LRB1=(RB1/Rsheet)*Lsheet+LP
34 .param LRB2=(RB2/Rsheet)*Lsheet+LP
35 .param LP1=LP
36 .param LP2=LP
37
38 B1 1 2 jjmit area=B1
39 B2 6 7 jjmit area=B2
40 IB1 0 5 pwl(0 0 5p IB1)
41 L1 a 1 2.082E-12
42 L2 1 4 2.06E-12
43 L3 4 6 2.067E-12
44 L4 6 q 2.075E-12
45 LP1 2 0 4.998E-13
46 LP2 7 0 5.011E-13
47 LB1 5 4 LB1
48 RB1 1 3 RB1
49 RB2 6 8 RB2
50 LRB1 3 0 LRB1
51 LRB2 8 0 LRB2
52 .end

```

**Listing 2.1:** RSFQ JTL JoSIM netlist.

The simulation results for the RSFQ JTL using JoSIM is shown in Fig. 2.3. The testbench is included within the cell library for user verification. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit.



**Figure 2.3:** RSFQ JTL analog simulation results.

## Digital model

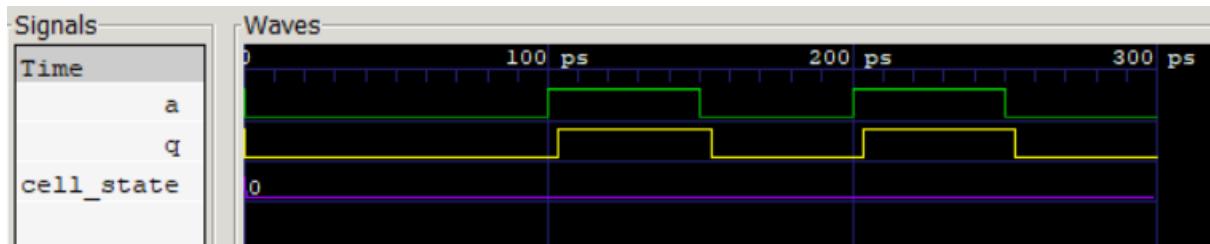
```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 12 January 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_JTL (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 real
20   delay_state0_a_q = 3.5,
21   ct_state0_a_a = 3.5;
22
23 reg
24   errorsignal_a;
25
26 integer
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q = 0; // All outputs start at 0
35 end
36
37 always @(posedge a or negedge a) // execute at positive and negative edges of input
38 begin
39   if ($time>4) // arbitrary steady-state time)
40     begin
41       if (errorsignal_a == 1'b1) // A critical timing is active for this input
42         begin
43           outfile = $fopen("errors.txt", "a");
44           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
45           ↪ ", $stime);
46           $fclose(outfile);
47           q <= 1'bX; // Set all outputs to unknown
48         end
49       if (errorsignal_a == 0)
50         begin
51           case (cell_state)
52             0: begin
53               q <= #(delay_state0_a_q) !q;
54               errorsignal_a = 1; // Critical timing on this input; assign
55               ↪ immediately
56               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
57               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

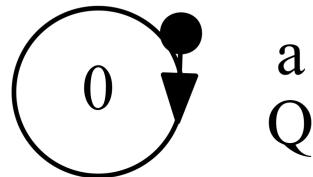
```

**Listing 2.2:** RSFQ JTL verilog model with self-contained timing.

The digital simulation results for the RSFQ JTL is shown in Fig. 2.4 and the Mealy finite state machine diagram, extracted using *TimEx*, is shown in Fig. 2.5.



**Figure 2.4:** RSFQ JTL digital simulation results.



**Figure 2.5:** RSFQ JTL Mealy finite state machine diagram.

## Power Consumption

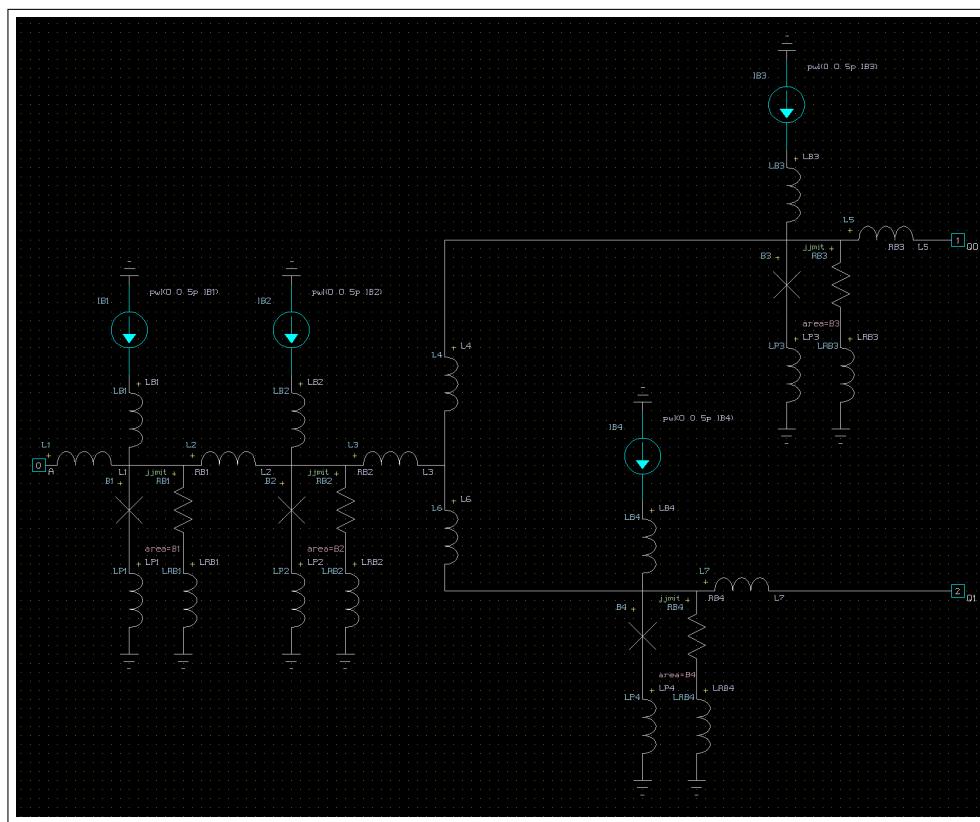
**Table 2.2:** RSFQ JTL power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	910	1.03
2	910	2.07
5	910	5.17
10	910	10.3
20	910	20.7
50	910	51.7

## 2.1.2 SPLIT

The SPLIT cell is used to split a single pulse signal line into two duplicate output pulse signal lines. The cell is not designed to be directly connected to a PTL.

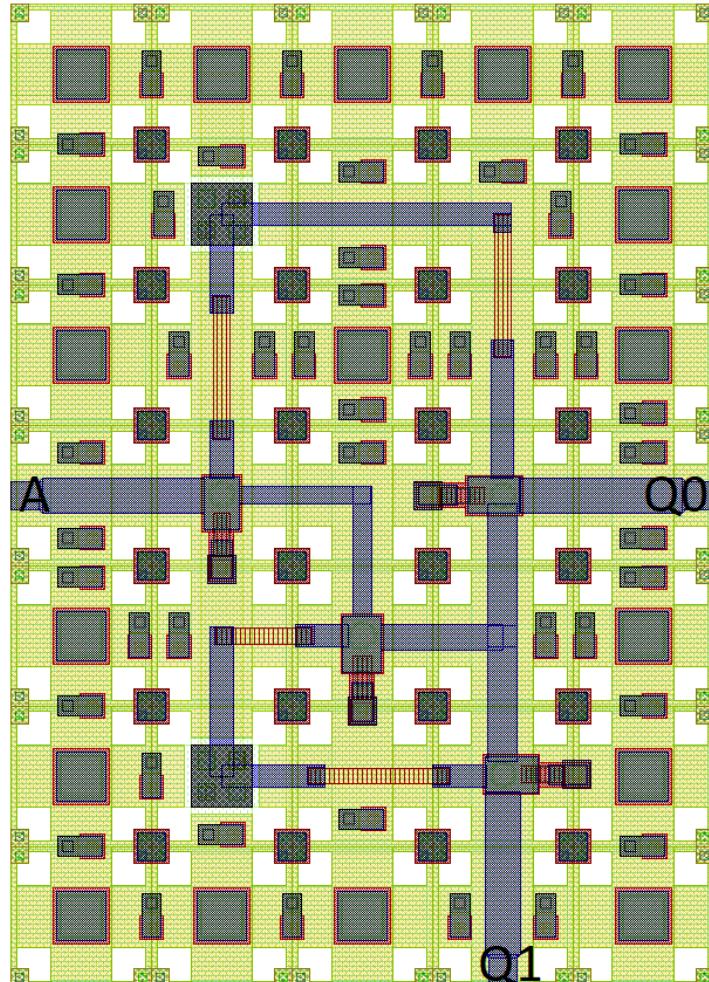
### Schematic



**Figure 2.6:** Schematic of RSFQ SPLIT.

## Layout

The physical layout for the RSFQ SPLIT is shown in Fig. 2.7. The layout height is  $70 \mu\text{m}$  and the width is  $50 \mu\text{m}$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Two bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.7:** RSFQ SPLIT layout.

## Analog model

```

1  * Back-annotated simulation file written      43 | .param RB2=B0Rs/B2
2   ↪ by InductEx v.6.0.4 on 1-4-21.          44 | .param RB3=B0Rs/B3
3  * Author: L. Schindler                     45 | .param RB4=B0Rs/B4
4  * Version: 2.1                           46 | .param LRB1=(RB1/Rsheet)*Lsheet
5  * Last modification date: 9 March 2021    47 | .param LRB2=(RB2/Rsheet)*Lsheet
6  * Last modification by: L. Schindler       48 | .param LRB3=(RB3/Rsheet)*Lsheet
7  *$Ports a q0 q1                         49 | .param LRB4=(RB4/Rsheet)*Lsheet
8 .subckt LSmitll_SPLIT a q0 q1           50 |
9 .model jjmit jj(rtype=1, vg=2.8mV, cap   51 | IB1 0 3 pwl(0 0 5p IB1)
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA   52 | IB2 0 6 pwl(0 0 5p IB2)
   ↪ )                                         53 | IB3 0 10 pwl(0 0 5p IB3)
10 .param Phi0=2.067833848E-15            54 | IB4 0 13 pwl(0 0 5p IB4)
11 .param B0=1                            55 | LB1 3 1 9.175E-13
12 .param Ic0=0.0001                      56 | LB2 6 4 7.666E-13
13 .param IcRs=100u*6.859904418          57 | LB3 10 8 1.928E-12
14 .param B0Rs=IcRs/Ic0*B0              58 | LB4 13 11 8.786E-13
15 .param Rsheet=2                        59 |
16 .param Lsheet=1.13e-12                  60 | B1 1 2 jjmit area=B1
17 .param LP=0.2p                         61 | B2 4 5 jjmit area=B2
18 .param IC=2.5                          62 | B3 8 9 jjmit area=B3
19 .param Lptl=2p                         63 | B4 11 12 jjmit area=B4
20 .param LB=2p                           64 | L1 a 1 2.063E-12
21 .param BiasCoef=0.7                   65 | L2 1 4 3.637E-12
22 .param RD=1.36                         66 | L3 4 7 1.278E-12
23                               67 | L4 7 8 1.305E-12
24 .param B1=2.5                          68 | L5 8 q0 2.05E-12
25 .param B2=3.0                           69 | L6 7 11 1.315E-12
26 .param B3=2.5                          70 | L7 11 q1 2.06E-12
27 .param B4=2.5                          71 |
28                               72 | LP1 2 0 4.676E-13
29 .param IB1=175u                        73 | LP2 5 0 4.498E-13
30 .param IB2=280u                        74 | LP3 9 0 5.183E-13
31 .param IB3=175u                        75 | LP4 12 0 4.639E-13
32 .param IB4=175u                        76 | RB1 1 101 RB1
33                               77 | LRB1 101 0 LRB1
34 .param L1=Lptl                         78 | RB2 4 104 RB2
35 .param L2=Phi0/(2*B1*Ic0)             79 | LRB2 104 0 LRB2
36 .param L3=(Phi0/(2*B2*Ic0))/2        80 | RB3 8 108 RB3
37 .param L4=L3                           81 | LRB3 108 0 LRB3
38 .param L5=Lptl                         82 | RB4 11 111 RB4
39 .param L6=L3                           83 | LRB4 111 0 LRB4
40 .param L7=Lptl                         84 | .ends
41                               84 |
42 .param RB1=B0Rs/B1

```

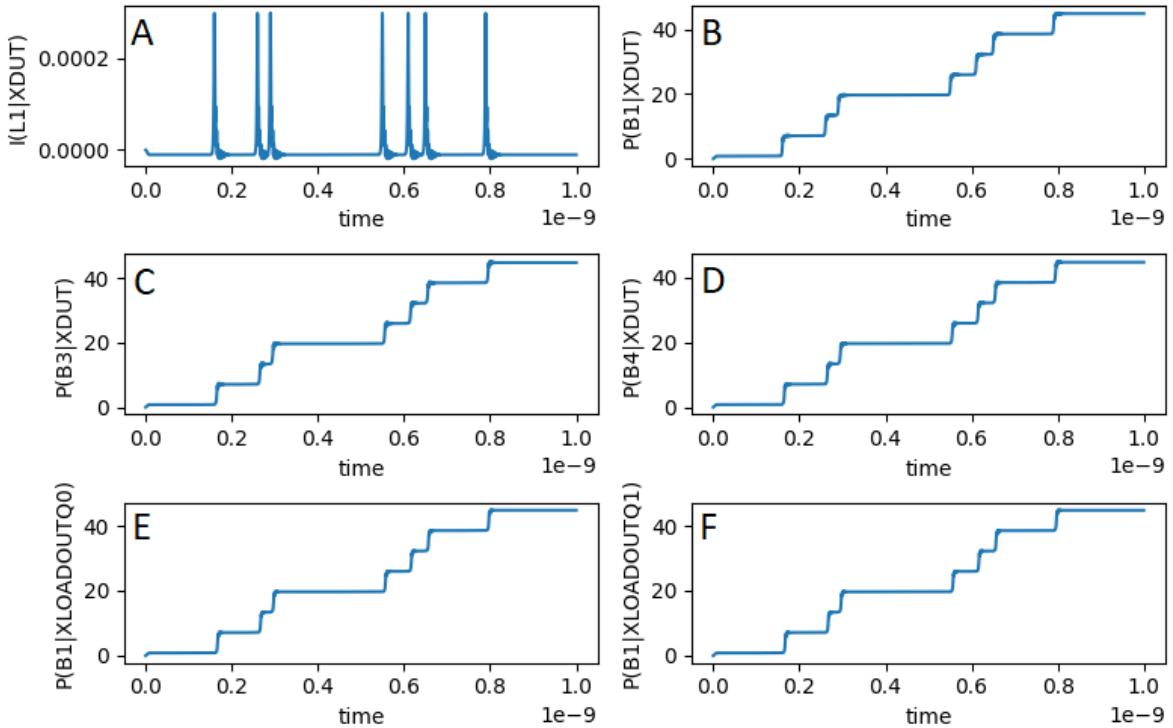
**Listing 2.3:** RSFQ SPLIT JoSIM netlist.

**Table 2.3:** RSFQ SPLIT pin list.

Pin	Description
a	Data input
q0	Data output
q1	Data output

The JoSIM simulation results for the RSFQ SPLIT are shown in Fig. 2.8. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q0**,
- (d) the phase over the output JJ of pin **q1**,
- (e) the phase over the input JJ of the load cell connected to pin **q0**, and
- (f) the phase over the input JJ of the load cell connected to pin **q1**.



**Figure 2.8:** RSFQ SPLIT analog simulation results.

## Digital model

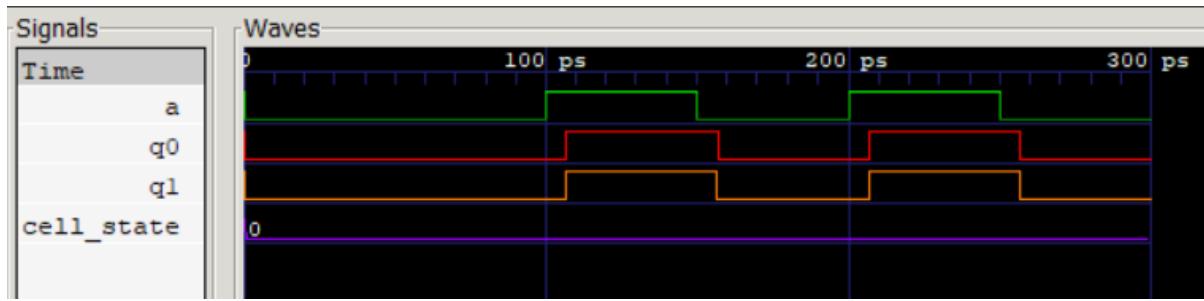
```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 'timescale 1ps/100fs
8 module LSmitll_SPLIT_v2p1_optimized (a, q0, q1);
9
10 input
11   a;
12
13 output
14   q0, q1;
15
16 reg
17   q0, q1;
18
19 real
20   delay_state0_a_q0 = 6.8,
21   delay_state0_a_q1 = 6.5,
22   ct_state0_a_a = 3.4;
23
24 reg
25   errorsignal_a;
26 integer
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q0 = 0; // All outputs start at 0
35   q1 = 0; // All outputs start at 0
36 end
37
38 always @(posedge a or negedge a) // execute at positive and negative edges of input
39 begin
40   if ($time>4) // arbitrary steady-state time)
41     begin
42       if (errorsignal_a == 1'b1) // A critical timing is active for this input
43         begin
44           outfile = $fopen("errors.txt", "a");
45           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
46           ↪ ", $stime);
47           $fclose(outfile);
48           q0 <= 1'bX; // Set all outputs to unknown
49           q1 <= 1'bX; // Set all outputs to unknown
50         end
51       if (errorsignal_a == 0)
52         begin
53           case (cell_state)
54             0: begin
55               q0 <= #(delay_state0_a_q0) !q0;
56               q1 <= #(delay_state0_a_q1) !q1;
57               errorsignal_a = 1; // Critical timing on this input; assign
               ↪ immediately
               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

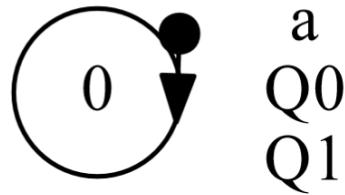
```

**Listing 2.4:** RSFQ SPLIT verilog model.

The digital simulation results for the RSFQ SPLIT is shown in Fig. 2.9 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.10.



**Figure 2.9:** RSFQ SPLIT digital simulation results.



**Figure 2.10:** RSFQ SPLIT Mealy finite state diagram.

## Power consumption

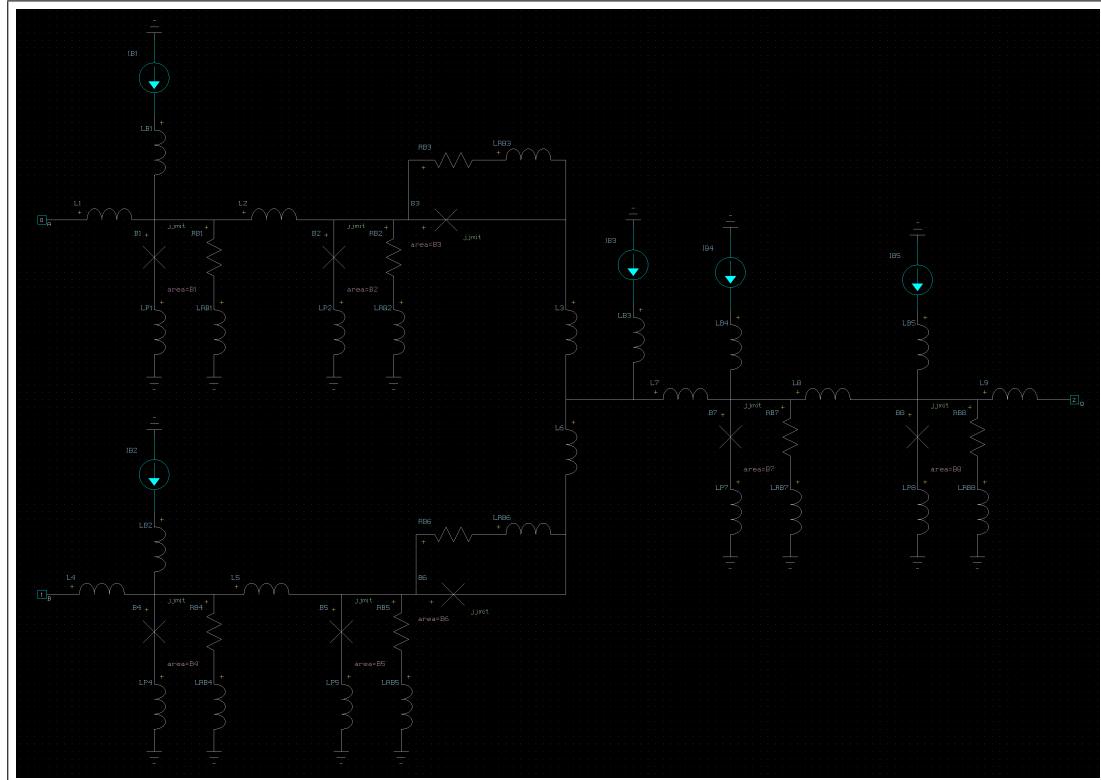
**Table 2.4:** RSFQ SPLIT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2093	2.17
2	2093	4.34
5	2093	10.9
10	2093	21.7
20	2093	43.4
50	2093	108.6

### 2.1.3 MERGE

The MERGE joins two input pulse signal lines and provides a single output pulse signal line. If there is a pulse on either input lines, the MERGE will generate a pulse on the output signal line. The MERGE is not designed to be directly connected to a PTL.

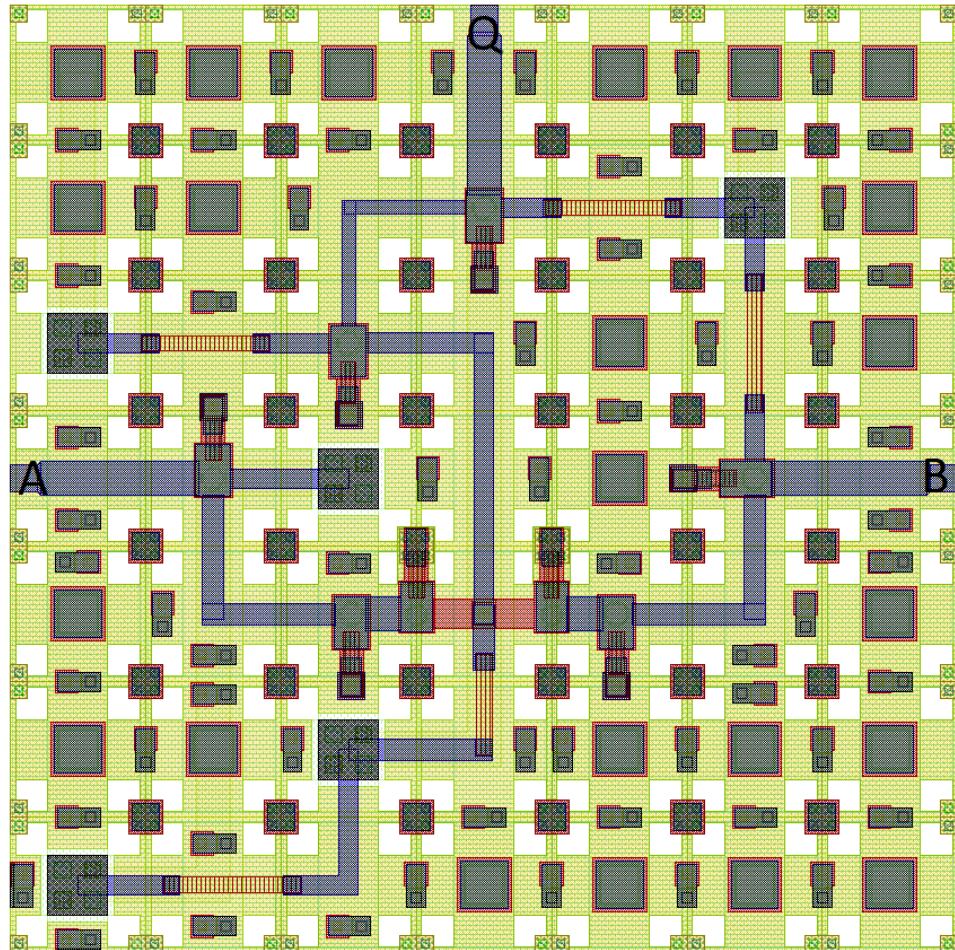
## Schematic



**Figure 2.11:** Schematic of RSFQ MERGE.

## Layout

The physical layout of the RSFQ MERGE is shown in Fig. 2.12. The height of the layout is  $70 \mu m$  and the width is  $70 \mu m$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.12:** RSFQ MERGE layout.

## Analog model

```

1  * Back-annotated simulation file written
2   ↪ by InductEx v.6.0.4 on 19-3-21.
3  * Author: L. Schindler
4  * Version: 2.1
5  * Last modification date: 3 June 2021
6  * Last modification by: L. Schindler
7
8  *$Ports a b q
9 .subckt LSmitt1_MERGE a b q
10 .model jjmit jj(rtype=1, vg=2.8mV, cap
11   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA
12   ↪ )
13 .param Phi0=2.067833848E-15
14 .param B0=1
15 .param Ic0=0.0001
16 .param IcRs=100u*6.859904418
17 .param B0Rs=IcRs/Ic0*B0
18 .param Rsheet=2
19 .param Lsheet=1.13e-12
20 .param LP=0.2p
21 .param IC=2.5
22 .param LB=2p
23 .param BiasCoef=0.70
24 .param RD=1.36
25 .param B1=IC
26 .param B2=2.5
27 .param B3=1.92
28 .param B4=B1
29 .param B5=B2
30 .param B6=B3
31 .param B7=2.53
32 .param B8=IC
33 .param IB1=BiasCoef*Ic0*B1
34 .param IB2=IB1
35 .param IB3=254E-6
36 .param IB4=192E-6
37 .param IB5=BiasCoef*Ic0*B8
38 .param L1=Phi0/(4*IC*Ic0)
39 .param L2=3.173E-12
40 .param L3=1.2E-12
41 .param L4=L1
42 .param L5=L2
43 .param L6=L3
44 .param L7=5.354E-12
45 .param L8=4.456E-12
46 .param L9=Phi0/(4*B8*Ic0)
47 .param LB1=LB
48 .param LB2=LB
49 .param LB3=LB
50 .param LB4=LB
51 .param LB5=LB
52 .param LP1=LP
53 .param LP2=LP
54 .param LP4=LP
55 .param LP5=LP
56 .param LP7=LP
57 .param LP8=LP
58 .param RB1=B0Rs/B1
59 .param RB2=B0Rs/B2
60 .param RB3=B0Rs/B3
61 .param RB4=B0Rs/B4
62 .param RB5=B0Rs/B5
63 .param RB6=B0Rs/B6
64
65 .param RB7=B0Rs/B7
66 .param RB8=B0Rs/B8
67 .param LRB1=(RB1/Rsheet)*Lsheet
68 .param LRB2=(RB2/Rsheet)*Lsheet
69 .param LRB3=(RB3/Rsheet)*Lsheet
70 .param LRB4=(RB4/Rsheet)*Lsheet
71 .param LRB5=(RB5/Rsheet)*Lsheet
72 .param LRB6=(RB6/Rsheet)*Lsheet
73 .param LRB7=(RB7/Rsheet)*Lsheet
74 .param LRB8=(RB8/Rsheet)*Lsheet
75
76 B1 1 2 jjmit area=B1
77 B2 4 5 jjmit area=B2
78 B3 4 6 jjmit area=B3
79 B4 8 9 jjmit area=B4
80 B5 11 12 jjmit area=B5
81 B6 11 13 jjmit area=B6
82 B7 15 16 jjmit area=B7
83 B8 18 19 jjmit area=B8
84
85 IB1 0 3 pwl(0 0 5p IB1)
86 IB2 0 10 pwl(0 0 5p IB2)
87 IB3 0 14 pwl(0 0 5p IB3)
88 IB4 0 17 pwl(0 0 5p IB4)
89 IB5 0 20 pwl(0 0 5p IB5)
90
91 L1 a 1 2.117E-12
92 L2 1 4 3.17E-12
93 L3 6 7 1.234E-12
94 L4 b 8 2.082E-12
95 L5 8 11 3.165E-12
96 L6 13 7 1.224E-12
97 L7 7 15 5.299E-12
98 L8 15 18 4.489E-12
99 L9 18 q 2.077E-12
100
101 LP1 2 0 4.652E-13
102 LP2 5 0 4.457E-13
103 LP4 9 0 5.293E-13
104 LP5 12 0 4.452E-13
105 LP7 16 0 5.039E-13
106 LP8 19 0 4.984E-13
107 LB1 1 3 LB1
108 LB2 8 10 LB2
109 LB3 7 14 LB3
110 LB4 15 17 LB4
111 LB5 18 20 LB5
112 RB1 1 101 RB1
113 LRB1 101 0 LRB1
114 RB2 4 104 RB2
115 LRB2 104 0 LRB2
116 RB3 4 106 RB3
117 LRB3 106 6 LRB3
118 RB4 8 108 RB4
119 LRB4 108 0 LRB4
120 RB5 11 111 RB5
121 LRB5 111 0 LRB5
122 RB6 11 113 RB6
123 LRB6 113 13 LRB6
124 RB7 15 115 RB7
125 LRB7 115 0 LRB7
126 RB8 18 118 RB8
127 LRB8 118 0 LRB8
128 .ends

```

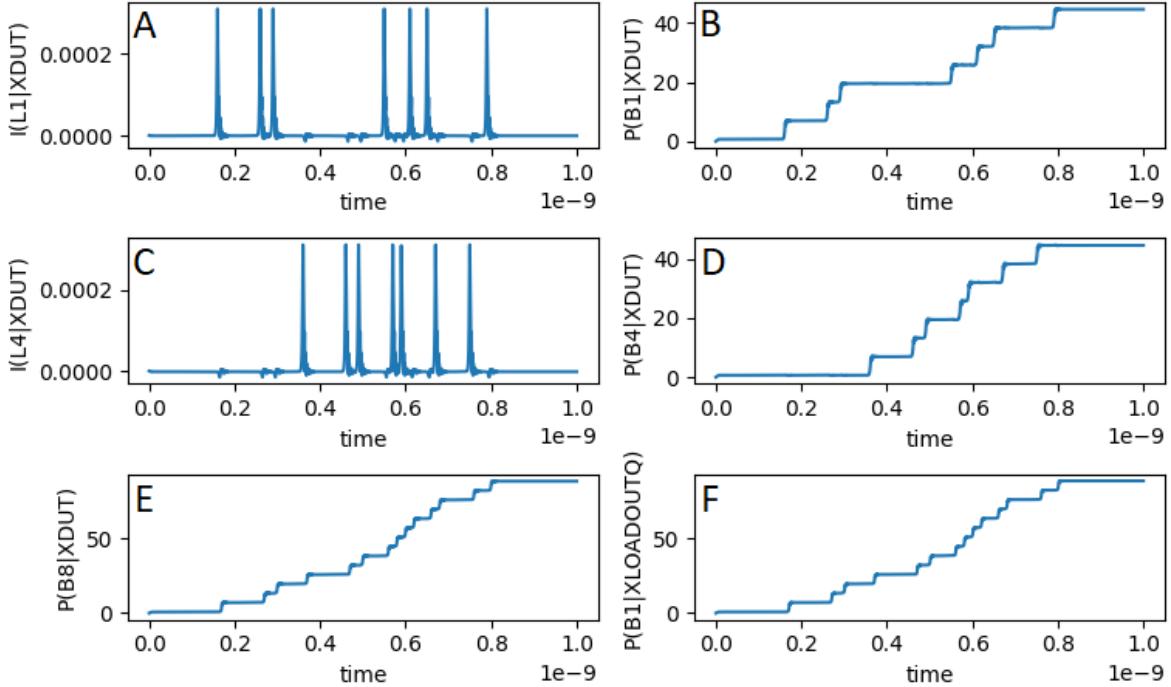
**Listing 2.5:** RSFQ MERGE JoSIM netlist.

**Table 2.5:** RSFQ MERGE pin list.

Pin	Description
a	Data input
b	Data input
q	Data output

The JoSIM simulation results for the RSFQ MERGE are shown in Fig. 2.13. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the phase over the output JJ of pin **q**,
- (f) the phase over the input JJ of the load cell connected to pin **q**.

**Figure 2.13:** RSFQ MERGE analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 // -----
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 // -----
15 'timescale 1ps/100fs
16 module LSmitll_MERGE_v2p1_optimized (a, b, q);
17
18 input
19   a, b;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state0_a_q = 10.7,
29   delay_state0_b_q = 10.7,
30   ct_state0_a_a = 8.4,
31   ct_state0_a_b = 3.0,
32   ct_state0_b_a = 3.0,
33   ct_state0_b_b = 8.9;
34
35 reg
36   errorsignal_a,
37   errorsignal_b;
38
39 integer
40   outfile,
41   cell_state; // internal state of the cell
42
43 initial
44 begin
45   errorsignal_a = 0;
46   errorsignal_b = 0;
47   cell_state = 0; // Startup state
48   q = 0; // All outputs start at 0
49 end
50
51 always @(posedge a or negedge a) // execute at positive and negative edges of input
52 begin
53   if ($time>4) // arbitrary steady-state time)
54     begin
55       if (errorsignal_a == 1'b1) // A critical timing is active for this input
56         begin
57           outfile = $fopen("errors.txt", "a");
58           $fdisplay(outfile, "Violation of critical timing in module %m; %0d ps.\n",
59           $stime);
60           $fclose(outfile);
61           q <= 1'bX; // Set all outputs to unknown
62         end
63       if (errorsignal_a == 0)
64         begin
65           case (cell_state)
66             0: begin
67               q <= #(delay_state0_a_q) !q;
68             end
69           endcase
70         end
71     end
72   end
73 end
74
75 endmodule

```

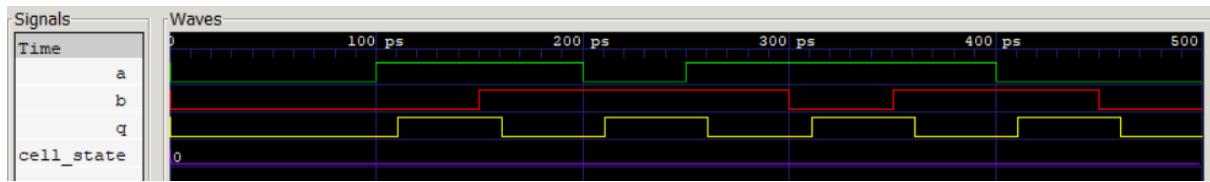
```

67          errorsignal_a = 1; // Critical timing on this input; assign
68          //      ↪ immediately
69          errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
70          //      ↪ after critical timing expires
71          errorsignal_b = 1; // Critical timing on this input; assign
72          //      ↪ immediately
73          errorsignal_b <= #(ct_state0_a_b) 0; // Clear error signal
74          //      ↪ after critical timing expires
75      end
76  endcase
77 end
78
79 always @ (posedge b or negedge b) // execute at positive and negative edges of input
80 begin
81     if ($time>4) // arbitrary steady-state time)
82     begin
83         if (errorsignal_b == 1'b1) // A critical timing is active for this input
84         begin
85             outfile = $fopen("errors.txt", "a");
86             $fdisplay(outfile, "Violation of critical timing in module %m; %0d ps.\n"
87                         //      ↪ ", $stime);
88             $fclose(outfile);
89             q <= 1'bX; // Set all outputs to unknown
90         end
91         if (errorsignal_b == 0)
92         begin
93             case (cell_state)
94                 0: begin
95                     q <= #(delay_state0_b_q) !q;
96                     errorsignal_a = 1; // Critical timing on this input; assign
97                     //      ↪ immediately
98                     errorsignal_a <= #(ct_state0_b_a) 0; // Clear error signal
99                     //      ↪ after critical timing expires
100                    errorsignal_b = 1; // Critical timing on this input; assign
101                    //      ↪ immediately
102                    errorsignal_b <= #(ct_state0_b_b) 0; // Clear error signal
103                    //      ↪ after critical timing expires
104                end
105            endcase
106        end
107    end
108 endmodule

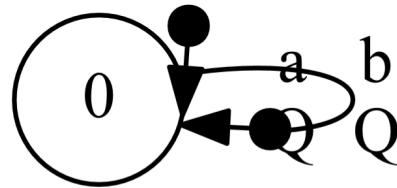
```

**Listing 2.6:** RSFQ MERGE verilog model.

The digital simulation results for the RSFQ MERGE is shown in Fig. 2.14 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.15.



**Figure 2.14:** RSFQ MERGE digital simulation results.



**Figure 2.15:** RSFQ MERGE Mealy finite state diagram.

## Power consumption

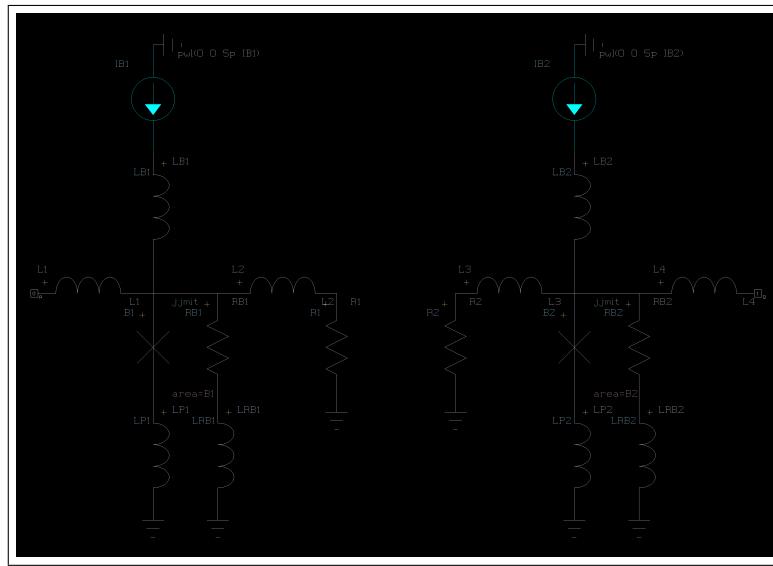
**Table 2.6:** RSFQ MERGE power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2526	3.09
2	2526	7.80
5	2526	19.5
10	2526	39.0
20	2526	78.0
50	2526	195

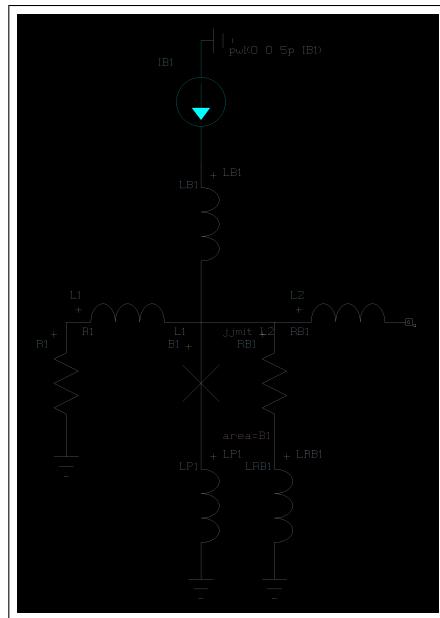
## 2.1.4 Always0 Asynchronous

The Always0 Asynchronous cell provides an output which is always zero. Two versions of the cell exist: One with an **a** input port, as seen in Fig. 2.16, and one without an **a** input port, as seen in Fig. 2.17. The Always0 Asynchronous is not designed to be directly connected to a PTL.

### Schematic



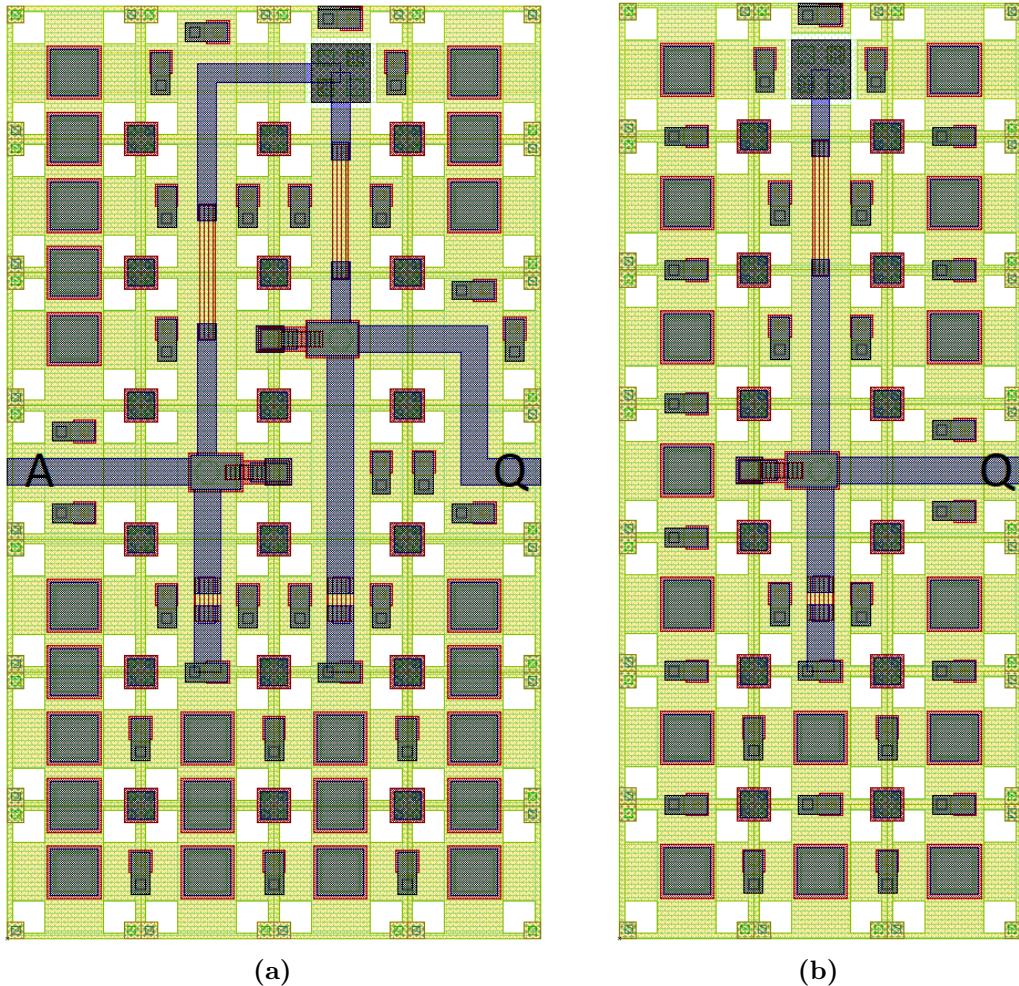
**Figure 2.16:** Schematic of RSFQ Always0 Asynchronous.



**Figure 2.17:** Schematic of RSFQ Always0 Asynchronous without an **a** input port.

## Layout

The physical layouts of the two RSFQ Always0 Asynchronous cell versions are shown in Fig. 2.18a and 2.18b respectively. The height of the Always0 Asynchronous layout is  $70 \mu m$  and the width is  $40 \mu m$ . For the version without the **a** input port, the width of the layout is  $30 \mu m$ . The cells include an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.18:** The physical layouts for (a) the RSFQ Always0 Asynchronous and (b) the RSFQ Always0 Asynchronous without an **a** input port.

## Analog model

```

1  * Back-annotated simulation file written      31 | .param LB2=LB
2  *   ↪ by InductEx v.6.0.4 on 2-6-21.          32 | .param RB1=B0Rs/B1
3  * Author: L. Schindler                      33 | .param RB2=B0Rs/B2
4  * Version: 2.1                                34 | .param LRB1=(RB1/Rsheet)*Lsheet+LP
5  * Last modification date: 2 June 2021        35 | .param LRB2=(RB2/Rsheet)*Lsheet+LP
6  * Last modification by: L. Schindler         36 | .param LP1=LP
7  *$Ports                                         37 | .param LP2=LP
8  .subckt LSMITLL_Always0_async a q           38 | .param R1=2
9  .model jjmit jj(rtype=1, vg=2.8mV, cap     39 | .param R2=2
10 *=0.07pF, r0=160, rn=16, icrit=0.1mA       40 |
11 .param Phi0=2.067833848E-15                  41 | B1 1 2 jjmit area=B1
12 .param B0=1                                    42 | B2 6 7 jjmit area=B2
13 .param Ic0=0.0001                             43 | IB1 0 3 pwl(0 0 5p IB1)
14 .param IcRs=100u*6.859904418                  44 | IB2 0 8 pwl(0 0 5p IB2)
15 .param B0Rs=IcRs/Ic0*B0                      45 | L1 a 1 2.47E-12
16 .param Rsheet=2                              46 | L2 1 4 1.4E-12
17 .param Lsheet=1.13e-12                        47 | L3 5 6 2.948E-12
18 .param LP=0.2p                               48 | L4 6 q 3.768E-12
19 .param IC=2.5                                49 | R1 4 0 R1
20 .param Lptl=2p                               50 | R2 5 0 R2
21 .param BiasCoef=0.7                          51 | LB1 1 3 2.199E-12
22 .param B1=IC                                 52 | LB2 6 8 1.087E-12
23 .param B2=IC                                 53 | LP1 2 0 5.282E-13
24 .param IB1=B1*Ic0*BiasCoef                  54 | LP2 7 0 4.908E-13
25 .param IB2=B2*Ic0*BiasCoef                  55 | RB1 1 101 RB1
26 .param L1=Phi0/(4*B1*Ic0)                   56 | LRB1 101 0 LRB1
27 .param L2=Phi0/(2*B1*Ic0)                   57 | RB2 6 106 RB2
28 .param L3=Phi0/(2*B2*Ic0)                   58 | LRB2 106 0 LRB2
29 .param L4=Phi0/(4*B2*Ic0)                   59 | .ends
30 .param LB1=LB

```

**Listing 2.7:** RSFQ Always0 Asynchronous JoSIM netlist.

**Table 2.7:** RSFQ Always0 Asynchronous pin list.

Pin	Description
a	Data input
q	Data output

```

1  * Back-annotated simulation file written      22 | .param B1=IC
2  *   ↪ by InductEx v.6.0.4 on 2-6-21.          23 | .param IB1=B1*Ic0*BiasCoef
3  * Author: L. Schindler                      24 | .param L1=Phi0/(2*B1*Ic0)
4  * Version: 2.1                                25 | .param L2=Phi0/(4*B1*Ic0)
5  * Last modification date: 2 June 2021        26 | .param LB1=LB
6  * Last modification by: L. Schindler         27 | .param RB1=B0Rs/B1
7  *$Ports                         q           28 | .param LRB1=(RB1/Rsheet)*Lsheet+LP
8  .subckt LSMITLL_Always0_async_noA q          29 | .param LP1=LP
9  .model jjmit jj(rtype=1, vg=2.8mV, cap     30 | .param R1=2
10 .param Phi0=2.067833848E-15                  31 | B1 2 3 jjmit area=B1
11 .param B0=1                                    32 | IB1 0 5 pwl(0 0 5p IB1)
12 .param Ic0=0.0001                            33 | L1 1 2 1.397E-12
13 .param IcRs=100u*6.859904418                 34 | L2 2 q 2.465E-12
14 .param B0Rs=IcRs/Ic0*B0                     35 | R1 1 0 R1
15 .param Rsheet=2                             36 | LB1 2 4 3.177E-12
16 .param Lsheet=1.13e-12                      37 | LP1 3 0 5.306E-13
17 .param LP=0.2p                           38 | RB1 2 102 RB1
18 .param IC=2.5                           39 | LRB1 102 0 LRB1
19 .param Lptl=2p                          40 | .ends
20 .param LB=2p                           41 |
21 .param BiasCoef=0.7

```

**Listing 2.8:** RSFQ Always0 Asynchronous, without an **a** input port, JoSIM netlist.

**Table 2.8:** RSFQ Always0 Asynchronous, without an **a** input port, pin list.

Pin	Description
<b>q</b>	Data output

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 2 June 2021
5 // Last modification by: L. Schindler
6 'timescale 1ps/100fs
7 module LSmitll_Always0_async (a, q);
8
9 input
10   a;
11
12 output
13   q;
14
15 reg
16   q;
17
18 initial
19   begin
20     q = 0; // Output always 0
21   end
22
23 always
24   begin
25     #10 q = 0; // Output always 0
26   end
27 endmodule

```

**Listing 2.9:** RSFQ Always0 Asynchronous verilog model.

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 2 June 2021
5 // Last modification by: L. Schindler
6 'timescale 1ps/100fs
7 module LSmitll_Always0_async_noA (q);
8
9
10 output
11   q;
12
13 reg
14   q;
15
16 initial
17   begin
18     q = 0; // Output always 0
19   end
20
21 always
22   begin
23     #10 q = 0; // Output always 0
24   end
25 endmodule

```

**Listing 2.10:** RSFQ Always0 Asynchronous, without an **a** input port, verilog model.

## Power consumption

**Table 2.9:** RSFQ Always0 Asynchronous power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	910	0.52
2	910	1.03
5	910	2.58
10	910	5.17
20	910	10.3
50	910	25.8

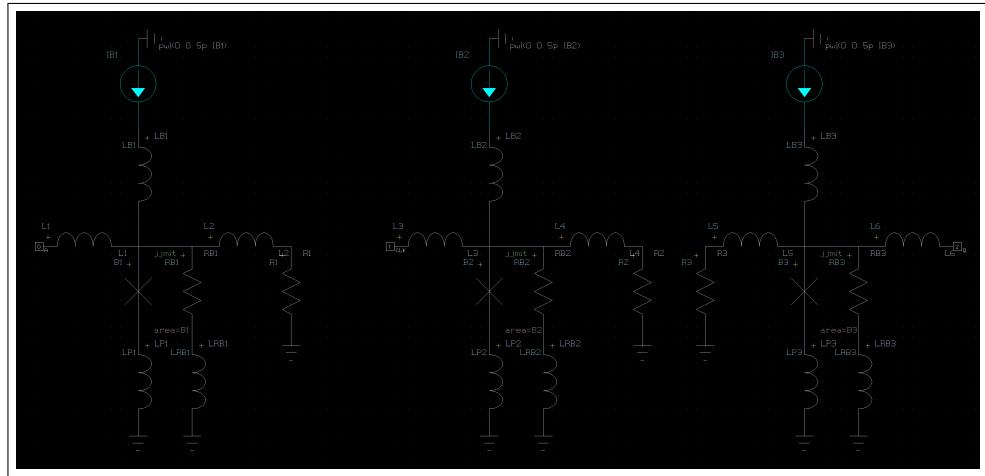
**Table 2.10:** RSFQ Always0 Asynchronous, without an **a** input port, power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	455	N/A
2	455	N/A
5	455	N/A
10	455	N/A
20	455	N/A
50	455	N/A

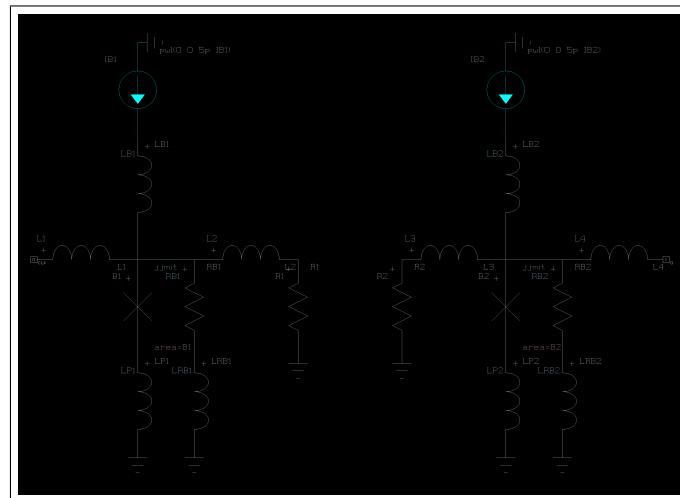
## 2.1.5 Always0 Synchronous

The Always0 Synchronous cell provides an output which is always zero synchronous to a clock signal. Two versions of the cell exist: One with an **a** input port, as seen in Fig. 2.19, and one without an **a** input port, as seen in Fig. 2.20. The Always0 Synchronous is not designed to be directly connected to a PTL.

### Schematic



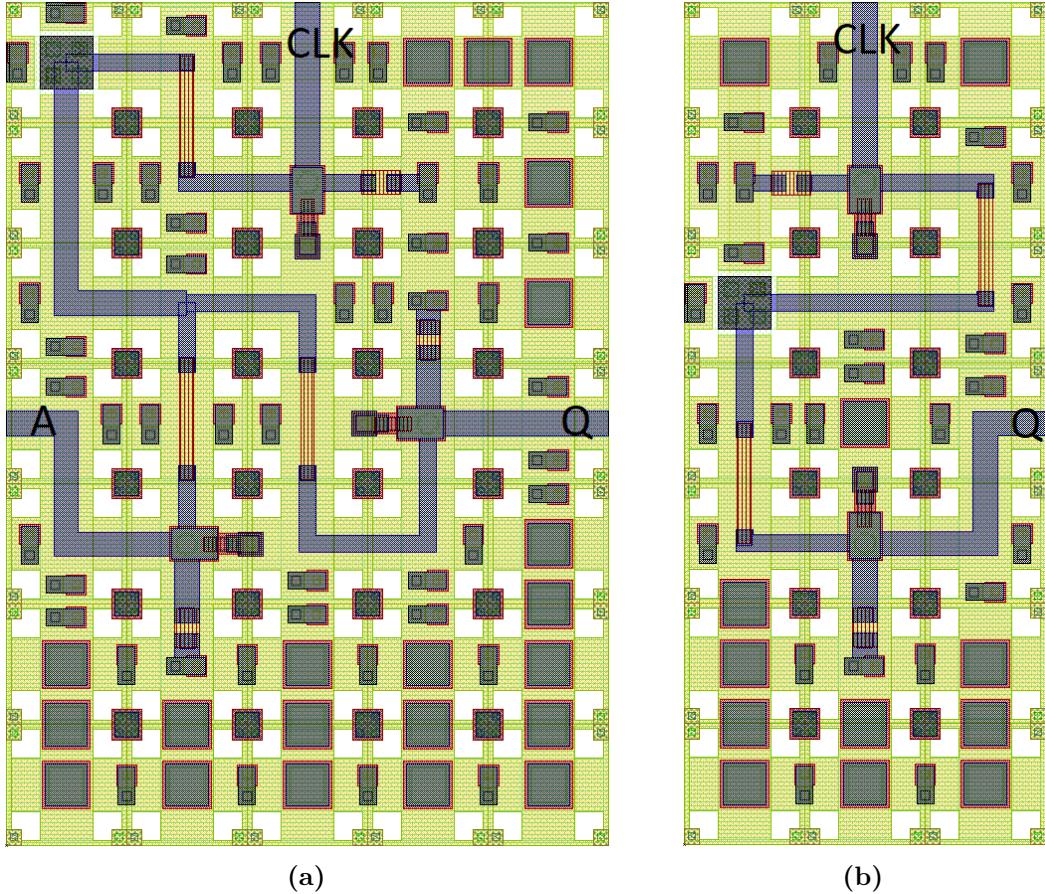
**Figure 2.19:** Schematic of RSFQ Always0 Synchronous.



**Figure 2.20:** Schematic of RSFQ Always0 Synchronous without an **a** input port.

## Layout

The physical layouts of the two RSFQ Always0 Synchronous cell versions are shown in Fig. 2.21a and 2.21b respectively. The height of the Always0 Synchronous layout is  $70 \mu\text{m}$  and the width is  $50 \mu\text{m}$ . For the version without the **a** input port, the width of the layout is  $30 \mu\text{m}$ . The cells include an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.21:** The physical layouts for (a) the RSFQ Always0 Synchronous and (b) the RSFQ Always0 Synchronous without an **a** input port.

## Analog model

```

1  * Back-annotated simulation file written      40 | .param LRB1=(RB1/Rsheet)*Lsheet+LP
2  *   ↪ by InductEx v.6.0.4 on 2-6-21.          41 | .param LRB2=(RB2/Rsheet)*Lsheet+LP
3  * Author: L. Schindler                      42 | .param LRB3=(RB3/Rsheet)*Lsheet+LP
4  * Version: 2.1                                43 | .param LP1=LP
5  * Last modification date: 2 June 2021        44 | .param LP2=LP
6  * Last modification by: L. Schindler         45 | .param LP3=LP
7  *$Ports                                         a clk q      46 | .param R1=2
8  .subckt LSMITLL_Always0_sync a clk q          47 | .param R2=2
9  .model jjmit jj(rtype=1, vg=2.8mV, cap      48 | .param R3=2
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA      49 |
   ↪ )                                             
10 .param Phi0=2.067833848E-15                  50 | B1 1 2 jjmit area=B1
11 .param B0=1                                    51 | B2 5 6 jjmit area=B2
12 .param Ic0=0.0001                            52 | B3 10 11 jjmit area=B3
13 .param IcRs=100u*6.859904418                 53 | IB1 0 3 pw1(0 0 5p IB1)
14 .param B0Rs=IcRs/Ic0*B0                     54 | IB2 0 7 pw1(0 0 5p IB2)
15 .param Rsheet=2                             55 | IB3 0 12 pw1(0 0 5p IB3)
16 .param Lsheet=1.13e-12                      56 | L1 a 1 3.78E-12
17 .param LP=0.2p                               57 | L2 1 4 1.016E-12
18 .param IC=2.5                                58 | L3 clk 5 2.5E-12
19 .param Lptl=2p                             59 | L4 5 8 1.048E-12
20 .param LB=2p                                60 | L5 9 10 1.005E-12
21 .param BiasCoef=0.7                         61 | L6 10 q 2.488E-12
22 .param B1=IC                                62 | R1 4 0 R1
23 .param B2=IC                                63 | R2 8 0 R2
24 .param B3=IC                                64 | R3 9 0 R3
25 .param IB1=B1*Ic0*BiasCoef                65 | LB1 1 3 1.243E-12
26 .param IB2=B2*Ic0*BiasCoef                66 | LB2 5 7 2.181E-12
27 .param IB3=B3*Ic0*BiasCoef                67 | LB3 10 12 5.092E-12
28 .param L1=Phi0/(4*B1*Ic0)                  68 | LP1 2 0 4.931E-13
29 .param L2=Phi0/(2*B1*Ic0)                  69 | LP2 6 0 4.919E-13
30 .param L3=Phi0/(4*B2*Ic0)                  70 | LP3 11 0 5.015E-13
31 .param L4=Phi0/(2*B2*Ic0)                  71 | RB1 1 101 RB1
32 .param L5=Phi0/(2*B3*Ic0)                  72 | LRB1 101 0 LRB1
33 .param L6=Phi0/(4*B3*Ic0)                  73 | RB2 5 105 RB2
34 .param LB1=LB                                74 | LRB2 105 0 LRB2
35 .param LB2=LB                                75 | RB3 10 110 RB3
36 .param LB3=LB                                76 | LRB3 110 0 LRB3
37 .param RB1=B0Rs/B1                          77 | .ends
38 .param RB2=B0Rs/B2
39 .param RB3=B0Rs/B3

```

**Listing 2.11:** RSFQ Always0 Synchronous JoSIM netlist.

**Table 2.11:** RSFQ Always0 Synchronous pin list.

Pin	Description
a	Data input
clk	Clock input
q	Data output

```

1  * Back-annotated simulation file written      31 | .param LB2=LB
2  *   ↪ by InductEx v.6.0.4 on 2-6-21.          32 | .param RB1=B0Rs/B1
3  * Author: L. Schindler                      33 | .param RB2=B0Rs/B2
4  * Version: 2.1                                34 | .param LRB1=(RB1/Rsheet)*Lsheet+LP
5  * Last modification date: 2 June 2021        35 | .param LRB2=(RB2/Rsheet)*Lsheet+LP
6  * Last modification by: L. Schindler         36 | .param LP1=LP
7  *$Ports                                         37 | .param LP2=LP
8  .subckt LSMITLL_Always0_sync_noA clk q      38 | .param R1=2
9  .model jjmit jj(rtype=1, vg=2.8mV, cap      39 | .param R2=2
10 |   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    40 |
11 |   ↪ )                                         41 | B1 1 2 jjmit area=B1
12 .param Phi0=2.067833848E-15                  42 | B2 6 7 jjmit area=B2
13 .param B0=1                                    43 | IB1 0 3 pwl(0 0 5p IB1)
14 .param Ic0=0.0001                             44 | IB2 0 8 pwl(0 0 5p IB2)
15 .param IcRs=100u*6.859904418                 45 | L1 clk 1 2.507E-12
16 .param B0Rs=IcRs/Ic0*B0                      46 | L2 1 4 1.057E-12
17 .param Rsheet=2                               47 | L3 5 6 1.062E-12
18 .param LP=0.2p                                48 | L4 6 q 3.747E-12
19 .param IC=2.5                                 49 | R1 4 0 R1
20 .param Lptl=2p                                50 | R2 5 0 R2
21 .param BiasCoef=0.7                           51 | LB1 1 3 2.133E-12
22 .param B1=IC                                  52 | LB2 6 8 2.17E-12
23 .param B2=IC                                  53 | LP1 2 0 4.927E-13
24 .param IB1=B1*Ic0*BiasCoef                  54 | LP2 7 0 4.925E-13
25 .param IB2=B2*Ic0*BiasCoef                  55 | RB1 1 101 RB1
26 .param L1=Phi0/(4*B1*Ic0)                    56 | LRB1 101 0 LRB1
27 .param L2=Phi0/(2*B1*Ic0)                    57 | RB2 6 106 RB2
28 .param L3=Phi0/(2*B2*Ic0)                    58 | LRB2 106 0 LRB2
29 .param L4=Phi0/(4*B2*Ic0)                    59 | .ends
30 .param LB1=LB

```

**Listing 2.12:** RSFQ Always0 Synchronous, without an **a** input port, JoSIM netlist.

**Table 2.12:** RSFQ Always0 Synchronous, without an **a** input port, pin list.

Pin	Description
<b>clk</b>	Clock input
<b>q</b>	Data output

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 2 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_Always0_sync (a, clk, q);
9
10 input
11   a;
12   clk;
13
14 output
15   q;
16
17 reg
18   q;
19
20 initial
21 begin
22   q = 0; // Output always 0
23 end
24
25 always
26 begin
27   #10 q = 0; // Output always 0
28 end
29 endmodule

```

**Listing 2.13:** RSFQ Always0 Synchronous verilog model.

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 2 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 // Timing description and structural design for IARPA-BAA-14-03 via
8 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
9 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
10 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
11 // (c) 2016-2020 Stellenbosch University
12 // -----
13 `timescale 1ps/100fs
14 module LSmitll_Always0_sync_noA (clk, q);
15
16 input
17   clk;
18
19 output
20   q;
21
22 reg
23   q;
24
25 initial
26 begin
27   q = 0; // Output always 0
28 end
29
30 always
31 begin
32   #10 q = 0; // Output always 0
33 end
34 endmodule

```

**Listing 2.14:** RSFQ Always0 Synchronous, without an **a** input port, verilog model.

## Power consumption

**Table 2.13:** RSFQ Always0 Synchronous power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	1365	1.03
2	1365	2.07
5	1365	5.17
10	1365	10.3
20	1365	20.7
50	1365	51.7

**Table 2.14:** RSFQ Always0 Synchronous, without an **a** input port, power consumption.

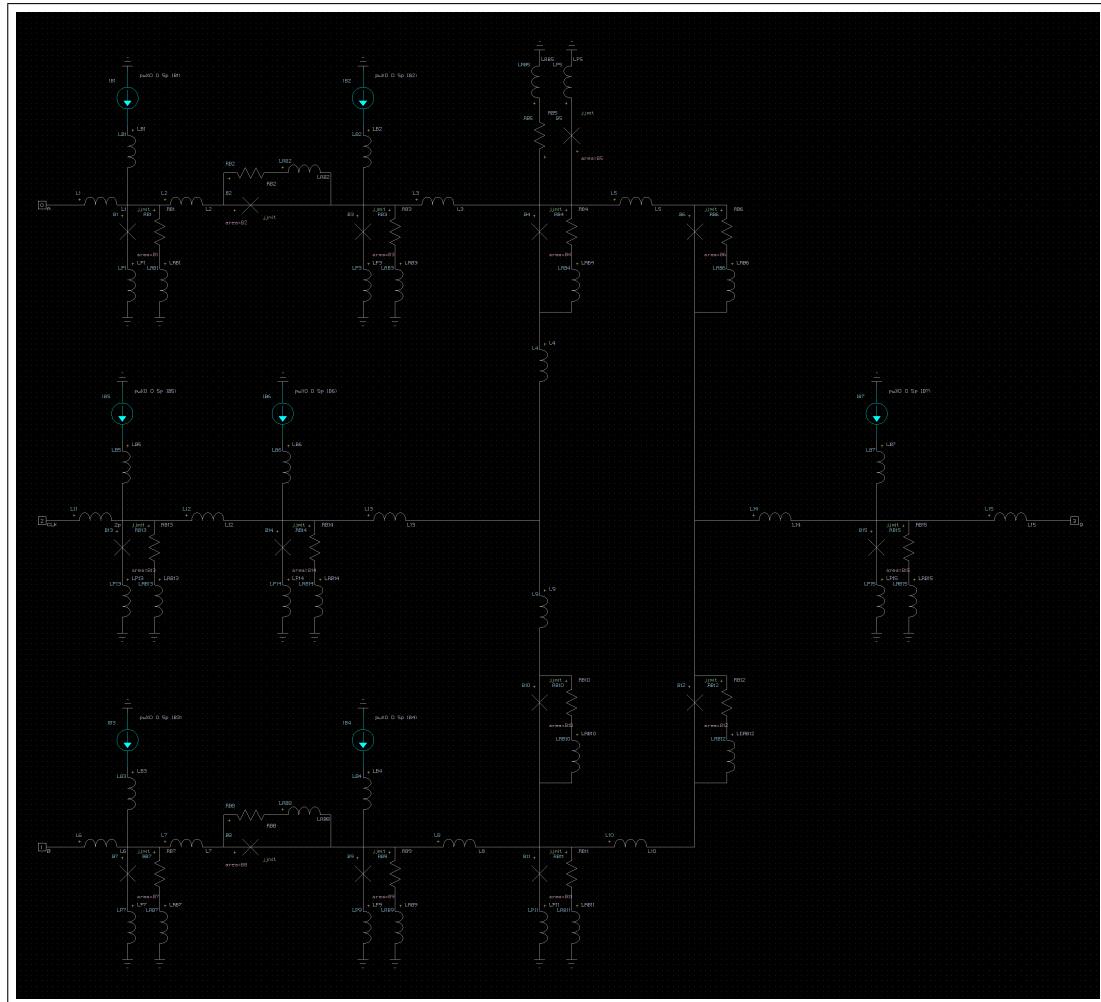
Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	910	0.52
2	910	1.03
5	910	2.58
10	910	5.17
20	910	10.3
50	910	25.8

## 2.2 Logic Cells

### 2.2.1 AND2

The RSFQ AND2 cell generates an output pulse if pulses from both input signal lines were received before the clock signal. The cell is not designed to be directly connected to a PTL.

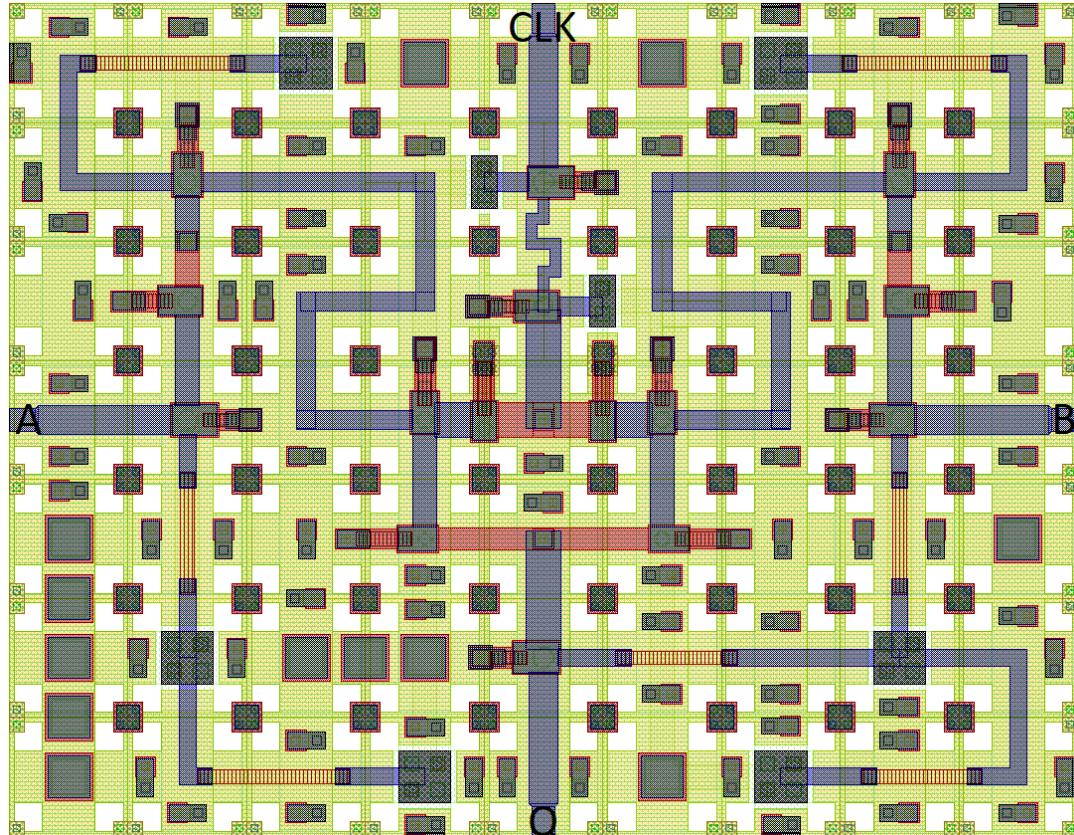
#### Schematic



**Figure 2.22:** Schematic of RSFQ AND2.

## Layout

The physical layout for the RSFQ AND2 is shown in Fig. 2.23. The layout height is  $70 \mu\text{m}$  and the width is  $90 \mu\text{m}$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.23:** RSFQ AND2 Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param L10=L5
2  	↳ by InductEx v.6.0.4 on 25-3-21.        65  .param L11=Phi0/(4*IC*Ic0)
3  * Author: L. Schindler                      66  .param L12=Phi0/(2*B13*Ic0)
4  * Version: 2.1                               67  .param L13=1p
5  * Last modification date: 7 January 2021    68  .param L14=1p
6  * Last modification by: L. Schindler        69  .param L15=Phi0/(4*IC*Ic0)
7
8 *$Ports a b clk q
9 .subckt LSMITLL_AND2 a b clk q
10 .model jjmit jj(rtype=1, vg=2.8mV, cap
11   ↳ =0.07pF, r0=160, rn=16, icrit=0.1mA
12   ↳ )
13 .param Phi0=2.067833848E-15
14 .param B0=1
15 .param Ic0=0.0001
16 .param IcRs=100u*6.859904418
17 .param B0Rs=IcRs/Ic0*B0
18 .param Rsheet=2
19 .param Lsheet=1.13e-12
20 .param LP=0.2p
21 .param IC=2.5
22 .param Lptl=2p
23 .param LB=2p
24 .param BiasCoef=0.7
25 .param B1=IC
26 .param B2=2.01
27 .param B3=1.91
28 .param B4=1.26
29 .param B5=1.57
30 .param B6=1.19
31 .param B7=B1
32 .param B8=B2
33 .param B9=B3
34 .param B10=B4
35 .param B11=B5
36 .param B12=B6
37 .param B13=IC
38 .param B14=2.06
39 .param B15=IC
40 .param IB1=BiasCoef*Ic0*B1
41 .param IB2=123u
42 .param IB3=IB1
43 .param IB4=IB2
44 .param IB5=BiasCoef*Ic0*B13
45 .param IB6=133u
46 .param IB7=BiasCoef*Ic0*B15
47 .param LB1=LB
48 .param LB2=LB
49 .param LB3=LB
50 .param LB4=LB
51 .param LB5=LB
52 .param LB6=LB
53 .param LB7=LB
54 .param L1=Phi0/(4*IC*Ic0)
55 .param L2=Phi0/(2*B1*Ic0)
56 .param L3=Phi0/(B3*Ic0)
57 .param L4=1p
58 .param L5=Phi0/(2*B5*Ic0)
59 .param L6=L1
60 .param L7=L2
61 .param L8=L3
62 .param L9=L4
63
64  .param L10=L5
65  .param L11=Phi0/(4*IC*Ic0)
66  .param L12=Phi0/(2*B13*Ic0)
67  .param L13=1p
68  .param L14=1p
69  .param L15=Phi0/(4*IC*Ic0)
70
71  .param LP1=LP
72  .param LP3=LP
73  .param LP5=LP
74  .param LP7=LP
75  .param LP9=LP
76  .param LP11=LP
77  .param LP13=LP
78  .param LP14=LP
79  .param LP15=LP
80
81  .param RB1=B0Rs/B1
82  .param RB2=B0Rs/B2
83  .param RB3=B0Rs/B3
84  .param RB4=B0Rs/B4
85  .param RB5=B0Rs/B5
86  .param RB6=B0Rs/B6
87  .param RB7=B0Rs/B7
88  .param RB8=B0Rs/B8
89  .param RB9=B0Rs/B9
90  .param RB10=B0Rs/B10
91  .param RB11=B0Rs/B11
92  .param RB12=B0Rs/B12
93  .param RB13=B0Rs/B13
94  .param RB14=B0Rs/B14
95  .param RB15=B0Rs/B15
96  .param LRB1=(RB1/Rsheet)*Lsheet
97  .param LRB2=(RB2/Rsheet)*Lsheet
98  .param LRB3=(RB3/Rsheet)*Lsheet
99  .param LRB4=(RB4/Rsheet)*Lsheet
100 .param LRB5=(RB5/Rsheet)*Lsheet
101 .param LRB6=(RB6/Rsheet)*Lsheet
102 .param LRB7=(RB7/Rsheet)*Lsheet
103 .param LRB8=(RB8/Rsheet)*Lsheet
104 .param LRB9=(RB9/Rsheet)*Lsheet
105 .param LRB10=(RB10/Rsheet)*Lsheet
106 .param LRB11=(RB11/Rsheet)*Lsheet
107 .param LRB12=(RB12/Rsheet)*Lsheet
108 .param LRB13=(RB13/Rsheet)*Lsheet
109 .param LRB14=(RB14/Rsheet)*Lsheet
110 .param LRB15=(RB15/Rsheet)*Lsheet
111
112 B1 1 2 jjmit area=B1
113 B2 4 5 jjmit area=B2
114 B3 5 6 jjmit area=B3
115 B4 8 9 jjmit area=B4
116 B5 8 11 jjmit area=B5
117 B6 12 13 jjmit area=B6
118 B7 14 15 jjmit area=B7
119 B8 17 18 jjmit area=B8
120 B9 18 19 jjmit area=B9
121 B10 21 22 jjmit area=B10
122 B11 21 23 jjmit area=B11
123 B12 24 13 jjmit area=B12
124 B13 25 26 jjmit area=B13
125 B14 31 32 jjmit area=B14
126 B15 28 29 jjmit area=B15
127
128 IB1 0 3 pwl(0 0 5p IB1)
129 IB2 0 7 pwl(0 0 5p IB2)

```

```

130 | IB3 0 16 pwl(0 0 5p IB3)      167 | L14 13 28 1.06E-12
131 | IB4 0 20 pwl(0 0 5p IB4)      168 | L15 28 q 2.069E-12
132 | IB5 0 27 pwl(0 0 5p IB5)      169
133 | IB6 0 33 pwl(0 0 5p IB6)      170 | RB1 1 101 RB1
134 | IB7 0 30 pwl(0 0 5p IB7)      171 | LRB1 101 0 LRB1
135
136 | LB1 3 1 LB1                   172 | RB2 4 104 RB2
137 | LB2 7 5 LB2                   173 | LRB2 104 5 LRB2
138 | LB3 16 14 LB3                  174 | RB3 5 105 RB3
139 | LB4 20 18 LB4                  175 | LRB3 105 0 LRB3
140 | LB5 27 25 LB5                  176 | RB4 8 109 RB4
141 | LB6 30 28 LB6                  177 | LRB4 109 9 LRB4
142 | LB7 33 31 LB7                  178 | RB5 8 108 RB5
143
144 | LP1 2 0 4.864E-13             179 | LRB5 108 0 LRB5
145 | LP3 6 0 5.474E-13             180 | RB6 12 112 RB6
146 | LP5 11 0 5.279E-13            181 | LRB6 112 13 LRB6
147 | LP7 15 0 4.901E-13            182 | RB7 14 114 RB7
148 | LP9 19 0 5.414E-13            183 | LRB7 114 0 LRB7
149 | LP11 23 0 5.306E-13           184 | RB8 17 117 RB8
150 | LP13 26 0 5.084E-13           185 | LRB8 117 18 LRB8
151 | LP14 32 0 5.329E-13           186 | RB9 18 118 RB9
152 | LP15 29 0 4.92E-13            187 | LRB9 118 0 LRB9
153
154 | L1 a 1 2.075E-12              188 | RB10 21 122 RB10
155 | L2 1 4 2.812E-12              189 | LRB10 122 22 LRB10
156 | L3 5 8 9.756E-12              190 | RB11 21 121 RB11
157 | L4 9 10 1.079E-12             191 | LRB11 121 0 LRB11
158 | L5 8 12 3.105E-12             192 | RB12 24 124 RB12
159 | L6 b 14 2.073E-12             193 | LRB12 124 13 LRB12
160 | L7 14 17 2.811E-12             194 | RB13 25 125 RB13
161 | L8 18 21 9.768E-12             195 | LRB13 125 0 LRB13
162 | L9 22 10 1.084E-12             196 | RB14 31 131 RB14
163 | L10 21 24 3.095E-12            197 | LRB14 131 0 LRB14
164 | L11 clk 25 2.063E-12            198 | RB15 28 128 RB15
165 | L12 25 31 2.96E-12             199 | LRB15 128 0 LRB15
166 | L13 31 10 1.002E-12            200 .ends

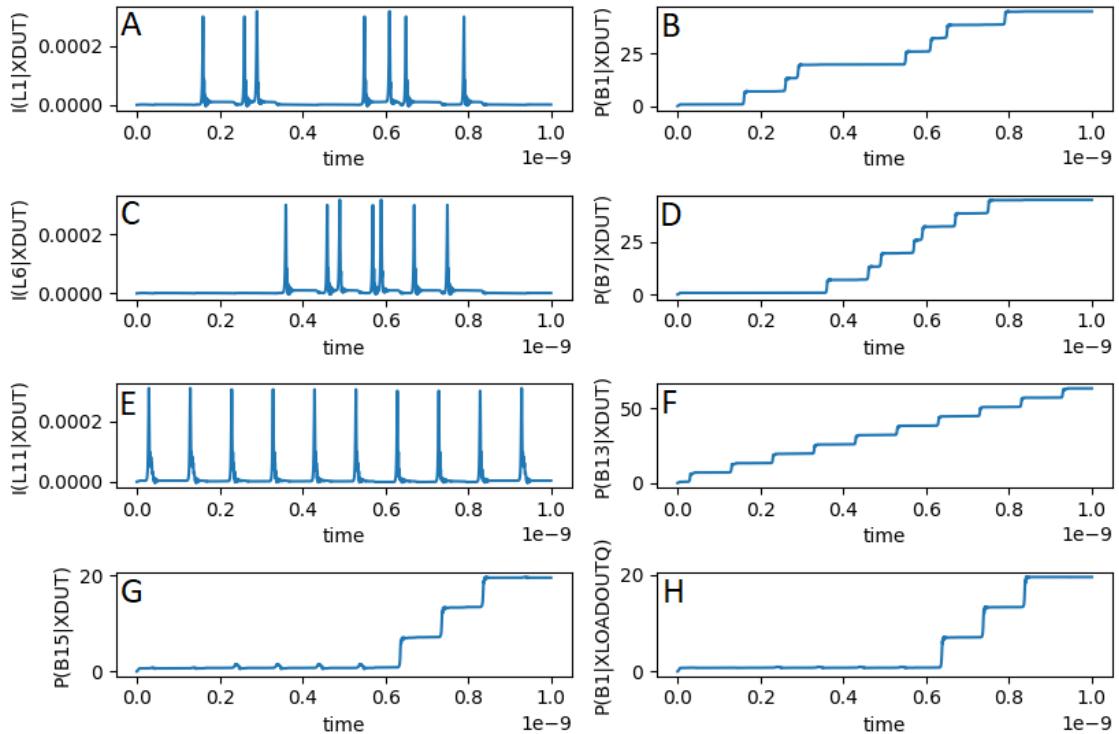
```

**Listing 2.15:** RSFQ AND2 JoSIM netlist.**Table 2.15:** RSFQ AND2 pin list.

Pin	Description
<b>a</b>	Data input
<b>b</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ AND2 using JoSIM is shown in Fig. 2.24. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 2.24:** RSFQ AND2 analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 2 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 'timescale 1ps/100fs
16 module LSmitll_AND2 (a, b, clk, q);
17
18 input
19   a, b, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state3_clk_q = 7.0,
29   ct_state0_clk_a = 2.2,
30   ct_state0_clk_b = 2.2,
31   ct_state1_clk_a = 1.6,
32   ct_state1_clk_b = 1.8,
33   ct_state2_clk_a = 1.8,
34   ct_state2_clk_b = 1.6,
35   ct_state3_clk_a = 0.7,
36   ct_state3_clk_b = 0.7;
37
38 reg
39   errorsignal_a,
40   errorsignal_b,
41   errorsignal_clk;
42
43 integer
44   outfile,
45   cell_state; // internal state of the cell
46
47 initial
48 begin
49   errorsignal_a = 0;
50   errorsignal_b = 0;
51   errorsignal_clk = 0;
52   cell_state = 0; // Startup state
53   q = 0; // All outputs start at 0
54 end
55
56 always @ (posedge a or negedge a) // execute at positive and negative edges of input
57 begin
58   if ($time > 4) // arbitrary steady-state time)
59   begin
60     if (errorsignal_a == 1'b1) // A critical timing is active for this input
61     begin
62       outfile = $fopen("errors.txt", "a");
63       $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
64       ↪ ", $stime);
65       $fclose(outfile);
66       q <= 1'bX; // Set all outputs to unknown
67     end

```

```

67         if (errorsignal_a == 0)
68             begin
69                 case (cell_state)
70                     0: begin
71                         cell_state = 1; // Blocking statement -- immediately
72                     end
73                     1: begin
74                         end
75                     2: begin
76                         cell_state = 3; // Blocking statement -- immediately
77                     end
78                     3: begin
79                         end
80                 endcase
81             end
82         end
83     end
84
85 always @(posedge b or negedge b) // execute at positive and negative edges of input
86 begin
87     if ($time>4) // arbitrary steady-state time)
88     begin
89         if (errorsignal_b == 1'b1) // A critical timing is active for this input
90             begin
91                 outfile = $fopen("errors.txt", "a");
92                 $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
93                             ↪ ", $stime);
94                 $fclose(outfile);
95                 q <= 1'bX; // Set all outputs to unknown
96             end
97         if (errorsignal_b == 0)
98             begin
99                 case (cell_state)
100                     0: begin
101                         cell_state = 2; // Blocking statement -- immediately
102                     end
103                     1: begin
104                         cell_state = 3; // Blocking statement -- immediately
105                     end
106                     2: begin
107                         end
108                     3: begin
109                         end
110                     endcase
111             end
112         end
113     end
114 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
115 begin
116     if ($time>4) // arbitrary steady-state time)
117     begin
118         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
119             begin
120                 outfile = $fopen("errors.txt", "a");
121                 $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
122                             ↪ ", $stime);
123                 $fclose(outfile);
124                 q <= 1'bX; // Set all outputs to unknown
125             end
126         if (errorsignal_clk == 0)
127             begin
128                 case (cell_state)
129                     0: begin
130                         errorsignal_a = 1; // Critical timing on this input; assign
131                             ↪ immediately
130                         errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
131                             ↪ after critical timing expires
131                         errorsignal_b = 1; // Critical timing on this input; assign
131                             ↪ immediately

```

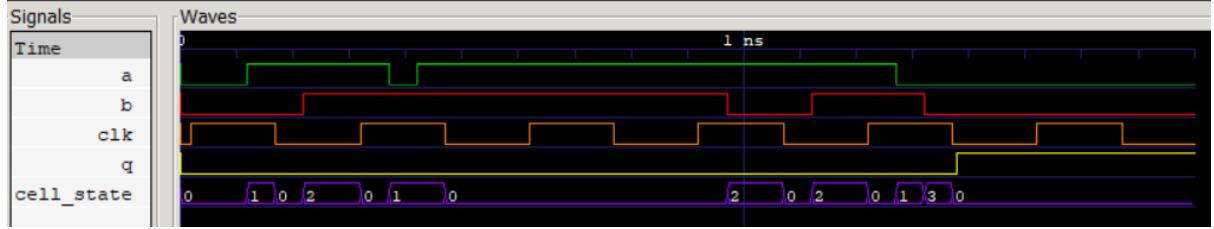
```

132           errorsignal_b <= #(ct_state0_clk_b) 0; // Clear error signal
133           // after critical timing expires
134       end
135   1: begin
136       cell_state = 0; // Blocking statement -- immediately
137       errorsignal_a = 1; // Critical timing on this input; assign
138           // immediately
139       errorsignal_a <= #(ct_state1_clk_a) 0; // Clear error signal
140           // after critical timing expires
141       errorsignal_b = 1; // Critical timing on this input; assign
142           // immediately
143       errorsignal_b <= #(ct_state1_clk_b) 0; // Clear error signal
144           // after critical timing expires
145   2: begin
146       cell_state = 0; // Blocking statement -- immediately
147       errorsignal_a = 1; // Critical timing on this input; assign
148           // immediately
149       errorsignal_a <= #(ct_state2_clk_a) 0; // Clear error signal
150           // after critical timing expires
151       errorsignal_b = 1; // Critical timing on this input; assign
152           // immediately
153       errorsignal_b <= #(ct_state2_clk_b) 0; // Clear error signal
154           // after critical timing expires
155   end
156 endcase
157 end
158 end
159
160
161 endmodule

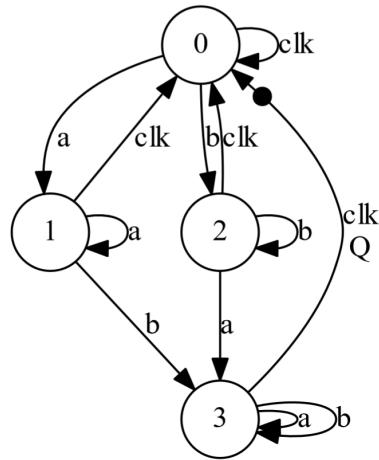
```

Listing 2.16: RSFQ AND2 verilog model.

The digital simulation results for the RSFQ AND2 is shown in Fig. 2.25 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.26.



**Figure 2.25:** RSFQ AND2 digital simulation results.



**Figure 2.26:** RSFQ AND2 Mealy finite state machine diagram.

## Power Consumption

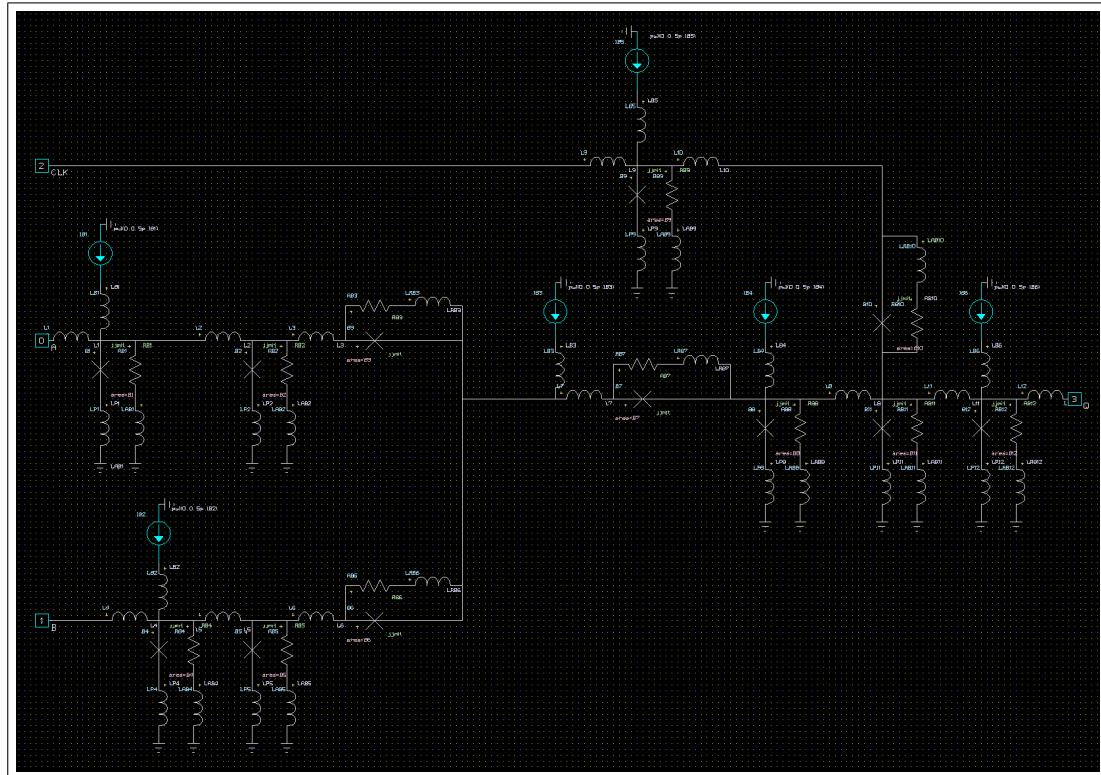
**Table 2.16:** RSFQ AND2 power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2805	5.78
2	2805	11.6
5	2805	28.9
10	2805	57.8
20	2805	116
50	2805	289

## 2.2.2 OR2

The RSFQ OR2 cell generates an output pulse if an input pulse from either input lines was received before the clock signal. The OR2 cell is not designed to be directly connected to a PTL.

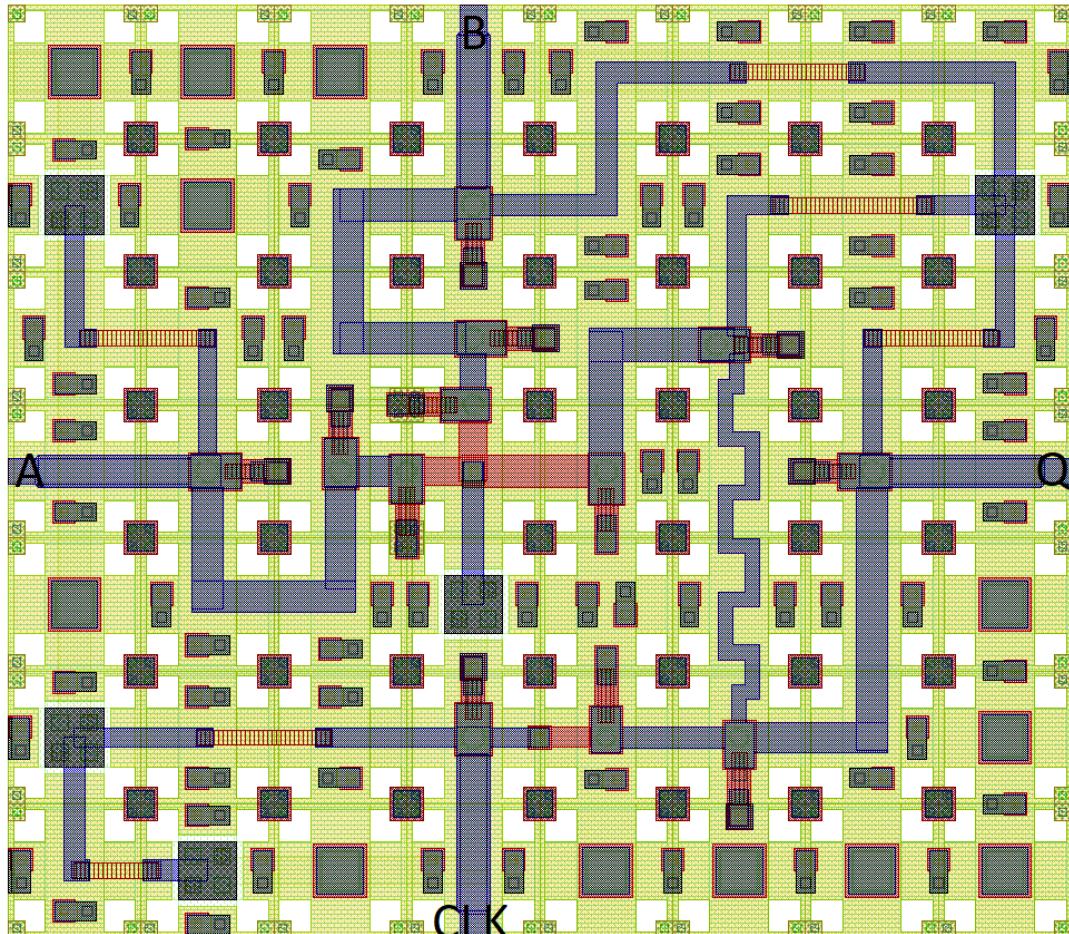
### Schematic



**Figure 2.27:** Schematic of RSFQ OR2.

## Layout

The physical layout for the RSFQ OR2 is shown in Fig. 2.28. The layout height is  $70 \mu\text{m}$  and the width is  $80 \mu\text{m}$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.28:** RSFQ OR2 Layout

## Analog model

```

1  * Back-annotated simulation file written      64  .param RB9=B0Rs/B9
2   ↪ by InductEx v.6.0.4 on 29-3-21.          65  .param RB10=B0Rs/B10
3  * Author: L. Schindler                      66  .param RB11=B0Rs/B11
4  * Version: 2.1                               67  .param RB12=B0Rs/B12
5  * Last modification date: 3 June 2021       68  .param LRB1=(RB1/Rsheet)*Lsheet+LP
6  * Last modification by: L. Schindler        69  .param LRB2=(RB2/Rsheet)*Lsheet+LP
7  *$Ports a b clk q                         70  .param LRB3=(RB3/Rsheet)*Lsheet+LP
8  .SUBCKT LSMITLL_OR2 a b clk q             71  .param LRB4=(RB4/Rsheet)*Lsheet+LP
9   .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param LRB5=(RB5/Rsheet)*Lsheet+LP
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA     73  .param LRB6=(RB6/Rsheet)*Lsheet+LP
   ↪ )                                         74  .param LRB7=(RB7/Rsheet)*Lsheet+LP
10 .param Phi0=2.067833848E-15                75  .param LRB8=(RB8/Rsheet)*Lsheet+LP
11 .param B0=1                                 76  .param LRB9=(RB9/Rsheet)*Lsheet+LP
12 .param Ic0=0.0001                           77  .param LRB10=(RB10/Rsheet)*Lsheet+LP
13 .param IcRs=100u*6.859904418               78  .param LRB11=(RB11/Rsheet)*Lsheet+LP
14 .param B0Rs=IcRs/Ic0*B0                   79  .param LRB12=(RB12/Rsheet)*Lsheet+LP
15 .param Rsheet=2                            80
16 .param Lsheet=1.13e-12                     81 L1 a 1 2.051E-12
17 .param LP=0.2p                            82 L2 1 4 3.232E-12
18 .param IC=2.5                            83 L3 4 6 1.198E-12
19 .param Lptl=2p                           84 L4 b 8 2.046E-12
20 .param LB=2p                             85 L5 8 11 3.242E-12
21 .param BiasCoef=0.7                      86 L6 11 13 1.191E-12
22                               87 L7 7 15 3.341E-12
23 .param B1=2.5                            88 L8 16 19 7.998E-12
24 .param B2=2.22                           89 L9 clk 20 2.062E-12
25 .param B3=1.86                           90 L10 20 23 3.408E-12
26 .param B4=B1                            91 L11 19 25 3.54E-12
27 .param B5=B2                            92 L12 25 q 2.05E-12
28 .param B6=B3                            93
29 .param B7=2.28                           94 B1 1 2 jjmit area=B1
30 .param B8=2.09                           95 B2 4 5 jjmit area=B2
31 .param B9=2.5                            96 B3 6 7 jjmit area=B3
32 .param B10=1.52                           97 B4 8 9 jjmit area=B4
33 .param B11=1.60                           98 B5 11 12 jjmit area=B5
34 .param B12=2.5                           99 B6 13 7 jjmit area=B6
35                               100 B7 15 16 jjmit area=B7
36 .param IB1=175u                           101 B8 16 17 jjmit area=B8
37 .param IB2=IB1                           102 B9 20 21 jjmit area=B9
38 .param IB3=304u                           103 B10 23 19 jjmit area=B10
39 .param IB4=142u                           104 B11 19 24 jjmit area=B11
40 .param IB5=175u                           105 B12 25 26 jjmit area=B12
41 .param IB6=175u                           106
42                               107 IB1 0 3 pw1(0 0 5p IB1)
43 .param L1=Phi0/(4*IC*Ic0)                 108 IB2 0 10 pw1(0 0 5p IB2)
44 .param L2=Phi0/(2*B1*Ic0)                 109 IB3 0 14 pw1(0 0 5p IB3)
45 .param L3=1p                             110 IB4 0 18 pw1(0 0 5p IB4)
46 .param L4=L1                            111 IB5 0 22 pw1(0 0 5p IB5)
47 .param L5=L2                            112 IB6 0 27 pw1(0 0 5p IB6)
48 .param L6=L3                           113
49 .param L7=Phi0/(2*B2*Ic0)                 114 LB1 1 3 LB
50 .param L8=Phi0/(B8*Ic0)                  115 LB2 8 10 LB
51 .param L9=Phi0/(4*IC*Ic0)                 116 LB3 7 14 LB
52 .param L10=Phi0/(2*B9*Ic0)                117 LB4 16 18 LB
53 .param L11=Phi0/(2*B11*Ic0)               118 LB5 20 22 LB
54 .param L12=Phi0/(4*IC*Ic0)                 119 LB6 25 27 LB
55                               120
56 .param RB1=B0Rs/B1                      121 LP1 2 0 5.253E-13
57 .param RB2=B0Rs/B2                      122 LP2 5 0 5.141E-13
58 .param RB3=B0Rs/B3                      123 LP4 9 0 5.352E-13
59 .param RB4=B0Rs/B4                      124 LP5 12 0 5.154E-13
60 .param RB5=B0Rs/B5                      125 LP8 17 0 4.905E-13
61 .param RB6=B0Rs/B6                      126 LP9 21 0 5.216E-13
62 .param RB7=B0Rs/B7                      127 LP11 24 0 5.649E-13
63 .param RB8=B0Rs/B8                      128 LP12 26 0 5.28E-13
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
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```

```

130 | RB1 1 101 RB1
131 | LRB1 101 0 LRB1
132 | RB2 4 104 RB2
133 | LRB2 104 0 LRB2
134 | RB3 6 105 RB3
135 | LRB3 105 7 LRB3
136 | RB4 8 108 RB4
137 | LRB4 108 0 LRB4
138 | RB5 11 111 RB5
139 | LRB5 111 0 LRB5
140 | RB6 13 113 RB6
141 | LRB6 113 7 LRB6
142 | RB7 15 115 RB7
143 | LRB7 115 16 LRB7
144 | RB8 16 116 RB8
145 | LRB8 116 0 LRB8
146 | RB9 20 120 RB9
147 | LRB9 120 0 LRB9
148 | RB10 23 123 RB10
149 | LRB10 123 19 LRB10
150 | RB11 19 119 RB11
151 | LRB11 119 0 LRB11
152 | RB12 25 125 RB12
153 | LRB12 125 0 LRB12
154 | .ends

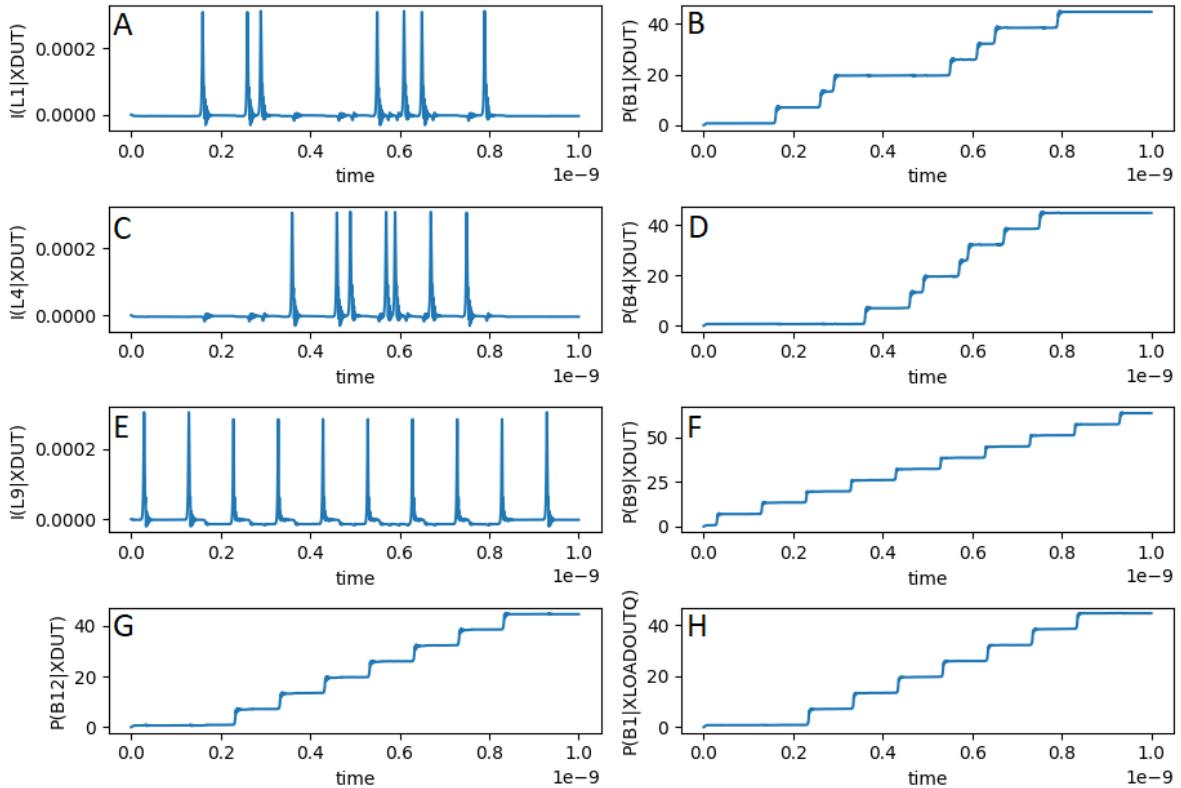
```

**Listing 2.17:** RSFQ OR2 JoSIM netlist.**Table 2.17:** RSFQ OR2 pin list.

Pin	Description
a	Data input
b	Data input
clk	Clock input
q	Data output

The simulation results for the RSFQ OR2 using JoSIM is shown in Fig. 2.29. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 2.29:** RSFQ OR2 analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmit11_OR2_v2p1_optimized (a, b, clk, q);
9
10 input
11     a, b, clk;
12
13 output
14     q;
15
16 reg
17     q;
18
19 real
20     delay_state1_clk_q = 5.5,
21     ct_state0_a_clk = 3.2,
22     ct_state0_b_clk = 3.2,
23     ct_state1_a_clk = 5.6,
24     ct_state1_b_clk = 5.6;
25
26 reg
27     errorsignal_a,
28     errorsignal_b,
29     errorsignal_clk;
30
31 integer
32     outfile,
33     cell_state; // internal state of the cell
34
35 initial
36 begin
37     errorsignal_a = 0;
38     errorsignal_b = 0;
39     errorsignal_clk = 0;
40     cell_state = 0; // Startup state
41     q = 0; // All outputs start at 0
42 end
43 always @ (posedge a or negedge a) // execute at positive and negative edges of input
44 begin
45     if ($time > 4) // arbitrary steady-state time
46         begin
47             if (errorsignal_a == 1'b1) // A critical timing is active for this input
48                 begin
49                     outfile = $fopen("errors.txt", "a");
50                     $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m; %0d_ps.\n"
51                                     ↪ ", $time);
52                     $fclose(outfile);
53                     q <= 1'bX; // Set all outputs to unknown
54                 end
55             if (errorsignal_a == 0)
56                 begin
57                     case (cell_state)
58                         0: begin
59                             cell_state = 1; // Blocking statement -- immediately
60                             errorsignal_clk = 1; // Critical timing on this input; assign
61                                     ↪ immediately
62                             errorsignal_clk <= #(ct_state0_a_clk) 0; // Clear error signal
63                                     ↪ after critical timing expires
64                         end
65                     1: begin
66                         errorsignal_clk = 1; // Critical timing on this input; assign
67                                     ↪ immediately

```

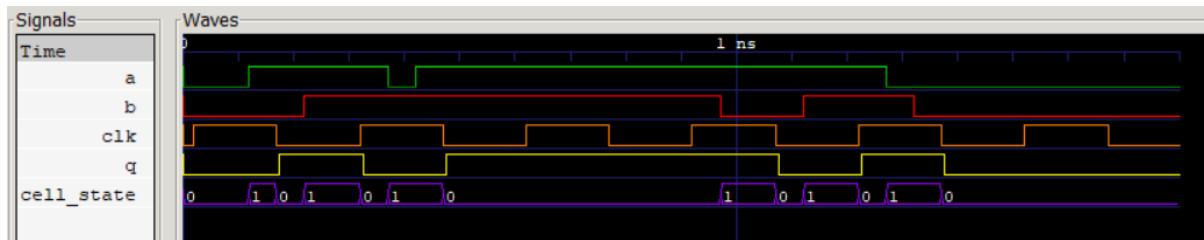
```

64           errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
65           // after critical timing expires
66       end
67   endcase
68 end
69
70
71 always @(posedge b or negedge b) // execute at positive and negative edges of input
72 begin
73     if ($time>4) // arbitrary steady-state time)
74     begin
75         if (errorsignal_b == 1'b1) // A critical timing is active for this input
76         begin
77             outfile = $fopen("errors.txt", "a");
78             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n
79             ", $stime);
80             $fclose(outfile);
81             q <= 1'bX; // Set all outputs to unknown
82         end
83         if (errorsignal_b == 0)
84         begin
85             case (cell_state)
86             0: begin
87                 cell_state = 1; // Blocking statement -- immediately
88                 errorsignal_clk = 1; // Critical timing on this input; assign
89                 // immediately
90                 errorsignal_clk <= #(ct_state0_b_clk) 0; // Clear error signal
91                 // after critical timing expires
92             end
93             1: begin
94                 errorsignal_clk = 1; // Critical timing on this input; assign
95                 // immediately
96                 errorsignal_clk <= #(ct_state1_b_clk) 0; // Clear error signal
97                 // after critical timing expires
98             end
99         endcase
100    end
101
102 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
103 begin
104     if ($time>4) // arbitrary steady-state time)
105     begin
106         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
107         begin
108             outfile = $fopen("errors.txt", "a");
109             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n
110             ", $stime);
111             $fclose(outfile);
112             q <= 1'bX; // Set all outputs to unknown
113         end
114         if (errorsignal_clk == 0)
115         begin
116             case (cell_state)
117             0: begin
118                 end
119             1: begin
120                 q <= #(delay_state1_clk_q) !q;
121                 cell_state = 0; // Blocking statement -- immediately
122             end
123         endcase
124     end
125 end
126
127 endmodule

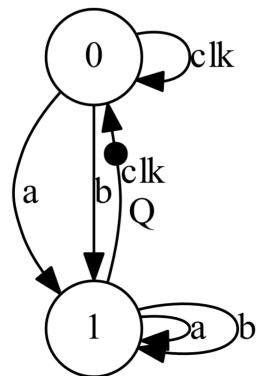
```

Listing 2.18: RSFQ OR2 verilog model.

The digital simulation results for the RSFQ OR2 is shown in Fig. 2.30 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.31.



**Figure 2.30:** RSFQ OR2 digital simulation results.



**Figure 2.31:** RSFQ OR2 Mealy finite state machine diagram.

## Power Consumption

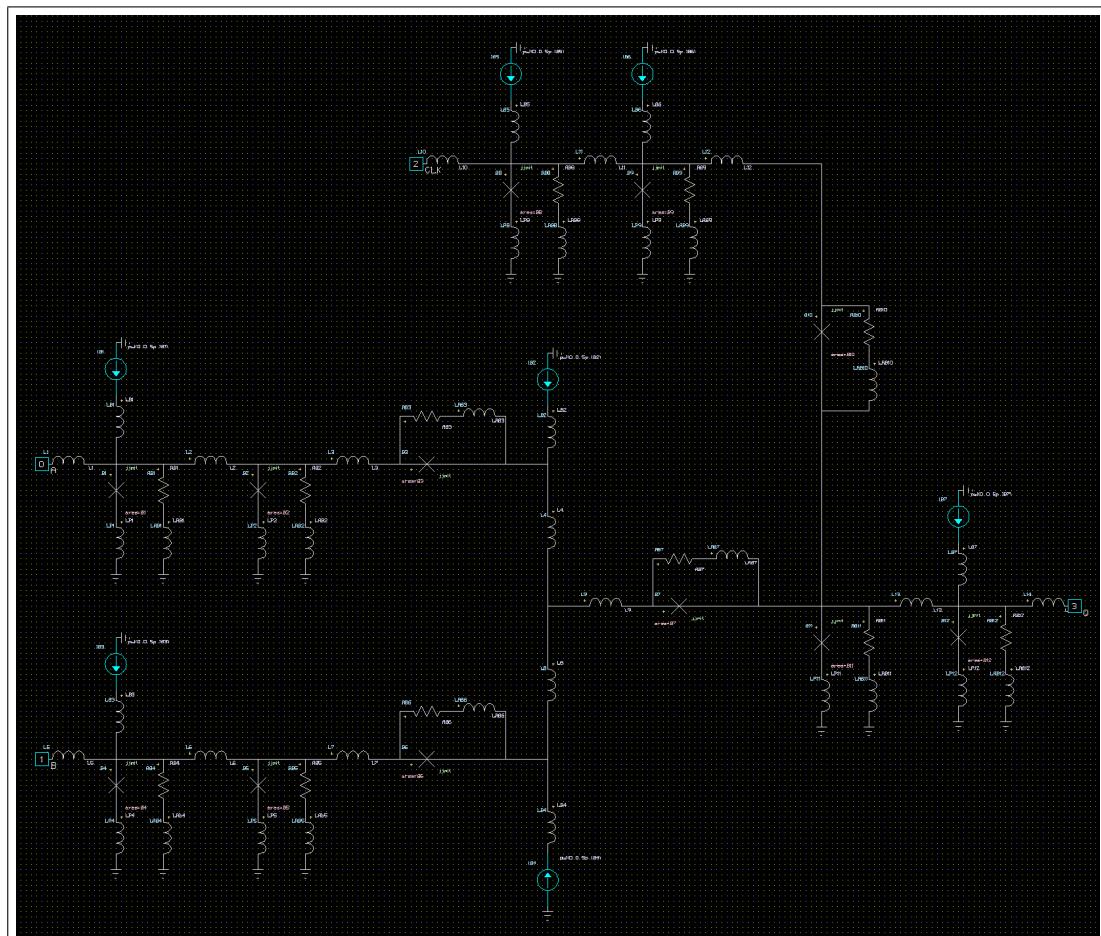
**Table 2.18:** RSFQ OR2 power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2980	5.30
2	2980	10.6
5	2980	26.5
10	2980	53.0
20	2980	106
50	2980	265

### 2.2.3 XOR

The RSFQ XOR cell generates an output pulse exclusively if a pulse from a single input line was received before the clock signal. The XOR cell is not designed to be directly connected to a PTL.

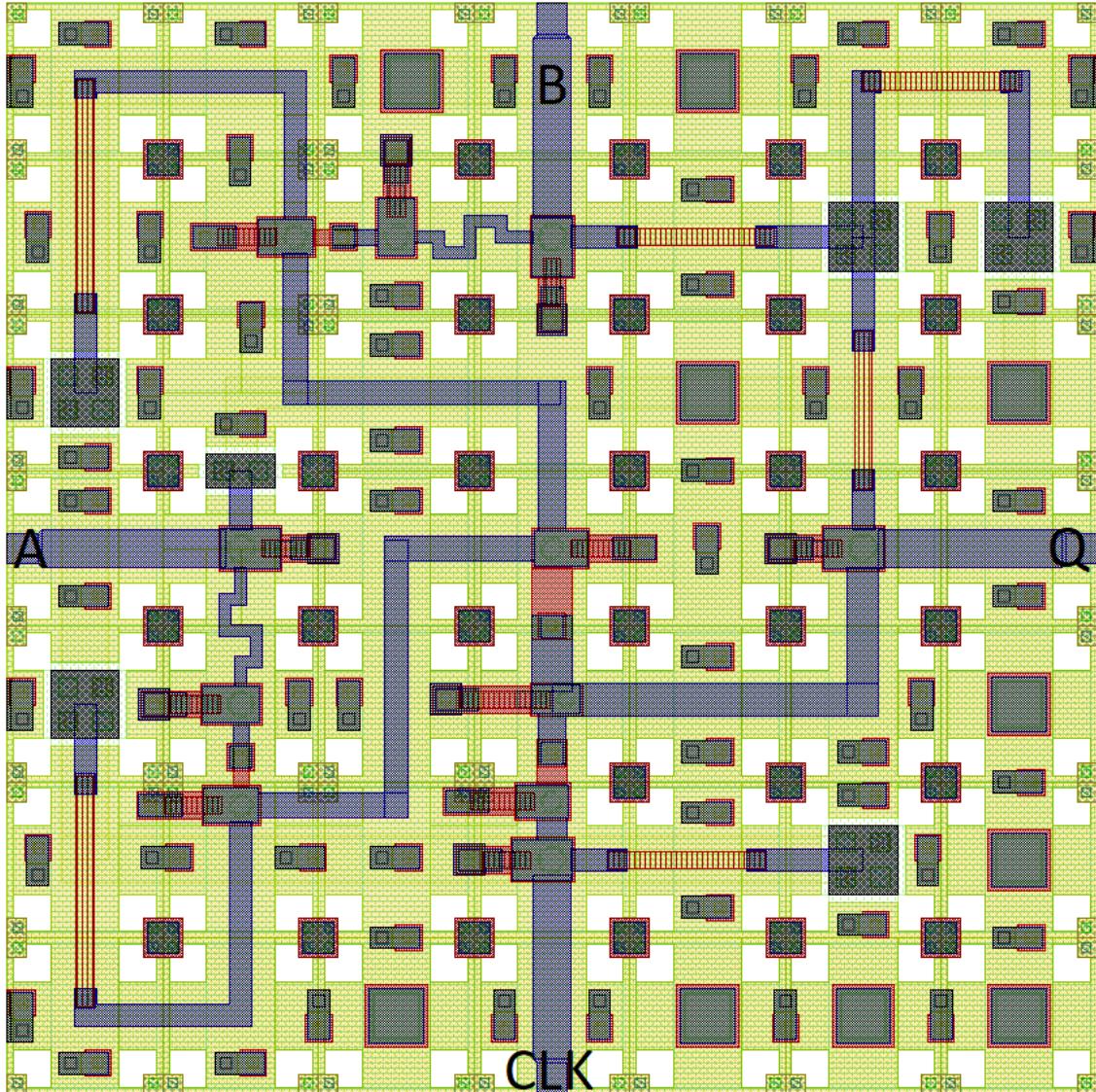
#### Schematic



**Figure 2.32:** Schematic of RSFQ XOR.

## Layout

The physical layout for the RSFQ XOR is shown in Fig. 2.33. The layout height is  $70 \mu\text{m}$  and the width is  $70 \mu\text{m}$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.33:** RSFQ XOR Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param LRB3=(RB3/Rsheet)*Lsheet+LP
2   ↪ by InductEx v.6.0.4 on 1-4-21.          65  .param LRB4=(RB4/Rsheet)*Lsheet+LP
3  * Author: L. Schindler                     66  .param LRB5=(RB5/Rsheet)*Lsheet+LP
4  * Version: 2.1                            67  .param LRB6=(RB6/Rsheet)*Lsheet+LP
5  * Last modification date: 4 June 2021     68  .param LRB7=(RB7/Rsheet)*Lsheet+LP
6  * Last modification by: L. Schindler       69  .param LRB8=(RB8/Rsheet)*Lsheet+LP
7  *$Ports a b clk q                      70  .param LRB9=(RB9/Rsheet)*Lsheet+LP
8  .subckt LSmitll_XOR      a b clk q        71  .param LRB10=(RB10/Rsheet)*Lsheet+LP
9  .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param LRB11=(RB11/Rsheet)*Lsheet+LP
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    73  B1 1 2 jjmit area=B1
   ↪ )                                         74  B2 4 5 jjmit area=B2
10 .param Phi0=2.067833848E-15                75  B3 25 6 jjmit area=B3
11 .param B0=1                                76  B4 9 10 jjmit area=B4
12 .param Ic0=0.0001                           77  B5 12 13 jjmit area=B5
13 .param IcRs=100u*6.859904418               78  B6 26 14 jjmit area=B6
14 .param B0Rs=IcRs/Ic0*B0                   79  B7 27 16 jjmit area=B7
15 .param Rsheet=2                            80  B8 17 18 jjmit area=B8
16 .param Lsheet=1.13e-12                     81  B9 20 16 jjmit area=B9
17 .param LP=0.5p                            82  B10 16 21 jjmit area=B10
18 .param IC=2.5                             83  B11 22 23 jjmit area=B11
19 .param LB=2p                             84  IB1 0 3 pwl(0 0 5p IB1)
20 .param BiasCoef=0.70                     85  IB2 0 7 pwl(0 0 5p IB2)
21 .param B1=2.5                            86  IB3 0 11 pwl(0 0 5p IB3)
22 .param B2=2.09                           87  IB4 0 15 pwl(0 0 5p IB4)
23 .param B3=1.71                           88  IB5 0 19 pwl(0 0 5p IB5)
24 .param B4=B1                            89  IB6 0 24 pwl(0 0 5p IB6)
25 .param B5=B2                            90  LB1 3 1 LB
26 .param B6=B3                            91  LB2 7 6 LB
27 .param B7=1.62                           92  LB3 11 9 LB
28 .param B8=2.5                            93  LB4 15 14 LB
29 .param B9=1.45                           94  LB5 19 17 LB
30 .param B10=0.89                          95  LB6 24 22 LB
31 .param B11=2.5                           96  L1 a 1 2.06E-12
32 .param IB1=175u                           97  L2 1 4 3.233E-12
33 .param IB2=112u                           98  L3 4 25 1.419E-12
34 .param IB3=IB1                           99  L4 6 8 6.051E-12
35 .param IB4=IB2                           100 L5 b 9 2.092E-12
36 .param IB5=175u                           101 L6 9 12 3.221E-12
37 .param IB6=175u                           102 L7 12 26 1.384E-12
38 .param L1=Phi0/(4*IC*Ic0)                 103 L8 14 8 6.059E-12
39 .param L2=Phi0/(2*B1*Ic0)                 104 L9 8 27 1.301E-12
40 .param L3=1.2p                            105 L10 clk 17 2.082E-12
41 .param L4=Phi0/(B2*Ic0)                  106 L11 17 20 1.43E-12
42 .param L5=L1                            107 L12 16 22 3.892E-12
43 .param L6=L2                            108 L13 22 q 2.077E-12
44 .param L7=L3                            109 LP1 2 0 5.508E-13
45 .param L8=L4                            110 LP2 5 0 4.769E-13
46 .param L9=1.2p                           111 LP4 10 0 4.767E-13
47 .param L10=Phi0/(4*IC*Ic0)                112 LP5 13 0 4.812E-13
48 .param L11=Phi0/(2*B8*Ic0)                113 LP8 18 0 4.526E-13
49 .param L12=Phi0/(2*B10*Ic0)               114 LP10 21 0 5.69E-13
50 .param L13=Phi0/(4*IC*Ic0)                115 LP11 23 0 4.746E-13
51 .param RB1=B0Rs/B1                      116 RB1 1 101 RB1
52 .param RB2=B0Rs/B2                      117 LRB1 101 0 LRB1
53 .param RB3=B0Rs/B3                      118 RB2 4 104 RB2
54 .param RB4=B0Rs/B4                      119 LRB2 104 0 LRB2
55 .param RB5=B0Rs/B5                      120 RB3 4 106 RB3
56 .param RB6=B0Rs/B6                      121 LRB3 106 6 LRB3
57 .param RB7=B0Rs/B7                      122 RB4 9 109 RB4
58 .param RB8=B0Rs/B8                      123 LRB4 109 0 LRB4
59 .param RB9=B0Rs/B9                      124 RB5 12 112 RB5
60 .param RB10=B0Rs/B10                     125 LRB5 112 0 LRB5
61 .param RB11=B0Rs/B11                     126 RB6 12 114 RB6
62 .param LRB1=(RB1/Rsheet)*Lsheet+LP      127 LRB6 114 14 LRB6
63 .param LRB2=(RB2/Rsheet)*Lsheet+LP      128 RB7 8 108 RB7
                                         129 LRB7 108 16 LRB7

```

```

130 | RB8 17 117 RB8
131 | LRB8 117 0 LRB8
132 | RB9 20 120 RB9
133 | LRB9 120 16 LRB9
134 | RB10 16 116 RB10
135 | LRB10 116 0 LRB10
136 | RB11 22 122 RB11
137 | LRB11 122 0 LRB11
138 | .ends

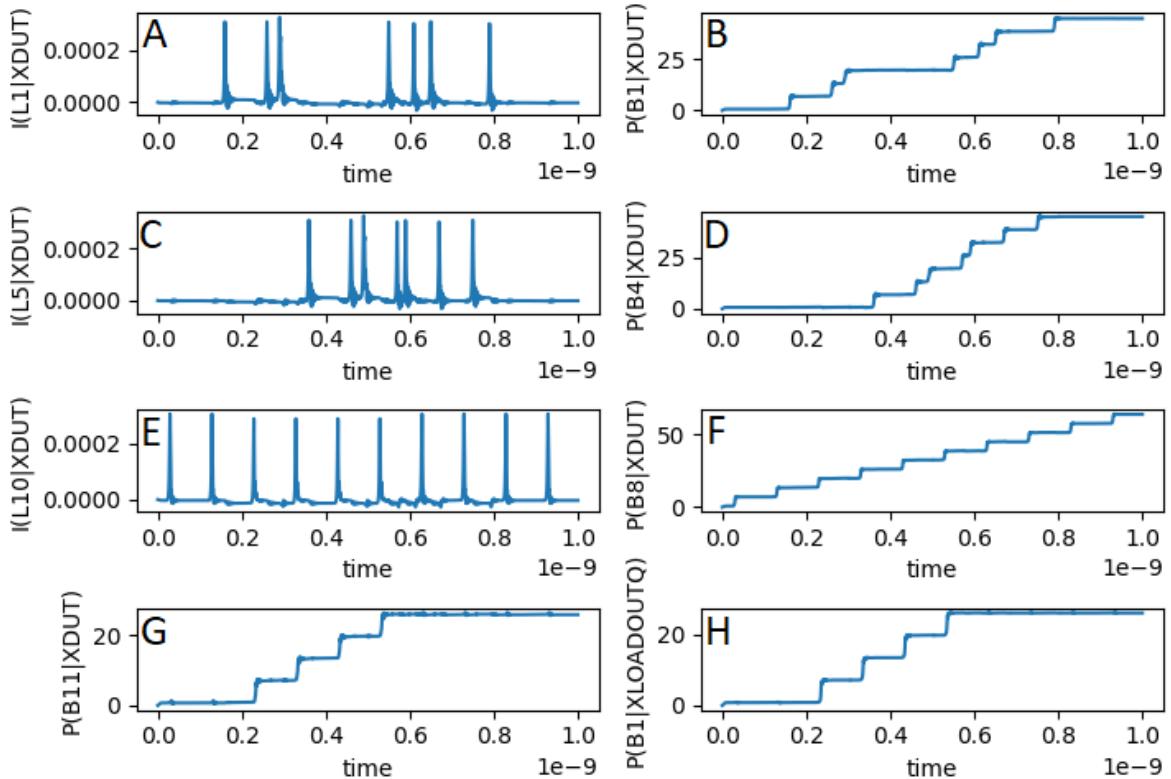
```

**Listing 2.19:** RSFQ XOR JoSIM netlist.**Table 2.19:** RSFQ XOR pin list.

<b>Pin</b>	<b>Description</b>
<b>a</b>	Data input
<b>b</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ XOR using JoSIM is shown in Fig. 2.34. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 2.34:** RSFQ XOR analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 4 June 2021
5 // Last modification by: L. Schindler
6 // -----
7
8 // -----
9 // Automatically extracted verilog file, created with TimEx v2.05
10 // Timing description and structural design for IARPA-BAA-14-03 via
11 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
12 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
13 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
14 // (c) 2016-2018 Stellenbosch University
15 // -----
16 `timescale 1ps/100fs
17 module LSmitll_XOR_v2p1_optimized (a, b, clk, q);
18
19 input
20   a, b, clk;
21
22 output
23   q;
24
25 reg
26   q;
27
28 real
29   delay_state1_clk_q = 5.8,
30   delay_state2_clk_q = 5.8,
31   ct_state0_a_clk = 0.2,
32   ct_state1_a_b = 8.0,
33   ct_state1_a_clk = 8.1,
34   ct_state1_b_b = 3.5,
35   ct_state1_clk_b = 4.3,
36   ct_state2_a_a = 3.5,
37   ct_state2_b_a = 7.9,
38   ct_state2_b_clk = 7.9,
39   ct_state2_clk_a = 4.4;
40
41 reg
42   errorsignal_a,
43   errorsignal_b,
44   errorsignal_clk;
45
46 integer
47   outfile,
48   cell_state; // internal state of the cell
49
50 initial
51 begin
52   errorsignal_a = 0;
53   errorsignal_b = 0;
54   errorsignal_clk = 0;
55   cell_state = 0; // Startup state
56   q = 0; // All outputs start at 0
57 end
58
59 always @ (posedge a or negedge a) // execute at positive and negative edges of input
60 begin
61   if ($time>4) // arbitrary steady-state time)
62     begin
63       if (errorsignal_a == 1'b1) // A critical timing is active for this input
64         begin
65           outfile = $fopen("errors.txt", "a");
66           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
67             , $stime);

```

```

67          $fclose(outfile);
68          q <= 1'bX; // Set all outputs to unknown
69      end
70      if (errorsignal_a == 0)
71      begin
72          case (cell_state)
73              0: begin
74                  cell_state = 1; // Blocking statement -- immediately
75                  errorsignal_clk = 1; // Critical timing on this input; assign
76                      // immediately
77                  errorsignal_clk <= #(ct_state0_a_clk) 0; // Clear error signal
78                      // after critical timing expires
79              end
80              1: begin
81                  errorsignal_b = 1; // Critical timing on this input; assign
82                      // immediately
83                  errorsignal_b <= #(ct_state1_a_b) 0; // Clear error signal
84                      // after critical timing expires
85                  errorsignal_clk = 1; // Critical timing on this input; assign
86                      // immediately
87                  errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
88                      // after critical timing expires
89              end
90          endcase
91      end
92  end
93
94 always @ (posedge b or negedge b) // execute at positive and negative edges of input
95 begin
96     if ($time>4) // arbitrary steady-state time)
97     begin
98         if (errorsignal_b == 1'b1) // A critical timing is active for this input
99         begin
100             outfile = $fopen("errors.txt", "a");
101             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
102                         // ", $stime);
103             $fclose(outfile);
104             q <= 1'bX; // Set all outputs to unknown
105         end
106         if (errorsignal_b == 0)
107         begin
108             case (cell_state)
109                 0: begin
110                     cell_state = 2; // Blocking statement -- immediately
111                 end
112                 1: begin
113                     cell_state = 0; // Blocking statement -- immediately
114                     errorsignal_b = 1; // Critical timing on this input; assign
115                         // immediately
116                     errorsignal_b <= #(ct_state1_b_b) 0; // Clear error signal
117                         // after critical timing expires
118                 end
119                 2: begin
120                     errorsignal_a = 1; // Critical timing on this input; assign
121                         // immediately
122                     errorsignal_a <= #(ct_state2_b_a) 0; // Clear error signal
123                         // after critical timing expires
124                     errorsignal_clk = 1; // Critical timing on this input; assign
125                         // immediately
126                     errorsignal_clk <= #(ct_state2_b_clk) 0; // Clear error signal
127                         // after critical timing expires
128                 end
129             endcase
130         end
131     end
132 
```

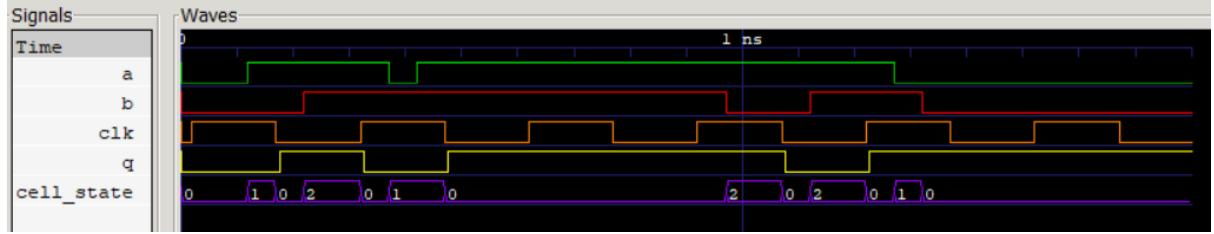
```

122           endcase
123       end
124   end
125
126
127 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
128 begin
129     if ($time>4) // arbitrary steady-state time)
130 begin
131     if (errorsignal_clk == 1'b1) // A critical timing is active for this input
132 begin
133         outfile = $fopen("errors.txt", "a");
134         $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
135             ↪ ", $stime);
136         $fclose(outfile);
137         q <= 1'bX; // Set all outputs to unknown
138     end
139     if (errorsignal_clk == 0)
140     begin
141         case (cell_state)
142             0: begin
143                 end
144             1: begin
145                 q <= #(delay_state1_clk_q) !q;
146                 cell_state = 0; // Blocking statement -- immediately
147                 errorsignal_b = 1; // Critical timing on this input; assign
148                     ↪ immediately
149                 errorsignal_b <= #(ct_state1_clk_b) 0; // Clear error signal
150                     ↪ after critical timing expires
151             end
152             2: begin
153                 q <= #(delay_state2_clk_q) !q;
154                 cell_state = 0; // Blocking statement -- immediately
155                 errorsignal_a = 1; // Critical timing on this input; assign
156                     ↪ immediately
157                 errorsignal_a <= #(ct_state2_clk_a) 0; // Clear error signal
158                     ↪ after critical timing expires
159             end
160         endcase
161     end
162 end
163
164 endmodule

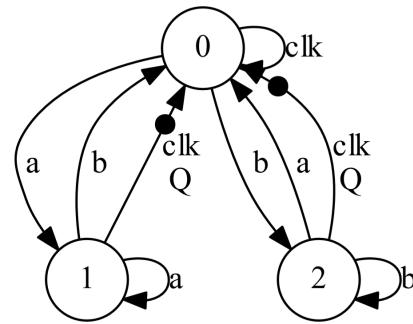
```

Listing 2.20: RSFQ XOR verilog model.

The digital simulation results for the RSFQ XOR is shown in Fig. 2.35 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.36.



**Figure 2.35:** RSFQ XOR digital simulation results.



**Figure 2.36:** RSFQ XOR Mealy finite state machine diagram.

## Power Consumption

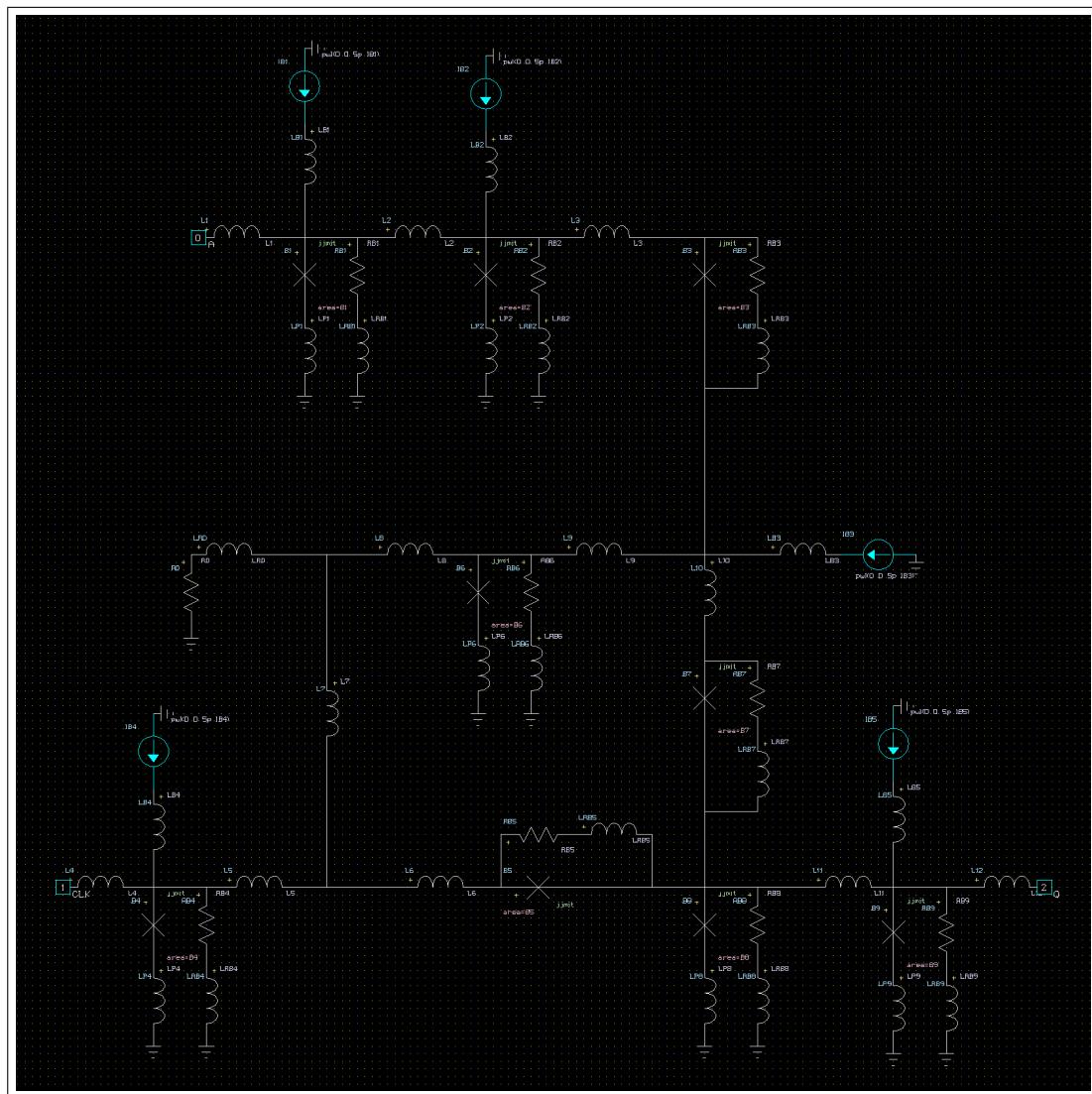
**Table 2.20:** RSFQ XOR power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2402	4.64
2	2402	9.29
5	2402	23.2
10	2402	46.4
20	2402	92.9
50	2402	232

## 2.2.4 NOT

The RSFQ NOT cell is a signal inverting cell driven by a clock pulse signal line. The NOT cell is not designed to be directly connected to a PTL.

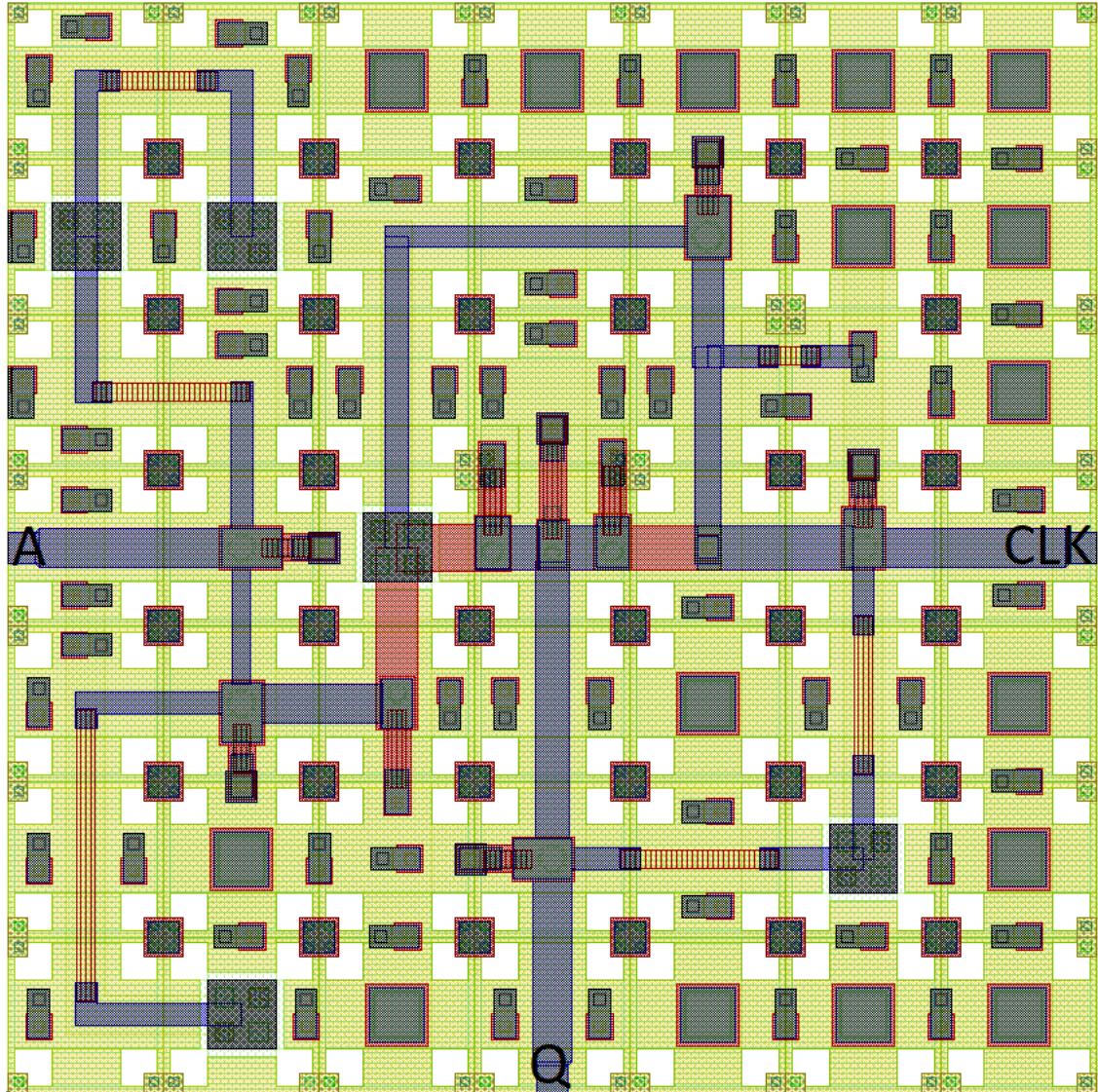
### Schematic



**Figure 2.37:** Schematic of RSFQ NOT.

## Layout

The physical layout for the RSFQ NOT is shown in Fig. 2.38. The layout height is  $70 \mu\text{m}$  and the width is  $70 \mu\text{m}$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.38:** RSFQ NOT Layout.

## Analog model

```

1  * Back-annotated simulation file written      65 | .param LRD=2p
2   ↪ by InductEx v.6.0.4 on 8-4-21.          66 | B1 1 2 jjmit area=B1
3  * Author: L. Schindler                     67 | B2 4 5 jjmit area=B2
4  * Version: 2.1                            68 | B3 7 8 jjmit area=B3
5  * Last modification date: 3 June 2021     69 | B4 13 14 jjmit area=B4
6  * Last modification by: L. Schindler       70 | B5 17 18 jjmit area=B5
7  *$Ports a clk q                         71 | B6 10 11 jjmit area=B6
8 .subckt LSMITLL_NOT a clk q             72 | B7 20 18 jjmit area=B7
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    73 | B8 18 19 jjmit area=B8
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    74 | B9 21 22 jjmit area=B9
   ↪ )                                         75 |
10 .param Phi0=2.067833848E-15            76 |
11 .param B0=1                           77 | IB1 0 3 pwl(0 0 5p IB1)
12 .param Ic0=0.0001                     78 | IB2 0 6 pwl(0 0 5p IB2)
13 .param IcRs=100u*6.859904418        79 | IB3 0 9 pwl(0 0 5p IB3)
14 .param B0Rs=IcRs/Ic0*B0              80 | IB4 0 15 pwl(0 0 5p IB4)
15 .param Rsheet=2                      81 | IB5 0 23 pwl(0 0 5p IB5)
16 .param Lsheet=1.13e-12                82 |
17 .param LP=0.2p                       83 | LB1 3 1 LB1
18 .param IC=2.5                        84 | LB2 6 4 LB2
19 .param LB=2p                         85 | LB3 8 9 LB3
20 .param BiasCoef=0.7                 86 | LB4 13 15 LB4
21                                         87 | LB5 21 23 LB5
22 .param B1=IC                         88 |
23 .param B2=2.57                       89 | L1 a 1 2.062E-12
24 .param B3=1.07                       90 | L2 1 4 1.889E-12
25 .param B4=IC                         91 | L3 4 7 2.72E-12
26 .param B5=1.34                       92 | L4 clk 13 2.057E-12
27 .param B6=3.03                       93 | L5 13 16 1.029E-12
28 .param B7=1.38                       94 | L6 16 17 1.241E-12
29 .param B8=0.8                         95 | L7 16 12 1.973E-12
30 .param B9=IC                         96 | L8 10 12 1.003E-12
31                                         97 | L9 10 8 7.524E-12
32 .param IB1=BiasCoef*Ic0*B1          98 | L10 8 20 1.234E-12
33 .param IB2=87u                       99 | L11 18 21 2.607E-12
34 .param IB3=257u                      100 | L12 21 q 2.062E-12
35 .param IB4=BiasCoef*Ic0*B4          101 |
36 .param IB5=BiasCoef*Ic0*B9          102 | LP1 2 0 5.271E-13
37                                         103 | LP2 5 0 5.237E-13
38 .param LB1=LB                         104 | LP4 14 0 4.759E-13
39 .param LB2=LB                         105 | LP6 11 0 5.021E-13
40 .param LB3=LB                         106 | LP8 19 0 6.33E-13
41 .param LB4=LB                         107 | LP9 22 0 4.749E-13
42 .param LB5=LB                         108 |
43                                         109 | RB1 1 101 RB1
44 .param RB1=B0Rs/B1                  110 | LRB1 101 0 LRB1
45 .param RB2=B0Rs/B2                  111 | RB2 4 104 RB2
46 .param RB3=B0Rs/B3                  112 | LRB2 104 5 LRB2
47 .param RB4=B0Rs/B4                  113 | RB3 7 107 RB3
48 .param RB5=B0Rs/B5                  114 | LRB3 107 8 LRB3
49 .param RB6=B0Rs/B6                  115 | RB4 13 113 RB4
50 .param RB7=B0Rs/B7                  116 | LRB4 113 0 LRB4
51 .param RB8=B0Rs/B8                  117 | RB5 17 117 RB5
52 .param RB9=B0Rs/B9                  118 | LRB5 117 18 LRB5
53                                         119 | RB6 10 110 RB6
54 .param LRB1=(RB1/Rsheet)*Lsheet     120 | LRB6 110 0 LRB6
55 .param LRB2=(RB2/Rsheet)*Lsheet     121 | RB7 20 120 RB7
56 .param LRB3=(RB3/Rsheet)*Lsheet     122 | LRB7 120 18 LRB7
57 .param LRB4=(RB4/Rsheet)*Lsheet     123 | RB8 18 118 RB8
58 .param LRB5=(RB5/Rsheet)*Lsheet     124 | LRB8 118 0 LRB8
59 .param LRB6=(RB6/Rsheet)*Lsheet     125 | RB9 21 121 RB9
60 .param LRB7=(RB7/Rsheet)*Lsheet     126 | LRB9 121 0 LRB9
61 .param LRB8=(RB8/Rsheet)*Lsheet     127 | LRD 12 112 LRD
62 .param LRB9=(RB9/Rsheet)*Lsheet     128 | RD 112 0 RD
63                                         129 | .ends
64 .param RD=4

```

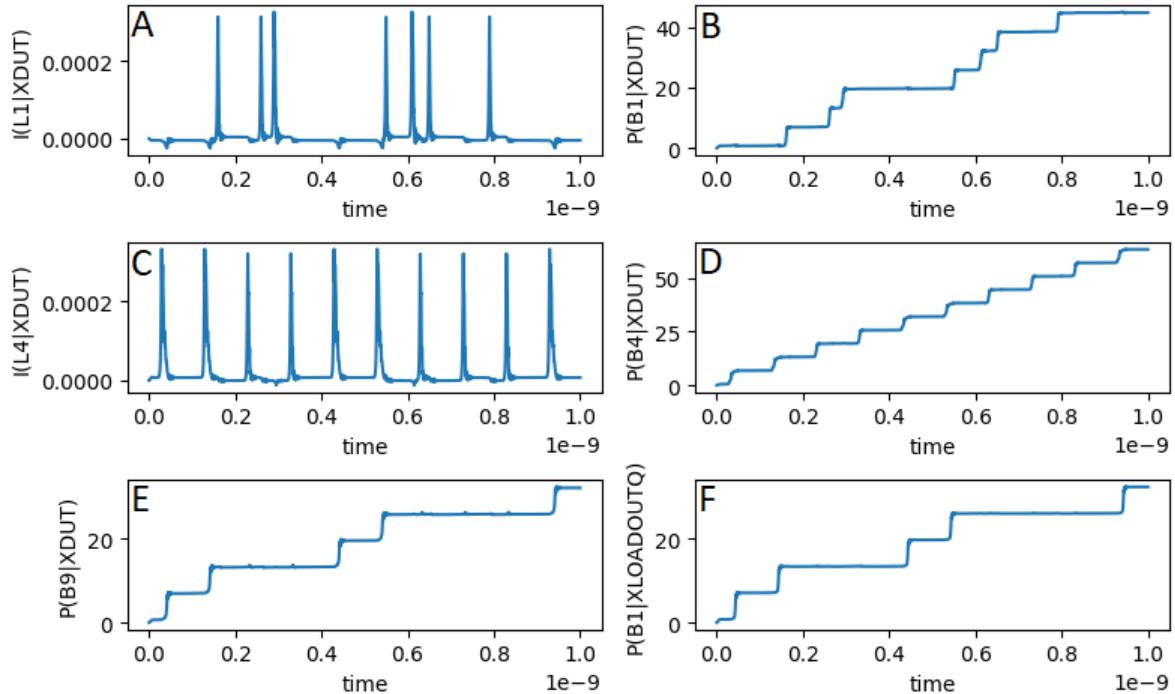
**Listing 2.21:** RSFQ NOT JoSIM netlist.

**Table 2.21:** RSFQ NOT pin list.

Pin	Description
<b>a</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ NOT using JoSIM is shown in Fig. 2.39. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **clk**,
- (d) the phase over the input JJ of pin **clk**,
- (e) the phase over the output JJ of pin **q**, and
- (f) the phase over the input JJ of the load circuit connected to pin **q**.

**Figure 2.39:** RSFQ NOT analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 8 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 `timescale 1ps/100fs
16 module LSmitll_NOT_v2p1_optimized (a, clk, q);
17
18 input
19   a, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state0_clk_q = 10.8,
29   ct_state0_a_clk = 2.6,
30   ct_state0_clk_a = 8.4,
31   ct_state0_clk_clk = 12.8,
32   ct_state1_a_clk = 4.2;
33
34 reg
35   errorsignal_a,
36   errorsignal_clk;
37
38 integer
39   outfile,
40   cell_state; // internal state of the cell
41
42 initial
43 begin
44   errorsignal_a = 0;
45   errorsignal_clk = 0;
46   cell_state = 0; // Startup state
47   q = 0; // All outputs start at 0
48 end
49
50 always @ (posedge a or negedge a) // execute at positive and negative edges of input
51 begin
52   if ($time > 4) // arbitrary steady-state time)
53     begin
54       if (errorsignal_a == 1'b1) // A critical timing is active for this input
55         begin
56           outfile = $fopen("errors.txt", "a");
57           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
58           ↪ ", $stime);
59           $fclose(outfile);
60           q <= 1'bX; // Set all outputs to unknown
61         end
62       if (errorsignal_a == 0)
63         begin
64           case (cell_state)
65             0: begin
66               cell_state = 1; // Blocking statement -- immediately
67               errorsignal_clk = 1; // Critical timing on this input; assign

```

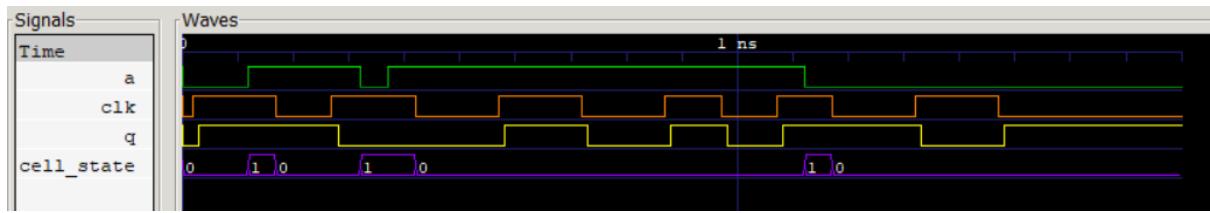
```

67           → immediately
68           errorsignal_clk <= #(ct_state0_a_clk) 0; // Clear error signal
69           → after critical timing expires
70       end
71   1: begin
72       errorsignal_clk = 1; // Critical timing on this input; assign
73           → immediately
74       errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
75           → after critical timing expires
76   end
77 endcase
78 end
79
80 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
81 begin
82     if ($time>4) // arbitrary steady-state time)
83     begin
84         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
85         begin
86             outfile = $fopen("errors.txt", "a");
87             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
88             → ", $time);
89             $fclose(outfile);
90             q <= 1'bX; // Set all outputs to unknown
91         end
92         if (errorsignal_clk == 0)
93         begin
94             case (cell_state)
95             0: begin
96                 q <= #(delay_state0_clk_q) !q;
97                 errorsignal_a = 1; // Critical timing on this input; assign
98                 → immediately
99                 errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
100                → after critical timing expires
101                errorsignal_clk = 1; // Critical timing on this input; assign
102                → immediately
103                errorsignal_clk <= #(ct_state0_clk_clk) 0; // Clear error
104                → signal after critical timing expires
105            end
106        end
107    endmodule

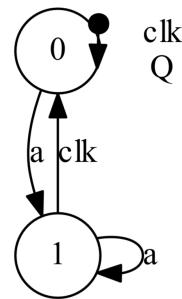
```

Listing 2.22: RSFQ NOT verilog model.

The digital simulation results for the RSFQ NOT is shown in Fig. 2.40 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.41.



**Figure 2.40:** RSFQ NOT digital simulation results.



**Figure 2.41:** RSFQ NOT Mealy finite state machine diagram.

## Power Consumption

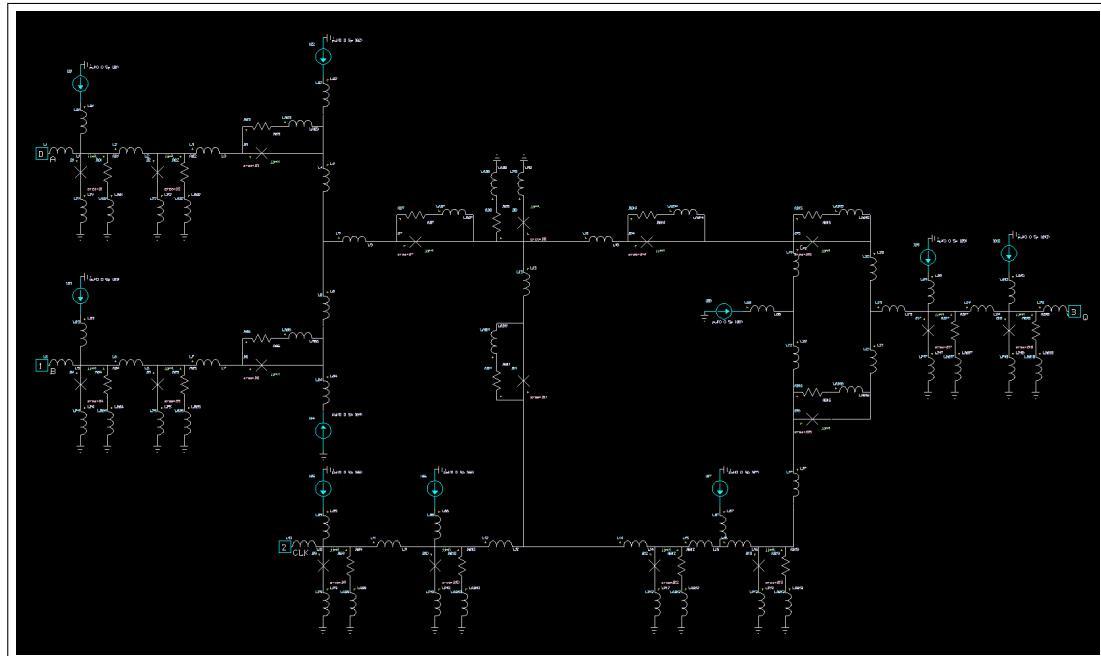
**Table 2.22:** RSFQ NOT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2259	3.66
2	2259	7.32
5	2259	18.3
10	2259	36.6
20	2259	73.2
50	2259	183

## 2.2.5 XNOR

The RSFQ XNOR cell is a combination of a NOT and XOR cell. It generates an output pulse exclusively if no input pulse was received or if a pulse from both input lines was received before the clock signal. The XNOR cell is not designed to be directly connected to a PTL.

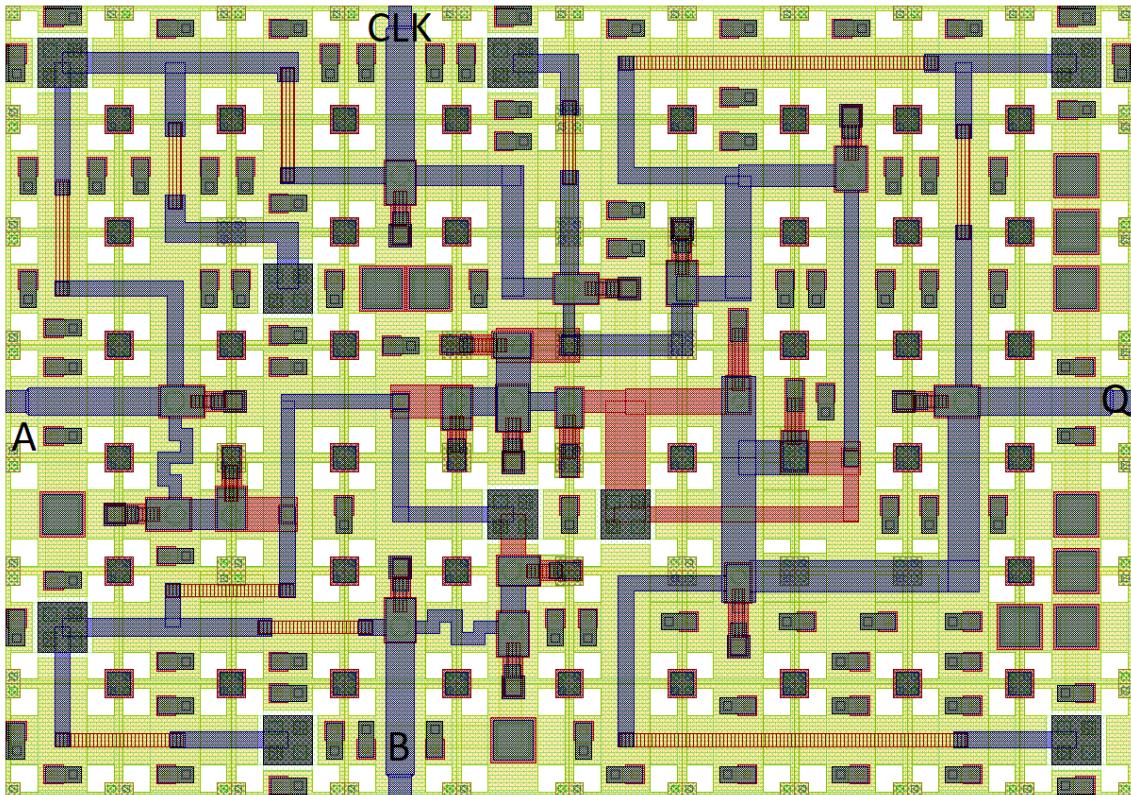
### Schematic



**Figure 2.42:** Schematic of RSFQ XNOR.

## Layout

The physical layout for the RSFQ XNOR is shown in Fig. 2.43. The layout height is  $70 \mu m$  and the width is  $100 \mu m$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.43:** RSFQ XNOR Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param L12=1p
2   ↪ by InductEx v.6.0.4 on 16-4-21.          65  .param L13=1p
3  * Author: L. Schindler                      66  .param L14=Phi0/(2*B10*Ic0)
4  * Version: 2.1                               67  .param L15=Phi0/(4*B12*Ic0)
5  * Last modification date: 3 June 2021       68  .param L16=Phi0/(4*B12*Ic0)
6  * Last modification by: L. Schindler        69  .param L17=Phi0/(B13*Ic0)
7  *$Ports a b clk q                         70  .param L18=1p
8 .subckt LSMITLL_XNOR a b clk q            71  .param L20=1p
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param L21=0.5p
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    73  .param L22=Phi0/(B16*Ic0)
   ↪ )                                         74  .param L23=Phi0/(4*B16*Ic0)
10 .param Phi0=2.067833848E-15                75  .param L24=Phi0/(2*B17*Ic0)
11 .param B0=1                                 76  .param L25=Lptl
12 .param Ic0=0.0001                           77
13 .param IcRs=100u*6.859904418               78  .param RB1=B0Rs/B1
14 .param B0Rs=IcRs/Ic0*B0                   79  .param RB2=B0Rs/B2
15 .param Rsheet=2                            80  .param RB3=B0Rs/B3
16 .param Lsheet=1.13e-12                     81  .param RB4=B0Rs/B4
17 .param LP=0.2p                             82  .param RB5=B0Rs/B5
18 .param IC=2.5                             83  .param RB6=B0Rs/B6
19 .param Lptl=2p                            84  .param RB7=B0Rs/B7
20 .param LB=2p                             85  .param RB8=B0Rs/B8
21 .param BiasCoef=0.7                       86  .param RB9=B0Rs/B9
22
23 .param B1=2.5                            87  .param RB10=B0Rs/B10
24 .param B2=2.66                           88  .param RB11=B0Rs/B11
25 .param B3=2.34                           89  .param RB12=B0Rs/B12
26 .param B4=B1                            90  .param RB13=B0Rs/B13
27 .param B5=B2                            91  .param RB14=B0Rs/B14
28 .param B6=B3                            92  .param RB15=B0Rs/B15
29 .param B7=2.31                           93  .param RB16=B0Rs/B16
30 .param B8=3.15                           94  .param RB17=B0Rs/B17
31 .param B9=2.5                            95  .param RB18=B0Rs/B18
32 .param B10=2.58                          96  .param LRB1=(RB1/Rsheet)*Lsheet
33 .param B11=1.44                          97  .param LRB2=(RB2/Rsheet)*Lsheet
34 .param B12=2.60                          98  .param LRB3=(RB3/Rsheet)*Lsheet
35 .param B13=2.71                          99  .param LRB4=(RB4/Rsheet)*Lsheet
36 .param B14=1.63                          100 .param LRB5=(RB5/Rsheet)*Lsheet
37 .param B15=0.95                          101 .param LRB6=(RB6/Rsheet)*Lsheet
38 .param B16=1.44                          102 .param LRB7=(RB7/Rsheet)*Lsheet
39 .param B17=1.40                          103 .param LRB8=(RB8/Rsheet)*Lsheet
40 .param B18=2.5                           104 .param LRB9=(RB9/Rsheet)*Lsheet
41
42 .param IB1=175E-6                         105 .param LRB10=(RB10/Rsheet)*Lsheet
43 .param IB2=153E-6                         106 .param LRB11=(RB11/Rsheet)*Lsheet
44 .param IB3=IB1                           107 .param LRB12=(RB12/Rsheet)*Lsheet
45 .param IB4=IB2                           108 .param LRB13=(RB13/Rsheet)*Lsheet
46 .param IB5=175E-6                         109 .param LRB14=(RB14/Rsheet)*Lsheet
47 .param IB6=260E-6                         110 .param LRB15=(RB15/Rsheet)*Lsheet
48 .param IB7=56E-6                          111 .param LRB16=(RB16/Rsheet)*Lsheet
49 .param IB8=248E-6                         112 .param LRB17=(RB17/Rsheet)*Lsheet
50 .param IB9=51E-6                          113 .param LRB18=(RB18/Rsheet)*Lsheet
51 .param IB10=175E-6                        114
52
53 .param L1=Lptl                           115 B1 1 2 jjmit area=B1
54 .param L2=Phi0/(2*B1*Ic0)                 116 B2 3 4 jjmit area=B2
55 .param L3=1p                            117 B3 5 6 jjmit area=B3
56 .param L4=Phi0/(B2*Ic0)                  118 B4 8 9 jjmit area=B4
57 .param L5=L1                            119 B5 10 11 jjmit area=B5
58 .param L6=L2                            120 B6 12 13 jjmit area=B6
59 .param L7=L3                            121 B7 14 15 jjmit area=B7
60 .param L8=L4                            122 B8 15 16 jjmit area=B8
61 .param L9=1p                            123 B9 17 18 jjmit area=B9
62 .param L10=Lptl                          124 B10 19 20 jjmit area=B10
63 .param L11=Phi0/(2*B9*Ic0)              125 B11 22 15 jjmit area=B11
                                         126 B12 23 24 jjmit area=B12
                                         127 B13 26 27 jjmit area=B13
                                         128 B14 29 34 jjmit area=B14
                                         129 B15 34 31 jjmit area=B15

```

```

130 | B16 28 33 jjmit area=B16
131 | B17 35 36 jjmit area=B17
132 | B18 37 38 jjmit area=B18
133 |
134 | LP1 2 0 5.29E-13
135 | LP2 4 0 4.956E-13
136 | LP4 9 0 4.424E-13
137 | LP5 11 0 5.101E-13
138 | LP8 16 0 5.051E-13
139 | LP9 18 0 5.321E-13
140 | LP10 20 0 5.07E-13
141 | LP12 24 0 5.287E-13
142 | LP13 27 0 5.393E-13
143 | LP17 36 0 5.753E-13
144 | LP18 38 0 5.361E-13
145 |
146 | IB1 0 1 pwl(0 0 5p IB1)
147 | IB2 0 6 pwl(0 0 5p IB2)
148 | IB3 0 8 pwl(0 0 5p IB3)
149 | IB4 0 13 pwl(0 0 5p IB4)
150 | IB5 0 17 pwl(0 0 5p IB5)
151 | IB6 0 19 pwl(0 0 5p IB6)
152 | IB7 0 25 pwl(0 0 5p IB7)
153 | IB8 0 34 pwl(0 0 5p IB8)
154 | IB9 0 35 pwl(0 0 5p IB9)
155 | IB10 0 37 pwl(0 0 5p IB10)
156 |
157 | L1 a 1 2.058E-12
158 | L2 1 3 2.395E-12
159 | L3 3 5 1.108E-12
160 | L4 6 7 4.1E-12
161 | L5 b 8 2.104E-12
162 | L6 8 10 2.374E-12
163 | L7 10 12 9.887E-13
164 | L8 13 7 4.048E-12
165 | L9 7 14 1.15E-12
166 | L10 clk 17 2.041E-12
167 | L11 17 19 3.442E-12
168 | L12 19 21 8.703E-13
169 | L13 21 22 1.117E-12
170 | L14 21 23 2.107E-12
171 | L15 23 25 1.641E-12
172 | L16 25 26 1.335E-12
173 | L17 26 28 5.203E-12
174 | L18 15 29 1.494E-12
175 | L20 31 32 2.081E-12

176 | L21 33 32 9.13E-13
177 | L22 34 28 6.448E-12
178 | L23 32 35 1.012E-12
179 | L24 35 37 3.546E-12
180 | L25 37 q 2.034E-12
181 |
182 | RB1 1 101 RB1
183 | LRB1 101 0 LRB1
184 | RB2 3 103 RB2
185 | LRB2 103 0 LRB2
186 | RB3 5 105 RB3
187 | LRB3 105 6 LRB3
188 | RB4 8 108 RB4
189 | LRB4 108 0 LRB4
190 | RB5 10 110 RB5
191 | LRB5 110 0 LRB5
192 | RB6 12 112 RB6
193 | LRB6 112 13 LRB6
194 | RB7 14 114 RB7
195 | LRB7 114 15 LRB7
196 | RB8 15 115 RB8
197 | LRB8 115 0 LRB8
198 | RB9 17 117 RB9
199 | LRB9 117 0 LRB9
200 | RB10 19 119 RB10
201 | LRB10 119 0 LRB10
202 | RB11 22 122 RB11
203 | LRB11 122 15 LRB11
204 | RB12 23 123 RB12
205 | LRB12 123 0 LRB12
206 | RB13 26 126 RB13
207 | LRB13 126 0 LRB13
208 | RB14 29 129 RB14
209 | LRB14 129 34 LRB14
210 | RB15 34 130 RB15
211 | LRB15 130 31 LRB15
212 | RB16 28 128 RB16
213 | LRB16 128 33 LRB16
214 | RB17 35 135 RB17
215 | LRB17 135 0 LRB17
216 | RB18 37 137 RB18
217 | LRB18 137 0 LRB18
218 | .ends

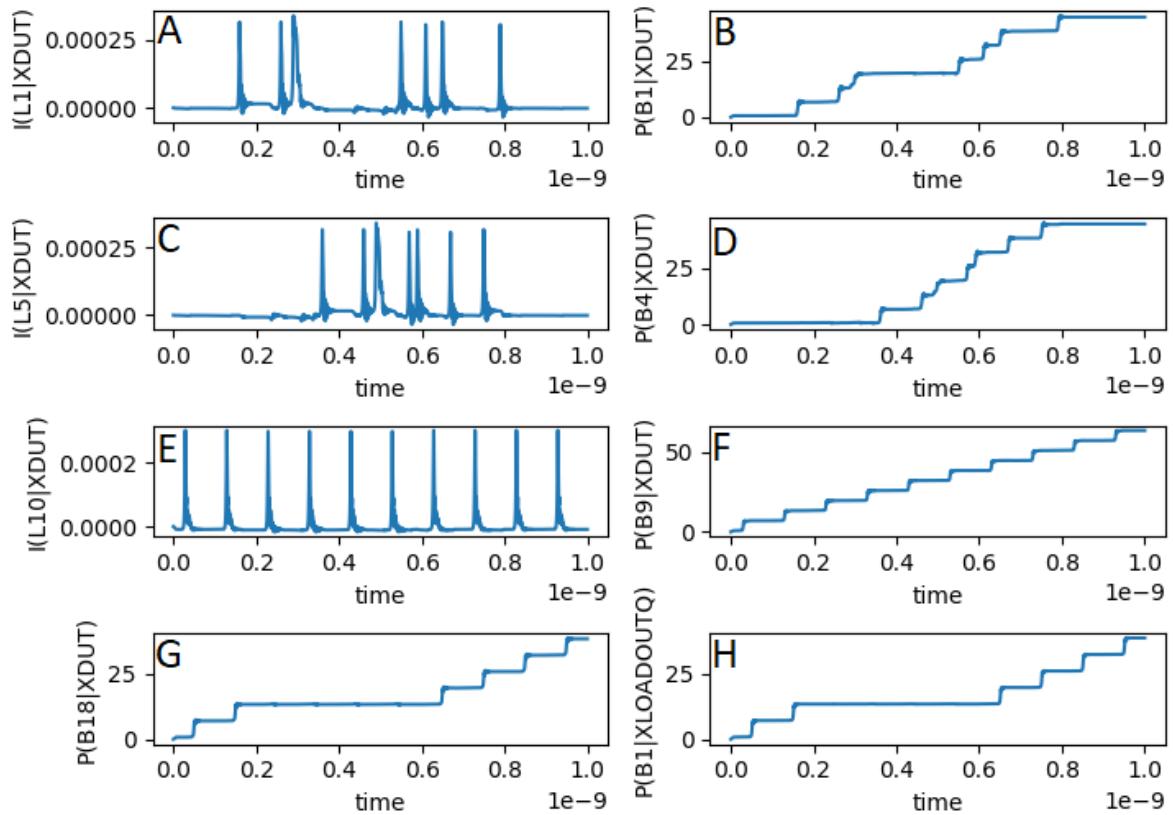
```

**Listing 2.23:** RSFQ XNOR JoSIM netlist.**Table 2.23:** RSFQ XNOR pin list.

Pin	Description
a	Data input
b	Data input
clk	Clock input
q	Data output

The simulation results for the RSFQ XNOR using JoSIM is shown in Fig. 2.44. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 2.44:** RSFQ XNOR analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 'timescale 1ps/100fs
16 module LSmitll_XNOR_v2p1_optimized (a, b, clk, q);
17
18 input
19   a, b, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state0_clk_q = 21.8,
29   ct_state0_clk_a = 6.6,
30   ct_state0_clk_b = 6.7,
31   ct_state0_clk_clk = 13.4,
32   ct_state1_b_b = 3.5,
33   ct_state1_clk_b = 8.5,
34   ct_state2_a_a = 3.4,
35   ct_state2_a_clk = 2.6,
36   ct_state2_b_a = 16.2,
37   ct_state2_b_clk = 12.9,
38   ct_state2_clk_a = 8.6;
39
40 reg
41   errorsignal_a,
42   errorsignal_b,
43   errorsignal_clk;
44
45 integer
46   outfile,
47   cell_state; // internal state of the cell
48
49 initial
50 begin
51   errorsignal_a = 0;
52   errorsignal_b = 0;
53   errorsignal_clk = 0;
54   cell_state = 0; // Startup state
55   q = 0; // All outputs start at 0
56 end
57
58 always @(posedge a or negedge a) // execute at positive and negative edges of input
59 begin
60   if ($time>4) // arbitrary steady-state time)
61     begin
62       if (errorsignal_a == 1'b1) // A critical timing is active for this input
63         begin
64           outfile = $fopen("errors.txt", "a");
65           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
66           ↪ ", $stime);
67           $fclose(outfile);

```

```

67           q <= 1'bX; // Set all outputs to unknown
68       end
69   if (errorsignal_a == 0)
70   begin
71       case (cell_state)
72       0: begin
73           cell_state = 1; // Blocking statement -- immediately
74       end
75       1: begin
76           end
77       2: begin
78           cell_state = 0; // Blocking statement -- immediately
79           errorsignal_a = 1; // Critical timing on this input; assign
80           // immediately
81           errorsignal_a <= #(ct_state2_a_a) 0; // Clear error signal
82           // after critical timing expires
83           errorsignal_clk = 1; // Critical timing on this input; assign
84           // immediately
85           errorsignal_clk <= #(ct_state2_a_clk) 0; // Clear error signal
86           // after critical timing expires
87       end
88   endcase
89 end
90
91 always @(posedge b or negedge b) // execute at positive and negative edges of input
92 begin
93     if ($time>4) // arbitrary steady-state time)
94     begin
95         if (errorsignal_b == 1'b1) // A critical timing is active for this input
96         begin
97             outfile = $fopen("errors.txt", "a");
98             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n
99             ", $stime);
100            $fclose(outfile);
101            q <= 1'bX; // Set all outputs to unknown
102        end
103        if (errorsignal_b == 0)
104        begin
105            case (cell_state)
106            0: begin
107                cell_state = 2; // Blocking statement -- immediately
108            end
109            1: begin
110                cell_state = 0; // Blocking statement -- immediately
111                errorsignal_b = 1; // Critical timing on this input; assign
112                // immediately
113                errorsignal_b <= #(ct_state1_b_b) 0; // Clear error signal
114                // after critical timing expires
115                errorsignal_a = 1; // Critical timing on this input; assign
116                // immediately
117                errorsignal_a <= #(ct_state2_b_a) 0; // Clear error signal
118                // after critical timing expires
119                errorsignal_clk = 1; // Critical timing on this input; assign
120                // immediately
121                errorsignal_clk <= #(ct_state2_b_clk) 0; // Clear error signal
122                // after critical timing expires
123            end
124        endcase
125    end
126 end
127
128 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
129 begin
130     if ($time>4) // arbitrary steady-state time)
131     begin

```

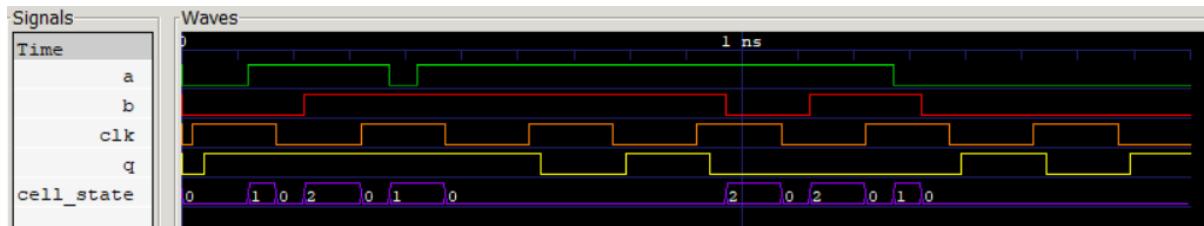
```

126      if (errorsignal_clk == 1'b1) // A critical timing is active for this input
127      begin
128          outfile = $fopen("errors.txt", "a");
129          $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
130                      ↪ ", $stime);
131          $fclose(outfile);
132          q <= 1'bX; // Set all outputs to unknown
133      end
134      if (errorsignal_clk == 0)
135      begin
136          case (cell_state)
137              0: begin
138                  q <= #(delay_state0_clk_q) !q;
139                  errorsignal_a = 1; // Critical timing on this input; assign
140                      ↪ immediately
141                  errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
142                      ↪ after critical timing expires
143                  errorsignal_b = 1; // Critical timing on this input; assign
144                      ↪ immediately
145                  errorsignal_b <= #(ct_state0_clk_b) 0; // Clear error signal
146                      ↪ after critical timing expires
147                  errorsignal_clk = 1; // Critical timing on this input; assign
148                      ↪ immediately
149                  errorsignal_clk <= #(ct_state0_clk_clk) 0; // Clear error
150                      ↪ signal after critical timing expires
151              end
152              1: begin
153                  cell_state = 0; // Blocking statement -- immediately
154                  errorsignal_b = 1; // Critical timing on this input; assign
155                      ↪ immediately
156                  errorsignal_b <= #(ct_state1_clk_b) 0; // Clear error signal
157                      ↪ after critical timing expires
158              end
159          endcase
160      end
161  endmodule

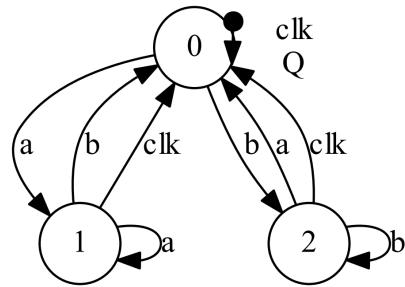
```

**Listing 2.24:** RSFQ XNOR verilog model.

The digital simulation results for the RSFQ XNOR is shown in Fig. 2.45 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.46.



**Figure 2.45:** RSFQ XNOR digital simulation results.



**Figure 2.46:** RSFQ XNOR Mealy finite state machine diagram.

## Power Consumption

**Table 2.24:** RSFQ XNOR power consumption.

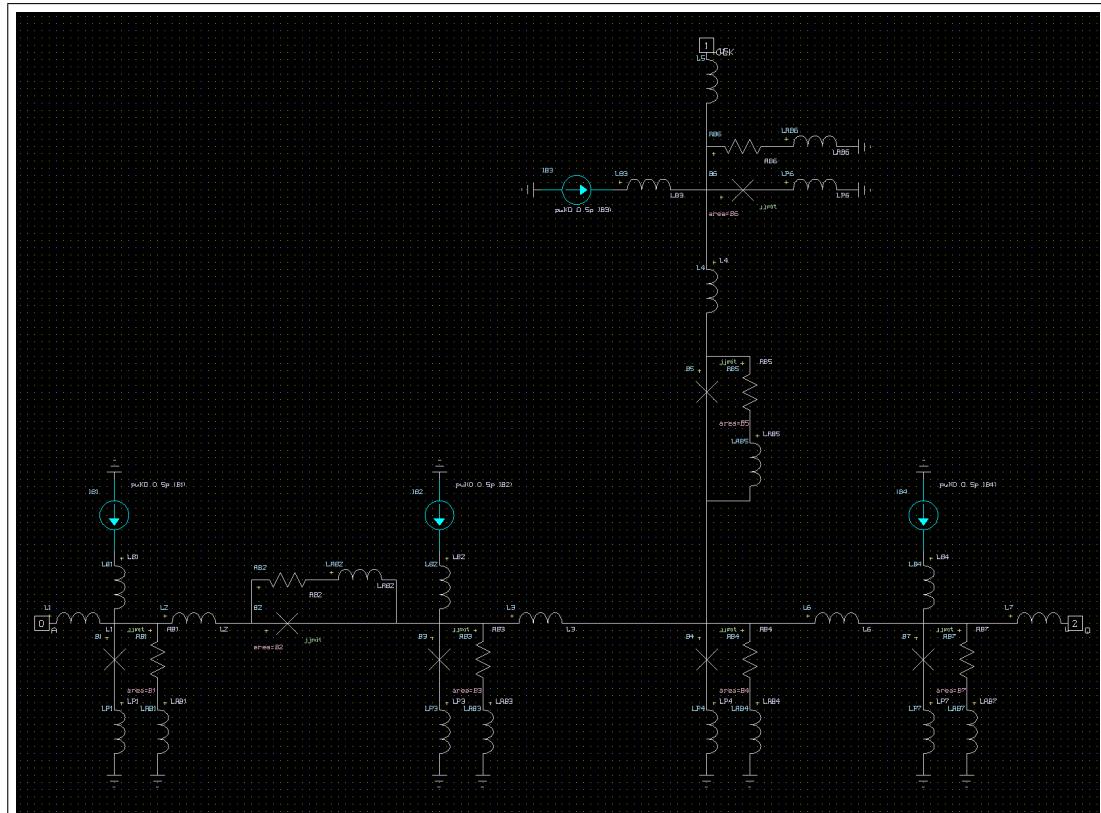
Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	4215	8.31
2	4215	16.6
5	4215	41.6
10	4215	83.1
20	4215	166
50	4215	416

## 2.3 Buffers

### 2.3.1 DFF

The RSFQ DFF, D flip-flop, is a multi-state device used to transmit an input set pulse synchronised with a reset (typically clock) signal. The DFF cell is not designed to be directly connected to a PTL.

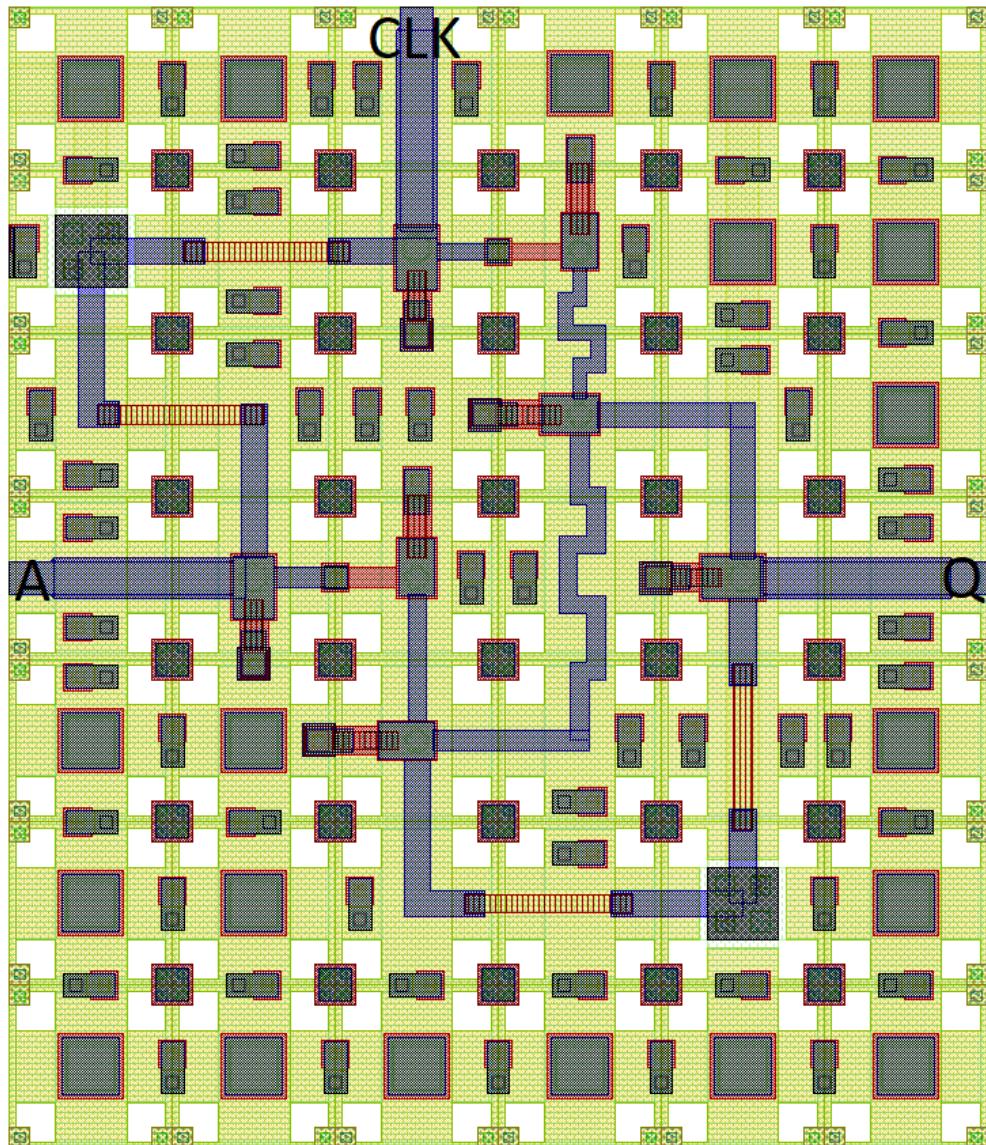
## Schematic



**Figure 2.47:** Schematic of RSFQ DFF.

## Layout

The physical layout for the RSFQ DFF is shown in Fig. 2.48. The layout height is  $70 \mu\text{m}$  and the width is  $60 \mu\text{m}$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.48:** RSFQ DFF Layout.

## Analog model

```

1  * Back-annotated simulation file written      57  .param RB7=B0Rs/B7
2  	↳ by InductEx v.6.0.4 on 12-3-21.          58  .param LRB1=(RB1/Rsheet)*Lsheet
3  * Author: L. Schindler                      59  .param LRB2=(RB2/Rsheet)*Lsheet
4  * Version: 2.1                               60  .param LRB3=(RB3/Rsheet)*Lsheet
5  * Last modification date: 3 June 2021       61  .param LRB4=(RB4/Rsheet)*Lsheet
6  * Last modification by: L. Schindler        62  .param LRB5=(RB5/Rsheet)*Lsheet
7  *$Ports a clk q                           63  .param LRB6=(RB6/Rsheet)*Lsheet
8  .subckt LSmitll_DFF      a      clk q      64  .param LRB7=(RB7/Rsheet)*Lsheet
9   .model jjmit jj(rtype=1, vg=2.8mV, cap    65  B1 1 2 jjmit area=B1
10  ↳ =0.07pF, r0=160, rn=16, icrit=0.1mA     66  B2 4 5 jjmit area=B2
11  .param Phi0=2.067833848E-15                67  B3 5 6 jjmit area=B3
12  .param B0=1                                68  B4 8 9 jjmit area=B4
13  .param Ic0=0.0001                          69  B5 10 8 jjmit area=B5
14  .param IcRs=100u*6.859904418               70  B6 11 12 jjmit area=B6
15  .param B0Rs=IcRs/Ic0*B0                   71  B7 14 15 jjmit area=B7
16  .param Rsheet=2                            72
17  .param Lsheet=1.13e-12                     73
18  .param LP=0.2p                            74  IB1 0 3 pwl(0 0 5p IB1)
19  .param IC=2.5                            75  IB2 0 7 pwl(0 0 5p IB2)
20  .param LB=2p                             76  IB3 0 13 pwl(0 0 5p IB3)
21  .param BiasCoef=0.70                     77  IB4 0 16 pwl(0 0 5p IB4)
22  .param B1=2.5                            78
23  .param B2=1.61                           79  LB1 3 1 LB1
24  .param B3=1.54                           80  LB2 7 5 LB2
25  .param B4=1.69                           81  LB3 11 13 LB3
26  .param B5=1.38                           82  LB4 16 14 LB4
27  .param B6=2.5                            83
28  .param B7=2.5                            84  L1 a 1 2.059E-12
29                                         85  L2 1 4 4.123E-12
30  .param IB1=175u                          86  L3 5 8 6.873E-12
31  .param IB2=173u                          87  L4 10 11 5.195E-12
32  .param IB3=175u                          88  L5 clk 11 2.071E-12
33  .param IB4=175u                          89  L6 8 14 3.287E-12
34                                         90  L7 14 q 2.066E-12
35  .param L1=Phi0/(4*IC*Ic0)              91
36  .param L2=Phi0/(2*B1*Ic0)              92  LP1 2 0 5.042E-13
37  .param L3=Phi0/(B3*Ic0)              93  LP3 6 0 5.799E-13
38  .param L4=Phi0/(2*B6*Ic0)              94  LP4 9 0 5.733E-13
39  .param L5=Phi0/(4*IC*Ic0)              95  LP6 12 0 4.605E-13
40  .param L6=Phi0/(2*B4*Ic0)              96  LP7 15 0 4.961E-13
41  .param L7=Phi0/(4*B7*Ic0)              97
42  .param LB1=LB                           98  RB1 1 101 RB1
43  .param LB2=LB                           99  LRB1 101 0 LRB1
44  .param LB3=LB                           100  RB2 4 104 RB2
45  .param LB4=LB                           101  LRB2 104 5 LRB2
46  .param LP1=LP                           102  RB3 5 105 RB3
47  .param LP3=LP                           103  LRB3 105 0 LRB3
48  .param LP4=LP                           104  RB4 8 108 RB4
49  .param LP6=LP                           105  LRB4 108 0 LRB4
50  .param LP7=LP                           106  RB5 10 110 RB5
51  .param RB1=B0Rs/B1                     107  LRB5 110 8 LRB5
52  .param RB2=B0Rs/B2                     108  RB6 11 111 RB6
53  .param RB3=B0Rs/B3                     109  LRB6 111 0 LRB6
54  .param RB4=B0Rs/B4                     110  RB7 14 114 RB7
55  .param RB5=B0Rs/B5                     111  LRB7 114 0 LRB7
56  .param RB6=B0Rs/B6                     112  .ends

```

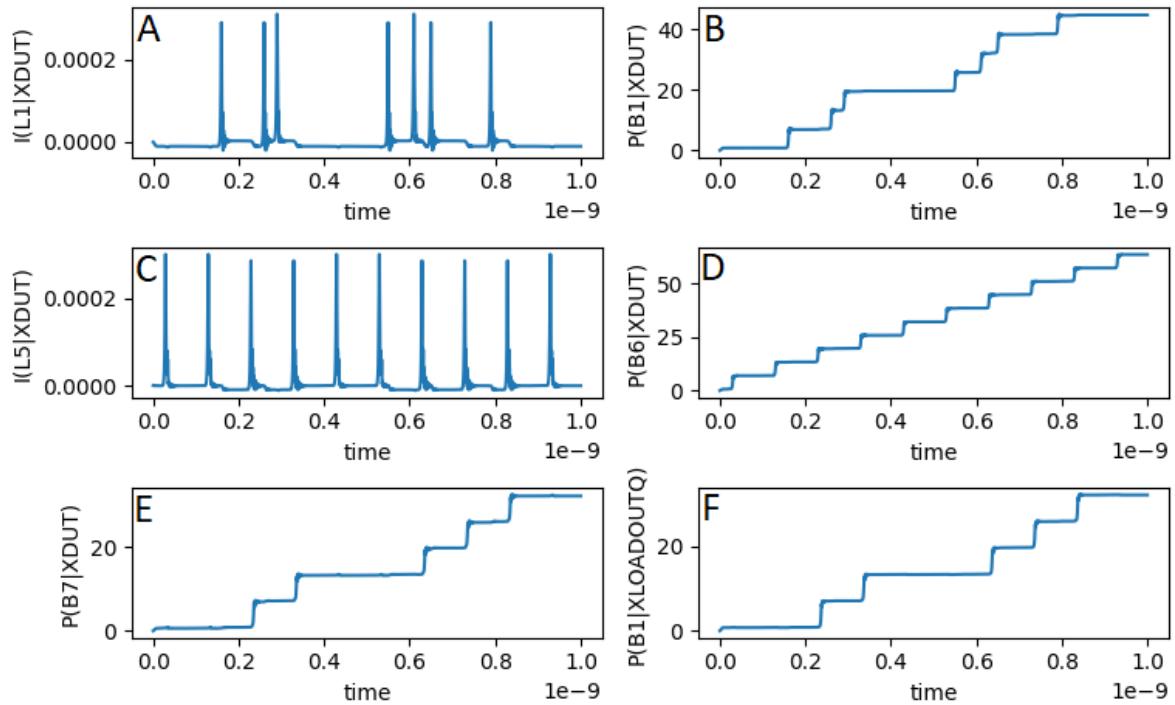
**Listing 2.25:** RSFQ DFF JoSIM netlist.

**Table 2.25:** RSFQ DFF pin list.

Pin	Description
<b>a</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ DFF using JoSIM is shown in Fig. 2.49. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **clk**,
- (d) the phase over the input JJ of pin **clk**,
- (e) the phase over the output JJ of pin **q**, and
- (f) the phase over the input JJ of the load circuit connected to pin **q**.

**Figure 2.49:** RSFQ DFF analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 4 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 // -----
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 // -----
15 `timescale 1ps/100fs
16 module LSmitll_DFF_v2p1_optimized (a, clk, q);
17
18 input
19   a, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state1_clk_q = 5.8,
29   ct_state0_clk_a = 0.9,
30   ct_state1_a_clk = 0.6;
31
32 reg
33   errorsignal_a,
34   errorsignal_clk;
35
36 integer
37   outfile,
38   cell_state; // internal state of the cell
39
40 initial
41 begin
42   errorsignal_a = 0;
43   errorsignal_clk = 0;
44   cell_state = 0; // Startup state
45   q = 0; // All outputs start at 0
46 end
47
48 always @ (posedge a or negedge a) // execute at positive and negative edges of input
49 begin
50   if ($time>4) // arbitrary steady-state time)
51     begin
52       if (errorsignal_a == 1'b1) // A critical timing is active for this input
53         begin
54           outfile = $fopen("errors.txt", "a");
55           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
56           ↪ ", $stime);
57           $fclose(outfile);
58           q <= 1'bX; // Set all outputs to unknown
59         end
60       if (errorsignal_a == 0)
61         begin
62           case (cell_state)
63             0: begin
64               cell_state = 1; // Blocking statement -- immediately
65             end
66             1: begin
67               errorsignal_clk = 1; // Critical timing on this input; assign

```

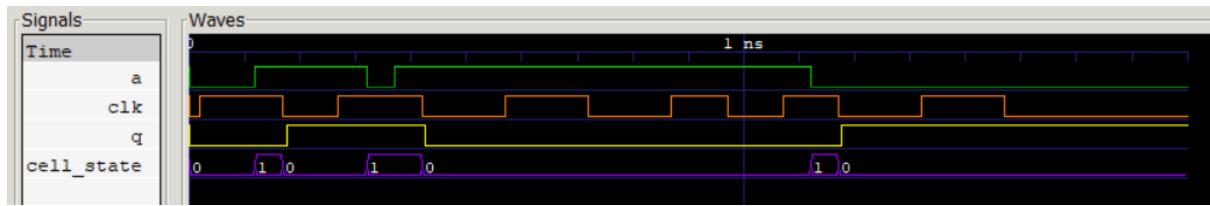
```

67           ↪ immediately
68           errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
69           ↪ after critical timing expires
70       end
71   endcase
72 end
73
74 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
75 begin
76     if ($time>4) // arbitrary steady-state time)
77     begin
78         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
79         begin
80             outfile = $fopen("errors.txt", "a");
81             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n
82             ↪ ", $stime);
83             $fclose(outfile);
84             q <= 1'bX; // Set all outputs to unknown
85         end
86         if (errorsignal_clk == 0)
87         begin
88             case (cell_state)
89             0: begin
90                 errorsignal_a = 1; // Critical timing on this input; assign
91                 ↪ immediately
92                 errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
93                 ↪ after critical timing expires
94             end
95             1: begin
96                 q <= #(delay_state1_clk_q) !q;
97                 cell_state = 0; // Blocking statement -- immediately
98             end
99         endcase
100    end
101 endmodule

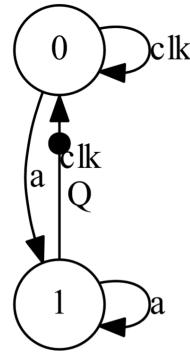
```

Listing 2.26: RSFQ DFF verilog model.

The digital simulation results for the RSFQ DFF is shown in Fig. 2.50 and the Mealy finite state machine diagram, extracted using *TimEx*, is shown in Fig. 2.51.



**Figure 2.50:** RSFQ DFF digital simulation results.



**Figure 2.51:** RSFQ DFF Mealy finite state machine diagram.

## Power Consumption

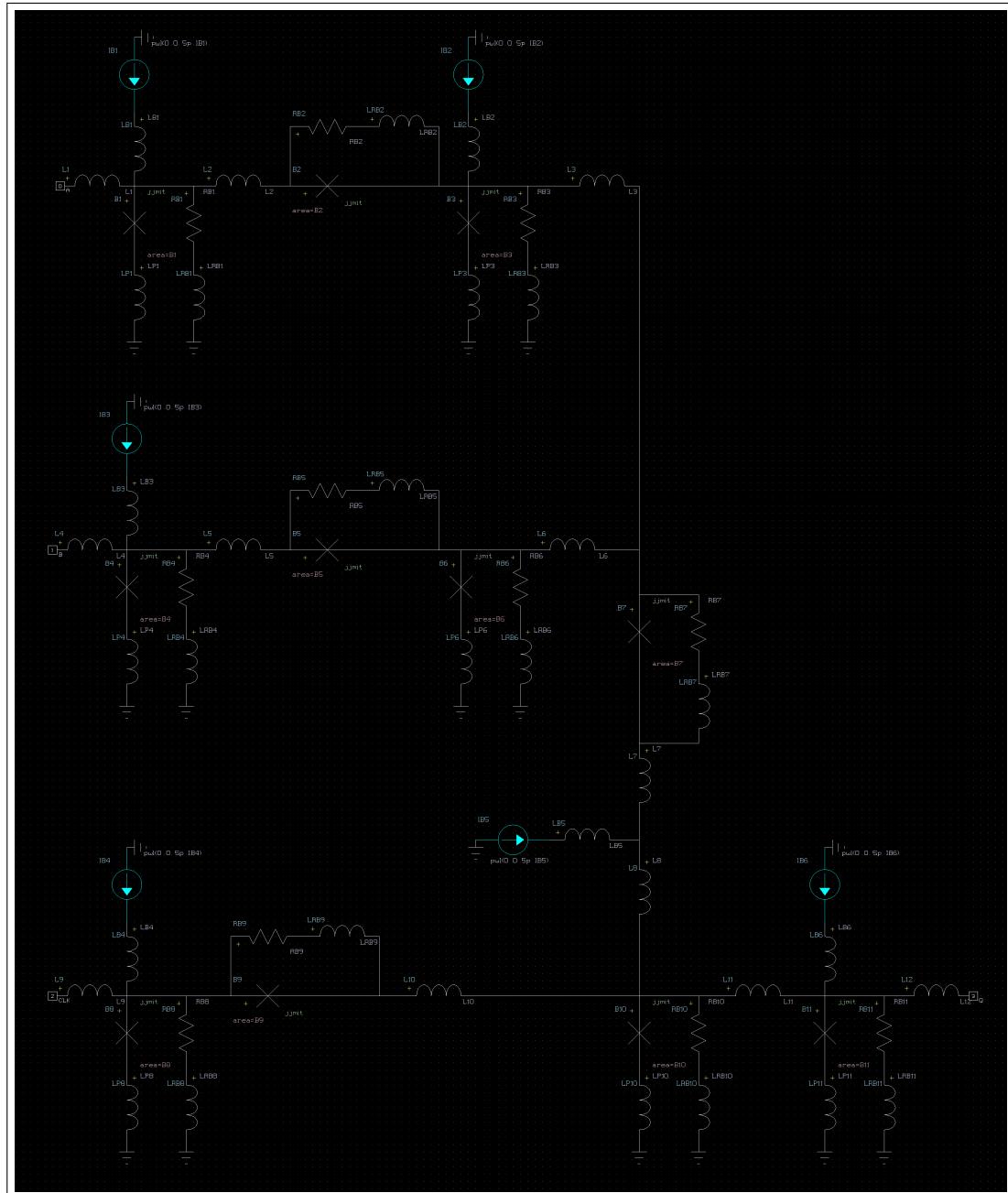
**Table 2.26:** RSFQ DFF power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	1815	2.84
2	1815	5.67
5	1815	14.2
10	1815	28.4
20	1815	56.7
50	1815	142

### 2.3.2 NDRO

The NDRO, non-destructive readout, cell is a memory device controlled by a set, reset and clock input signal. When an input set signal is received, the NDRO will generate an output pulse after each clock signal until an input reset signal is received. The NDRO cell is not designed to be directly connected to a PTL.

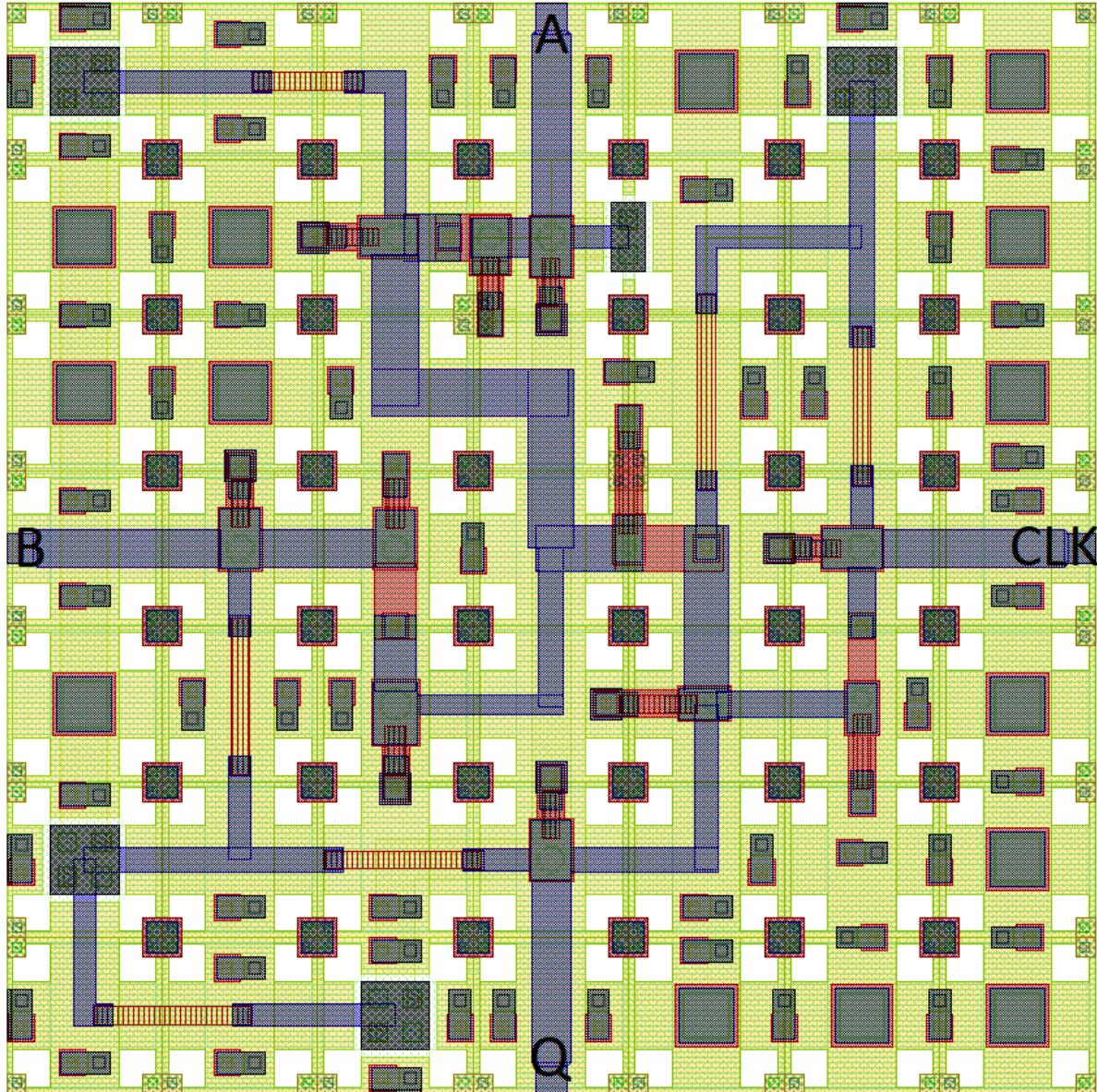
#### Schematic



**Figure 2.52:** Schematic of RSFQ NDRO.

## Layout

The physical layout for the RSFQ NDRO is shown in Fig. 2.53. The layout height is  $70 \mu m$  and the width is  $70 \mu m$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.53:** RSFQ NDRO Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param RB11=B0Rs/B11
2   ↪ by InductEx v.6.0.4 on 15-4-21.          65  .param LRB1=(RB1/Rsheet)*Lsheet+LP
3  * Author: L. Schindler                      66  .param LRB2=(RB2/Rsheet)*Lsheet+LP
4  * Version: 2.1                               67  .param LRB3=(RB3/Rsheet)*Lsheet+LP
5  * Last modification date: 9 June 2021       68  .param LRB4=(RB4/Rsheet)*Lsheet+LP
6  * Last modification by: L. Schindler        69  .param LRB5=(RB5/Rsheet)*Lsheet+LP
7  *$Ports a b clk q                         70  .param LRB6=(RB6/Rsheet)*Lsheet+LP
8  .subckt LSmitll_NDRO a b clk q           71  .param LRB7=(RB7/Rsheet)*Lsheet+LP
9  .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param LRB8=(RB8/Rsheet)*Lsheet+LP
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA     73  .param LRB9=(RB9/Rsheet)*Lsheet+LP
   ↪ )                                         74  .param LRB10=(RB10/Rsheet)*Lsheet+LP
10 .param Phi0=2.067833848E-15                75  .param LRB11=(RB11/Rsheet)*Lsheet+LP
11 .param B0=1                                 76
12 .param Ic0=0.0001                           77
13 .param IcRs=100u*6.859904418               78  .param LB1=LB
14 .param B0Rs=IcRs/Ic0*B0                   79  .param LB2=LB
15 .param Rsheet=2                            80  .param LB3=LB
16 .param Lsheet=1.13e-12                     81  .param LB4=LB
17 .param LP=0.2p                            82  .param LB5=LB
18 .param IC=2.5                            83  .param LB6=LB
19 .param LB=2p                             84
20 .param BiasCoef=0.7                       85  B1 1 2 jjmit area=B1
21                                         86  B2 3 4 jjmit area=B2
22 .param B1=2.5                            87  B3 4 5 jjmit area=B3
23 .param B2=1.99                           88  B4 7 8 jjmit area=B4
24 .param B3=2.2                            89  B5 9 10 jjmit area=B5
25 .param B4=2.5                            90  B6 10 11 jjmit area=B6
26 .param B5=2.35                           91  B7 6 12 jjmit area=B7
27 .param B6=3.24                           92  B8 14 15 jjmit area=B8
28 .param B7=0.74                           93  B9 14 16 jjmit area=B9
29 .param B8=2.5                            94  B10 17 18 jjmit area=B10
30 .param B9=1.17                           95  B11 19 20 jjmit area=B11
31 .param B10=1.09                          96
32 .param B11=2.5                           97  IB1 0 21 pw1(0 0 5p IB1)
33                                         98  IB2 0 22 pw1(0 0 5p IB2)
34 .param IB1=175u                           99  IB3 0 23 pw1(0 0 5p IB3)
35 .param IB2=271u                           100 IB4 0 24 pw1(0 0 5p IB4)
36 .param IB3=175u                           101 IB5 0 25 pw1(0 0 5p IB5)
37 .param IB4=175u                           102 IB6 0 26 pw1(0 0 5p IB6)
38 .param IB5=136u                           103
39 .param IB6=175u                           104  LB1 1 21 LB1
40                                         105  LB2 4 22 LB2
41 .param L1=Phi0/(4*IC*Ic0)                 106  LB3 7 23 LB3
42 .param L2=Phi0/(2*B1*Ic0)                 107  LB4 14 24 LB4
43 .param L3=Phi0/(2*B3*Ic0)                 108  LB5 13 25 LB5
44 .param L4=Phi0/(4*IC*Ic0)                 109  LB6 19 26 LB6
45 .param L5=Phi0/(2*B4*Ic0)                 110
46 .param L6=Phi0/(2*B6*Ic0)                 111  L1 a 1 2.067E-12
47 .param L7=1p                             112  L2 1 3 9.786E-13
48 .param L8=1p                             113  L3 4 6 2.693E-12
49 .param L9=Phi0/(4*IC*Ic0)                 114  L4 b 7 2.068E-12
50 .param L10=Phi0/(2*B8*Ic0)                115  L5 7 9 2.319E-12
51 .param L11=Phi0/(2*B10*Ic0)               116  L6 10 6 3.438E-12
52 .param L12=Phi0/(4*IC*Ic0)                117  L7 12 13 1.12E-12
53                                         118  L8 13 17 1.028E-12
54 .param RB1=B0Rs/B1                      119  L9 clk 14 2.106E-12
55 .param RB2=B0Rs/B2                      120  L10 16 17 3.135E-12
56 .param RB3=B0Rs/B3                      121  L11 17 19 3.223E-12
57 .param RB4=B0Rs/B4                      122  L12 19 q 2.071E-12
58 .param RB5=B0Rs/B5                      123
59 .param RB6=B0Rs/B6                      124  LP1 2 0 5.174E-13
60 .param RB7=B0Rs/B7                      125  LP3 5 0 5.135E-13
61 .param RB8=B0Rs/B8                      126  LP4 8 0 4.756E-13
62 .param RB9=B0Rs/B9                      127  LP6 11 0 4.841E-13
63 .param RB10=B0Rs/B10                     128  LP8 15 0 4.705E-13
64                                         129  LP10 18 0 5.961E-13

```

```

130 | LP11 20 0 4.832E-13
131 | RB1 1 101 RB1
132 | LRB1 101 0 LRB1
133 | RB2 3 103 RB2
134 | LRB2 103 4 LRB2
135 | RB3 4 104 RB3
136 | LRB3 104 0 LRB3
137 | RB4 7 107 RB4
138 | LRB4 107 0 LRB4
139 | RB5 9 109 RB5
140 | LRB5 109 10 LRB5
141 | RB6 10 110 RB6
142 | LRB6 110 0 LRB6
144 | RB7 6 106 RB7
145 | LRB7 106 12 LRB7
146 | RB8 14 114 RB8
147 | LRB8 114 0 LRB8
148 | RB9 14 116 RB9
149 | LRB9 116 16 LRB9
150 | RB10 17 117 RB10
151 | LRB10 117 0 LRB10
152 | RB11 19 119 RB11
153 | LRB11 119 0 LRB11
154 | .ends

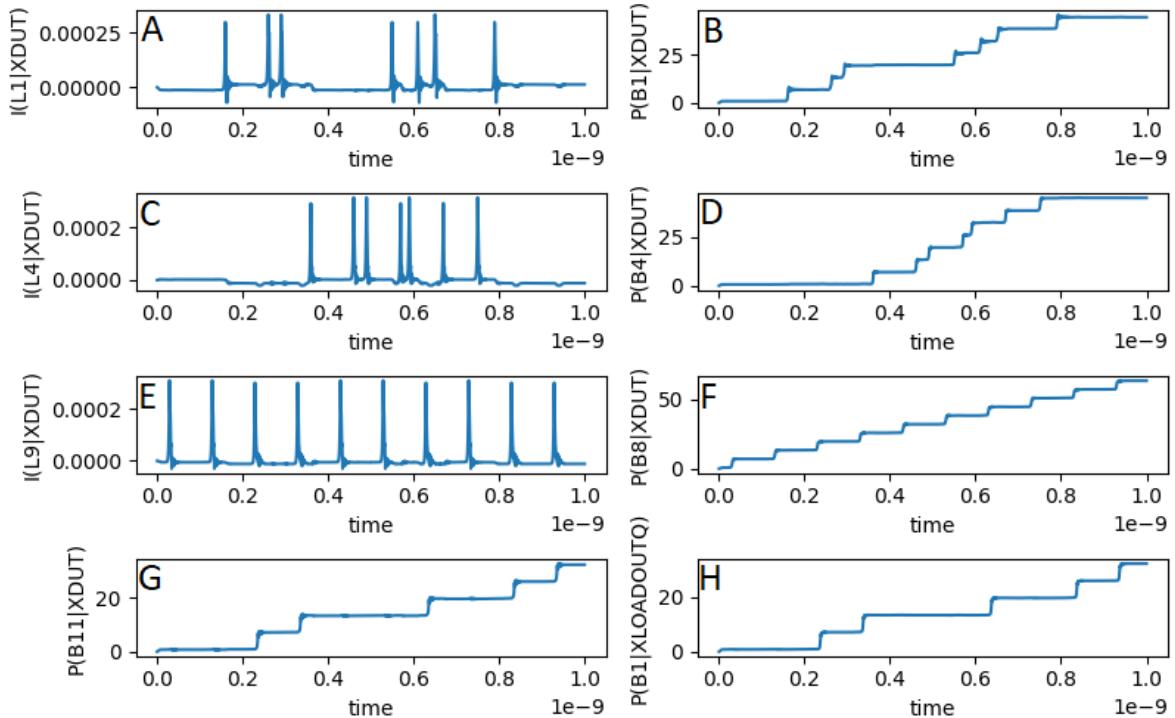
```

**Listing 2.27:** RSFQ NDRO JoSIM netlist.**Table 2.27:** RSFQ NDRO pin list.

Pin	Description
a	Data input (set signal)
b	Data input (reset signal)
clk	Clock input
q	Data output

The simulation results for the RSFQ NDRO using JoSIM is shown in Fig. 2.54. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a** (set signal),
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b** (reset signal),
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 2.54:** RSFQ NDRO analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 11 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmit11_NDRO_v2p1_optimized (a, b, clk, q);
9
10 input
11     a, b, clk;
12
13 output
14     q;
15
16 reg
17     q;
18
19 real
20     delay_state1_clk_q = 5.0,
21     ct_state0_b_a = 1.9,
22     ct_state1_a_b = 1.5,
23     ct_state1_clk_clk = 6.9;
24
25 reg
26     errorsignal_a,
27     errorsignal_b,
28     errorsignal_clk;
29
30 integer
31     outfile,
32     cell_state; // internal state of the cell
33
34 initial
35 begin
36     errorsignal_a = 0;
37     errorsignal_b = 0;
38     errorsignal_clk = 0;
39     cell_state = 0; // Startup state
40     q = 0; // All outputs start at 0
41 end
42
43 always @(posedge a or negedge a) // execute at positive and negative edges of input
44 begin
45     if ($time>4) // arbitrary steady-state time)
46         begin
47             if (errorsignal_a == 1'b1) // A critical timing is active for this input
48                 begin
49                     outfile = $fopen("errors.txt", "a");
50                     $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m; %0d_ps.\n"
51                                     ↪ ", $time);
52                     $fclose(outfile);
53                     q <= 1'bX; // Set all outputs to unknown
54                 end
55             if (errorsignal_a == 0)
56                 begin
57                     case (cell_state)
58                         0: begin
59                             cell_state = 1; // Blocking statement -- immediately
60                         end
61                         1: begin
62                             errorsignal_b = 1; // Critical timing on this input; assign
63                                         ↪ immediately
64                             errorsignal_b <= #(ct_state1_a_b) 0; // Clear error signal
65                                         ↪ after critical timing expires
66                         end
67                     endcase
68                 end
69             end
70         end
71     end
72 end

```

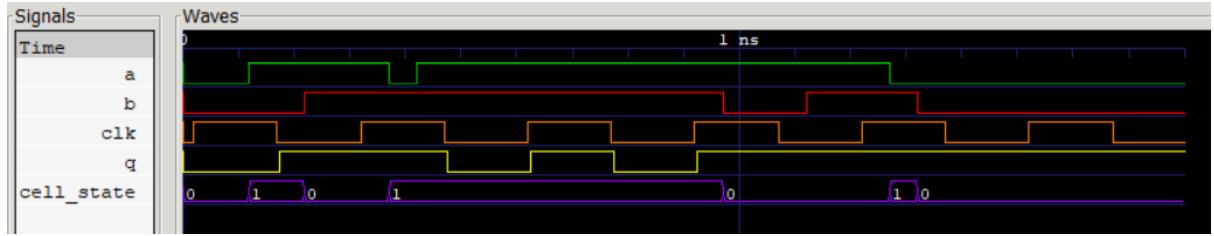
```

65           end
66       end
67   end
68
69 always @(posedge b or negedge b) // execute at positive and negative edges of input
70   begin
71     if ($time>4) // arbitrary steady-state time)
72     begin
73       if (errorsignal_b == 1'b1) // A critical timing is active for this input
74       begin
75         outfile = $fopen("errors.txt", "a");
76         $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
77                     ↪ ", $stime);
78         $fclose(outfile);
79         q <= 1'bX; // Set all outputs to unknown
80       end
81     if (errorsignal_b == 0)
82     begin
83       case (cell_state)
84         0: begin
85           errorsignal_a = 1; // Critical timing on this input; assign
86           ↪ immediately
87           errorsignal_a <= #(ct_state0_b_a) 0; // Clear error signal
88           ↪ after critical timing expires
89         end
90       1: begin
91         cell_state = 0; // Blocking statement -- immediately
92       end
93     endcase
94   end
95
96 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
97   begin
98     if ($time>4) // arbitrary steady-state time)
99     begin
100       if (errorsignal_clk == 1'b1) // A critical timing is active for this input
101       begin
102         outfile = $fopen("errors.txt", "a");
103         $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
104                     ↪ ", $stime);
105         $fclose(outfile);
106         q <= 1'bX; // Set all outputs to unknown
107       end
108     if (errorsignal_clk == 0)
109     begin
110       case (cell_state)
111         0: begin
112           end
113         1: begin
114           q <= #(delay_state1_clk_q) !q;
115           errorsignal_clk = 1; // Critical timing on this input; assign
116           ↪ immediately
117           errorsignal_clk <= #(ct_state1_clk_clk) 0; // Clear error
118           ↪ signal after critical timing expires
119         end
120       endcase
121     end
122   end
123 endmodule

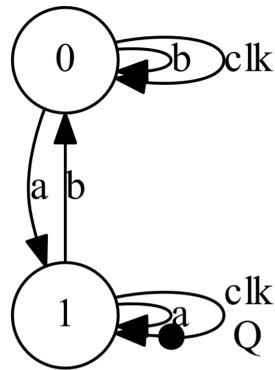
```

**Listing 2.28:** RSFQ NDRO verilog model.

The digital simulation results for the RSFQ NDRO is shown in Fig. 2.55 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 2.56.



**Figure 2.55:** RSFQ NDRO digital simulation results.



**Figure 2.56:** RSFQ NDRO Mealy finite state machine diagram.

## Power Consumption

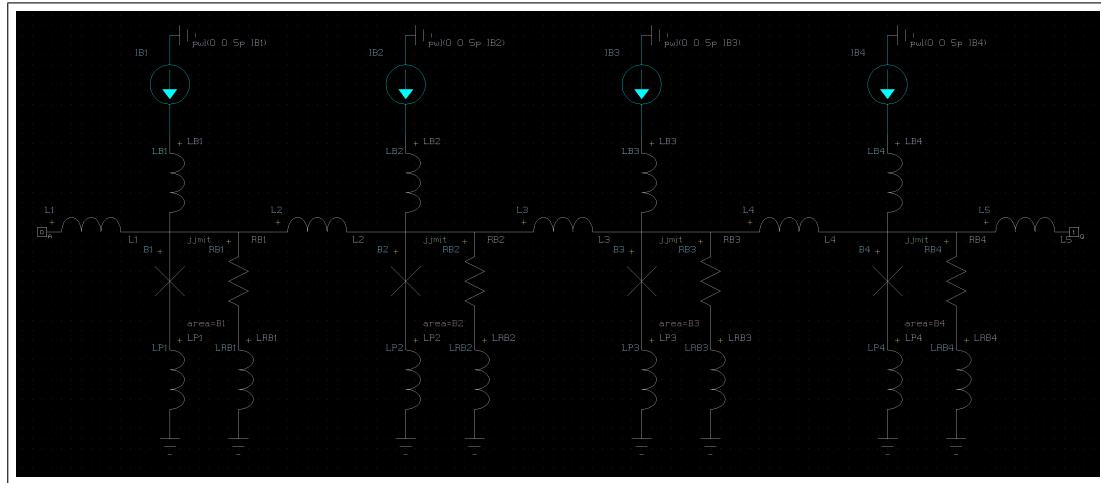
**Table 2.28:** RSFQ NDRO power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2878	4.71
2	2878	9.42
5	2878	23.6
10	2878	47.1
20	2878	94.2
50	2878	236

### 2.3.3 BUFF

The RSFQ BUFF cell is a buffer cell intended for clock balancing. It is designed to have the same a-to-q delay as the SPLIT cell. The BUFF does not have integrated PTL transmitters and receivers and connecting the cell directly to a PTL is not recommended.

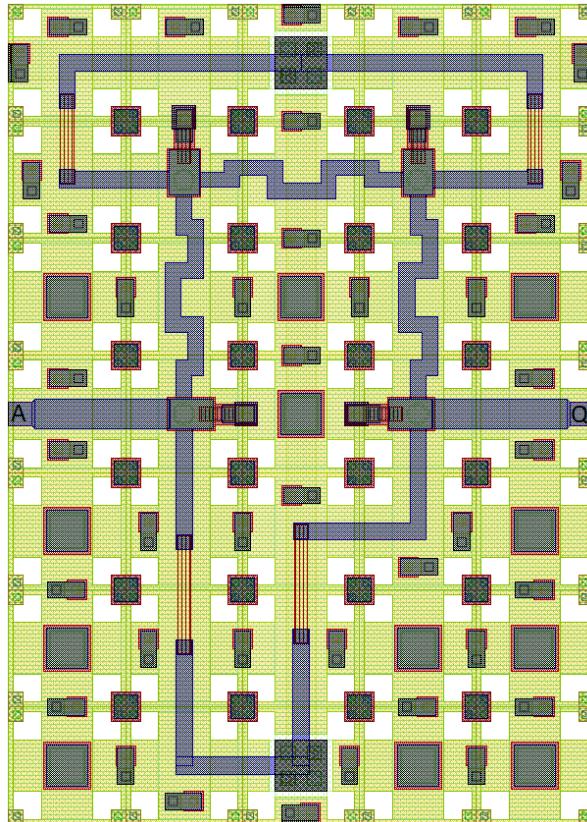
#### Schematic



**Figure 2.57:** Schematic of RSFQ BUFF.

## Layout

The physical layout for the RSFQ BUFF is shown in Fig. 2.58. The layout height is  $70 \mu m$  and the width is  $50 \mu m$ . The cell includes an integrated bias line on M0 within the top row of track blocks. Bias pillars from M0 to M6 connect the circuit to the integrated bias line.



**Figure 2.58:** RSFQ BUFF Layout.

## Analog model

```

1  * Back-annotated simulation file written      45 | .param LRB2=(RB2/Rsheet)*Lsheet+LP
2  *   ↪ by InductEx v.6.0.4 on 11-6-21.        46 | .param LRB3=(RB3/Rsheet)*Lsheet+LP
3  * Author: L. Schindler                      47 | .param LRB4=(RB4/Rsheet)*Lsheet+LP
4  * Version: 2.1                               48 | .param LP1=LP
5  * Last modification date: 11 June 2021       49 | .param LP2=LP
6  * Last modification by: L. Schindler         50 | .param LP3=LP
7  *$Ports a q                                51 | .param LP4=LP
8  .subckt LSMITLL_BUFF a q
9  .model jjmit jj(rtype=1, vg=2.8mV, cap      52 | B1 1 2 jjmit area=B1
10 .      ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    53 | B2 4 5 jjmit area=B2
11 .      ↪ )
12 .param Phi0=2.067833848E-15                 54 | B3 7 8 jjmit area=B3
13 .param B0=1                                  55 | B4 10 11 jjmit area=B4
14 .param Ic0=0.0001                            56 |
15 .param IcRs=100u*6.859904418                  57 | IB1 0 3 pwl(0 0 5p IB1)
16 .param B0Rs=IcRs/Ic0*B0                     58 | IB2 0 6 pwl(0 0 5p IB2)
17 .param Rsheet=2p                            59 | IB3 0 9 pwl(0 0 5p IB3)
18 .param Lsheet=1.13e-12                      60 | IB4 0 12 pwl(0 0 5p IB4)
19 .param LP=0.2p                             61 |
20 .param IC=2.5                               62 | L1 a 1 2.057E-12
21 .param Lptl=2p                            63 | L2 1 4 4.026E-12
22 .param LB=2p                               64 | L3 4 7 4.155E-12
23 .param BiasCoef=0.7                         65 | L4 7 10 4.057E-12
24 .param B1=IC                               66 | L5 10 q 2.057E-12
25 .param B2=IC                               67 |
26 .param B3=IC                               68 | LP1 2 0 5.283E-13
27 .param B4=IC                               69 | LP2 5 0 5.327E-13
28 .param IB1=B1*Ic0*BiasCoef                70 | LP3 8 0 5.084E-13
29 .param IB2=B2*Ic0*0.95                   71 | LP4 11 0 5.269E-13
30 .param IB3=B3*Ic0*0.95                   72 |
31 .param IB4=B4*Ic0*BiasCoef                73 | LB1 1 3 LB1
32 .param LB1=LB                            74 | LB2 4 6 LB2
33 .param LB2=LB                            75 | LB3 7 9 LB3
34 .param LB3=LB                            76 | LB4 10 12 LB4
35 .param LB4=LB                            77 |
36 .param L1=Phi0/(4*IC*Ic0)                 78 | RB1 1 101 RB1
37 .param L2=Phi0/(2*B1*Ic0)                 79 | RB2 4 104 RB2
38 .param L3=Phi0/(2*B2*Ic0)                 80 | RB3 7 107 RB3
39 .param L4=Phi0/(2*B3*Ic0)                 81 | RB4 10 110 RB4
40 .param L5=Phi0/(4*IC*Ic0)                 82 |
41 .param RB1=B0Rs/B1                       83 | LRB1 101 0 LRB1
42 .param RB2=B0Rs/B2                       84 | LRB2 104 0 LRB2
43 .param RB3=B0Rs/B3                       85 | LRB3 107 0 LRB3
44 .param RB4=B0Rs/B4                       86 | LRB4 110 0 LRB4
45 .param LRB1=(RB1/Rsheet)*Lsheet+LP

```

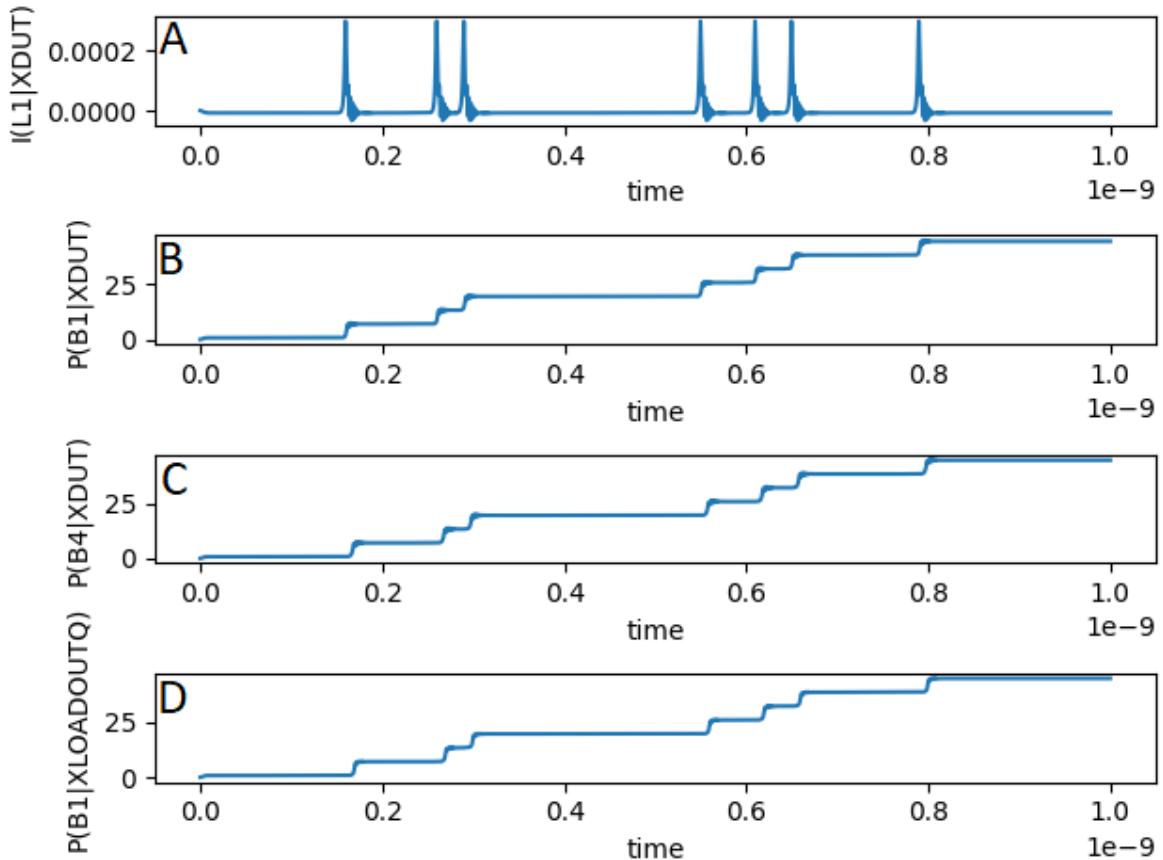
**Listing 2.29:** RSFQ BUFF JoSIM netlist.

**Table 2.29:** RSFQ BUFF pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ BUFF using JoSIM is shown in Fig. 2.59. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 2.59:** RSFQ BUFF analog simulation results.

## Digital model

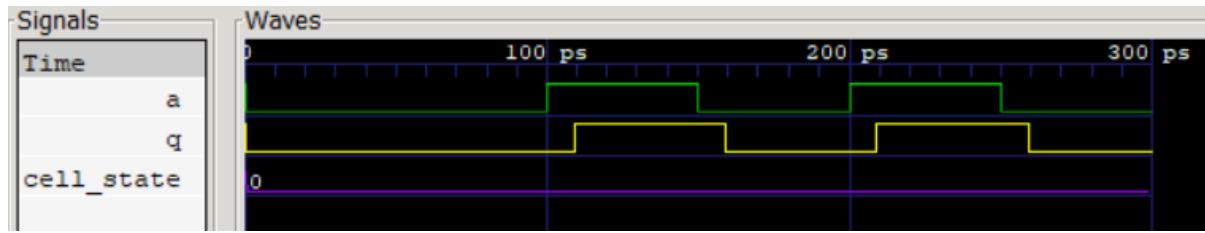
```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 11 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmit11_BUFF_v2p1_annotated (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 real
20   delay_state0_a_q = 6.8,
21   ct_state0_a_a = 3.4;
22
23 reg
24   errorsignal_a;
25
26 integer
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q = 0; // All outputs start at 0
35 end
36
37 always @(posedge a or negedge a) // execute at positive and negative edges of input
38 begin
39   if ($time>4) // arbitrary steady-state time)
40     begin
41       if (errorsignal_a == 1'b1) // A critical timing is active for this input
42         begin
43           outfile = $fopen("errors.txt", "a");
44           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
45           ↪ ", $stime);
46           $fclose(outfile);
47           q <= 1'bX; // Set all outputs to unknown
48         end
49       if (errorsignal_a == 0)
50         begin
51           case (cell_state)
52             0: begin
53               q <= #(delay_state0_a_q) !q;
54               errorsignal_a = 1; // Critical timing on this input; assign
55               ↪ immediately
56               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
57               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

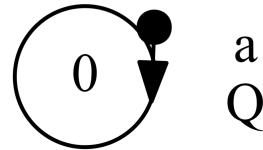
```

**Listing 2.30:** RSFQ BUFF verilog model.

The digital simulation results for the RSFQ BUFF is shown in Fig. 2.60 and the Mealy finite state machine diagram, extracted using *TimEx*, is shown in Fig. 2.61.



**Figure 2.60:** RSFQ BUFF digital simulation results.



**Figure 2.61:** RSFQ BUFF Mealy finite state machine diagram.

## Power Consumption

**Table 2.30:** RSFQ BUFF power consumption.

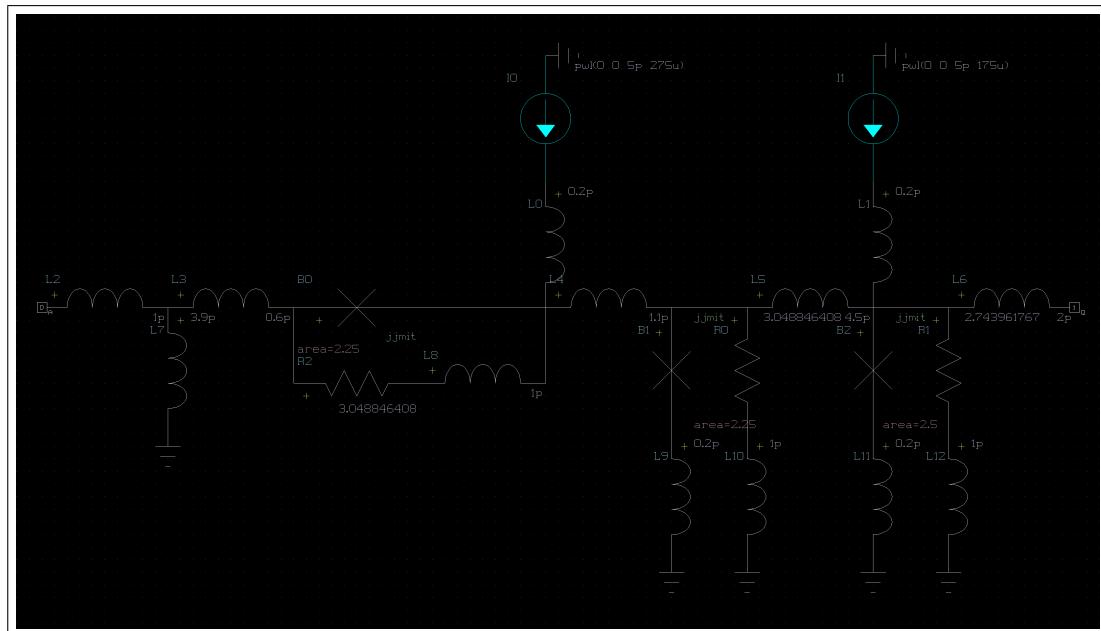
Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2132	2.07
2	2132	4.14
5	2132	10.3
10	2132	20.7
20	2132	41.4
50	2132	103

## 2.4 Interface cells

### 2.4.1 DCSFQ

The RSFQ DCSFQ is an interface cell designed to convert input voltage pulses into SFQ pulses. The DCSFQ does not have an integrated PTL transmitter and is not intended to connect directly to a PTL output.

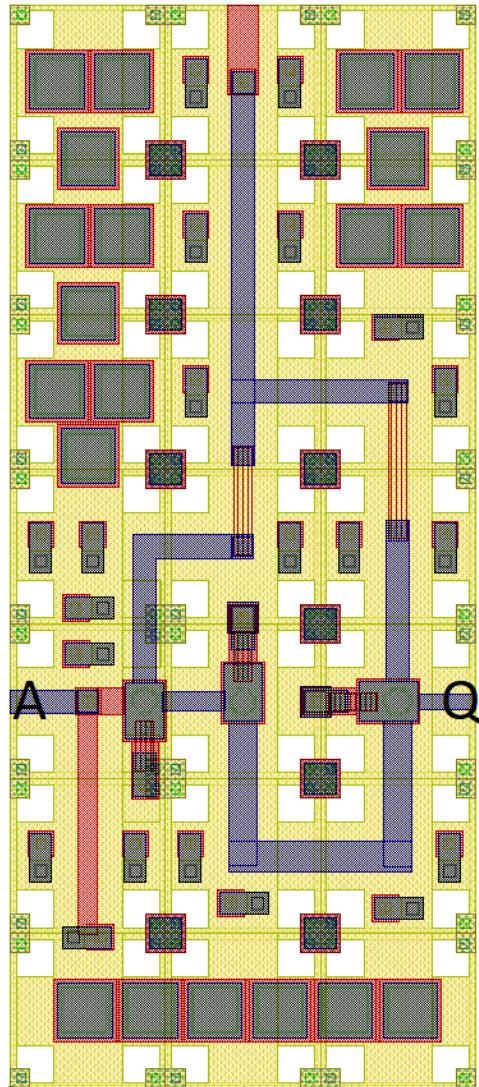
#### Schematic



**Figure 2.62:** Schematic of RSFQ DCSFQ.

## Layout

The physical layout for the RSFQ DCSFQ is shown in Fig. 2.63. The layout height is  $70 \mu m$  and the width is  $30 \mu m$ . The bias line is located on M5 at the top centre of the cell.



**Figure 2.63:** RSFQ DCSFQ Layout.

## Analog model

```

1 | * Back-annotated simulation file written by InductEx v.6.0.4 on 2-6-21.
2 | * Author: L. Schindler
3 | * Version: 2.1
4 | * Last modification date: 2 June 2021
5 | * Last modification by: L. Schindler
6 |
7 |*$Ports a q
8 .subckt LSmitll_DCSFQ a q
9 .model jjmit jj(rtype=1, vg=2.8mV, cap=0.07pF, r0=160, rn=16, icrit=0.1mA)
10 .param B0=1.0
11 .param Ic0=0.0001
12 .param IcRs=100u*6.859904418
13 .param B0Rs=IcRs/Ic0*B0
14 .param Rsheet=2
15 .param Lsheet=1.13e-12
16 .param LB=2p
17 .param LP=0.2p
18
19 .param B1=2.25
20 .param B2=2.25
21 .param B3=2.5
22 .param L1=1p
23 .param L2=3.9p
24 .param L3=0.6p
25 .param L4=1.1p
26 .param L5=4.5p
27 .param L6=2p
28 .param IB1=275u
29 .param IB2=175u
30 .param LB1=LB
31 .param LB2=LB
32 .param LP2=LP
33 .param LP3=LP
34 .param RB1=B0Rs/B1
35 .param RB2=B0Rs/B2
36 .param RB3=B0Rs/B3
37 .param LRB1=(RB1/Rsheet)*Lsheet
38 .param LRB2=(RB2/Rsheet)*Lsheet
39 .param LRB3=(RB3/Rsheet)*Lsheet
40
41 B1 2 3 jjmit area=B1
42 B2 5 6 jjmit area=B2
43 B3 7 8 jjmit area=B3
44 IB1 0 4 pwl(0 0 5p IB1)
45 IB2 0 9 pwl(0 0 5p IB2)
46 LB1 3 4 3.12E-12
47 LB2 7 9 2.281E-12
48 L1 a 1 1.295E-12
49 L2 1 0 3.904E-12
50 L3 1 2 5.998E-13
51 L4 3 5 1.095E-12
52 L5 5 7 4.448E-12
53 L6 7 q 1.334E-12
54 LP2 6 0 5.16E-13
55 LP3 8 0 4.733E-13
56 RB1 2 102 RB1
57 LRB1 102 3 LRB1
58 RB2 5 105 RB2
59 LRB2 105 0 LRB2
60 RB3 7 107 RB3
61 LRB3 107 0 LRB3
62 .ends

```

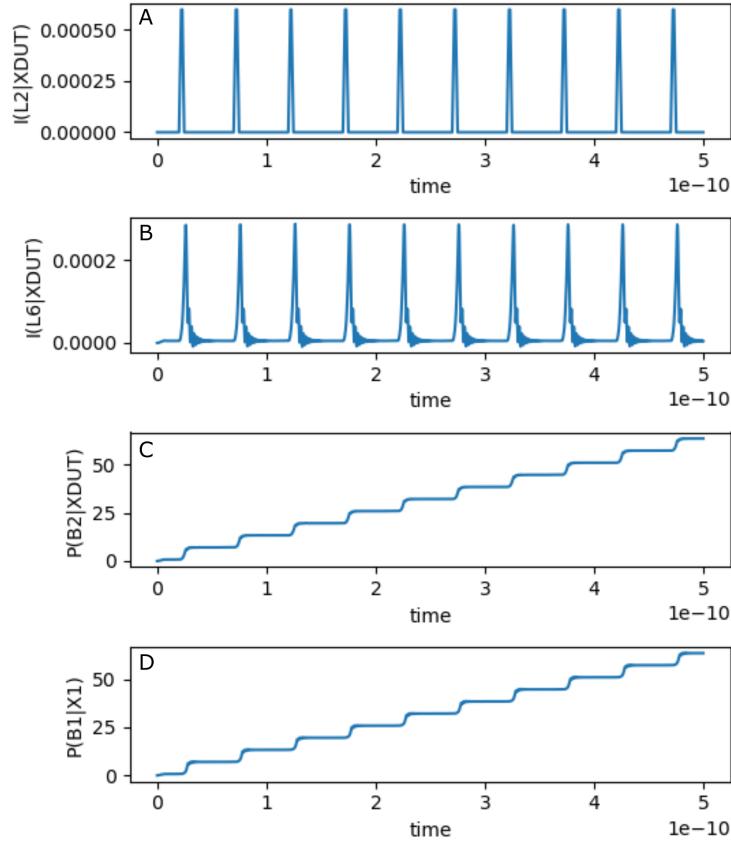
**Listing 2.31:** RSFQ DCSFQ JoSIM netlist.

**Table 2.31:** RSFQ DCSFQ pin list.

Pin	Description
<b>a</b>	Data input
<b>q</b>	Data output

The simulation results for the RSFQ DCSFQ using JoSIM is shown in Fig. 2.64. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the current through the output inductor connected to pin **q**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit connected to pin **q**.

**Figure 2.64:** RSFQ DCSFQ analog simulation results.

## 2.4.2 SFQDC

The RSFQ SFQDC is an interface cell designed to convert SFQ pulses to an output voltage level which can be measured by standard equipment. The SFQDC does not have an integrated PTL receiver and is not intended to be connected directly to a PTL input.

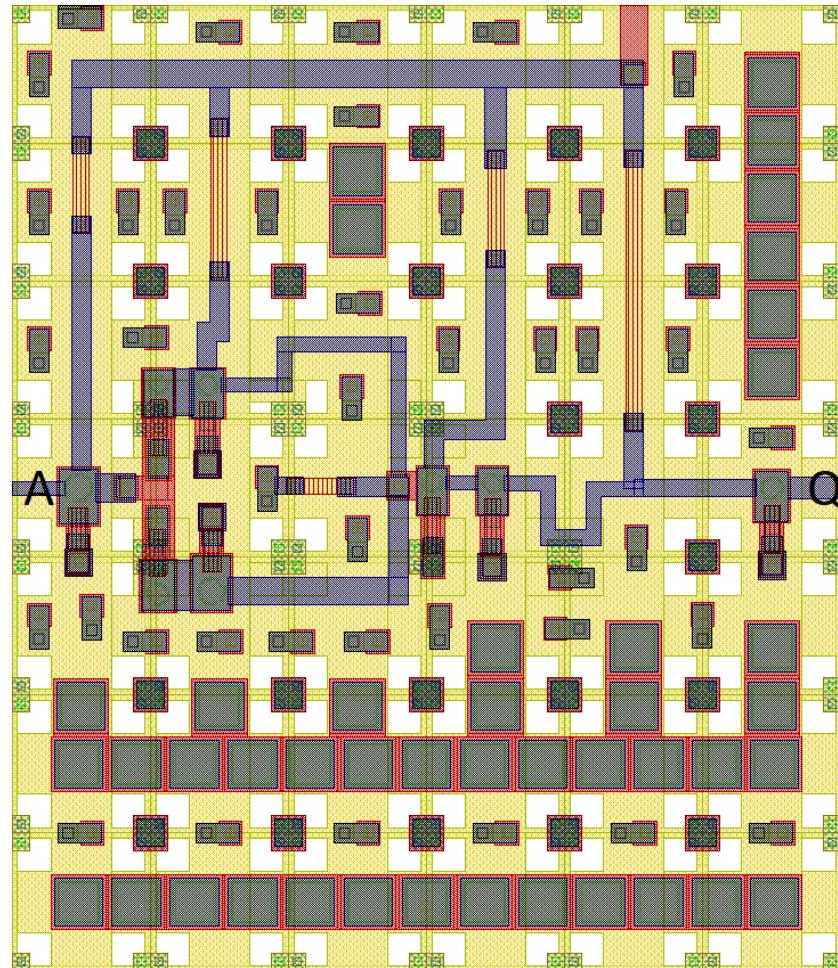
### Schematic



**Figure 2.65:** Schematic of RSFQ SFQDC.

## Layout

The physical layout for the RSFQ SFQDC is shown in Fig. 2.66. The layout height is  $70 \mu m$  and the width is  $60 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 2.66:** RSFQ SFQDC Layout.

## Analog model

```

1  * Adapted from Fluxonics SDQDC_v5
2  * Author: L. Schindler
3  * Version: 2.1
4  * Last modification date: 27 April 2021
5  * Last modification by: L. Schindler
6
7  *$Ports a q
8 .subckt LSmitll_SFQDC a q
9 .model jjmit jj(rtype=1, vg=2.8mV, cap
  ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA
  ↪ )
10 .param B0=1
11 .param Ic0=0.0001
12 .param IcRs=100u*6.859904418
13 .param B0Rs=IcRs/Ic0*B0
14 .param Rsheet=2
15 .param Lsheet=1.13e-12
16 .param B1=3.25
17 .param B2=2.00
18 .param B3=1.50
19 .param B4=3.00
20 .param B5=1.75
21 .param B6=1.50
22 .param B7=1.50
23 .param B8=2.00
24 .param L1=1.522p
25 .param L3=0.827p
26 .param L4=1.12884p
27 .param L5=1.11098p
28 .param L6=5.940p
29 .param L7=3.216p
30 .param L10=0.215p
31 .param L13=3.699p
32 .param L17=1.510p
33 .param L18=2.010p
34 .param L19=0.954p
35 .param L4b=0.178p
36 .param LRB1=(RB1/Rsheet)*Lsheet
37 .param LRB2=(RB2/Rsheet)*Lsheet
38 .param LRB3=(RB3/Rsheet)*Lsheet
39 .param LRB4=(RB4/Rsheet)*Lsheet
40 .param LRB5=(RB5/Rsheet)*Lsheet
41 .param LRB6=(RB6/Rsheet)*Lsheet
42 .param LRB7=(RB7/Rsheet)*Lsheet
43 .param LRB8=(RB8/Rsheet)*Lsheet
44 .param LP1=0.140p
45 .param LP4=0.524p
46 .param LP5=0.516p
47 .param LP7=0.086p
48 .param LP8=0.226p
49 .param LR1=0.91p
50 .param R1=0.375
51 .param RB1=B0Rs/B1
52 .param RB2=B0Rs/B2
53 .param RB3=B0Rs/B3
54 .param RB4=B0Rs/B4
55 .param RB5=B0Rs/B5
56 .param RB6=B0Rs/B6
57 .param RB7=B0Rs/B7
58 .param RB8=B0Rs/B8
59 .param IB1=280u
60 .param IB2=150u
61 .param IB3=220u
62 .param IB4=80u
63 B1 8 20 jjmit area=B1
64 B2 12 13 jjmit area=B2
65 B3 3 4 jjmit area=B3
66 B4 13 29 jjmit area=B4
67 B5 5 16 jjmit area=B5
68 B6 6 7 jjmit area=B6
69 B7 10 22 jjmit area=B7
70 B8 11 24 jjmit area=B8
71 IB1 0 8 pw1(0 0 5p IB1)
72 IB2 0 4 pw1(0 0 5p IB2)
73 IB3 0 7 pw1(0 0 5p IB3)
74 IB4 0 18 pw1(0 0 5p IB4)
75 L1 a 8 L1
76 L3 8 17 L3
77 L4 3 17 L4
78 L5 17 12 L5
79 L6 5 9 L6
80 L7 9 13 L7
81 L10 9 6 L10
82 L13 10 18 L13
83 L17 11 q L17
84 L18 18 11 L18
85 L19 7 10 L19
86 L4b 4 5 L4b
87 LRB1 8 21 LRB1
88 LRB2 12 27 LRB2
89 LRB3 3 14 LRB3
90 LRB4 13 28 LRB4
91 LRB5 5 15 LRB5
92 LRB6 6 19 LRB6
93 LRB7 10 23 LRB7
94 LRB8 11 25 LRB8
95 LP1 20 0 LP1
96 LP4 29 0 LP4
97 LP5 16 0 LP5
98 LP7 22 0 LP7
99 LP8 24 0 LP8
100 LR1 9 26 LR1
101 R1 26 0 R1
102 RB1 21 0 RB1
103 RB2 27 13 RB2
104 RB3 14 4 RB3
105 RB4 28 0 RB4
106 RB5 15 0 RB5
107 RB6 19 7 RB6
108 RB7 23 0 RB7
109 RB8 25 0 RB8
110 .ends

```

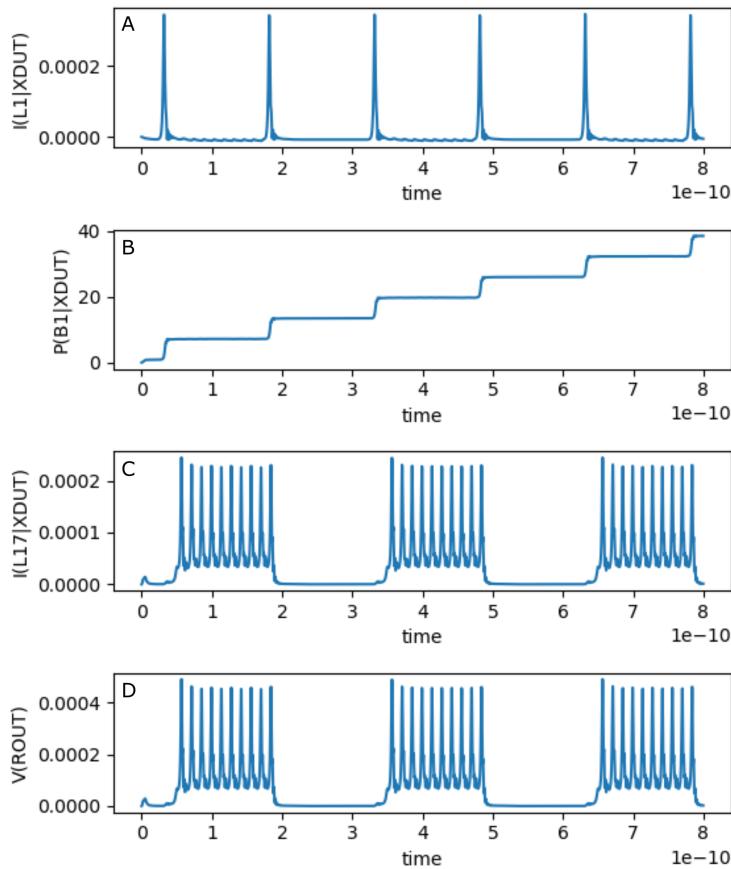
**Listing 2.32:** RSFQ SFQDC JoSIM netlist.

**Table 2.32:** RSFQ SFQDC pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ SFQDC using JoSIM is shown in Fig. 2.67. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the output inductor connected to pin **q**, and
- (c) the voltage over the load resistor connected to pin **q**.

**Figure 2.67:** RSFQ SFQDC analog simulation results.

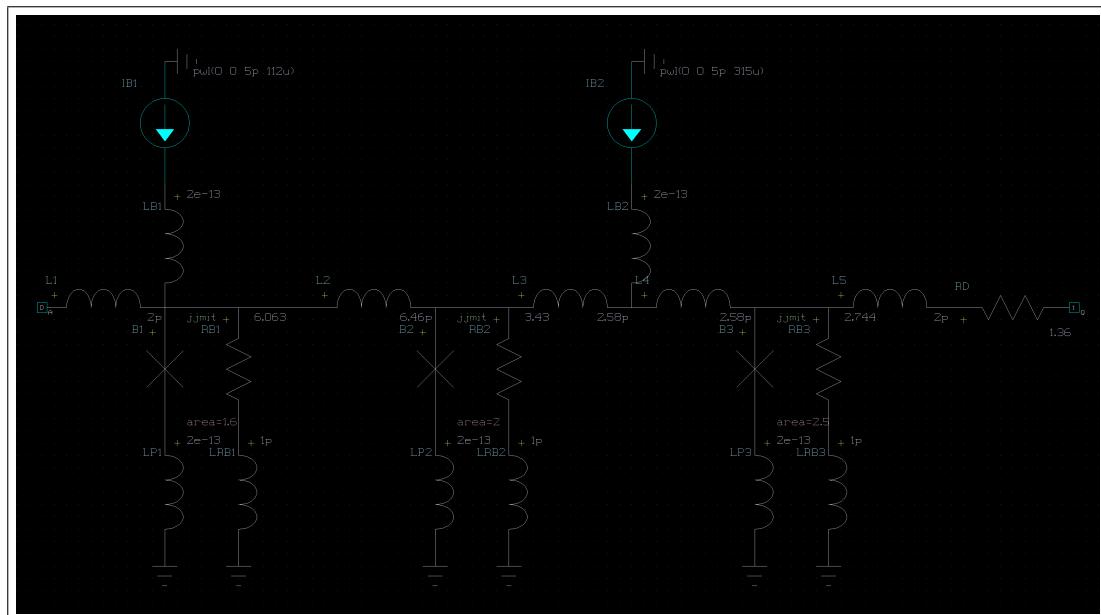
## 3. RSFQ Cell Library: PTL Connections

### 3.1 Interconnects

#### 3.1.1 JTLT

The JTLT, Josephson transmission line, cell is commonly used to reestablish and propagate RSFQ pulses when long PTL connections are required. The cell has integrated PTL transmitters and receivers and is meant to connect directly to a PTL.

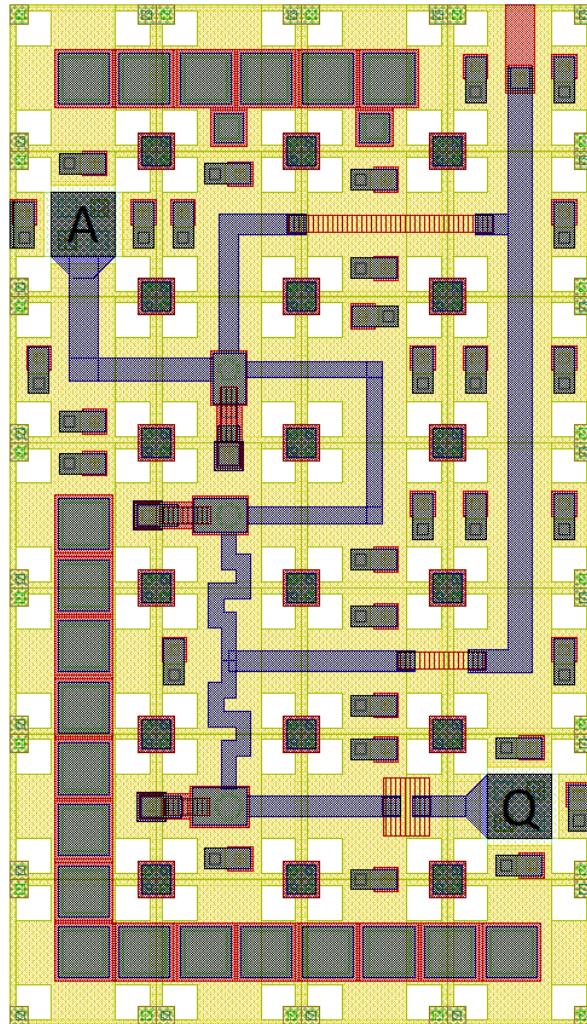
#### Schematic



**Figure 3.1:** Schematic of RSFQ JTLT.

## Layout

The physical layout for the RSFQ JTLT is shown in Fig. 3.2. The layout height is  $70 \mu\text{m}$  and the width is  $40 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.2:** RSFQ JTLT Layout.

**Table 3.1:** RSFQ JTLT pin list.

Pin	Description
a	Data input
q	Data output

**Analog model**

```

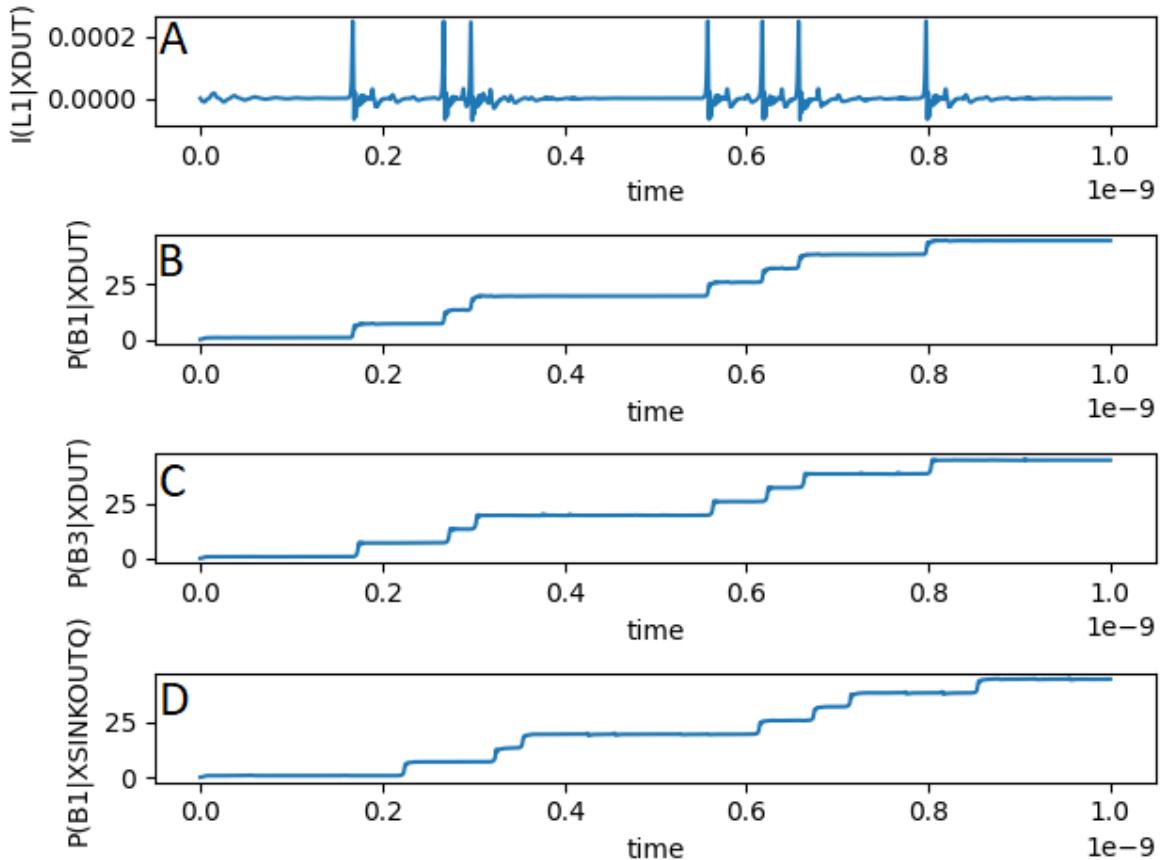
1 * Back-annotated simulation file written      34 .param LP1=LP
2   ↪ by InductEx v.6.0.4 on 26-4-21.          35 .param LP2=LP
3 * Author: L. Schindler                      36 .param LP3=LP
4 * Version: 2.1                               37 .param LB1=LB
5 * Last modification date: 8 June 2021       38 .param LB2=LB
6 * Last modification by: L. Schindler        39 .param RB1=B0Rs/B1
7 *$Ports a q                                40 .param RB2=B0Rs/B2
8 .subckt LSMITLL_JTLT a q                   41 .param RB3=B0Rs/B3
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    42 .param LRB1=(RB1/Rsheet)*Lsheet+LP
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA     43 .param LRB2=(RB2/Rsheet)*Lsheet+LP
   ↪ )                                         44 .param LRB3=(RB3/Rsheet)*Lsheet+LP
10 .param Phi0=2.067833848E-15                45 B1 6 7 jjmit area=B1
11 .param B0=1                                 46 B2 9 10 jjmit area=B2
12 .param Ic0=0.0001                           47 B3 12 13 jjmit area=B3
13 .param IcRs=100u*6.859904418               48 IB1 0 18 pwl(0 0 5p IB1)
14 .param B0Rs=IcRs/Ic0*B0                     49 IB2 0 19 pwl(0 0 5p IB2)
15 .param Rsheet=2                            50 L1 a 6 2.914E-12
16 .param Lsheet=1.13e-12                      51 L2 6 9 6.425E-12
17 .param LP=0.2p                             52 L3 9 16 2.566E-12
18 .param ICreceive=1.6                       53 L4 16 12 2.538E-12
19 .param ICtrans=2.5                         54 L5 12 17 2.312E-12
20 .param Lptl=2p                            55 LB1 6 18 2.904E-12
21 .param LB=2p                               56 LB2 16 19 2.517E-12
22 .param BiasCoef=0.7                        57 LP1 0 7 5.462E-13
23 .param RD=1.36                            58 LP2 0 10 5.434E-13
24 .param B1=1.62                            59 LP3 0 13 5.144E-13
25 .param B2=2.0                           60 LRB1 0 8 LRB1
26 .param B3=2.5                           61 LRB2 0 11 LRB2
27 .param IB1=112u                           62 LRB3 0 14 LRB3
28 .param IB2=315u                           63 RB1 8 6 RB1
29 .param L1=Lptl                            64 RB2 11 9 RB2
30 .param L2=Phi0/(2*B1*Ic0)                 65 RB3 14 12 RB3
31 .param L3=(Phi0/(2*B2*Ic0))/2            66 RD 17 q RD
32 .param L4=L3                             67 .ends
33 .param L5=Lptl

```

**Listing 3.1:** RSFQ JTLT JoSIM netlist.

The simulation results for the RSFQ JTLT using JoSIM is shown in Fig. 3.3. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit connected via a PTL to the JTLT.



**Figure 3.3:** RSFQ JTLT analog simulation results.

## Digital model

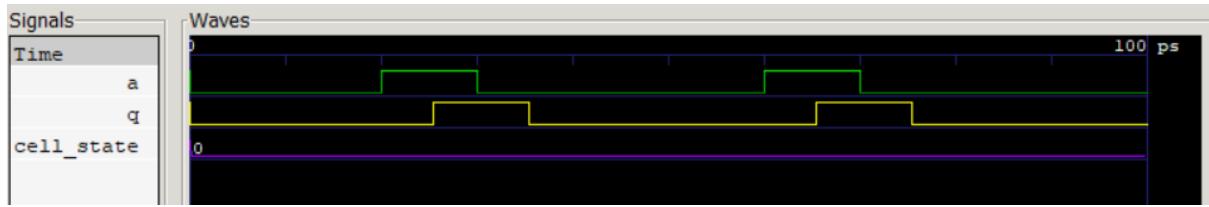
```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_JTLT_v2p1_optimized (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 real
20   delay_state0_a_q = 6.2,
21   ct_state0_a_a = 6.8;
22
23 reg
24   errorsignal_a;
25
26 integer
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q = 0; // All outputs start at 0
35 end
36
37 always @(posedge a or negedge a) // execute at positive and negative edges of input
38 begin
39   if ($time>4) // arbitrary steady-state time)
40     begin
41       if (errorsignal_a == 1'b1) // A critical timing is active for this input
42         begin
43           outfile = $fopen("errors.txt", "a");
44           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
45           ↪ ", $stime);
46           $fclose(outfile);
47           q <= 1'bX; // Set all outputs to unknown
48         end
49       if (errorsignal_a == 0)
50         begin
51           case (cell_state)
52             0: begin
53               q <= #(delay_state0_a_q) !q;
54               errorsignal_a = 1; // Critical timing on this input; assign
55               ↪ immediately
56               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
57               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

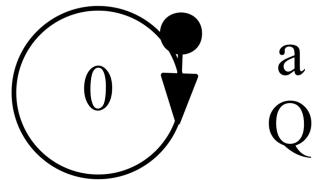
```

**Listing 3.2:** RSFQ JTLT verilog model.

The digital simulation results for the RSFQ JTLT is shown in Fig. 3.4 and the Mealy finite state machine diagram, extracted using *TimEx*, is shown in Fig. 3.5.



**Figure 3.4:** RSFQ JTLT digital simulation results.



**Figure 3.5:** RSFQ JTLT Mealy finite state machine diagram.

## Power Consumption

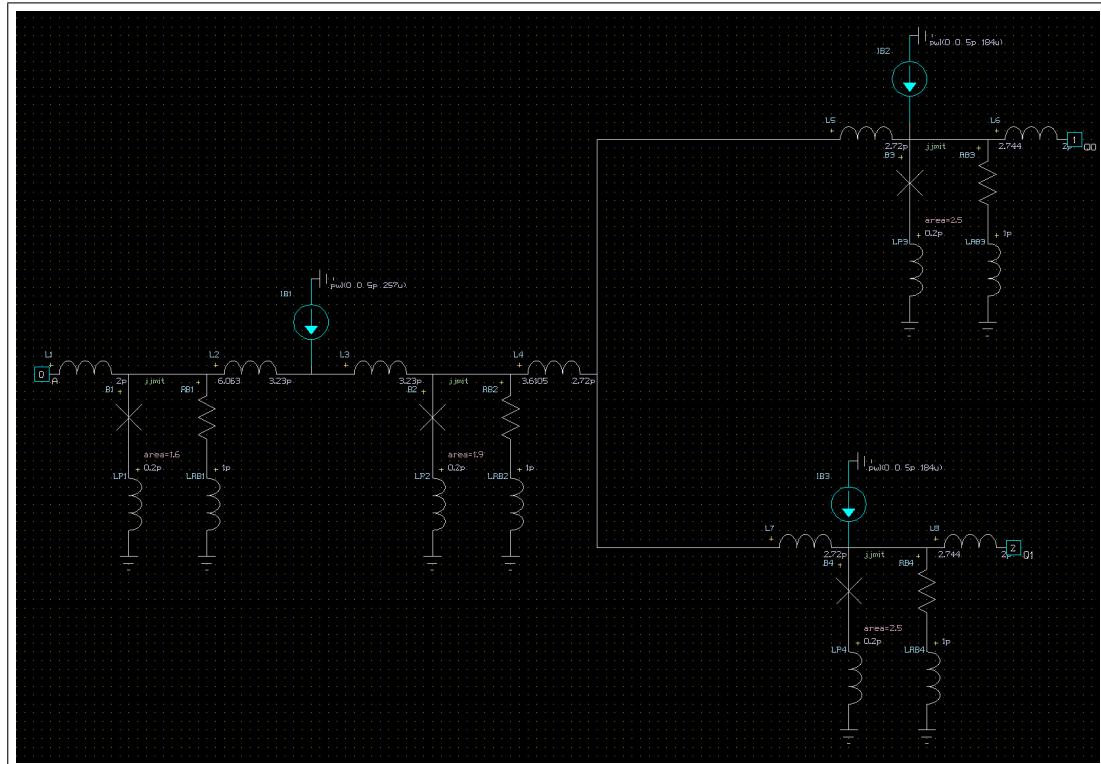
**Table 3.2:** RSFQ JTLT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	1110	1.26
2	1110	2.52
5	1110	6.31
10	1110	12.6
20	1110	25.2
50	1110	63.1

### 3.1.2 SPLITT

The SPLITT cell is used to split a single pulse signal line into two duplicate output pulse signal lines. The cell has integrated PTL transmitters and receivers and is meant to connect directly to a PTL.

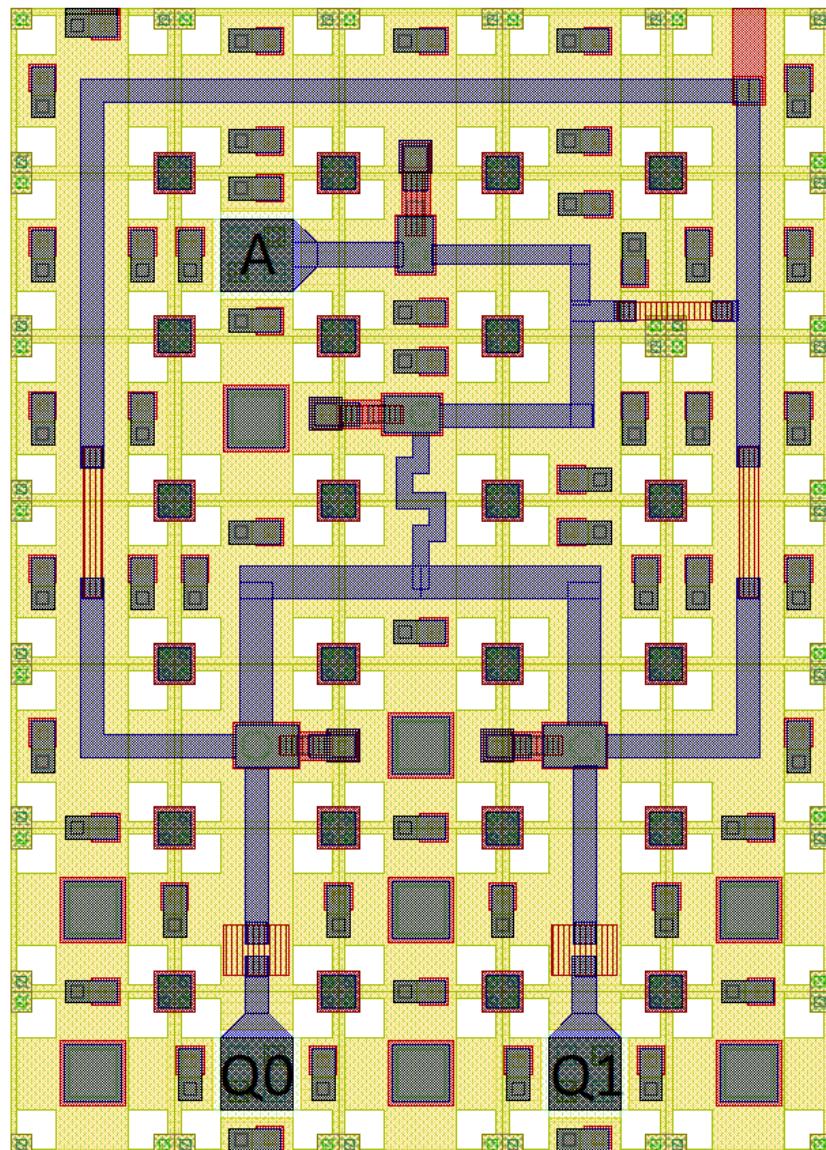
#### Schematic



**Figure 3.6:** Schematic of RSFQ SPLITT.

## Layout

The physical layout for the RSFQ SPLITT is shown in Fig. 3.7. The layout height is  $70 \mu m$  and the width is  $50 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.7:** RSFQ SPLITT layout.

## Analog model

```

1  * Back-annotated simulation file written      39 | .param L8=Lptl
2   ↪ by InductEx v.6.0.4 on 26-4-21.          40 | .param RB1=B0Rs/B1
3  * Author: L. Schindler                      41 | .param RB2=B0Rs/B2
4  * Version: 2.1                               42 | .param RB3=B0Rs/B3
5  * Last modification date: 26 April 2021     43 | .param RB4=B0Rs/B4
6  * Last modification by: L. Schindler        44 | .param LRB1=(RB1/Rsheet)*Lsheet
7  *$Ports                                         a q0 q1    45 | .param LRB2=(RB2/Rsheet)*Lsheet
8 .subckt LSMITLL_SPLITT a q0 q1              46 | .param LRB3=(RB3/Rsheet)*Lsheet
9 .model jjmit jj(rtype=1, vg=2.8mV, cap     47 | .param LRB4=(RB4/Rsheet)*Lsheet
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    48 | IB1 0 4 pwl(0 0 5p IB1)
   ↪ )                                           49 | IB2 0 8 pwl(0 0 5p IB2)
10 .param Phi0=2.067833848E-15                50 | IB3 0 11 pwl(0 0 5p IB3)
11 .param B0=1                                    51 | B1 2 3 jjmit area=B1
12 .param Ic0=0.0001                            52 | B2 5 6 jjmit area=B2
13 .param IcRs=100u*6.859904418                 53 | B3 8 9 jjmit area=B3
14 .param B0Rs=IcRs/Ic0*B0                     54 | B4 11 12 jjmit area=B4
15 .param Rsheet=2                                55 | L1 a 2 1.515E-12
16 .param Lsheet=1.13e-12                         56 | L2 2 4 2.836E-12
17 .param LP=0.2p                                57 | L3 4 5 2.85E-12
18 .param IC=2.5                                 58 | L4 5 7 2.68E-12
19 .param ICreceive=1.6                          59 | L5 7 8 2.699E-12
20 .param ICtrans=2.5                           60 | L6 8 10 2.364E-12
21 .param Lptl=2p                                61 | L7 7 11 2.704E-12
22 .param BiasCoef=0.7                          62 | L8 11 13 2.369E-12
23 .param RD=1.36                                63 | LP1 3 0 4.521E-13
24                                         64 | LP2 6 0 5.395E-13
25 .param B1=1.6                                 65 | LP3 9 0 5.061E-13
26 .param B2=1.67                                66 | LP4 12 0 5.078E-13
27 .param B3=2.5                                 67 | RB1 2 102 RB1
28 .param B4=2.5                                 68 | LRB1 102 0 LRB1
29 .param IB1=225u                               69 | RB2 5 105 RB2
30 .param IB2=185u                               70 | LRB2 105 0 LRB2
31 .param IB3=185u                               71 | RB3 8 108 RB3
32 .param L1=Lptl                                72 | LRB3 108 0 LRB3
33 .param L2=(Phi0/(2*B1*Ic0))/2                73 | RB4 11 111 RB4
34 .param L3=(Phi0/(2*B1*Ic0))/2                74 | LRB4 111 0 LRB4
35 .param L4=(Phi0/(2*B2*Ic0))/2                75 | RD1 13 q0 RD
36 .param L5=(Phi0/(2*B2*Ic0))/2                76 | RD2 10 q1 RD
37 .param L6=Lptl                                77 | .ends
38 .param L7=(Phi0/(2*B2*Ic0))/2

```

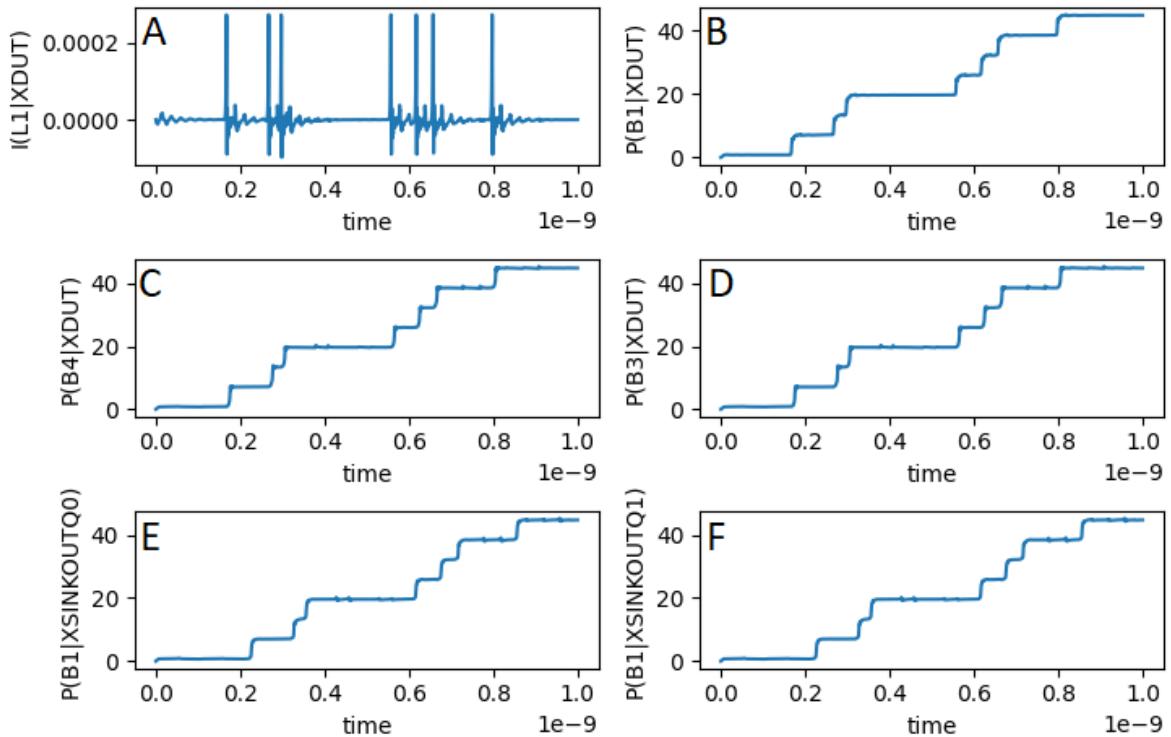
**Listing 3.3:** RSFQ SPLITT JoSIM netlist.

**Table 3.3:** RSFQ SPLITT pin list.

Pin	Description
a	Data input
q0	Data output
q1	Data output

The JoSIM simulation results for the RSFQ SPLITT are shown in Fig. 3.8. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q0**,
- (d) the phase over the output JJ of pin **q1**,
- (e) the phase over the input JJ of the load cell connected to pin **q0** through a PTL, and
- (f) the phase over the input JJ of the load cell connected to pin **q1** through a PTL.



**Figure 3.8:** RSFQ SPLITT analog simulation results.

## Digital model

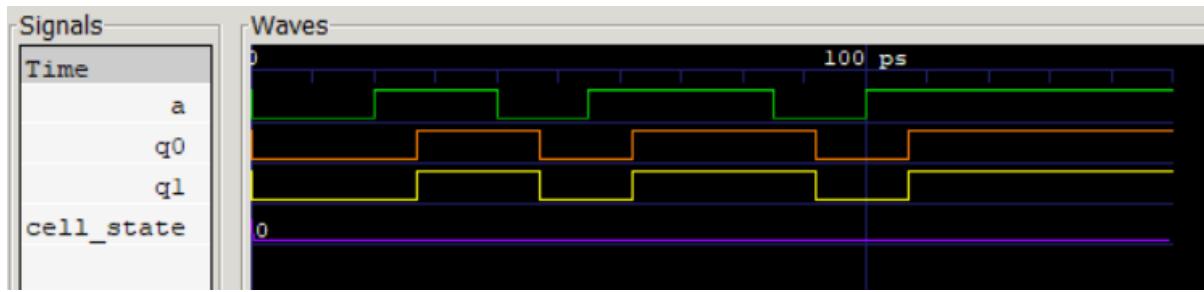
```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 8 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_SPLITT_v2p1_optimized (a, q0, q1);
9   input
10    a;
11   output
12    q0, q1;
13   reg
14    q0, q1;
15   real
16    delay_state0_a_q0 = 7.3,
17    delay_state0_a_q1 = 7.3,
18    ct_state0_a_a = 9.1;
19
20   reg
21    errorsignal_a;
22
23   integer
24    outfile,
25    cell_state; // internal state of the cell
26   initial
27    begin
28      errorsignal_a = 0;
29      cell_state = 0; // Startup state
30      q0 = 0; // All outputs start at 0
31      q1 = 0; // All outputs start at 0
32    end
33
34   always @(posedge a or negedge a) // execute at positive and negative edges of input
35   begin
36     if ($time>4) // arbitrary steady-state time)
37     begin
38       if (errorsignal_a == 1'b1) // A critical timing is active for this input
39         begin
40           outfile = $fopen("errors.txt", "a");
41           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m; %0d_ps.\n"
42                         , $stime);
43           $fclose(outfile);
44           q0 <= 1'bX; // Set all outputs to unknown
45           q1 <= 1'bX; // Set all outputs to unknown
46         end
47       if (errorsignal_a == 0)
48         begin
49           case (cell_state)
50             0: begin
51               q0 <= #(delay_state0_a_q0) !q0;
52               q1 <= #(delay_state0_a_q1) !q1;
53               errorsignal_a = 1; // Critical timing on this input; assign
54                                         // immediately
55               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
56                                         // after critical timing expires
57             end
58           endcase
59         end
60       end
61     end
62   endmodule

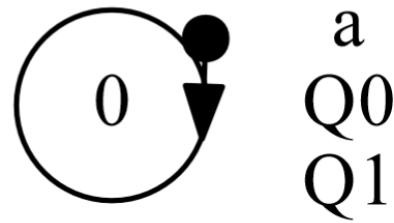
```

**Listing 3.4:** RSFQ SPLITT verilog model.

The digital simulation results for the RSFQ SPLITT is shown in Fig. 3.9 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.10.



**Figure 3.9:** RSFQ SPLITT digital simulation results.



**Figure 3.10:** RSFQ SPLITT Mealy finite state diagram.

### Power consumption

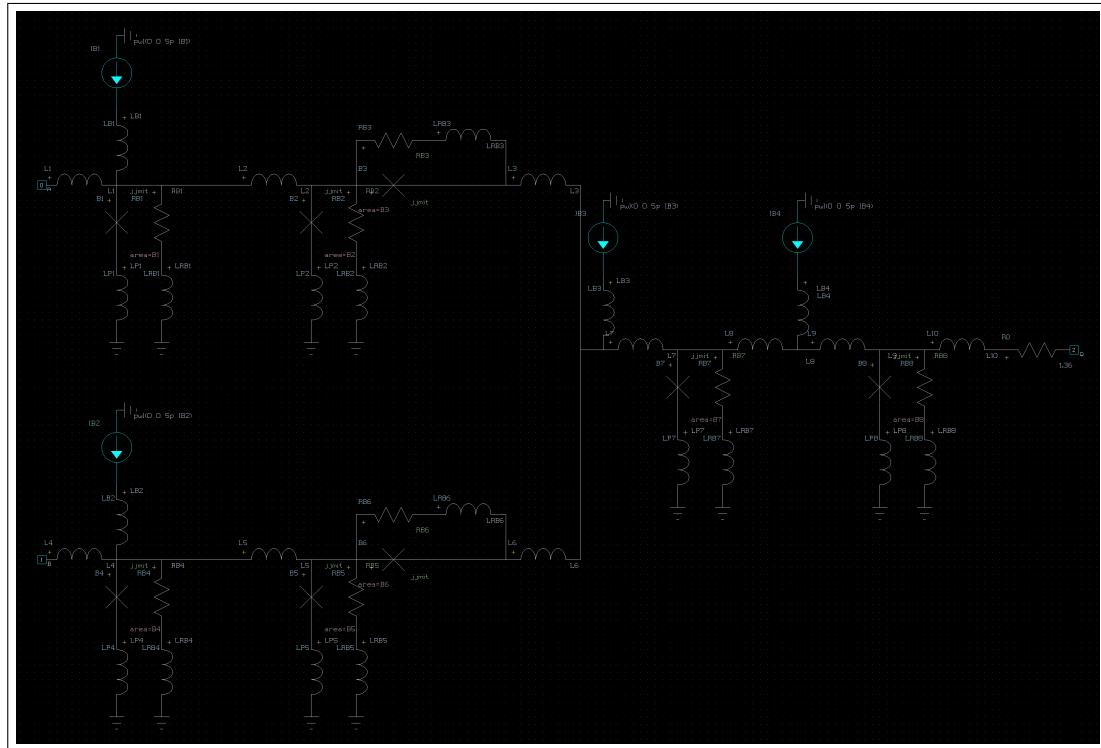
**Table 3.4:** RSFQ SPLITT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	1547	1.71
2	1547	3.42
5	1547	8.55
10	1547	17.1
20	1547	34.2
50	1547	85.5

### 3.1.3 MERGET

The MERGET joins two input pulse signal lines and provides a single output pulse signal line. If there is a pulse on either input lines, the MERGET will generate a pulse on the output signal line. The MERGET has integrated PTL transmitters and receivers is designed to be directly connected to a PTL.

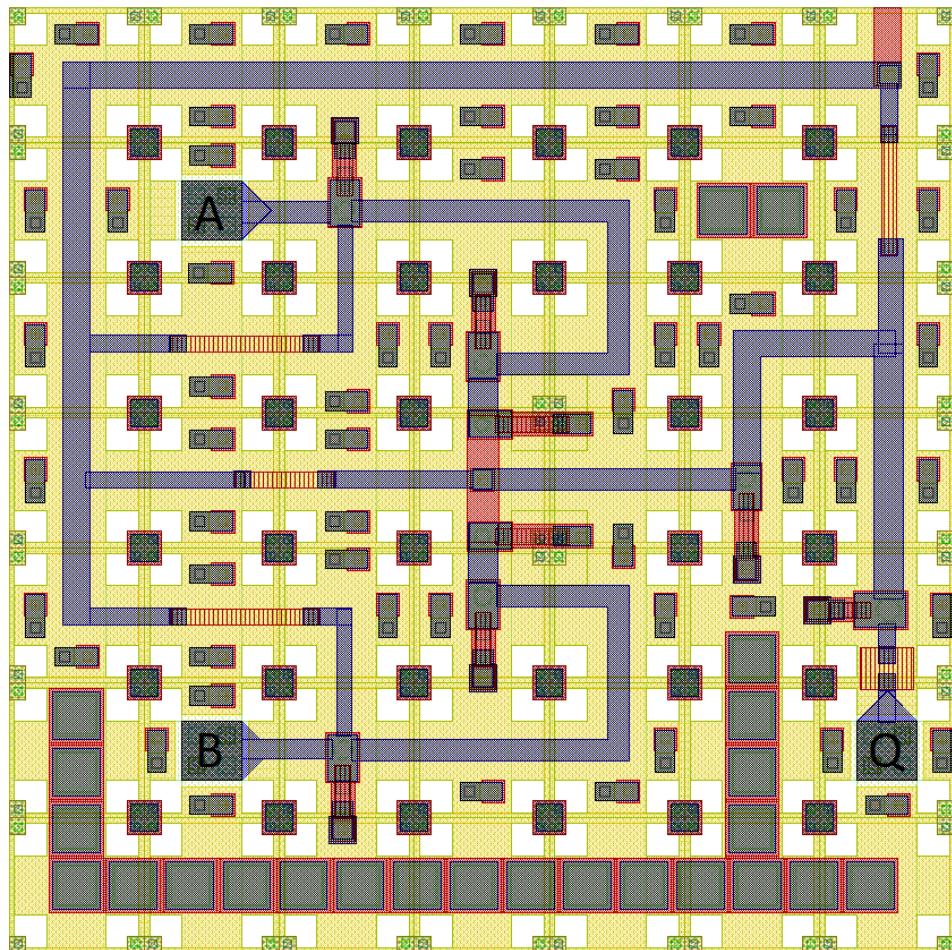
#### Schematic



**Figure 3.11:** Schematic of RSFQ MERGET.

## Layout

The physical layout of the RSFQ MERGET is shown in Fig. 3.12. The height of the layout is  $70 \mu\text{m}$  and the width is  $70 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.12:** RSFQ MERGET layout.

## Analog model

```

1  * Back-annotated simulation file written      58 | .param LRB3=(RB3/Rsheet)*Lsheet
2  *   ↪ by InductEx v.6.0.4 on 27-4-21.        59 | .param LRB4=(RB4/Rsheet)*Lsheet
3  * Author: L. Schindler                      60 | .param LRB5=(RB5/Rsheet)*Lsheet
4  * Version: 2.1                                61 | .param LRB6=(RB6/Rsheet)*Lsheet
5  * Last modification date: 27 April 2021       62 | .param LRB7=(RB7/Rsheet)*Lsheet
6  * Last modification by: L. Schindler          63 | .param LRB8=(RB8/Rsheet)*Lsheet
7  *$ports a b q
8  .subckt LSmitll_MERGET a b q
9  .model jjmit jj(rtype=1, vg=2.8mV, cap
10    ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA
11    ↪ )
12 .param Phi0=2.067833848E-15
13 .param B0=1
14 .param Ic0=0.0001
15 .param IcRs=100u*6.859904418
16 .param B0Rs=IcRs/Ic0*B0
17 .param Rsheet=2
18 .param Lsheet=1.13e-12
19 .param LP=0.2p
20 .param IC=2.5
21 .param ICreceive=1.6
22 .param ICtrans=2.5
23 .param Lptl=2p
24 .param LB=2p
25 .param BiasCoef=0.70
26 .param RD=1.36
27 .param B1=1.6
28 .param B2=1.54
29 .param B3=0.95
30 .param B4=B1
31 .param B5=B2
32 .param B6=B3
33 .param B7=1.16
34 .param B8=2.5
35 .param L1=Lptl
36 .param L2=Phi0/(2*B1*Ic0)
37 .param L3=Phi0/(2*B2*Ic0)*(B7/(B2+B7))
38 .param L4=L1
39 .param L5=L2
40 .param L6=L3
41 .param L7=Phi0/(2*B3*Ic0)*(B2/(B2+B7))
42 .param L8=(Phi0/(2*B7*Ic0))*(B8/(B7+B8))
43 .param L9=(Phi0/(2*B7*Ic0))*(B7/(B7+B8))
44 .param L10=Lptl
45 .param IB1=148u
46 .param IB2=148u
47 .param IB3=241u
48 .param IB4=176u
49 .param RB1=B0Rs/B1
50 .param RB2=B0Rs/B2
51 .param RB3=B0Rs/B3
52 .param RB4=B0Rs/B4
53 .param RB5=B0Rs/B5
54 .param RB6=B0Rs/B6
55 .param RB7=B0Rs/B7
56 .param RB8=B0Rs/B8
57 .param LRB1=(RB1/Rsheet)*Lsheet
58 .param LRB2=(RB2/Rsheet)*Lsheet
59 .param LRB3=(RB3/Rsheet)*Lsheet
60 .param LRB4=(RB4/Rsheet)*Lsheet
61 .param LRB5=(RB5/Rsheet)*Lsheet
62 .param LRB6=(RB6/Rsheet)*Lsheet
63 .param LRB7=(RB7/Rsheet)*Lsheet
64 .param LRB8=(RB8/Rsheet)*Lsheet
65 L1 a 1 1.439E-12
66 L2 1 4 6.953E-12
67 L3 4 6 1.156E-12
68 L4 b 8 1.462E-12
69 L5 8 11 6.998E-12
70 L6 11 13 1.166E-12
71 L7 7 15 3.436E-12
72 L8 15 19 2.713E-12
73 L9 17 19 2.713E-12
74 L10 19 21 7.598E-13
75 RD 21 q RD
76 IB1 0 3 pwl(0 0 5p IB1)
77 IB2 0 10 pwl(0 0 5p IB2)
78 IB3 0 14 pwl(0 0 5p IB3)
79 IB4 0 18 pwl(0 0 5p IB4)
80 B1 1 2 jjmit area=B1
81 B2 4 5 jjmit area=B2
82 B3 6 7 jjmit area=B3
83 B4 8 9 jjmit area=B4
84 B5 11 12 jjmit area=B5
85 B6 13 7 jjmit area=B6
86 B7 15 16 jjmit area=B7
87 B8 19 20 jjmit area=B8
88 LP1 2 0 4.853E-13
89 LP2 5 0 5.381E-13
90 LP4 9 0 4.789E-13
91 LP5 12 0 5.351E-13
92 LP7 16 9 5.981E-13
93 LP8 20 0 3.813E-13
94 RB1 1 101 RB1
95 RB2 4 104 RB2
96 RB3 6 106 RB3
97 RB4 8 108 RB4
98 RB5 11 111 RB5
99 RB6 13 113 RB6
100 RB7 15 115 RB7
101 RB8 19 119 RB8
102 LRB1 101 0 LRB1
103 LRB2 104 0 LRB2
104 LRB3 106 7 LRB3
105 LRB4 108 0 LRB4
106 LRB5 111 0 LRB5
107 LRB6 113 7 LRB6
108 LRB7 115 0 LRB7
109 LRB8 119 0 LRB8
110 LB1 1 3 2.952E-12
111 LB2 8 10 2.928E-12
112 LB3 7 14 2.643E-12
113 LB4 17 18 1.428E-12
114 .ends

```

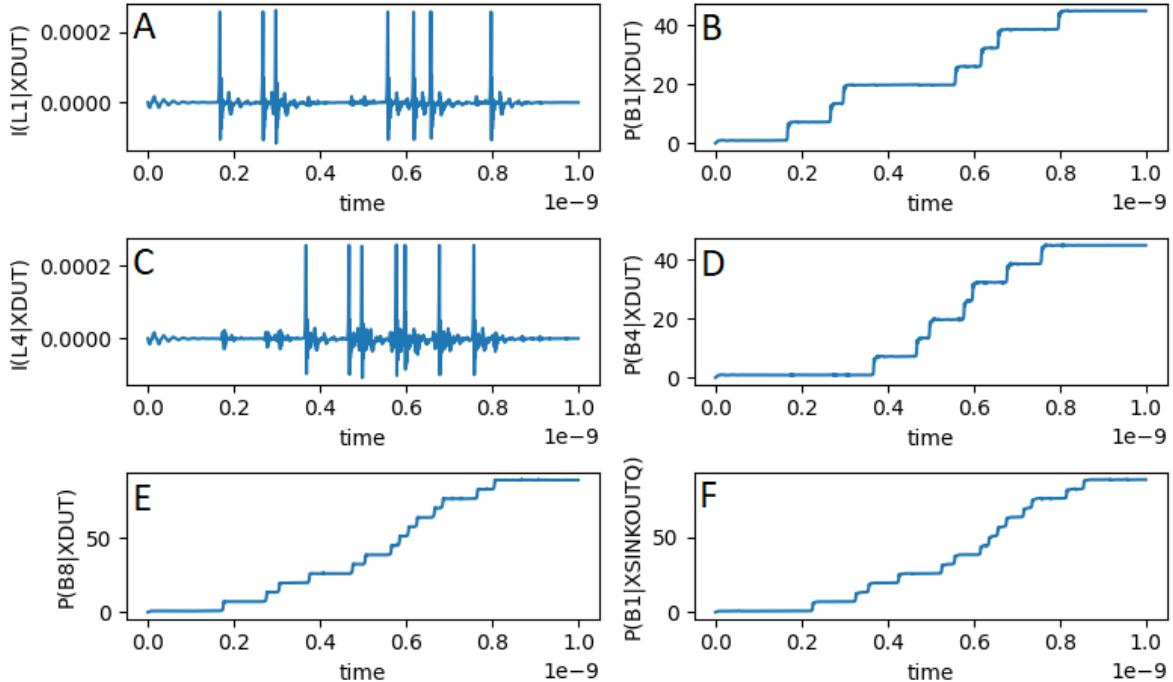
**Listing 3.5:** RSFQ MERGET JoSIM netlist.

**Table 3.5:** RSFQ MERGET pin list.

Pin	Description
<b>a</b>	Data input
<b>b</b>	Data input
<b>q</b>	Data output

The JoSIM simulation results for the RSFQ MERGET are shown in Fig. 3.13. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the phase over the output JJ of pin **q**,
- (f) the phase over the input JJ of the load cell connected to pin **q** via a PTL.

**Figure 3.13:** RSFQ MERGET analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 8 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 // -----
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 // -----
15 'timescale 1ps/100fs
16 module LSmitll_MERGET_v2p1_optimized (a, b, q);
17
18 input
19   a, b;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state0_a_q = 8.0,
29   delay_state0_b_q = 8.0,
30   ct_state0_a_a = 3.3,
31   ct_state0_a_b = 3.2,
32   ct_state0_b_a = 2.3,
33   ct_state0_b_b = 3.3;
34
35 reg
36   errorsignal_a,
37   errorsignal_b;
38
39 integer
40   outfile,
41   cell_state; // internal state of the cell
42
43 initial
44 begin
45   errorsignal_a = 0;
46   errorsignal_b = 0;
47   cell_state = 0; // Startup state
48   q = 0; // All outputs start at 0
49 end
50
51 always @(posedge a or negedge a) // execute at positive and negative edges of input
52 begin
53   if ($time>4) // arbitrary steady-state time)
54     begin
55       if (errorsignal_a == 1'b1) // A critical timing is active for this input
56         begin
57           outfile = $fopen("errors.txt", "a");
58           $fdisplay(outfile, "Violation of critical timing in module %m; %0d ps.\n",
59           ↪ ", $stime);
60           $fclose(outfile);
61           q <= 1'bX; // Set all outputs to unknown
62         end
63       if (errorsignal_a == 0)
64         begin
65           case (cell_state)
66             0: begin
67               q <= #(delay_state0_a_q) !q;

```

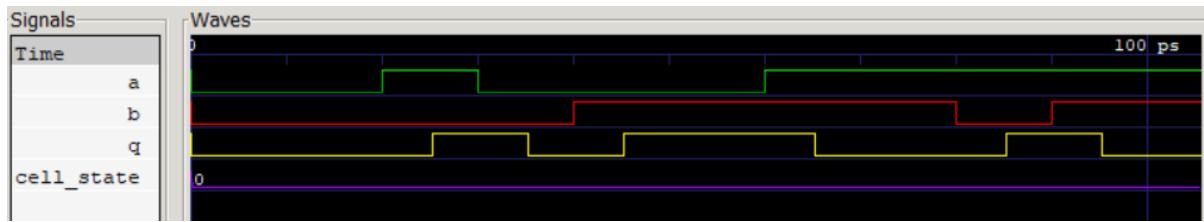
```

67          errorsignal_a = 1; // Critical timing on this input; assign
68          //      ↪ immediately
69          errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
70          //      ↪ after critical timing expires
71          errorsignal_b = 1; // Critical timing on this input; assign
72          //      ↪ immediately
73          errorsignal_b <= #(ct_state0_a_b) 0; // Clear error signal
74          //      ↪ after critical timing expires
75      end
76  endcase
77 end
78
79 always @ (posedge b or negedge b) // execute at positive and negative edges of input
80 begin
81     if ($time>4) // arbitrary steady-state time)
82     begin
83         if (errorsignal_b == 1'b1) // A critical timing is active for this input
84         begin
85             outfile = $fopen("errors.txt", "a");
86             $fdisplay(outfile, "Violation of critical timing in module %m; %0d ps.\n"
87             //      ↪ ", $stime);
88             $fclose(outfile);
89             q <= 1'bX; // Set all outputs to unknown
90         end
91         if (errorsignal_b == 0)
92         begin
93             case (cell_state)
94                 0: begin
95                     q <= #(delay_state0_b_q) !q;
96                     errorsignal_a = 1; // Critical timing on this input; assign
97                     //      ↪ immediately
98                     errorsignal_a <= #(ct_state0_b_a) 0; // Clear error signal
99                     //      ↪ after critical timing expires
100                    errorsignal_b = 1; // Critical timing on this input; assign
101                    //      ↪ immediately
102                    errorsignal_b <= #(ct_state0_b_b) 0; // Clear error signal
103                    //      ↪ after critical timing expires
104                end
105            endcase
106        end
107    end
108 endmodule

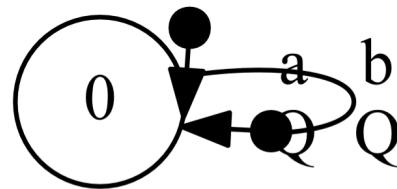
```

**Listing 3.6:** RSFQ MERGET verilog model.

The digital simulation results for the RSFQ MERGET is shown in Fig. 3.14 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.15.



**Figure 3.14:** RSFQ MERGET digital simulation results.



**Figure 3.15:** RSFQ MERGET Mealy finite state diagram.

## Power consumption

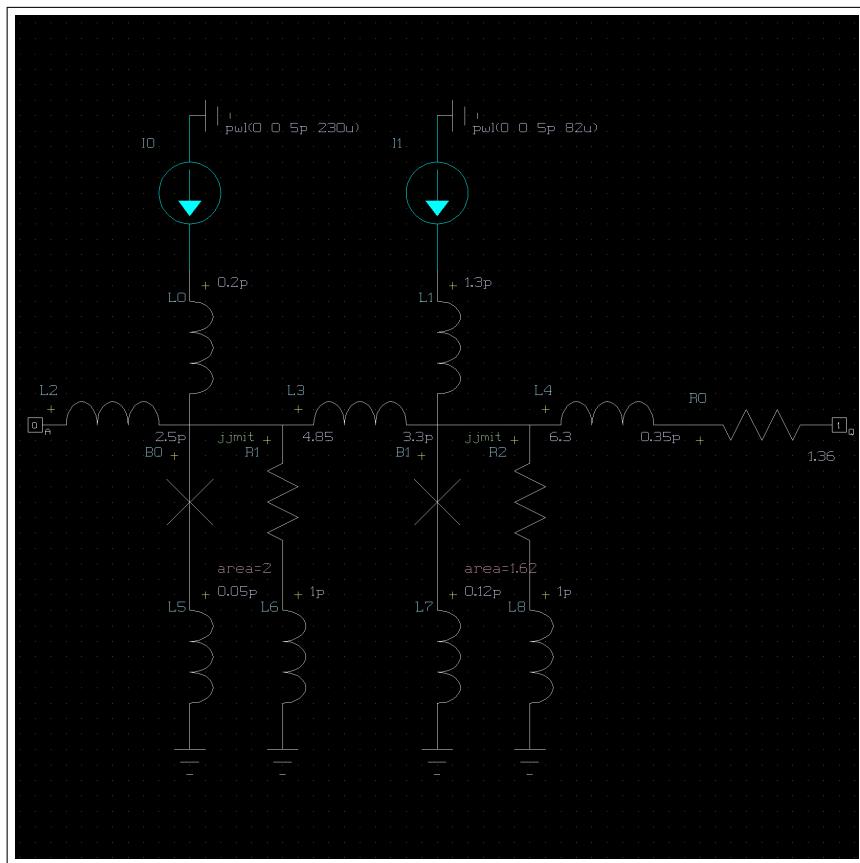
**Table 3.6:** RSFQ MERGET power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	1851	2.45
2	1851	4.90
5	1851	12.2
10	1851	24.5
20	1851	49.0
50	1851	122

### 3.1.4 PTLTX

The RSFQ PTLTX is a cell which transmits a pulse signal over a PTL. It is connected to a cell which is not designed to connect to PTLs, if a PTL connection is required.

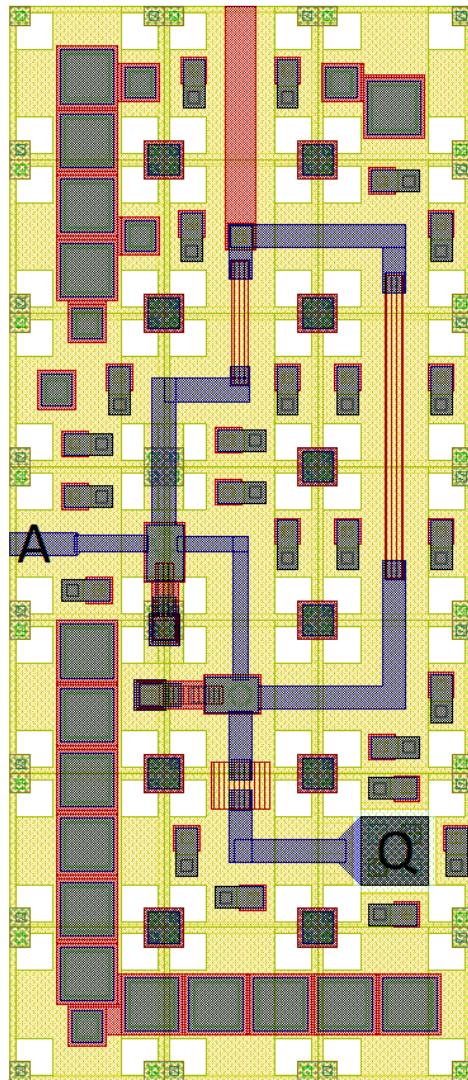
#### Schematic



**Figure 3.16:** Schematic of RSFQ PTLTX.

## Layout

The physical layout for the RSFQ PTLTX is shown in Fig. 3.17. The layout height is  $70 \mu\text{m}$  and the width is  $30 \mu\text{m}$ . The bias line is located on M5 at the top centre of the cell.



**Figure 3.17:** RSFQ PTLTX Layout.

## Analog model

```

1  * Back-annotated simulation file written      29 | .param L2=3.3p
2   ↪ by InductEx v.6.0.4 on 3-6-21.          30 | .param L3=Lptl
3  * Author: L. Schindler                     31 | .param LB1=LB
4  * Version: 2.1                            32 | .param LB2=LB
5  * Last modification date: 24 April 2021    33 | .param LP1=LP
6  * Last modification by: L. Schindler       34 | .param LP2=LP
7  *$Ports a q                                35 | .param RB1=B0Rs/B1
8 .subckt LSmitll_PTLTX a q                  36 | .param RB2=B0Rs/B2
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    37 | .param LRB1=(RB1/Rsheet)*Lsheet
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA     38 | .param LRB2=(RB2/Rsheet)*Lsheet
   ↪ )                                         39 |
10 .param Phi0=2.067833848E-15                40 |
11 .param B0=1                                  41 B1 3 8 jjmit area=B1
12 .param Ic0=0.0001                           42 B2 4 10 jjmit area=B2
13 .param IcRs=100u*6.859904418               43 IB1 0 5 pw1(0 0 5p IB1)
14 .param B0Rs=IcRs/Ic0*B0                   44 IB2 0 6 pw1(0 0 5p IB2)
15 .param Rsheet=2                            45 LB1 5 3 2.86E-12
16 .param Lsheet=1.13e-12                      46 LB2 6 4 3.424E-12
17 .param LP=0.2p                            47 L1 a 3 2.256E-12
18 .param LB=2p                             48 L2 3 4 3.32E-12
19 .param Lptl=2p                           49 L3 4 7 1.026E-12
20 .param RD=1.36                           50 RD 7 q RD
21 .param B1=2                               51 LP1 8 0 5.122E-13
22 .param B2=1.62                           52 LP2 10 0 4.727E-13
23 .param IB1=230u                           53 RB1 3 9 RB1
24 .param IB2=82u                           54 RB2 4 11 RB2
25 .param L1=2.5p                           55 LRB1 9 0 LRB1
26 .param L2=3.3p                           56 LRB2 11 0 LRB2
27 .param L3=Lptl                         57 .ends
28

```

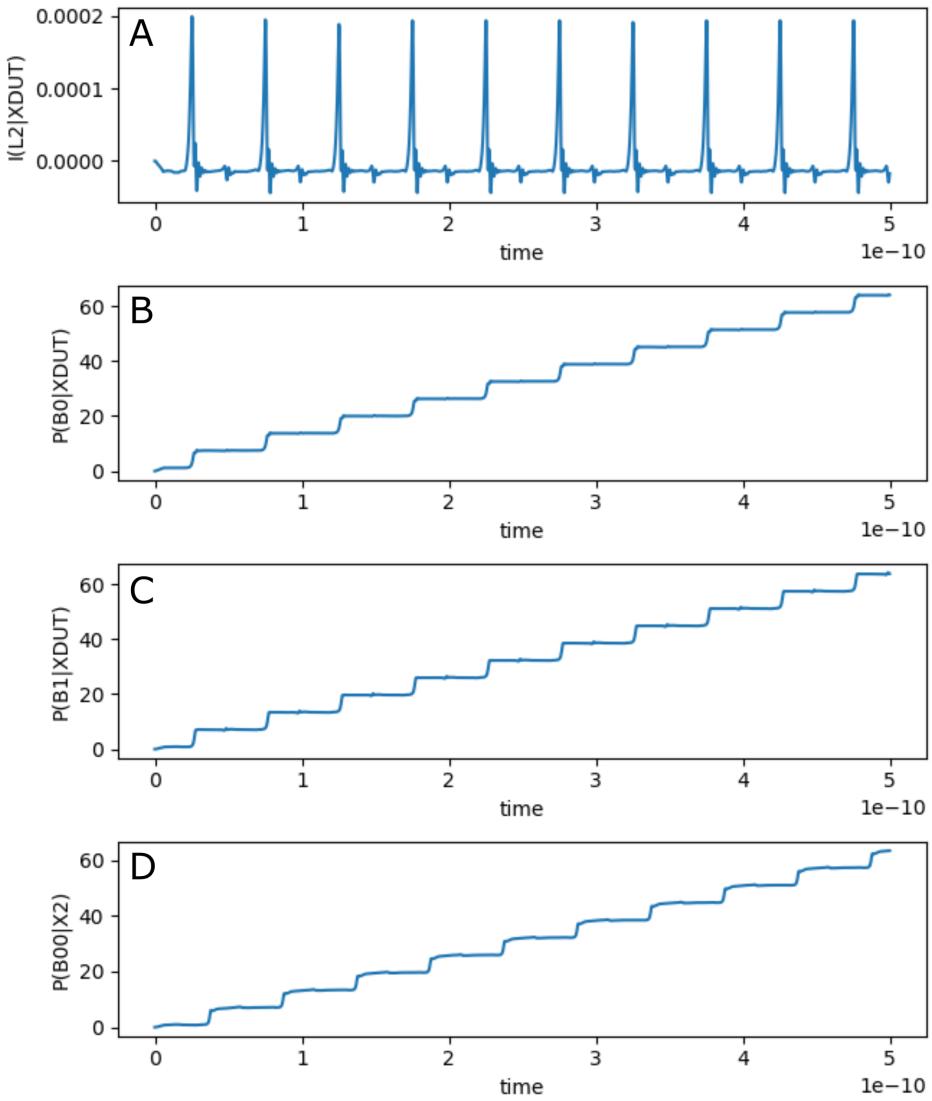
**Listing 3.7:** RSFQ PTLTX JoSIM netlist.

**Table 3.7:** RSFQ PTLTX pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ PTLTX using JoSIM is shown in Fig. 3.18. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit connected via a PTL to the PTLTX.



**Figure 3.18:** RSFQ PTLTX analog simulation results.

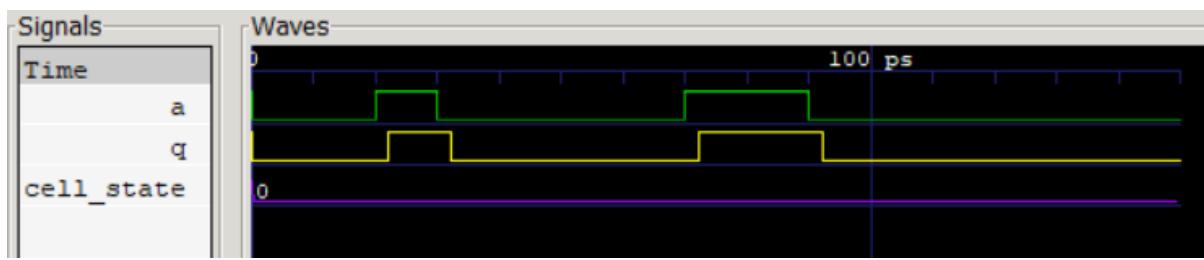
## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_ptltx_v2p1 (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 real
20   delay_state0_a_q = 2.2,
21   ct_state0_a_a = 3.5;
22
23 reg
24   errorsignal_a;
25
26 integer
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q = 0; // All outputs start at 0
35 end
36
37 always @(posedge a or negedge a) // execute at positive and negative edges of input
38 begin
39   if ($time>4) // arbitrary steady-state time)
40     begin
41       if (errorsignal_a == 1'b1) // A critical timing is active for this input
42         begin
43           outfile = $fopen("errors.txt", "a");
44           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
45           ↪ ", $stime);
46           $fclose(outfile);
47           q <= 1'bX; // Set all outputs to unknown
48         end
49       if (errorsignal_a == 0)
50         begin
51           case (cell_state)
52             0: begin
53               q <= #(delay_state0_a_q) !q;
54               errorsignal_a = 1; // Critical timing on this input; assign
55               ↪ immediately
56               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
57               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

```

**Listing 3.8:** RSFQ PTLTX verilog model.



**Figure 3.19:** RSFQ PTLTX digital simulation results.

The digital simulation results for the RSFQ PTLTX is shown in Fig. 3.19.

### Power Consumption

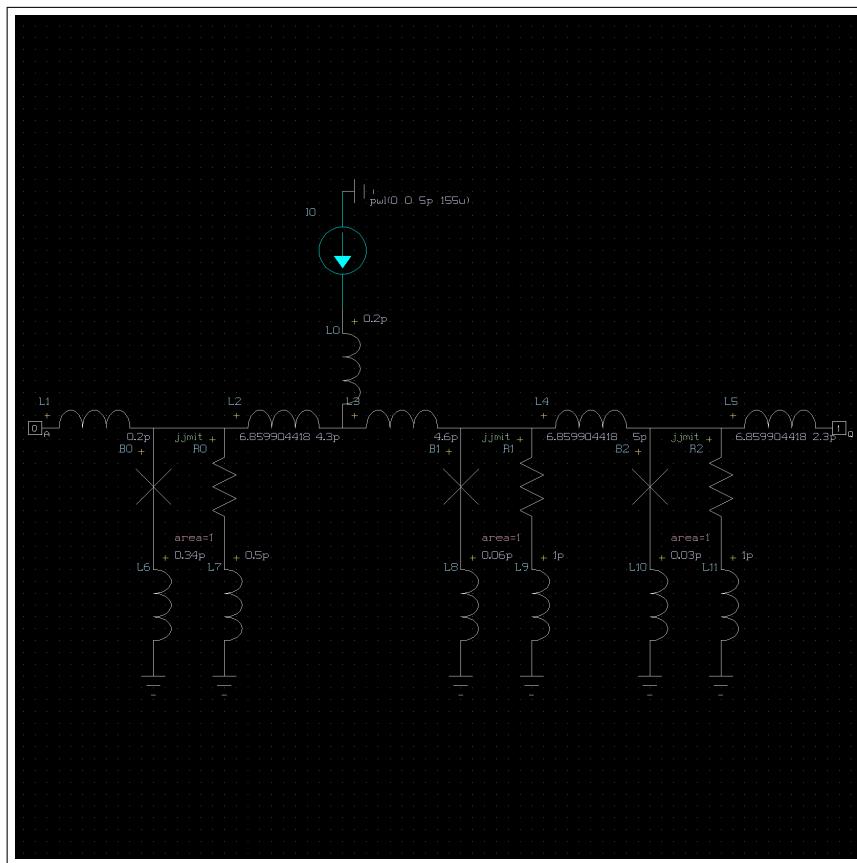
**Table 3.8:** RSFQ PTLTX power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	811	0.75
2	811	1.50
5	811	3.74
10	811	7.49
20	811	15.0
50	811	37.4

### 3.1.5 PTLRX

The PTLRX is a receiver cell which receives a pulse signal from a PTL. It is connected to cells that are not designed to connect to PTLs when a PTL connection is required.

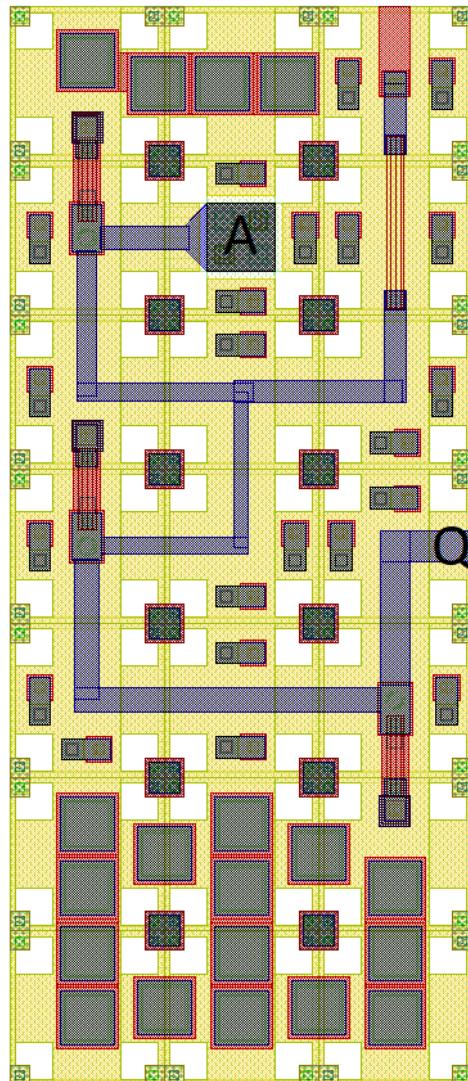
#### Schematic



**Figure 3.20:** Schematic of RSFQ PTLRX.

## Layout

The physical layout for the RSFQ PTLRX is shown in Fig. 3.21. The layout height is  $70 \mu m$  and the width is  $30 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.21:** RSFQ PTLRX Layout.

## Analog model

```

1  * Back-annotated simulation file written      34 | .param LP2=LP
2   ↪ by InductEx v.6.0.4 on 3-6-21.          35 | .param LP3=LP
3  * Author: L. Schindler                     36 |
4  * Version: 2.1                            37 | .param RB1=B0Rs/B1
5  * Last modification date: 3 June 2021     38 | .param RB2=B0Rs/B2
6  * Last modification by: L. Schindler       39 | .param RB3=B0Rs/B3
7  *$Ports a q                                40 | .param LRB1=(RB1/Rsheet)*Lsheet
8 .subckt LSmitll_PTLRX a q                  41 | .param LRB2=(RB2/Rsheet)*Lsheet
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    42 | .param LRB3=(RB3/Rsheet)*Lsheet
10  ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    43 |
11 .param B0=1                                 44 | B1 3 8 jjmit area=B1
12 .param Ic0=0.0001                           45 | B2 4 10 jjmit area=B2
13 .param B0Rs=IcRs/Ic0*B0                   46 | B3 5 12 jjmit area=B3
14 .param Rsheet=2                            47 |
15 .param Lsheet=1.13e-12                      48 | IB1 0 6 pwl(0 0 5p IB1)
16 .param LP=0.5p                             49 | LB1 6 7 3.274E-12
17 .param LB=2p                               50 | L1 a 3 1.499E-12
18 .param Lptl=2p                            51 | L2 3 7 4.327E-12
19                                         52 | L3 7 4 4.63E-12
20 .param B1=1                                 53 | L4 4 5 4.962E-12
21 .param B2=1                                 54 | L5 5 q 2.298E-12
22 .param B3=1                                 55 |
23                                         56 | LP1 8 0 5.404E-13
24 .param IB1=155u                            57 | LP2 10 0 6.269E-13
25                                         58 | LP3 12 0 6.253E-13
26 .param L1=Lptl                            59 |
27 .param L2=4.3p                            60 | RB1 3 9 RB1
28 .param L3=4.6p                            61 | RB2 4 11 RB2
29 .param L4=5p                               62 | RB3 5 13 RB3
30 .param L5=2.3p                            63 | LRB1 9 0 LRB1
31                                         64 | LRB2 11 0 LRB2
32 .param LB1=LB                            65 | LRB3 13 0 LRB3
33 .param LP1=LP                            66 | .ends

```

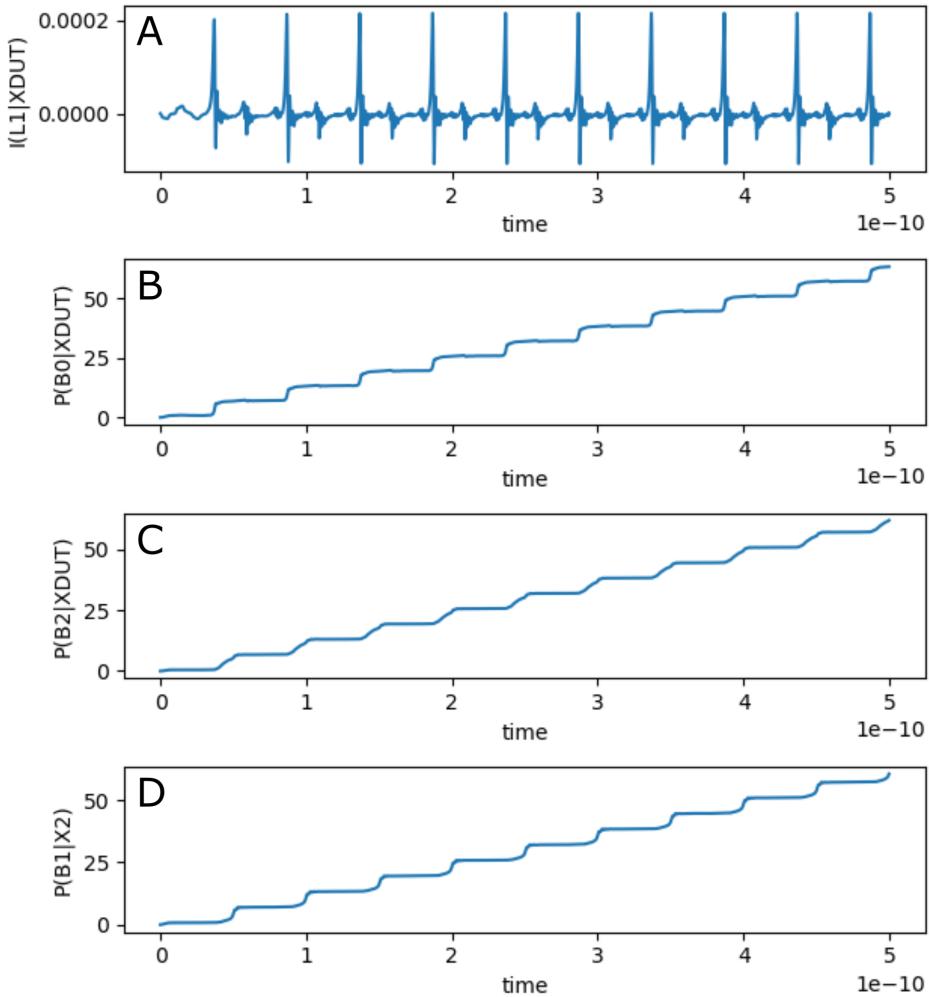
**Listing 3.9:** RSFQ PTLRX JoSIM netlist.

**Table 3.9:** RSFQ PTLRX pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ PTLRX using JoSIM is shown in Fig. 3.22. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit connected to pin **q**.



**Figure 3.22:** RSFQ PTLRX analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_ptlrx_v2p1 (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 real
20   delay_state0_a_q = 5.3,
21   ct_state0_a_a = 11.3;
22
23 reg
24   errorsignal_a;
25
26 integer
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q = 0; // All outputs start at 0
35 end
36
37 always @(posedge a or negedge a) // execute at positive and negative edges of input
38 begin
39   if ($time>4) // arbitrary steady-state time)
40     begin
41       if (errorsignal_a == 1'b1) // A critical timing is active for this input
42         begin
43           outfile = $fopen("errors.txt", "a");
44           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
45           ↪ ", $stime);
46           $fclose(outfile);
47           q <= 1'bX; // Set all outputs to unknown
48         end
49       if (errorsignal_a == 0)
50         begin
51           case (cell_state)
52             0: begin
53               q <= #(delay_state0_a_q) !q;
54               errorsignal_a = 1; // Critical timing on this input; assign
55               ↪ immediately
56               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
57               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

```

**Listing 3.10:** RSFQ PTLRX verilog model.



**Figure 3.23:** RSFQ PTLRX digital simulation results.

The digital simulation results for the RSFQ PTLRX is shown in Fig. 3.23.

### Power Consumption

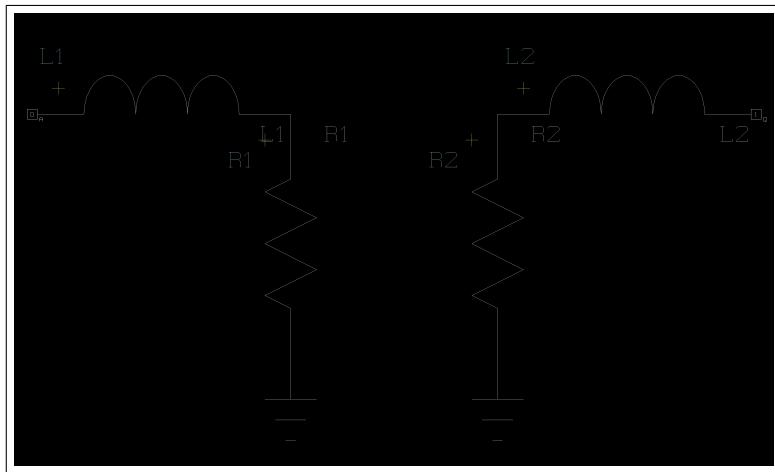
**Table 3.10:** RSFQ PTLRX power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	403	0.62
2	403	1.24
5	403	3.10
10	403	6.20
20	403	12.4
50	403	31.0

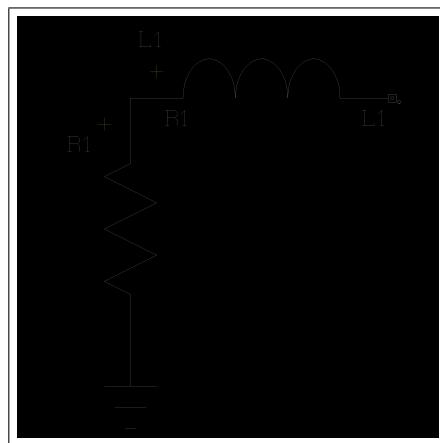
### 3.1.6 Always0T Asynchronous

The Always0T Asynchronous cell provides an output which is always zero. Two versions of the cell exist: One with an **a** input port, as seen in Fig. 3.24, and one without an **a** input port, as seen in Fig. 3.25. The Always0T Asynchronous is designed to be directly connected to a PTL.

#### Schematic



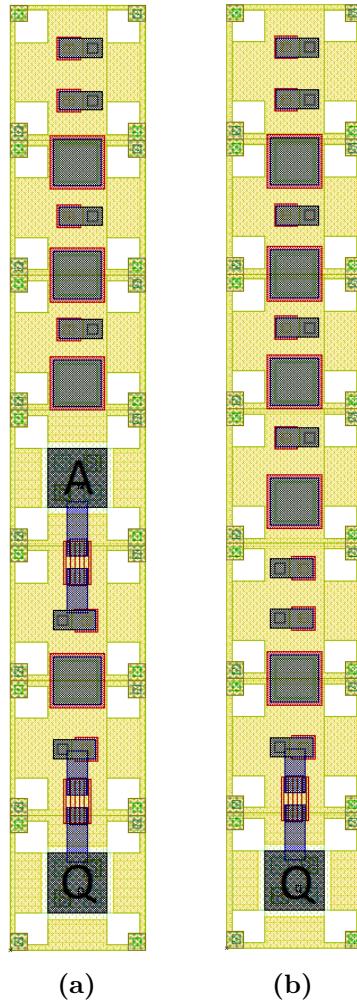
**Figure 3.24:** Schematic of RSFQ Always0T Asynchronous.



**Figure 3.25:** Schematic of RSFQ Always0T Asynchronous without an **a** input port.

## Layout

The physical layouts of the two RSFQ Always0T Asynchronous cell versions are shown in Fig. 3.26a and 3.26b respectively. The height of the layout for both versions of the cell is  $70 \mu\text{m}$  and the width is  $10 \mu\text{m}$ .



**Figure 3.26:** The physical layouts for (a) the RSFQ Always0T Asynchronous and (b) the RSFQ Always0T Asynchronous without an **a** input port.

## Analog model

```

1 * Author: L. Schindler
2 * Version: 2.1
3 * Last modification date: 13 August 2020
4 * Last modification by: L. Schindler
5
6 *$Ports           a q
7 .subckt LSMITLL_ALWAYS0T_ASYNC a q
8 La a 1 2p
9 Lq 2 q 2p
10 RA 1 0 2
11 RQ 2 0 2
12 .ends

```

**Listing 3.11:** RSFQ Always0T Asynchronous JoSIM netlist.

**Table 3.11:** RSFQ Always0T Asynchronous pin list.

Pin	Description
a	Data input
q	Data output

```

1 * Author: L. Schindler
2 * Version: 2.1
3 * Last modification date: 17 August 2020
4 * Last modification by: L. Schindler
5
6 *$Ports q
7 .subckt LSMITLL_ALWAYS0T_ASYNC_noA q
8 Lq 2 q 2p
9 RQ 2 0 2
10 .ends

```

**Listing 3.12:** RSFQ Always0T Asynchronous, without an **a** input port, JoSIM netlist.

**Table 3.12:** RSFQ Always0T Asynchronous, without an **a** input port, pin list.

Pin	Description
q	Data output

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 13 August 2020
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_always0T_async (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 initial
20   begin
21     q = 0; // Output always 0
22   end
23
24 always
25   begin
26     #10 q = 0; // Output always 0
27   end
28 endmodule

```

**Listing 3.13:** RSFQ Always0T Asynchronous verilog model.

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 17 August 2020
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_Always0T_async_noA (q);
9
10 output
11   q;
12
13 reg
14   q;
15
16 initial
17   begin
18     q = 0; // Output always 0
19   end
20
21 always
22   begin
23     #10 q = 0; // Output always 0
24   end
25 endmodule

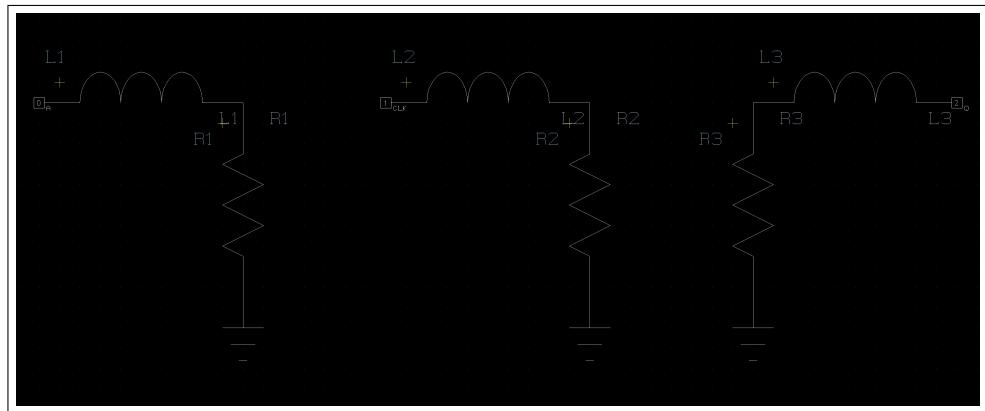
```

**Listing 3.14:** RSFQ Always0T Asynchronous, without an **a** input port, verilog model.

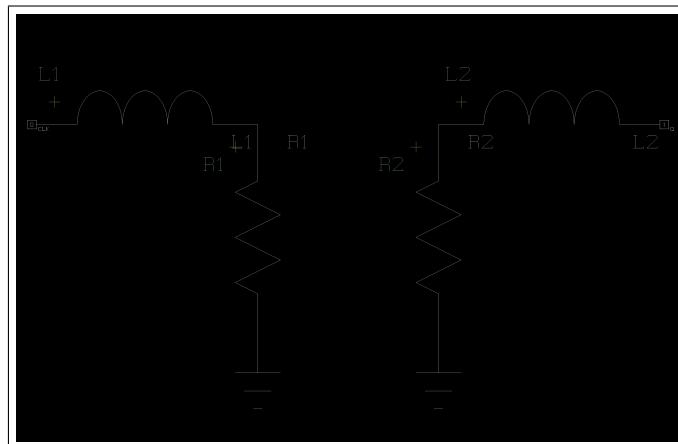
### 3.1.7 Always0T Synchronous

The Always0T Synchronous cell provides an output which is always zero synchronous to a clock signal. Two versions of the cell exist: One with an **a** input port, as seen in Fig. 3.27, and one without an **a** input port, as seen in Fig. 3.28. The Always0T Synchronous is designed to be directly connected to a PTL.

#### Schematic



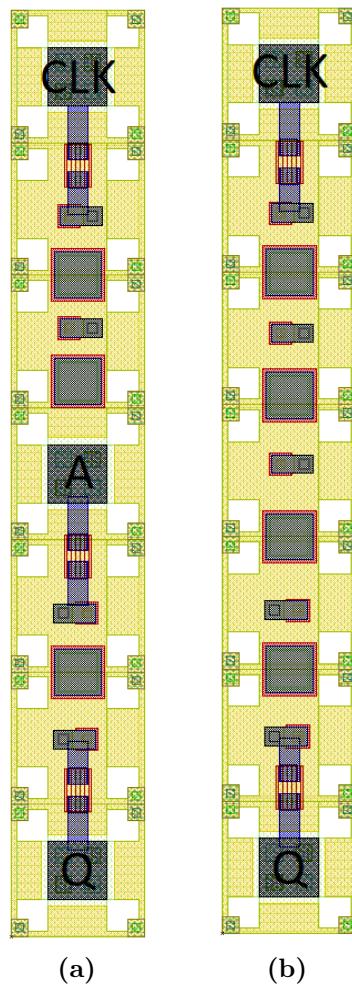
**Figure 3.27:** Schematic of RSFQ Always0T Synchronous.



**Figure 3.28:** Schematic of RSFQ Always0T Synchronous without an **a** input port.

## Layout

The physical layouts of the two RSFQ Always0T Synchronous cell versions are shown in Fig. 3.29a and 3.29b respectively. The height for both versions of the Always0T Synchronous layout is 70  $\mu\text{m}$  and the width is 10  $\mu\text{m}$ .



**Figure 3.29:** The physical layouts for (a) the RSFQ Always0T Synchronous and (b) the RSFQ Always0T Synchronous without an **a** input port.

## Analog model

```

1 * Author: L. Schindler
2 * Version: 2.1
3 * Last modification date: 13 August 2020
4 * Last modification by: L. Schindler
5
6 *$Ports a clk q
7 .subckt LSMITLL_ALWAYS0T_SYNC a clk q
8 La a 1 2p
9 Lclk clk 2 2p
10 Lq 3 q 2p
11 RA 1 0 2
12 RCLK 2 0 2
13 RQ 3 0 2
14 .ends

```

**Listing 3.15:** RSFQ Always0T Synchronous JoSIM netlist.

**Table 3.13:** RSFQ Always0T Synchronous pin list.

Pin	Description
a	Data input
clk	Clock input
q	Data output

```

1 * Author: L. Schindler
2 * Version: 2.1
3 * Last modification date: 17 August 2020
4 * Last modification by: L. Schindler
5
6 *$Ports clk q
7 .subckt LSMITLL_ALWAYS0T_SYNC_noA clk q
8 Lclk clk 2 2p
9 Lq 3 q 2p
10 RCLK 2 0 2
11 RQ 3 0 2
12 .ends

```

**Listing 3.16:** RSFQ Always0T Synchronous, without an **a** input port, JoSIM netlist.

**Table 3.14:** RSFQ Always0T Synchronous, without an **a** input port, pin list.

Pin	Description
clk	Clock input
q	Data output

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 13 August 2020
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_Always0T_sync (a, clk, q);
9
10 input
11   a, clk;
12
13 output
14   q;
15
16 reg
17   q;
18
19 initial
20   begin
21     q = 0; // Output always 0
22   end
23
24 always @(posedge clk or negedge clk)
25   begin
26     #10 q = 0; // Output always 0
27   end
28 endmodule

```

**Listing 3.17:** RSFQ Always0T Synchronous verilog model.

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 17 August 2020
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmitll_Always0T_sync_noA ( clk, q);
9
10 input
11   clk;
12
13 output
14   q;
15
16 reg
17   q;
18
19 initial
20   begin
21     q = 0; // Output always 0
22   end
23
24 always @(posedge clk or negedge clk)
25   begin
26     #10 q = 0; // Output always 0
27   end
28 endmodule

```

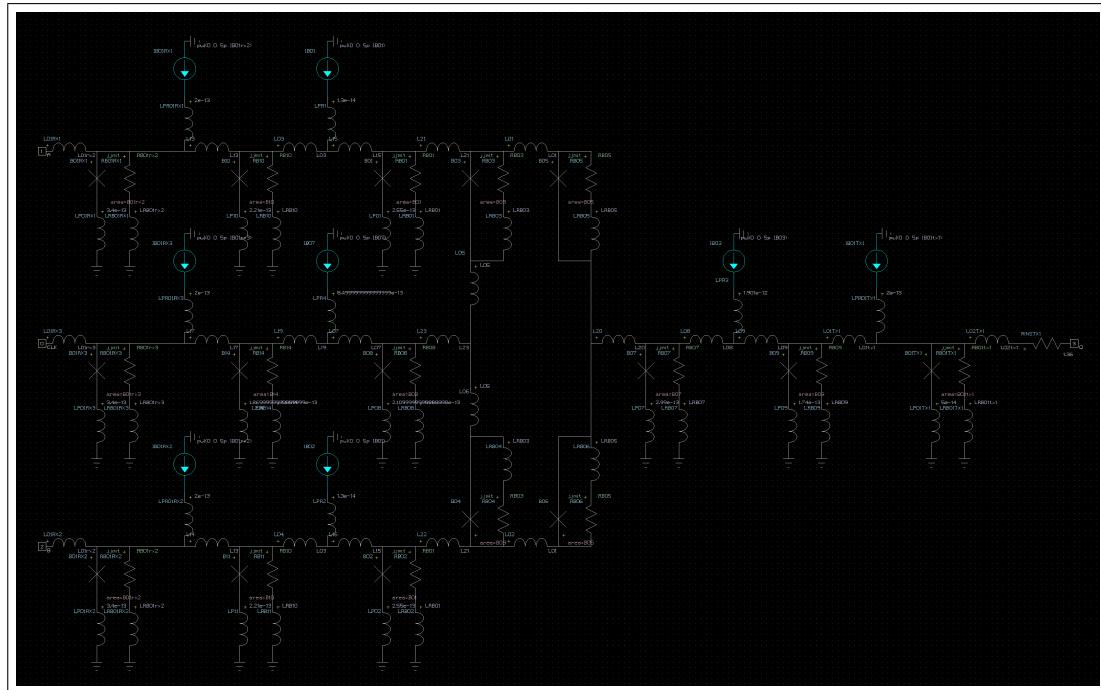
**Listing 3.18:** RSFQ Always0T Synchronous, without an **a** input port, verilog model.

## 3.2 Logic Cells

### 3.2.1 AND2T

The RSFQ AND2T cell generates an output pulse if pulses from both input signal lines were received before the clock signal. The AND2T is designed with integrated PTL transmitters and receivers and is meant to be connected directly to a PTL.

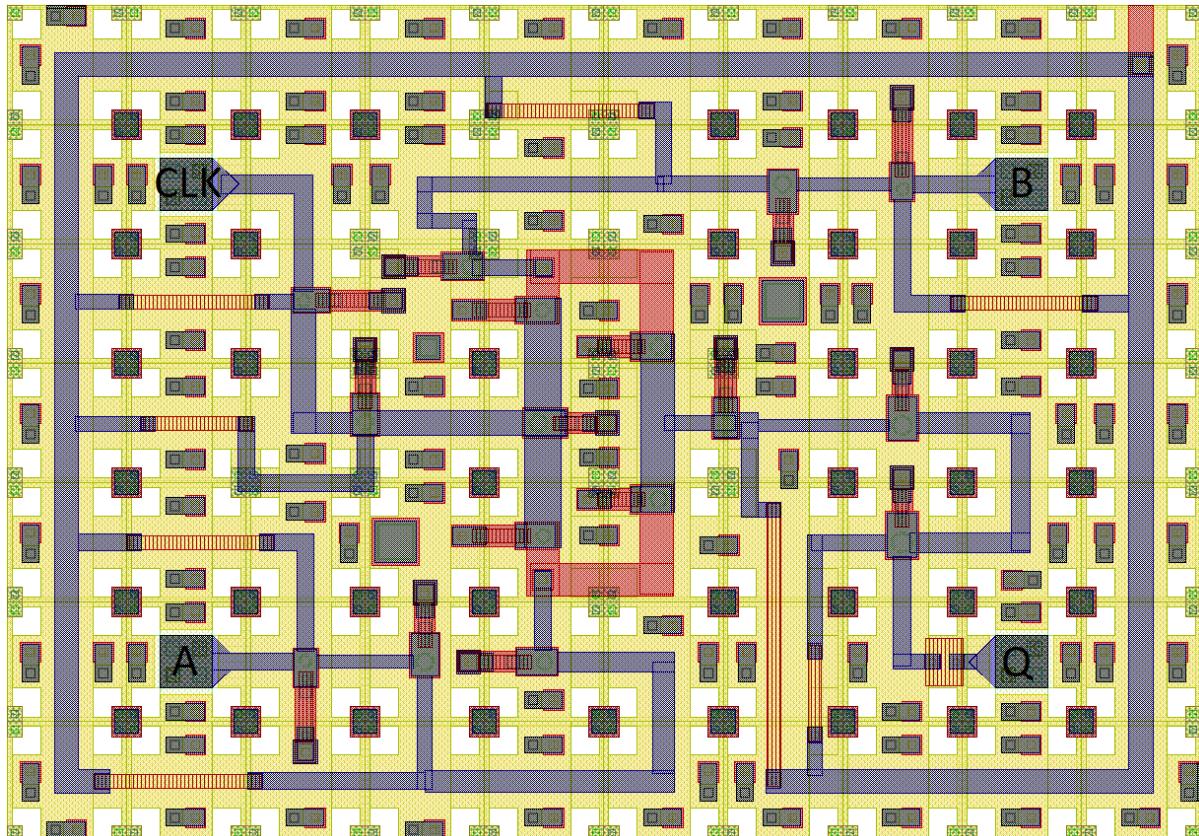
#### Schematic



**Figure 3.30:** Schematic of RSFQ AND2T.

## Layout

The physical layout for the RSFQ AND2T is shown in Fig. 3.31. The layout height is  $70 \mu\text{m}$  and the width is  $100 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.31:** RSFQ AND2T Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param L19=1.1464p
2   ↪ by InductEx v.6.0.4 on 30-4-21.          65  .param L20=0.9p
3  * Author: L. Schindler                      66  .param L21=0.2p
4  * Version: 2.1                               67  .param L22=2.925p
5  * Last modification date: 30 April 2021     68  .param L23=4.644p
6  * Last modification by: L. Schindler        69  .param L24=Lptl
7
8  *$Ports a b clk q
9  .subckt LSmitll_AND2T a b clk q
10 .model jjmit jj(rtype=1, vg=2.8mV, cap
11   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA
12   ↪ )
13 .param B0=1.0
14 .param Ic0=0.0001
15 .param IcRs=100u*6.859904418
16 .param B0Rs=IcRs/Ic0*B0
17 .param Rsheet=2
18 .param Lsheet=1.13e-12
19 .param RD=1.36
20 .param LB=0.2p
21 .param Lptl=2p
22 .param LP=0.2p
23 .param B1=0.88
24 .param B2=1.76
25 .param B3=1.32
26 .param B4=1.13
27 .param B5=1.53
28 .param B6=0.90
29 .param B7=1.50
30 .param B8=1.76
31 .param B9=B1
32 .param B10=B2
33 .param B11=B3
34 .param B12=B4
35 .param B13=B5
36 .param B14=1.26
37 .param B15=2.04
38 .param B16=2.27
39 .param IB1=131u
40 .param IB2=113u
41 .param IB3=128u
42 .param IB4=179u
43 .param IB5=IB1
44 .param IB6=IB2
45 .param IB7=63u
46 .param IB8=214u
47 .param L1=Lptl
48 .param L2=2.23p
49 .param L3=1.9325p
50 .param L4=6.105p
51 .param L5=1.2909p
52 .param L6=2.58p
53 .param L7=1.1464p
54 .param L8=Lptl
55 .param L9=1.9428p
56 .param L10=0.2p
57 .param L11=1.9932p
58 .param L13=Lptl
59 .param L14=2.23p
60 .param L15=1.9325p
61 .param L16=6.105p
62 .param L17=1.2909p
63 .param L18=2.58p
64 .param L19=1.1464p
65 .param L20=0.9p
66 .param L21=0.2p
67 .param L22=2.925p
68 .param L23=4.644p
69 .param L24=Lptl
70
71 .param LB1=LB
72 .param LB2=LB
73 .param LB3=LB
74 .param LB4=LB
75 .param LB5=LB
76 .param LB6=LB
77 .param LB7=LB
78 .param LB8=LB
79
80 .param LP1=LP
81 .param LP2=LP
82 .param LP3=LP
83 .param LP6=LP
84 .param LP7=LP
85 .param LP8=LP
86 .param LP9=LP
87 .param LP10=LP
88 .param LP11=LP
89 .param LP14=LP
90 .param LP15=LP
91 .param LP16=LP
92
93 .param RB1=B0Rs/B1
94 .param RB2=B0Rs/B2
95 .param RB3=B0Rs/B3
96 .param RB4=B0Rs/B4
97 .param RB5=B0Rs/B5
98 .param RB6=B0Rs/B6
99 .param RB7=B0Rs/B7
100 .param RB8=B0Rs/B8
101 .param RB9=B0Rs/B9
102 .param RB10=B0Rs/B10
103 .param RB11=B0Rs/B11
104 .param RB12=B0Rs/B12
105 .param RB13=B0Rs/B13
106 .param RB14=B0Rs/B14
107 .param RB15=B0Rs/B15
108 .param RB16=B0Rs/B16
109
110 .param LRB1=(RB1/Rsheet)*Lsheet
111 .param LRB2=(RB2/Rsheet)*Lsheet
112 .param LRB3=(RB3/Rsheet)*Lsheet
113 .param LRB4=(RB4/Rsheet)*Lsheet
114 .param LRB5=(RB5/Rsheet)*Lsheet
115 .param LRB6=(RB6/Rsheet)*Lsheet
116 .param LRB7=(RB7/Rsheet)*Lsheet
117 .param LRB8=(RB8/Rsheet)*Lsheet
118 .param LRB9=(RB9/Rsheet)*Lsheet
119 .param LRB10=(RB10/Rsheet)*Lsheet
120 .param LRB11=(RB11/Rsheet)*Lsheet
121 .param LRB12=(RB12/Rsheet)*Lsheet
122 .param LRB13=(RB13/Rsheet)*Lsheet
123 .param LRB14=(RB14/Rsheet)*Lsheet
124 .param LRB15=(RB15/Rsheet)*Lsheet
125 .param LRB16=(RB16/Rsheet)*Lsheet
126
127 B1 2 4 jjmit area=B1
128 B2 5 6 jjmit area=B2
129 B3 9 10 jjmit area=B3

```

```

130 | B4 11 13 jjmit area=B4          183 | L24 45 48 2.426E-12
131 | B5 12 38 jjmit area=B5          184 |
132 | B6 15 17 jjmit area=B6          185 | LP1 4 0 5.322E-13
133 | B7 20 19 jjmit area=B7          186 | LP2 6 0 5.415E-13
134 | B8 24 23 jjmit area=B8          187 | LP3 10 0 5.529E-13
135 | B9 26 28 jjmit area=B9          188 | LP6 17 0 5.48E-13
136 | B10 29 30 jjmit area=B10         189 | LP7 19 0 5.392E-13
137 | B11 33 34 jjmit area=B11         190 | LP8 23 0 5.294E-13
138 | B12 36 35 jjmit area=B12         191 | LP9 28 0 5.186E-13
139 | B13 38 37 jjmit area=B13         192 | LP10 30 0 4.924E-13
140 | B14 39 40 jjmit area=B14         193 | LP11 34 0 5.748E-13
141 | B15 43 44 jjmit area=B15         194 | LP14 40 0 5.268E-13
142 | B16 45 47 jjmit area=B16         195 | LP15 44 0 5.107E-13
143 |                               196 | LP16 47 0 5.28E-13
144 | IB1 0 3 pwl(0 0 5p IB1)          197 |
145 | IB2 0 8 pwl(0 0 5p IB2)          198 | RD 48 q RD
146 | IB3 0 16 pwl(0 0 5p IB3)         199 |
147 | IB4 0 21 pwl(0 0 5p IB4)          200 | RB1 2 102 RB1
148 | IB5 0 27 pwl(0 0 5p IB5)          201 | LRB1 102 0 LRB1
149 | IB6 0 32 pwl(0 0 5p IB6)          202 | RB2 5 105 RB2
150 | IB7 0 42 pwl(0 0 5p IB7)          203 | LRB2 105 0 LRB2
151 | IB8 0 46 pwl(0 0 5p IB8)          204 | RB3 9 109 RB3
152 |                               205 | LRB3 109 0 LRB3
153 | LB1 2 3 2.705E-12               206 | RB4 11 111 RB4
154 | LB2 7 8 3.072E-12               207 | LRB4 111 13 LRB4
155 | LB3 15 16 8.269E-13              208 | RB5 12 112 RB5
156 | LB4 20 21 3.807E-12              209 | LRB5 112 38 LRB5
157 | LB5 26 27 2.958E-12              210 | RB6 15 115 RB6
158 | LB6 31 32 1.53E-12               211 | LRB6 115 0 LRB6
159 | LB7 41 42 1.761E-12              212 | RB7 20 120 RB7
160 | LB8 45 46 3.373E-12              213 | LRB7 120 0 LRB7
161 |                               214 | RB8 24 122 RB8
162 | L1 a 2 1.603E-12                215 | LRB8 122 0 LRB8
163 | L2 2 5 2.243E-12                216 | RB9 26 126 RB9
164 | L3 5 7 1.928E-12                217 | LRB9 126 0 LRB9
165 | L4 7 9 6.173E-12                218 | RB10 29 129 RB10
166 | L5 9 11 1.295E-12               219 | LRB10 129 0 LRB10
167 | L6 11 12 2.568E-12              220 | RB11 33 133 RB11
168 | L7 13 24 1.332E-12              221 | LRB11 133 0 LRB11
169 | L8 clk 15 3.135E-12              222 | RB12 35 135 RB12
170 | L9 15 20 2.099E-12              223 | LRB12 135 36 LRB12
171 | L11 20 24 1.991E-12             224 | RB13 37 137 RB13
172 | L13 b 26 1.592E-12              225 | LRB13 137 38 LRB13
173 | L14 26 29 2.218E-12             226 | RB14 39 141 RB14
174 | L15 29 31 1.949E-12             227 | LRB14 141 0 LRB14
175 | L16 31 33 6.082E-12             228 | RB15 43 143 RB15
176 | L17 33 35 1.263E-12             229 | LRB15 143 0 LRB15
177 | L18 35 37 2.595E-12              230 | RB16 45 145 RB16
178 | L19 36 24 1.287E-12              231 | LRB16 145 0 LRB16
179 | L20 38 39 9.063E-13              232 | .ends
180 | L21 39 41 2.265E-13
181 | L22 41 43 2.896E-12
182 | L23 43 45 4.653E-12

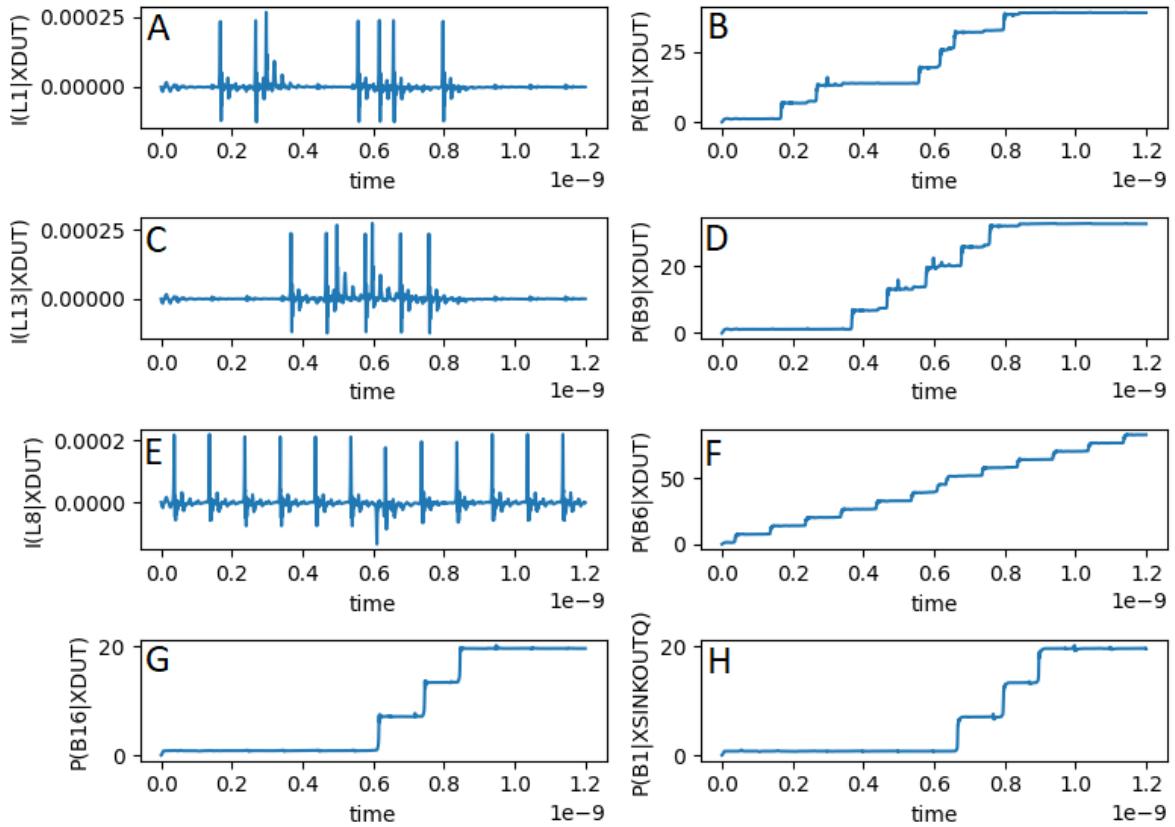
```

**Listing 3.19:** RSFQ AND2T JoSIM netlist.**Table 3.15:** RSFQ AND2T pin list.

Pin	Description
<b>a</b>	Data input
<b>b</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ AND2T using JoSIM is shown in Fig. 3.32. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.



**Figure 3.32:** RSFQ AND2T analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 2 June 2021
5 // Last modification by: L. Schindler
6 // -----
7
8 // -----
9 // Automatically extracted verilog file, created with TimEx v2.05
10 // Timing description and structural design for IARPA-BAA-14-03 via
11 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
12 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
13 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
14 // (c) 2016-2018 Stellenbosch University
15 // -----
16 `timescale 1ps/100fs
17 module LSmitll_AND2T (a, b, clk, q);
18
19 input
20   a, b, clk;
21
22 output
23   q;
24
25 reg
26   q;
27
28 real
29   delay_state3_clk_q = 9.3,
30   ct_state0_clk_a = 3.8,
31   ct_state0_clk_b = 3.8,
32   ct_state1_clk_a = 3.7,
33   ct_state1_clk_b = 3.5,
34   ct_state2_clk_a = 3.5,
35   ct_state2_clk_b = 3.8,
36   ct_state3_clk_a = 2.4,
37   ct_state3_clk_b = 2.3;
38
39 reg
40   errorsignal_a,
41   errorsignal_b,
42   errorsignal_clk;
43
44 integer
45   outfile,
46   cell_state; // internal state of the cell
47
48 initial
49 begin
50   errorsignal_a = 0;
51   errorsignal_b = 0;
52   errorsignal_clk = 0;
53   cell_state = 0; // Startup state
54   q = 0; // All outputs start at 0
55 end
56
57 always @(posedge a or negedge a) // execute at positive and negative edges of input
58 begin
59   if ($time>4) // arbitrary steady-state time
60     begin
61       if (errorsignal_a == 1'b1) // A critical timing is active for this input
62         begin
63           outfile = $fopen("errors.txt", "a");
64           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m; %0d_ps.\n"
65           ↪ ", $stime);
66           $fclose(outfile);
67           q <= 1'bX; // Set all outputs to unknown

```

```

67         end
68     if (errorsignal_a == 0)
69     begin
70         case (cell_state)
71             0: begin
72                 cell_state = 1; // Blocking statement -- immediately
73             end
74             1: begin
75                 end
76             2: begin
77                 cell_state = 3; // Blocking statement -- immediately
78             end
79             3: begin
80                 end
81             endcase
82         end
83     end
84 end
85
86 always @(posedge b or negedge b) // execute at positive and negative edges of input
87 begin
88     if ($time>4) // arbitrary steady-state time)
89     begin
90         if (errorsignal_b == 1'b1) // A critical timing is active for this input
91         begin
92             outfile = $fopen("errors.txt", "a");
93             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
94             ↪ ", $stime);
95             $fclose(outfile);
96             q <= 1'bX; // Set all outputs to unknown
97         end
98         if (errorsignal_b == 0)
99         begin
100             case (cell_state)
101                 0: begin
102                     cell_state = 2; // Blocking statement -- immediately
103                 end
104                 1: begin
105                     cell_state = 3; // Blocking statement -- immediately
106                 end
107                 2: begin
108                     end
109                 3: begin
110                     end
111             endcase
112         end
113     end
114 end
115
116 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
117 begin
118     if ($time>4) // arbitrary steady-state time)
119     begin
120         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
121         begin
122             outfile = $fopen("errors.txt", "a");
123             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
124             ↪ ", $stime);
125             $fclose(outfile);
126             q <= 1'bX; // Set all outputs to unknown
127         end
128         if (errorsignal_clk == 0)
129         begin
130             case (cell_state)
131                 0: begin
132                     errorsignal_a = 1; // Critical timing on this input; assign
133                     ↪ immediately
134                     errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
135                     ↪ after critical timing expires
136                     errorsignal_b = 1; // Critical timing on this input; assign

```

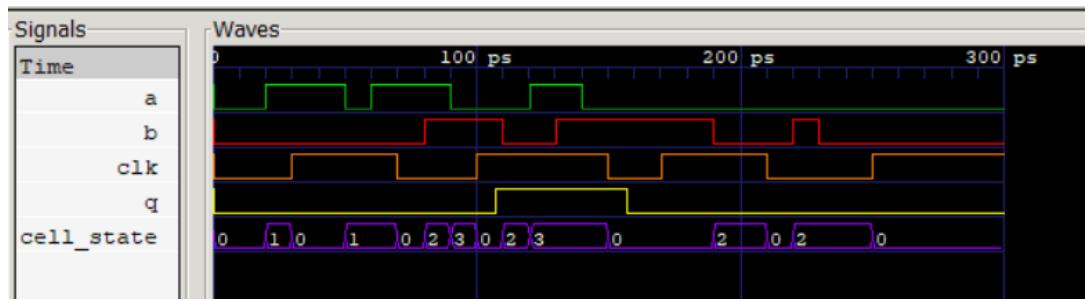
```

133           → immediately
134           errorsignal_b <= #(ct_state0_clk_b) 0; // Clear error signal
135           → after critical timing expires
136       end
137   begin
138       cell_state = 0; // Blocking statement -- immediately
139       errorsignal_a = 1; // Critical timing on this input; assign
140           → immediately
141           errorsignal_a <= #(ct_state1_clk_a) 0; // Clear error signal
142           → after critical timing expires
143       errorsignal_b = 1; // Critical timing on this input; assign
144           → immediately
145           errorsignal_b <= #(ct_state1_clk_b) 0; // Clear error signal
146           → after critical timing expires
147   end
148 end
149 begin
150     q <= #(delay_state3_clk_q) !q;
151     cell_state = 0; // Blocking statement -- immediately
152     errorsignal_a = 1; // Critical timing on this input; assign
153         → immediately
154         errorsignal_a <= #(ct_state3_clk_a) 0; // Clear error signal
155         → after critical timing expires
156         errorsignal_b = 1; // Critical timing on this input; assign
157             → immediately
158             errorsignal_b <= #(ct_state3_clk_b) 0; // Clear error signal
159             → after critical timing expires
160     end
161 end
162 endmodule

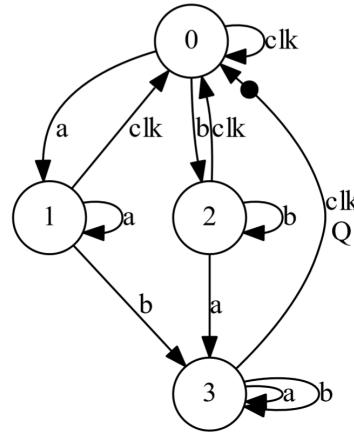
```

Listing 3.20: RSFQ AND2T verilog model.

The digital simulation results for the RSFQ AND2T is shown in Fig. 3.33 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.34.



**Figure 3.33:** RSFQ AND2T digital simulation results.



**Figure 3.34:** RSFQ AND2T Mealy finite state machine diagram.

## Power Consumption

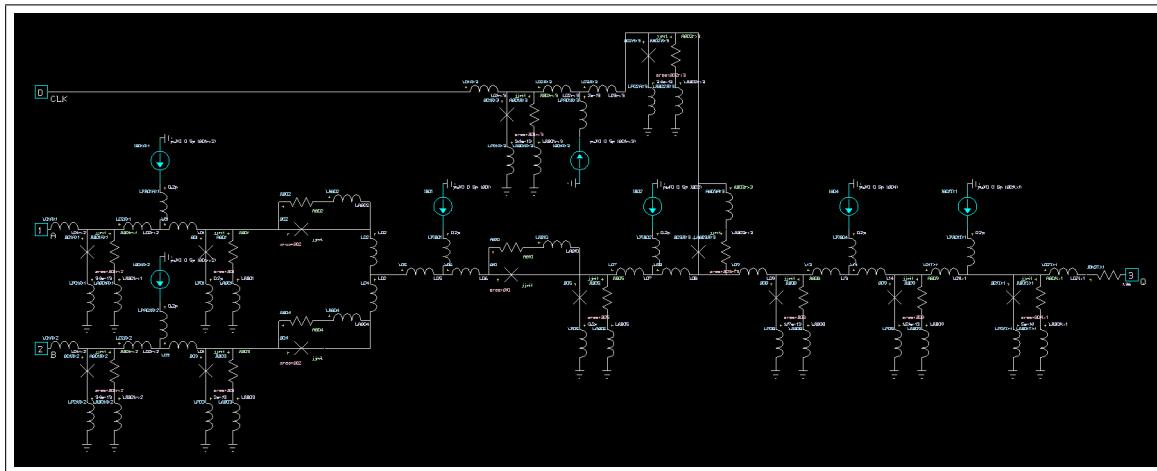
**Table 3.16:** RSFQ AND2T power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2787	4.75
2	2787	9.50
5	2787	23.7
10	2787	47.5
20	2787	95.0
50	2787	237

### 3.2.2 OR2T

The RSFQ OR2T cell generates an output pulse if an input pulse from either input lines was received before the clock signal. The OR2T cell is designed with integrated PTL transmitters and receivers and is intended to be connected directly to a PTL.

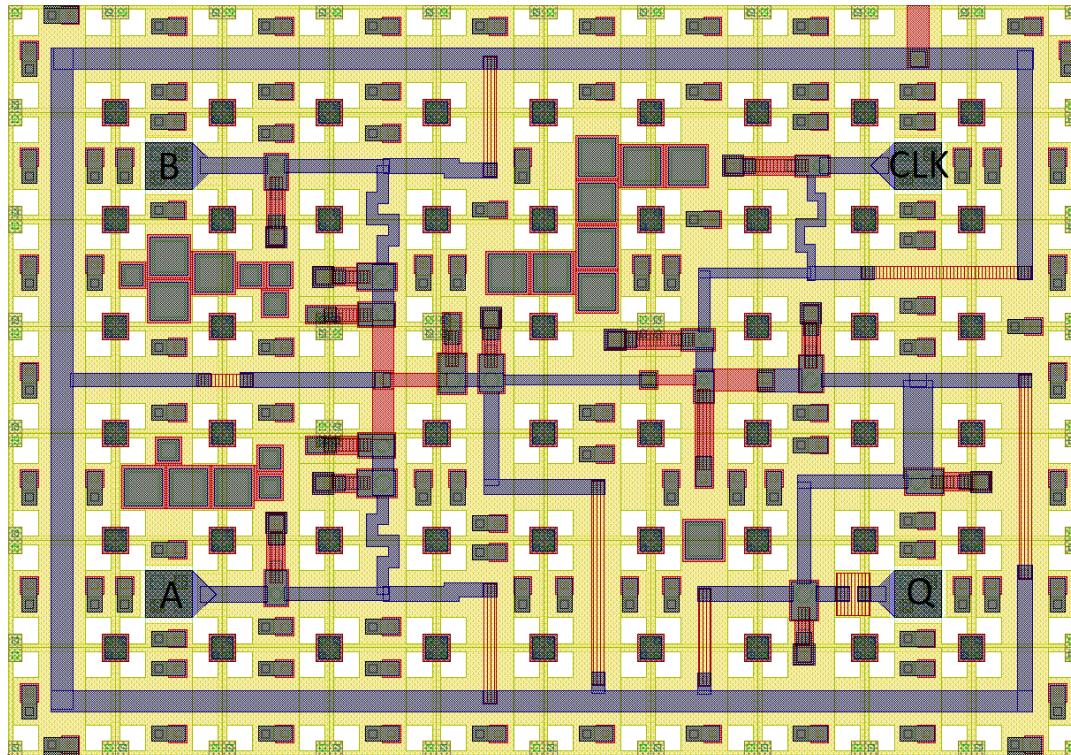
#### Schematic



**Figure 3.35:** Schematic of RSFQ OR2T.

## Layout

The physical layout for the RSFQ OR2T is shown in Fig. 3.36. The layout height is  $70 \mu\text{m}$  and the width is  $100 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.36:** RSFQ OR2T Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param LB1=LB
2   ↪ by InductEx v.6.0.4 on 28-4-21.          65  .param LB2=LB
3  * Author: L. Schindler                      66  .param LB3=LB
4  * Version: 2.1                               67  .param LB4=LB
5  * Last modification date: 28 April 2021     68  .param LB5=LB
6  * Last modification by: L. Schindler        69  .param LB6=LB
7  *$ports a b clk q                         70  .param LB7=LB
8 .subckt LSMITLL_OR2T a b clk q            71  .param LP1=LP
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param LP2=LP
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    73  .param LP4=LP
   ↪ )                                         74  .param LP5=LP
10 .param B0=1                                75  .param LP8=LP
11 .param Ic0=0.0001                           76  .param LP9=LP
12 .param IcRs=100u*6.859904418                77  .param LP10=LP
13 .param B0Rs=IcRs/Ic0*B0                   78  .param LP12=LP
14 .param Rsheet=2                            79  .param LP13=LP
15 .param Lsheet=1.13e-12                     80  .param LP14=LP
16 .param LP=0.2p                             81
17 .param Lptl=2p                            82  .param RB1=B0Rs/B1
18 .param LB=2p                              83  .param RB2=B0Rs/B2
19 .param RD=1.36                            84  .param RB3=B0Rs/B3
20
21 .param B1=1.17                            85  .param RB4=B0Rs/B4
22 .param B2=1.95                            86  .param RB5=B0Rs/B5
23 .param B3=1.31                            87  .param RB6=B0Rs/B6
24 .param B4=1.17                            88  .param RB7=B0Rs/B7
25 .param B5=1.95                            89  .param RB8=B0Rs/B8
26 .param B6=1.31                            90  .param RB9=B0Rs/B9
27 .param B7=2.20                            91  .param RB10=B0Rs/B10
28 .param B8=1.72                            92  .param RB11=B0Rs/B11
29 .param B9=0.81                            93  .param RB12=B0Rs/B12
30 .param B10=0.75                           94  .param RB13=B0Rs/B13
31 .param B11=0.63                           95  .param RB14=B0Rs/B14
32 .param B12=1.40                           96  .param LRB1=(RB1/Rsheet)*Lsheet+LP
33 .param B13=1.62                           97  .param LRB2=(RB2/Rsheet)*Lsheet+LP
34 .param B14=1.9                           98  .param LRB3=(RB3/Rsheet)*Lsheet+LP
35
36 .param IB1=141u                           99  .param LRB4=(RB4/Rsheet)*Lsheet+LP
37 .param IB2=141u                           100 .param LRB5=(RB5/Rsheet)*Lsheet+LP
38 .param IB3=328u                           101 .param LRB6=(RB6/Rsheet)*Lsheet+LP
39 .param IB4=81u                            102 .param LRB7=(RB7/Rsheet)*Lsheet+LP
40 .param IB5=98u                            103 .param LRB8=(RB8/Rsheet)*Lsheet+LP
41 .param IB6=81u                            104 .param LRB9=(RB9/Rsheet)*Lsheet+LP
42 .param IB7=177u                           105 .param LRB10=(RB10/Rsheet)*Lsheet+LP
43
44 .param L1=Lptl                           106 .param LRB11=(RB11/Rsheet)*Lsheet+LP
45 .param L2=2.0822p                          107 .param LRB12=(RB12/Rsheet)*Lsheet+LP
46 .param L3=2.6809p                          108 .param LRB13=(RB13/Rsheet)*Lsheet+LP
47 .param L4=1.3486p                          109 .param LRB14=(RB14/Rsheet)*Lsheet+LP
48 .param L5=Lptl                           110
49 .param L6=2.0822p                          111 B1 2 3      jjmit area=B1
50 .param L7=2.6809p                          112 B2 6 7      jjmit area=B2
51 .param L8=1.3486p                          113 B3 6 8      jjmit area=B3
52 .param L10=1.8890p                         114 B4 11 12     jjmit area=B4
53 .param L12=5.4916p                         115 B5 15 16     jjmit area=B5
54 .param L13=Lptl                           116 B6 15 43     jjmit area=B6
55 .param L14=3.3652p                         117 B7 19 22     jjmit area=B7
56 .param L15=4.0267p                         118 B8 22 21     jjmit area=B8
57 .param L16=0.7p                            119 B9 26 27     jjmit area=B9
58 .param L17=1.5727p                         120 B10 30 31    jjmit area=B10
59 .param L18=2.0776p                         121 B11 32 24    jjmit area=B11
60 .param L19=0.885p                          122 B12 33 34    jjmit area=B12
61 .param L20=4.2904p                         123 B13 37 38    jjmit area=B13
62 .param L21=Lptl                           124 B14 39 41    jjmit area=B14
63

```

```

130 | IB5 0 29 pwl(0 0 5p IB5)      167 | LP9 27 0          5.216E-13
131 | IB6 0 36 pwl(0 0 5p IB6)      168 | LP10 31 0         5.841E-13
132 | IB7 0 40 pwl(0 0 5p IB7)      169 | LP12 34 0         4.758E-13
133 |
134 | L1 a 2 1.593E-12             170 | LP13 38 0         5.26E-13
135 | L2 2 4 2.116E-12            171 | LP14 41 0         4.366E-13
136 | L3 4 6 2.655E-12            172
137 | L4 8 9 1.349E-12            173 RB1 2 102 RB1
138 | L5 b 11 1.596E-12           174 LRB1 102 0 LRB1
139 | L6 11 13 2.104E-12          175 RB2 6 106 RB2
140 | L7 13 15 2.655E-12          176 LRB2 106 0 LRB2
141 | L8 43 9 1.348E-12           177 RB3 6 108 RB3
142 | L10 9 19 1.883E-12          178 LRB3 108 8 LRB3
143 | L12 22 24 5.465E-12          179 RB4 11 111 RB4
144 | L13 clk 26 1.54E-12          180 LRB4 111 0 LRB4
145 | L14 26 28 3.367E-12          181 RB5 15 115 RB5
146 | L15 28 30 4.045E-12          182 LRB5 115 0 LRB5
147 | L16 30 32 5.696E-13          183 RB6 15 143 RB6
148 | L17 24 33 1.584E-12          184 LRB6 143 43 LRB6
149 | L18 33 35 2.075E-12          185 RB7 19 119 RB7
150 | L19 35 37 9.15E-13           186 LRB7 119 22 LRB7
151 | L20 37 39 4.26E-12           187 RB8 22 122 RB8
152 | L21 39 42 7.721E-13          188 LRB8 122 0 LRB8
153 | RD 42 q RD                  189 RB9 26 126 RB9
154 |
155 | LB1 4 5 2.162E-12            190 LRB9 126 0 LRB9
156 | LB2 13 14 2.177E-12          191 RB10 30 130 RB10
157 | LB3 9 18 2.831E-12           192 LRB10 130 0 LRB10
158 | LB4 22 23 3.933E-12          193 RB11 32 132 RB11
159 | LB5 28 29 1.367E-12          194 LRB11 132 24 LRB11
160 | LB6 35 36 2.221E-12          195 RB12 33 133 RB12
161 | LB7 39 40 2.035E-12          196 LRB12 133 0 LRB12
162 | LP1 3 0 4.886E-13            197 RB13 37 137 RB13
163 | LP2 7 0 4.645E-13            198 LRB13 137 0 LRB13
164 | LP4 12 0 4.935E-13           199 RB14 39 139 RB14
165 | LP5 16 0 4.65E-13             200 LRB14 139 0 LRB14
166 | LP8 21 0 5.102E-13           201 .ends

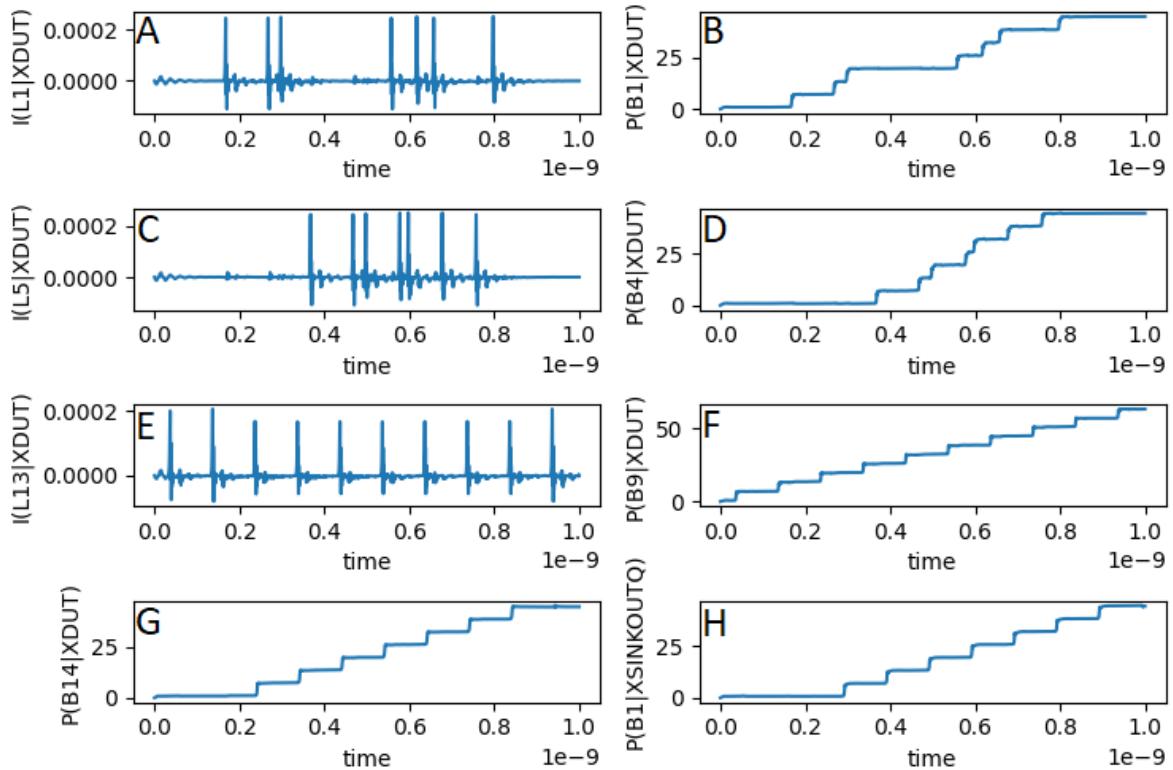
```

**Listing 3.21:** RSFQ OR2T JoSIM netlist.**Table 3.17:** RSFQ OR2T pin list.

Pin	Description
<b>a</b>	Data input
<b>b</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ OR2T using JoSIM is shown in Fig. 3.37. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.



**Figure 3.37:** RSFQ OR2T analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 `timescale 1ps/100fs
8 module LSmit11_OR2T_v2p1_optimized (a, b, clk, q);
9
10 input
11     a, b, clk;
12
13 output
14     q;
15
16 reg
17     q;
18
19 real
20     delay_state1_clk_q = 5.5,
21     ct_state0_a_clk = 2.0,
22     ct_state0_b_clk = 2.0,
23     ct_state1_a_clk = 1.2,
24     ct_state1_b_clk = 1.2;
25
26 reg
27     errorsignal_a,
28     errorsignal_b,
29     errorsignal_clk;
30
31 integer
32     outfile,
33     cell_state; // internal state of the cell
34
35 initial
36 begin
37     errorsignal_a = 0;
38     errorsignal_b = 0;
39     errorsignal_clk = 0;
40     cell_state = 0; // Startup state
41     q = 0; // All outputs start at 0
42 end
43
44 always @(posedge a or negedge a) // execute at positive and negative edges of input
45 begin
46     if ($time>4) // arbitrary steady-state time)
47         begin
48             if (errorsignal_a == 1'b1) // A critical timing is active for this input
49                 begin
50                     outfile = $fopen("errors.txt", "a");
51                     $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
52                                     ↪ ", $time);
53                     $fclose(outfile);
54                     q <= 1'bX; // Set all outputs to unknown
55                 end
56             if (errorsignal_a == 0)
57                 begin
58                     case (cell_state)
59                         0: begin
60                             cell_state = 1; // Blocking statement -- immediately
61                             errorsignal_clk = 1; // Critical timing on this input; assign
62                                     ↪ immediately
63                             errorsignal_clk <= #(ct_state0_a_clk) 0; // Clear error signal
64                                     ↪ after critical timing expires
65                         end
66                         1: begin
67                             errorsignal_clk = 1; // Critical timing on this input; assign

```

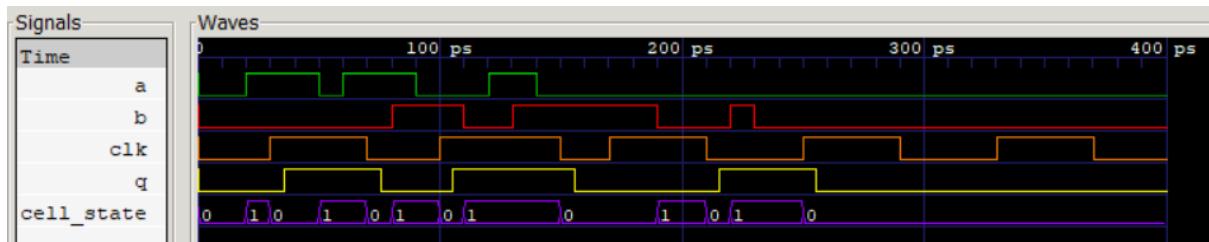
```

65           → immediately
66           errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
67           → after critical timing expires
68       end
69   endcase
70 end
71 always @(posedge b or negedge b) // execute at positive and negative edges of input
72 begin
73   if ($time>4) // arbitrary steady-state time)
74     begin
75       if (errorsignal_b == 1'b1) // A critical timing is active for this input
76         begin
77           outfile = $fopen("errors.txt", "a");
78           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;%0d_ps.\n
79           ↪ ", $stime);
80           $fclose(outfile);
81           q <= 1'bX; // Set all outputs to unknown
82         end
83       if (errorsignal_b == 0)
84         begin
85           case (cell_state)
86             0: begin
87               cell_state = 1; // Blocking statement -- immediately
88               errorsignal_clk = 1; // Critical timing on this input; assign
89               → immediately
90               errorsignal_clk <= #(ct_state0_b_clk) 0; // Clear error signal
91               → after critical timing expires
92             end
93           endcase
94         end
95       end
96     end
97   end
98 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
99 begin
100   if ($time>4) // arbitrary steady-state time)
101     begin
102       if (errorsignal_clk == 1'b1) // A critical timing is active for this input
103         begin
104           outfile = $fopen("errors.txt", "a");
105           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;%0d_ps.\n
106           ↪ ", $stime);
107           $fclose(outfile);
108           q <= 1'bX; // Set all outputs to unknown
109         end
110       if (errorsignal_clk == 0)
111         begin
112           case (cell_state)
113             0: begin
114             end
115             1: begin
116               q <= #(delay_state1_clk_q) !q;
117               cell_state = 0; // Blocking statement -- immediately
118             end
119           endcase
120         end
121     end
122 endmodule

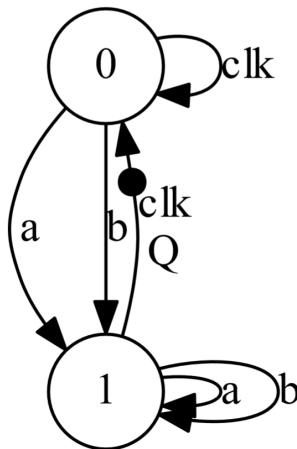
```

Listing 3.22: RSFQ OR2T verilog model.

The digital simulation results for the RSFQ OR2T is shown in Fig. 3.38 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.39.



**Figure 3.38:** RSFQ OR2T digital simulation results.



**Figure 3.39:** RSFQ OR2T Mealy finite state machine diagram.

## Power Consumption

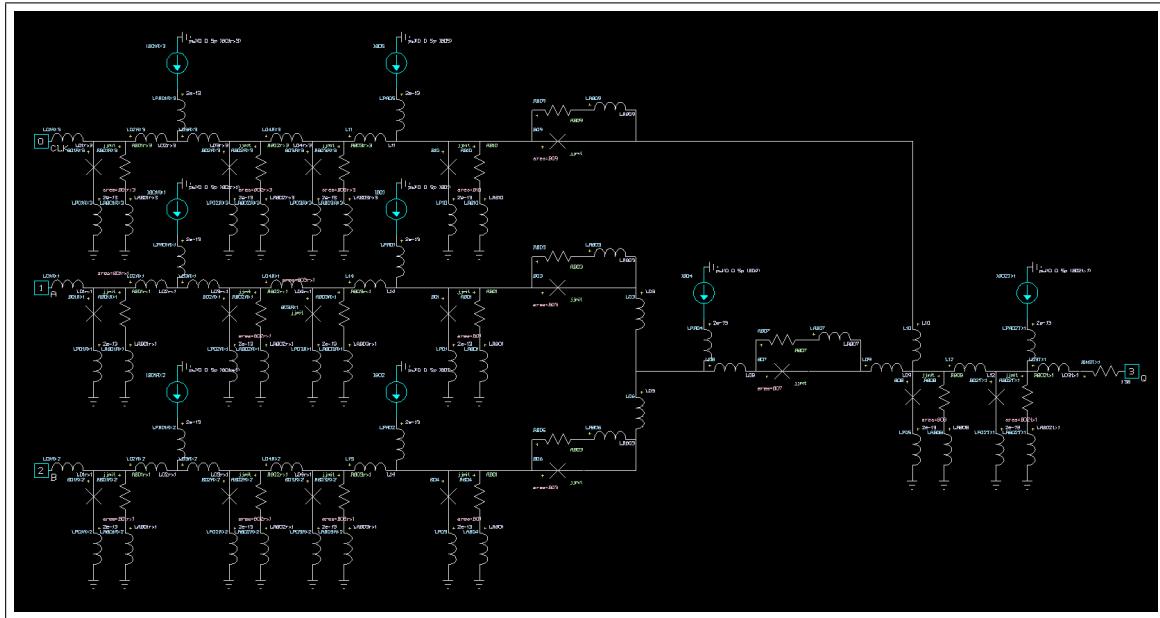
**Table 3.18:** RSFQ OR2T power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2722	4.11
2	2722	8.23
5	2722	20.6
10	2722	41.1
20	2722	82.3
50	2722	206

### 3.2.3 XORT

The RSFQ XORT cell generates an output pulse exclusively if a pulse from a single input line was received before the clock signal. The XORT cell is designed with integrated PTL transmitters and receivers and is intended to be connected directly to a PTL.

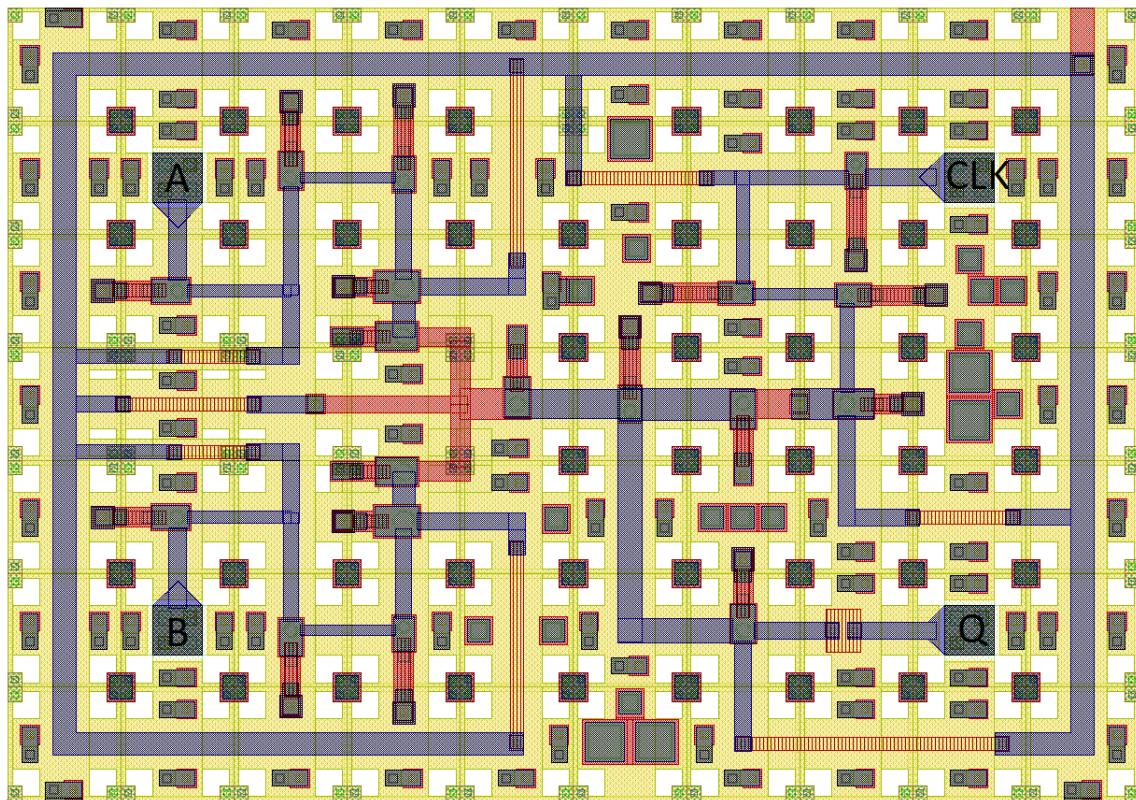
## Schematic



**Figure 3.40:** Schematic of RSFQ XORT.

## Layout

The physical layout for the RSFQ XORT is shown in Fig. 3.41. The layout height is  $70 \mu\text{m}$  and the width is  $100 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.41:** RSFQ XORT Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param L17=1.8033p
2  	↳ by InductEx v.6.0.4 on 29-4-21.          65  .param L18=2.2246p
3  * Author: L. Schindler                      66  .param L19=1.7515p
4  * Version: 2.1                               67  .param L20=3.8658p
5  * Last modification date: 29 April 2021     68  .param L21=Lptl
6  * Last modification by: L. Schindler        69
7  *$Ports a b clk q                         70  .param RB1=B0Rs/B1
8 .subckt LSmitll_XORT a b clk q            71  .param RB2=B0Rs/B2
9 .model jjmit jj(rttype=1, vg=2.8mV, cap    72  .param RB3=B0Rs/B3
   ↳ =0.07pF, r0=160, rn=16, icrit=0.1mA     73  .param RB4=B0Rs/B4
   ↳ )                                         74  .param RB5=B0Rs/B5
10 .param B0=1                                75  .param RB6=B0Rs/B6
11 .param Ic0=0.0001                           76  .param RB7=B0Rs/B7
12 .param IcRs=100u*6.859904418                77  .param RB8=B0Rs/B8
13 .param B0Rs=IcRs/Ic0*B0                     78  .param RB9=B0Rs/B9
14 .param Rsheet=2                            79  .param RB10=B0Rs/B10
15 .param Lsheet=1.13e-12                      80  .param RB11=B0Rs/B11
16 .param Lptl=2p                             81  .param RB12=B0Rs/B12
17 .param LB=2p                               82  .param RB13=B0Rs/B13
18 .param LP=0.5p                            83  .param RB14=B0Rs/B14
19
20 .param B1=1.21                            84  .param RB15=B0Rs/B15
21 .param B2=1.16                            85  .param RB16=B0Rs/B16
22 .param B3=0.90                            86  .param RB17=B0Rs/B17
23 .param B4=2.80                            87  .param RB18=B0Rs/B18
24 .param B5=1.92
25 .param B6=B1
26 .param B7=B2
27 .param B8=B3
28 .param B9=B4
29 .param B10=B5
30 .param B11=0.72
31 .param B12=0.77
32 .param B13=0.83
33 .param B14=1.69
34 .param B15=1.29
35 .param B16=1.49
36 .param B17=0.93
37 .param B18=1.37
38
39 .param IB1=230u
40 .param IB2=89u
41 .param IB3=IB1
42 .param IB4=IB2
43 .param IB5=132u
44 .param IB6=178u
45 .param IB7=134u
46 .param IB8=66u
47
48 .param L1=Lptl
49 .param L2=2.1529p
50 .param L3=1.9729p
51 .param L4=2.3966p
52 .param L5=1.6354p
53 .param L6=2.2793p
54 .param L7=L1
55 .param L8=L2
56 .param L9=L3
57 .param L10=L4
58 .param L11=L5
59 .param L12=L6
60 .param L13=Lptl
61 .param L14=2.2381p
62 .param L15=2.0205p
63 .param L16=2.0178p
64  .param L17=1.8033p
65  .param L18=2.2246p
66  .param L19=1.7515p
67  .param L20=3.8658p
68  .param L21=Lptl
69
70  .param RB1=B0Rs/B1
71  .param RB2=B0Rs/B2
72  .param RB3=B0Rs/B3
73  .param RB4=B0Rs/B4
74  .param RB5=B0Rs/B5
75  .param RB6=B0Rs/B6
76  .param RB7=B0Rs/B7
77  .param RB8=B0Rs/B8
78  .param RB9=B0Rs/B9
79  .param RB10=B0Rs/B10
80  .param RB11=B0Rs/B11
81  .param RB12=B0Rs/B12
82  .param RB13=B0Rs/B13
83  .param RB14=B0Rs/B14
84  .param RB15=B0Rs/B15
85  .param RB16=B0Rs/B16
86  .param RB17=B0Rs/B17
87  .param RB18=B0Rs/B18
88
89  .param LRB1=(RB1/Rsheet)*Lsheet
90  .param LRB2=(RB2/Rsheet)*Lsheet
91  .param LRB3=(RB3/Rsheet)*Lsheet
92  .param LRB4=(RB4/Rsheet)*Lsheet
93  .param LRB5=(RB5/Rsheet)*Lsheet
94  .param LRB6=(RB6/Rsheet)*Lsheet
95  .param LRB7=(RB7/Rsheet)*Lsheet
96  .param LRB8=(RB8/Rsheet)*Lsheet
97  .param LRB9=(RB9/Rsheet)*Lsheet
98  .param LRB10=(RB10/Rsheet)*Lsheet
99  .param LRB11=(RB11/Rsheet)*Lsheet
100 .param LRB12=(RB12/Rsheet)*Lsheet
101 .param LRB13=(RB13/Rsheet)*Lsheet
102 .param LRB14=(RB14/Rsheet)*Lsheet
103 .param LRB15=(RB15/Rsheet)*Lsheet
104 .param LRB16=(RB16/Rsheet)*Lsheet
105 .param LRB17=(RB17/Rsheet)*Lsheet
106 .param LRB18=(RB18/Rsheet)*Lsheet
107
108 .param LB1=LB
109 .param LB2=LB
110 .param LB3=LB
111 .param LB4=LB
112 .param LB5=LB
113 .param LB6=LB
114 .param LB7=LB
115 .param LB8=LB
116
117 .param LP1=LP
118 .param LP2=LP
119 .param LP3=LP
120 .param LP4=LP
121 .param LP6=LP
122 .param LP7=LP
123 .param LP8=LP
124 .param LP9=LP
125 .param LP11=LP
126 .param LP12=LP
127 .param LP13=LP
128 .param LP14=LP
129 .param LP17=LP

```

```

130 | .param LP18=LP
131 | B1 2 3 jjmit area=B1
132 | B2 6 7 jjmit area=B2
133 | B3 8 9 jjmit area=B3
134 | B4 10 11 jjmit area=B4
135 | B5 10 13 jjmit area=B5
136 | B6 16 17 jjmit area=B6
137 | B7 20 21 jjmit area=B7
138 | B8 22 23 jjmit area=B8
139 | B9 24 25 jjmit area=B9
140 | B10 24 27 jjmit area=B10
141 | B11 32 33 jjmit area=B11
142 | B12 36 37 jjmit area=B12
143 | B13 38 39 jjmit area=B13
144 | B14 40 41 jjmit area=B14
145 | B15 40 43 jjmit area=B15
146 | B16 29 30 jjmit area=B16
147 | B17 30 44 jjmit area=B17
148 | B18 45 46 jjmit area=B18
149 |
150 |
151 | IB1 0 5 pwl(0 0 5p IB1)
152 | IB2 0 12 pwl(0 0 5p IB2)
153 | IB3 0 19 pwl(0 0 5p IB3)
154 | IB4 0 26 pwl(0 0 5p IB4)
155 | IB5 0 35 pwl(0 0 5p IB5)
156 | IB6 0 42 pwl(0 0 5p IB6)
157 | IB7 0 28 pwl(0 0 5p IB7)
158 | IB8 0 47 pwl(0 0 5p IB8)
159 |
160 | L1 a 2 1.453E-12
161 | L2 2 4 2.162E-12
162 | L3 4 6 1.962E-12
163 | L4 6 8 2.392E-12
164 | L5 8 10 1.634E-12
165 | L6 13 14 2.263E-12
166 | L7 b 16 1.446E-12
167 | L8 16 18 2.158E-12
168 | L9 18 20 1.959E-12
169 | L10 20 22 2.389E-12
170 | L11 22 24 1.63E-12
171 | L12 27 14 2.268E-12
172 | L13 clk 32 1.608E-12
173 | L14 32 34 2.222E-12
174 | L15 34 36 2.02E-12
175 | L16 36 38 2.019E-12
176 | L17 38 40 1.796E-12
177 | L18 43 30 2.204E-12
178 | L19 14 29 1.754E-12
179 | L20 30 45 3.883E-12
180 | L21 45 48 1.589E-12
181 |
182 | LP1 3 0 5.123E-13
183 | LP2 7 0 5.755E-13
184 | LP3 9 0 5.799E-13
185 | LP4 11 0 4.826E-13
186 | LP6 17 0 5.124E-13
187 | LP7 21 0 5.734E-13
188 | LP8 23 0 5.803E-13
189 | LP9 25 0 4.745E-13
190 | LP11 33 0 5.105E-13
191 | LP12 37 0 6.091E-13
192 | LP13 39 0 5.955E-13
193 | LP14 41 0 5.33E-13
194 | LP17 44 0 6.204E-13
195 | LP18 46 0 5.407E-13
196 |
197 | LB1 4 5 1.862E-12
198 | LB2 10 12 2.299E-12
199 | LB3 18 19 1.858E-12
200 | LB4 24 26 2.318E-12
201 | LB5 34 35 9.457E-13
202 | LB6 40 42 2.935E-12
203 | LB7 14 28 4.089E-12
204 | LB8 45 47 2.014E-12
205 |
206 | RD 48 q 1.36
207 |
208 | RB1 2 102 RB1
209 | LRB1 102 0 LRB1
210 | RB2 6 106 RB2
211 | LRB2 106 0 LRB2
212 | RB3 8 108 RB3
213 | LRB3 108 0 LRB3
214 | RB4 10 110 RB4
215 | LRB4 110 0 LRB4
216 | RB5 10 113 RB5
217 | LRB5 113 13 LRB5
218 | RB6 16 116 RB6
219 | LRB6 116 0 LRB6
220 | RB7 20 120 RB7
221 | LRB7 120 0 LRB7
222 | RB8 22 122 RB8
223 | LRB8 122 0 LRB8
224 | RB9 24 124 RB9
225 | LRB9 124 0 LRB9
226 | RB10 24 127 RB10
227 | LRB10 127 27 LRB10
228 | RB11 32 132 RB11
229 | LRB11 132 0 LRB11
230 | RB12 36 136 RB12
231 | LRB12 136 0 LRB12
232 | RB13 38 138 RB13
233 | LRB13 138 0 LRB13
234 | RB14 40 140 RB14
235 | LRB14 140 0 LRB14
236 | RB15 40 143 RB15
237 | LRB15 143 43 LRB15
238 | RB16 29 129 RB16
239 | LRB16 129 30 LRB16
240 | RB17 30 130 RB17
241 | LRB17 130 0 LRB17
242 | RB18 45 145 RB18
243 | LRB18 145 0 LRB18
244 | .ends

```

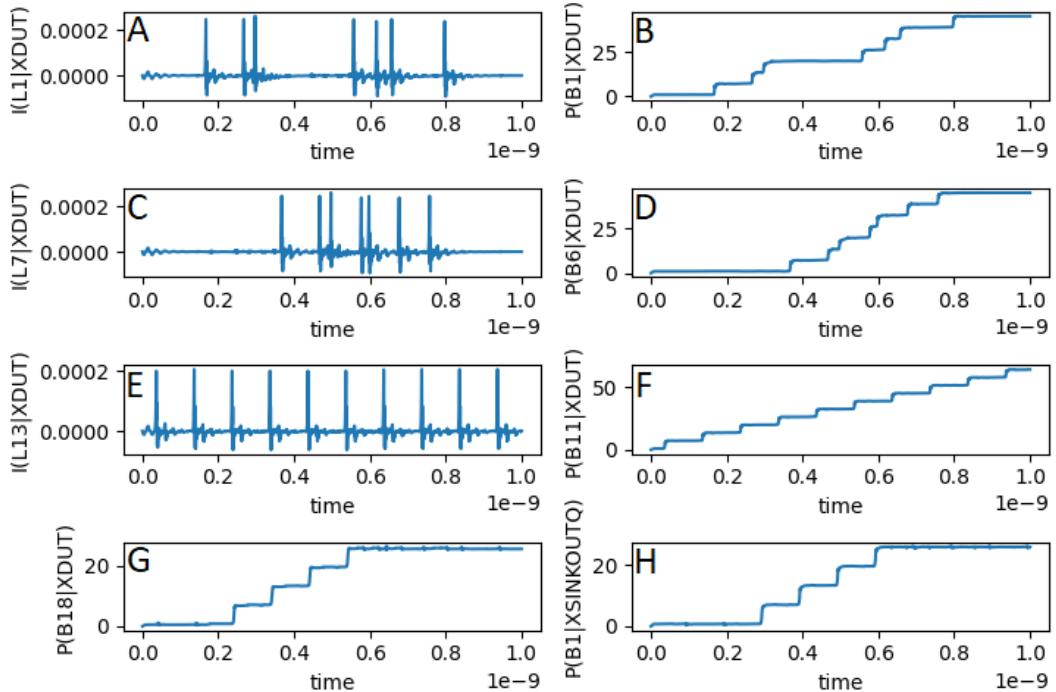
**Listing 3.23:** RSFQ XORT JoSIM netlist.

**Table 3.19:** RSFQ XORT pin list.

Pin	Description
<b>a</b>	Data input
<b>b</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ XORT using JoSIM is shown in Fig. 3.42. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.

**Figure 3.42:** RSFQ XORT analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 4 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 'timescale 1ps/100fs
16 module LSmitll_XORT_v2p1_optimized (a, b, clk, q);
17
18 input
19   a, b, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state1_clk_q = 5.5,
29   delay_state2_clk_q = 5.5,
30   ct_state0_a_clk = 2.3,
31   ct_state0_b_clk = 2.3,
32   ct_state1_a_b = 9.0,
33   ct_state1_a_clk = 11.4,
34   ct_state1_b_b = 3.3,
35   ct_state1_clk_b = 3.9,
36   ct_state2_a_a = 3.3,
37   ct_state2_b_a = 9.1,
38   ct_state2_b_clk = 11.6,
39   ct_state2_clk_a = 3.9;
40
41 reg
42   errorsignal_a,
43   errorsignal_b,
44   errorsignal_clk;
45
46 integer
47   outfile,
48   cell_state; // internal state of the cell
49
50 initial
51 begin
52   errorsignal_a = 0;
53   errorsignal_b = 0;
54   errorsignal_clk = 0;
55   cell_state = 0; // Startup state
56   q = 0; // All outputs start at 0
57 end
58
59 always @ (posedge a or negedge a) // execute at positive and negative edges of input
60 begin
61   if ($time>4) // arbitrary steady-state time)
62     begin
63       if (errorsignal_a == 1'b1) // A critical timing is active for this input
64         begin
65           outfile = $fopen("errors.txt", "a");
66           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
67             ↳ ", $stime);

```

```

67          $fclose(outfile);
68          q <= 1'bX; // Set all outputs to unknown
69      end
70      if (errorsignal_a == 0)
71      begin
72          case (cell_state)
73          0: begin
74              cell_state = 1; // Blocking statement -- immediately
75              errorsignal_clk = 1; // Critical timing on this input; assign
76                  // immediately
77              errorsignal_clk <= #(ct_state0_a_clk) 0; // Clear error signal
78                  // after critical timing expires
79          end
80          1: begin
81              errorsignal_b = 1; // Critical timing on this input; assign
82                  // immediately
83              errorsignal_b <= #(ct_state1_a_b) 0; // Clear error signal
84                  // after critical timing expires
85              errorsignal_clk = 1; // Critical timing on this input; assign
86                  // immediately
87              errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
88                  // after critical timing expires
89          end
90          endcase
91      end
92  end
93
94 always @ (posedge b or negedge b) // execute at positive and negative edges of input
95 begin
96     if ($time>4) // arbitrary steady-state time)
97     begin
98         if (errorsignal_b == 1'b1) // A critical timing is active for this input
99         begin
100             outfile = $fopen("errors.txt", "a");
101             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
102                         // ", $stime);
103             $fclose(outfile);
104             q <= 1'bX; // Set all outputs to unknown
105         end
106         if (errorsignal_b == 0)
107         begin
108             case (cell_state)
109             0: begin
110                 cell_state = 2; // Blocking statement -- immediately
111                 errorsignal_clk = 1; // Critical timing on this input; assign
112                     // immediately
113                 errorsignal_clk <= #(ct_state0_b_clk) 0; // Clear error signal
114                     // after critical timing expires
115             end
116             1: begin
117                 cell_state = 0; // Blocking statement -- immediately
118                 errorsignal_b = 1; // Critical timing on this input; assign
119                     // immediately
120                 errorsignal_b <= #(ct_state1_b_b) 0; // Clear error signal
121                     // after critical timing expires
122             end
123             2: begin
124                 errorsignal_a = 1; // Critical timing on this input; assign
125                     // immediately
126                 errorsignal_a <= #(ct_state2_b_a) 0; // Clear error signal
127                     // after critical timing expires
128                 errorsignal_clk = 1; // Critical timing on this input; assign

```

```

122           ↗ immediately
123           errorsignal_clk <= #(ct_state2_b_clk) 0; // Clear error signal
124           ↗ after critical timing expires
125       end
126   end
127 end
128
129 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
130 begin
131   if ($time>4) // arbitrary steady-state time)
132   begin
133     if (errorsignal_clk == 1'b1) // A critical timing is active for this input
134     begin
135       outfile = $fopen("errors.txt", "a");
136       $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
137                   ↗ ", $stime);
138       $fclose(outfile);
139       q <= 1'bX; // Set all outputs to unknown
140     end
141     if (errorsignal_clk == 0)
142     begin
143       case (cell_state)
144         0: begin
145           end
146         1: begin
147           q <= #(delay_state1_clk_q) !q;
148           cell_state = 0; // Blocking statement -- immediately
149           errorsignal_b = 1; // Critical timing on this input; assign
150           ↗ immediately
151           errorsignal_b <= #(ct_state1_clk_b) 0; // Clear error signal
152           ↗ after critical timing expires
153         end
154         2: begin
155           q <= #(delay_state2_clk_q) !q;
156           cell_state = 0; // Blocking statement -- immediately
157           errorsignal_a = 1; // Critical timing on this input; assign
158           ↗ immediately
159           errorsignal_a <= #(ct_state2_clk_a) 0; // Clear error signal
160           ↗ after critical timing expires
161         end
162       endcase
163     end
164   end
165 endmodule

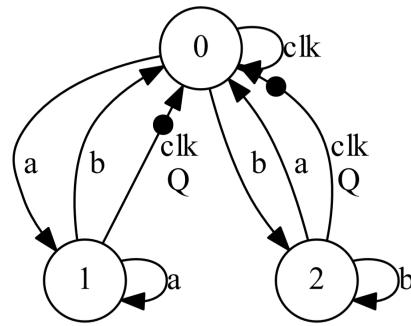
```

**Listing 3.24:** RSFQ XORT verilog model.

The digital simulation results for the RSFQ XORT is shown in Fig. 3.43 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.44.



**Figure 3.43:** RSFQ XORT digital simulation results.



**Figure 3.44:** RSFQ XORT Mealy finite state machine diagram.

## Power Consumption

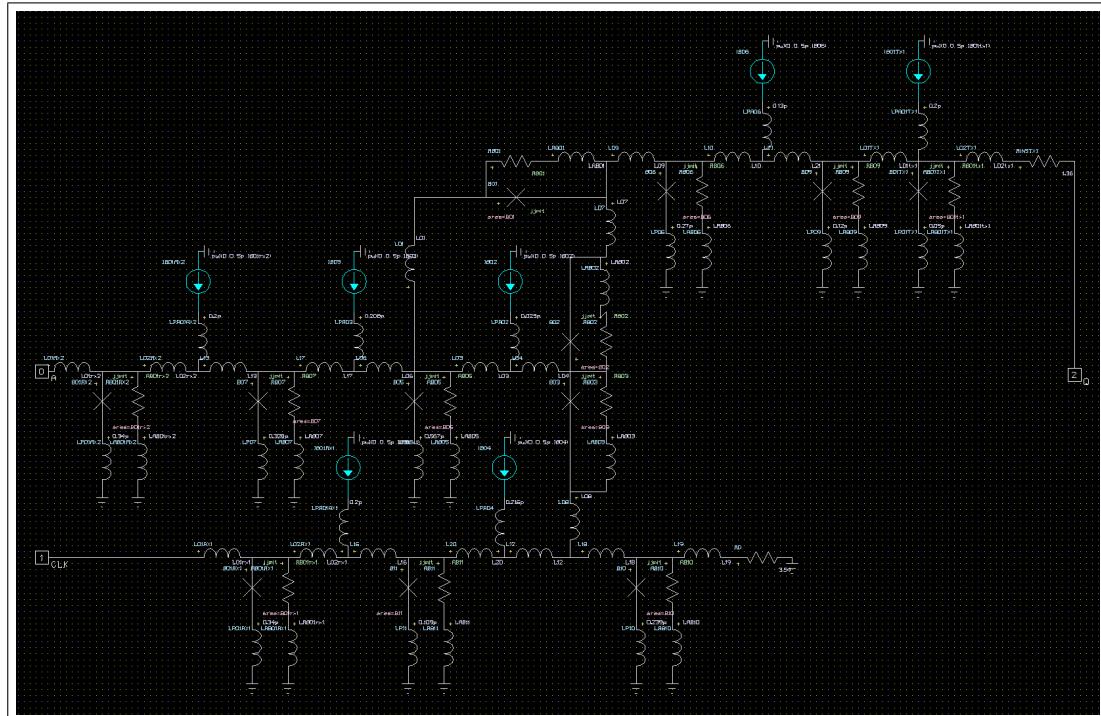
**Table 3.20:** RSFQ XORT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2985	5.18
2	2985	10.4
5	2985	25.9
10	2985	51.8
20	2985	104
50	2985	259

### 3.2.4 NOTT

The RSFQ NOTT cell is a signal inverting cell driven by a clock pulse signal line. The NOTT cell is designed with integrated PTL transmitters and receivers and is intended for direct connections with PTLs.

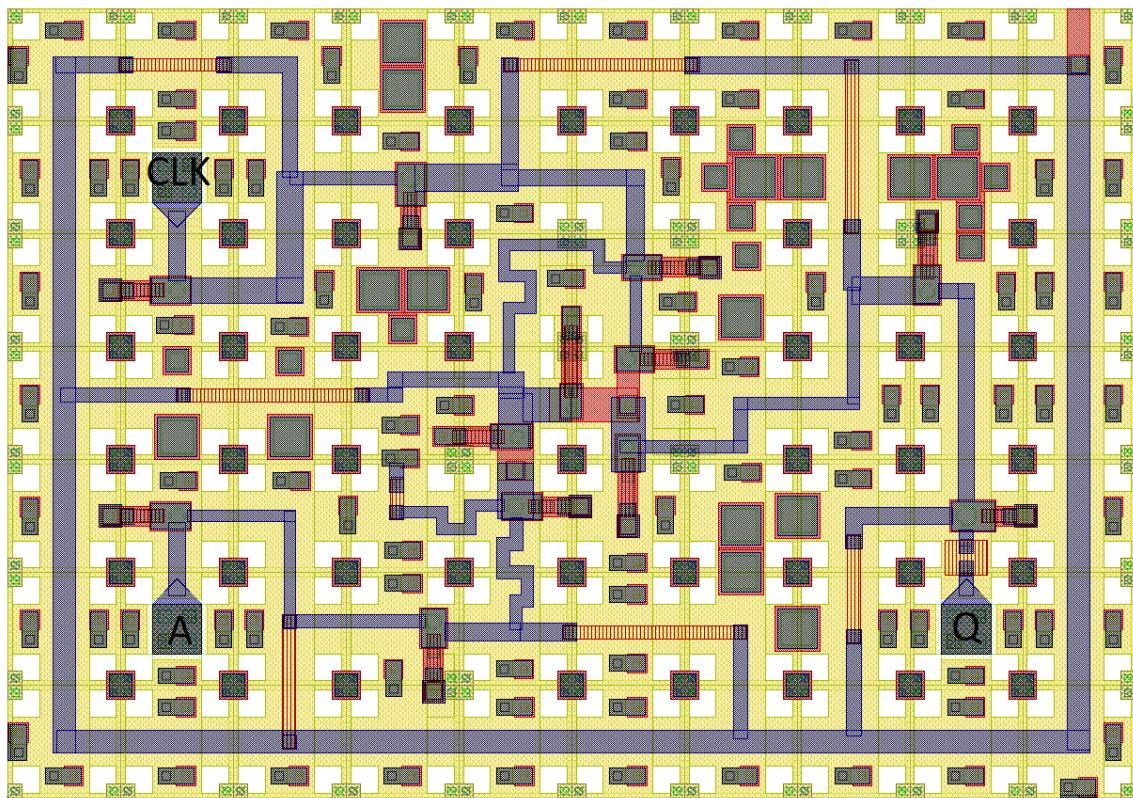
#### Schematic



**Figure 3.45:** Schematic of RSFQ NOTT.

## Layout

The physical layout for the RSFQ NOTT is shown in Fig. 3.46. The layout height is  $70 \mu\text{m}$  and the width is  $100 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.46:** RSFQ NOTT Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param L16=2.2847p
2   ↪ by InductEx v.6.0.4 on 3-6-21.          65  .param L17=0.49986p
3  * Author: L. Schindler                     66  .param L18=0.28417p
4  * Version: 2.1                            67  .param L19=7.3651p
5  * Last modification date: 3 June 2021     68  .param L20=0.74611p
6  * Last modification by: L. Schindler       69  .param L21=4.5195p
7  *$Ports a clk q                         70  .param L22=Lpt1
8 .subckt LSmitll_NOTT a clk q           71
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param RB1=B0Rs/B1
10  ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA   73  .param RB2=B0Rs/B2
11  ↪ )                                     74  .param RB3=B0Rs/B3
12 .param B0=1                               75  .param RB4=B0Rs/B4
13 .param Ic0=0.0001                         76  .param RB5=B0Rs/B5
14 .param IcRs=100u*6.859904418             77  .param RB6=B0Rs/B6
15 .param B0Rs=IcRs/Ic0*B0                  78  .param RB7=B0Rs/B7
16 .param Rsheet=2                          79  .param RB8=B0Rs/B8
17 .param Lsheet=1.13e-12                   80  .param RB9=B0Rs/B9
18 .param RD=1.36                           81  .param RB10=B0Rs/B10
19 .param LB=0.2p                           82  .param RB11=B0Rs/B11
20 .param Lpt1=2p                           83  .param RB12=B0Rs/B12
21 .param LP=0.5p                           84
22 .param B1=1.62                           85  .param LRB1=(RB1/Rsheet)*Lsheet
23 .param B2=1.42                           86  .param LRB2=(RB2/Rsheet)*Lsheet
24 .param B3=1.72                           87  .param LRB3=(RB3/Rsheet)*Lsheet
25 .param B4=1.22                           88  .param LRB4=(RB4/Rsheet)*Lsheet
26 .param B5=0.77                           89  .param LRB5=(RB5/Rsheet)*Lsheet
27 .param B6=1.62                           90  .param LRB6=(RB6/Rsheet)*Lsheet
28 .param B7=2.21                           91  .param LRB7=(RB7/Rsheet)*Lsheet
29 .param B8=1.22                           92  .param LRB8=(RB8/Rsheet)*Lsheet
30 .param B9=1.35                           93  .param LRB9=(RB9/Rsheet)*Lsheet
31 .param B10=1.04                          94  .param LRB10=(RB10/Rsheet)*Lsheet
32 .param B11=1.41                          95  .param LRB11=(RB11/Rsheet)*Lsheet
33 .param B12=2.5                           96  .param LRB12=(RB12/Rsheet)*Lsheet
34 .param IB1=146u                           97
35 .param IB2=102u                           98  B1 2 3 jjmit area=B1
36 .param IB3=181u                           99  B2 6 7 jjmit area=B2
37 .param IB4=95u                            100 B3 10 12 jjmit area=B3
38 .param IB5=97u                            101 B4 15 14 jjmit area=B4
39 .param IB6=108u                           102 B5 15 31 jjmit area=B5
40 .param IB7=187u                           103 B6 17 18 jjmit area=B6
41 .param LB1=LB                            104 B7 21 22 jjmit area=B7
42 .param LB2=LB                            105 B8 25 26 jjmit area=B8
43 .param LB3=LB                            106 B9 29 30 jjmit area=B9
44 .param LB4=LB                            107 B10 32 33 jjmit area=B10
45 .param LB5=LB                            108 B11 36 37 jjmit area=B11
46 .param LB6=LB                            109 B12 38 40 jjmit area=B12
47 .param LB7=LB                            110
48 .param L1=Lpt1                           111 IB1 0 5 pw1(0 0 5p IB1)
49 .param L2=4.4718p                         112 IB2 0 9 pw1(0 0 5p IB2)
50 .param L3=2.6117p                         113 IB3 0 20 pw1(0 0 5p IB3)
51 .param L4=1.1676p                         114 IB4 0 24 pw1(0 0 5p IB4)
52 .param L5=2.6532p                         115 IB5 0 28 pw1(0 0 5p IB5)
53 .param L7=3.1681p                         116 IB6 0 35 pw1(0 0 5p IB6)
54 .param L8=0.86946p                        117 IB7 0 39 pw1(0 0 5p IB7)
55 .param L9=Lpt1                           118
56 .param L10=2.5468p                          119 L1 a 2 1.512E-12
57 .param L11=2.1566p                          120 L2 2 4 4.457E-12
58 .param L12=0.99180p                         121 L3 4 6 2.653E-12
59 .param L13=3.286p                           122 L4 6 8 1.178E-12
60 .param L14=6.5962p                           123 L5 8 10 2.632E-12
61 .param L15=0.42413p                          124 L7 10 13 3.082E-12
62 .param L16=2.2847p                           125 L8 10 14 9.617E-13
63 .param L17=0.49986p                          126 L9 clk 17 1.474E-12
64 .param L18=0.28417p                          127 L10 17 19 2.503E-12
65 .param L19=7.3651p                           128 L11 19 21 2.138E-12
66 .param L20=0.74611p                          129 L12 21 23 1.01E-12
67 .param L21=4.5195p
68 .param L22=Lpt1

```

```

130 | L13 23 25 3.271E-12      160 | LP12 40 0 3.812E-13
131 | L14 25 27 6.557E-12      161 |
132 | L15 27 15 3.072E-13      162 | RB1 2 102 RB1
133 | L16 25 29 2.304E-12      163 | LRB1 102 0 LRB1
134 | L17 30 31 9.738E-13      164 | RB2 6 106 RB2
135 | L18 30 32 4.947E-13      165 | LRB2 106 0 LRB2
136 | L19 32 34 7.347E-12      166 | RB3 10 110 RB3
137 | L20 34 36 6.796E-13      167 | LRB3 110 0 LRB3
138 | L21 36 38 4.559E-12      168 | RB4 14 114 RB4
139 | L22 38 41 5.968E-13      169 | LRB4 114 15 LRB4
140 |
141 | RN 13 0 3.54
142 | RD 41 q RD
143 |
144 | LB1 4 5 3.007E-13
145 | LB2 8 9 1.087E-12
146 | LB3 19 20 3.264E-12
147 | LB4 23 24 1.957E-12
148 | LB5 27 28 2.946E-12
149 | LB6 34 35 1.302E-12
150 | LB7 38 39 2.399E-12
151 |
152 | LP1 3 0 4.817E-13
153 | LP2 7 0 4.958E-13
154 | LP3 12 0 5.177E-13
155 | LP6 18 0 4.916E-13
156 | LP7 22 0 4.956E-13
157 | LP8 26 0 5.494E-13
158 | LP10 33 0 6.002E-13
159 | LP11 37 0 5.068E-13
160 | LRB5 115 31 LRB5
161 |
162 | RB6 17 117 RB6
163 | LRB6 117 0 LRB6
164 | RB7 21 121 RB7
165 | LRB7 121 0 LRB7
166 | RB8 25 125 RB8
167 | LRB8 125 0 LRB8
168 | RB9 29 129 RB9
169 | LRB9 129 30 LRB9
170 | RB10 32 132 RB10
171 | LRB10 132 0 LRB10
172 |
173 | RB11 36 136 RB11
174 | LRB11 136 0 LRB11
175 | RB12 38 138 RB12
176 | LRB12 138 0 LRB12
177 |
178 | .ends
179 |
180 |
181 |
182 |
183 |
184 |
185 |
186 |

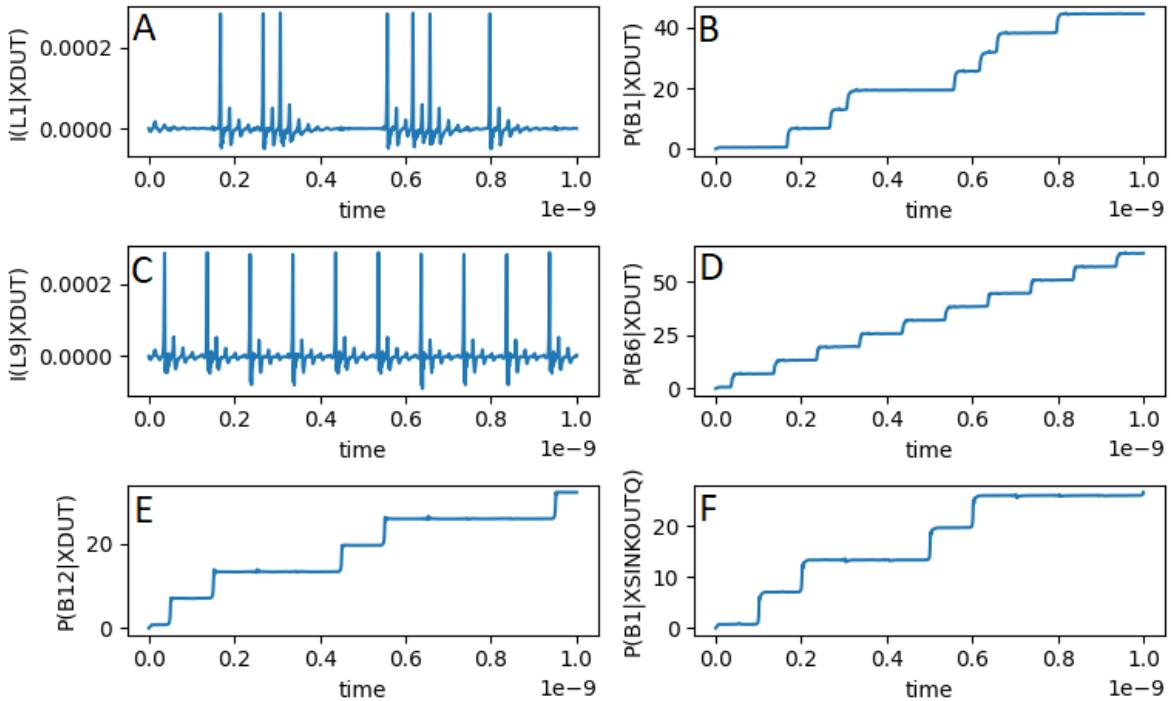
```

**Listing 3.25:** RSFQ NOTT JoSIM netlist.**Table 3.21:** RSFQ NOTT pin list.

Pin	Description
a	Data input
clk	Clock input
q	Data output

The simulation results for the RSFQ NOTT using JoSIM is shown in Fig. 3.47. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **clk**,
- (d) the phase over the input JJ of pin **clk**,
- (e) the phase over the output JJ of pin **q**, and
- (f) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.



**Figure 3.47:** RSFQ NOTT analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 'timescale 1ps/100fs
16 module LSmitll_NOTT_v2p1_optimized (a, clk, q);
17
18 input
19   a, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state0_clk_q = 14.0,
29   ct_state0_clk_a = 7.1,
30   ct_state0_clk_clk = 16.8,
31   ct_state1_a_clk = 13.6;
32
33 reg
34   errorsignal_a,
35   errorsignal_clk;
36
37 integer
38   outfile,
39   cell_state; // internal state of the cell
40
41 initial
42 begin
43   errorsignal_a = 0;
44   errorsignal_clk = 0;
45   cell_state = 0; // Startup state
46   q = 0; // All outputs start at 0
47 end
48
49 always @ (posedge a or negedge a) // execute at positive and negative edges of input
50 begin
51   if ($time > 4) // arbitrary steady-state time)
52     begin
53       if (errorsignal_a == 1'b1) // A critical timing is active for this input
54         begin
55           outfile = $fopen("errors.txt", "a");
56           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
57             ↪ ", $stime);
58           $fclose(outfile);
59           q <= 1'bX; // Set all outputs to unknown
60         end
61       if (errorsignal_a == 0)
62         begin
63           case (cell_state)
64             0: begin
65               cell_state = 1; // Blocking statement -- immediately
66             end
67             1: begin

```

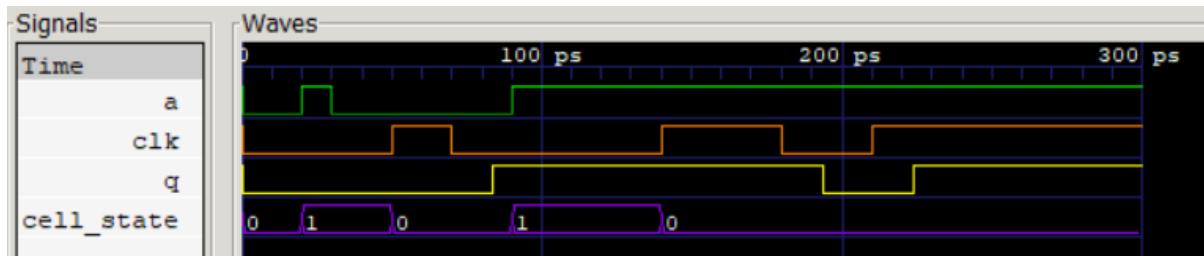
```

67          errorsignal_clk = 1; // Critical timing on this input; assign
68          ↪ immediately
69          errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
70          ↪ after critical timing expires
71      end
72  endcase
73 end
74
75 always @ (posedge clk or negedge clk) // execute at positive and negative edges of input
76 begin
77     if ($time>4) // arbitrary steady-state time)
78     begin
79         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
80             begin
81                 outfile = $fopen("errors.txt", "a");
82                 $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
83                             ↪ ", $stime);
84                 $fclose(outfile);
85                 q <= 1'bX; // Set all outputs to unknown
86             end
87         if (errorsignal_clk == 0)
88             begin
89                 case (cell_state)
90                     0: begin
91                         q <= #(delay_state0_clk_q) !q;
92                         errorsignal_a = 1; // Critical timing on this input; assign
93                         ↪ immediately
94                         errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
95                         ↪ after critical timing expires
96                         errorsignal_clk = 1; // Critical timing on this input; assign
97                         ↪ immediately
98                         errorsignal_clk <= #(ct_state0_clk_clk) 0; // Clear error
99                         ↪ signal after critical timing expires
100                    end
101                1: begin
102                    cell_state = 0; // Blocking statement -- immediately
103                end
104            endcase
105        end
106    end
107 end
108
109 endmodule

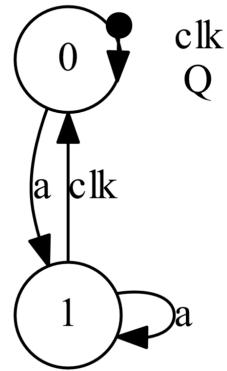
```

Listing 3.26: RSFQ NOTT verilog model.

The digital simulation results for the RSFQ NOTT is shown in Fig. 3.48 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.49.



**Figure 3.48:** RSFQ NOTT digital simulation results.



**Figure 3.49:** RSFQ NOTT Mealy finite state machine diagram.

## Power Consumption

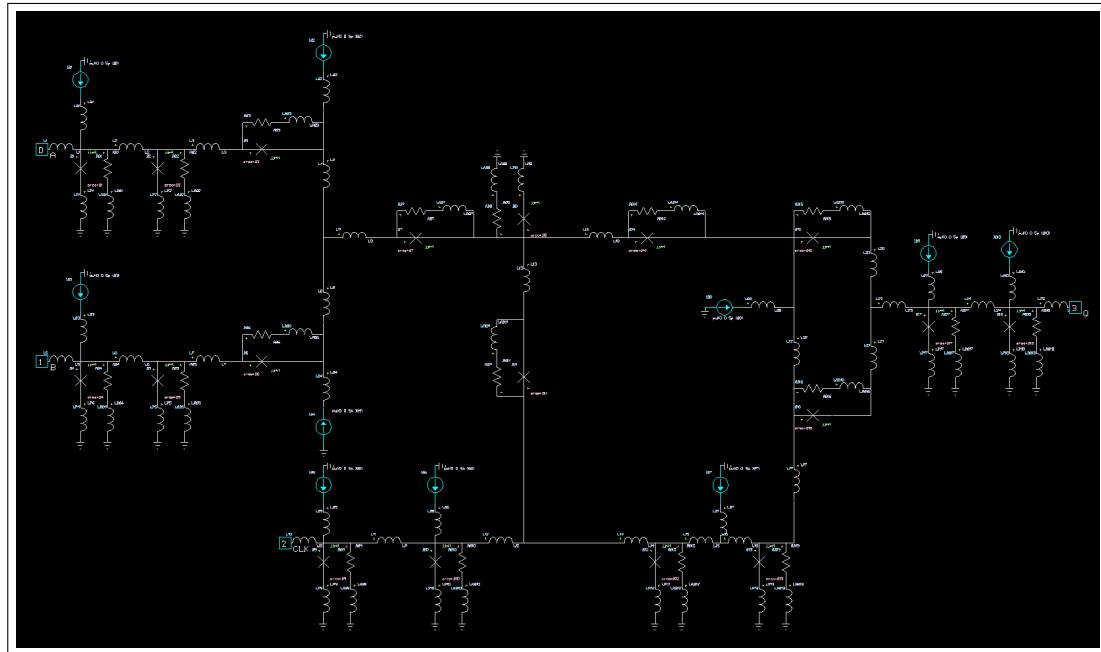
**Table 3.22:** RSFQ NOTT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2382	3.74
2	2382	7.49
5	2382	18.7
10	2382	37.4
20	2382	74.9
50	2382	187

### 3.2.5 XNORT

The RSFQ XNORT cell is a combination of a NOTT and XORT cell. It generates an output pulse exclusively if no input pulse was received or if a pulse from both input lines was received before the clock signal. The XNORT cell is designed with integrated PTL transmitters and receivers and is intended for direct connections with PTLs.

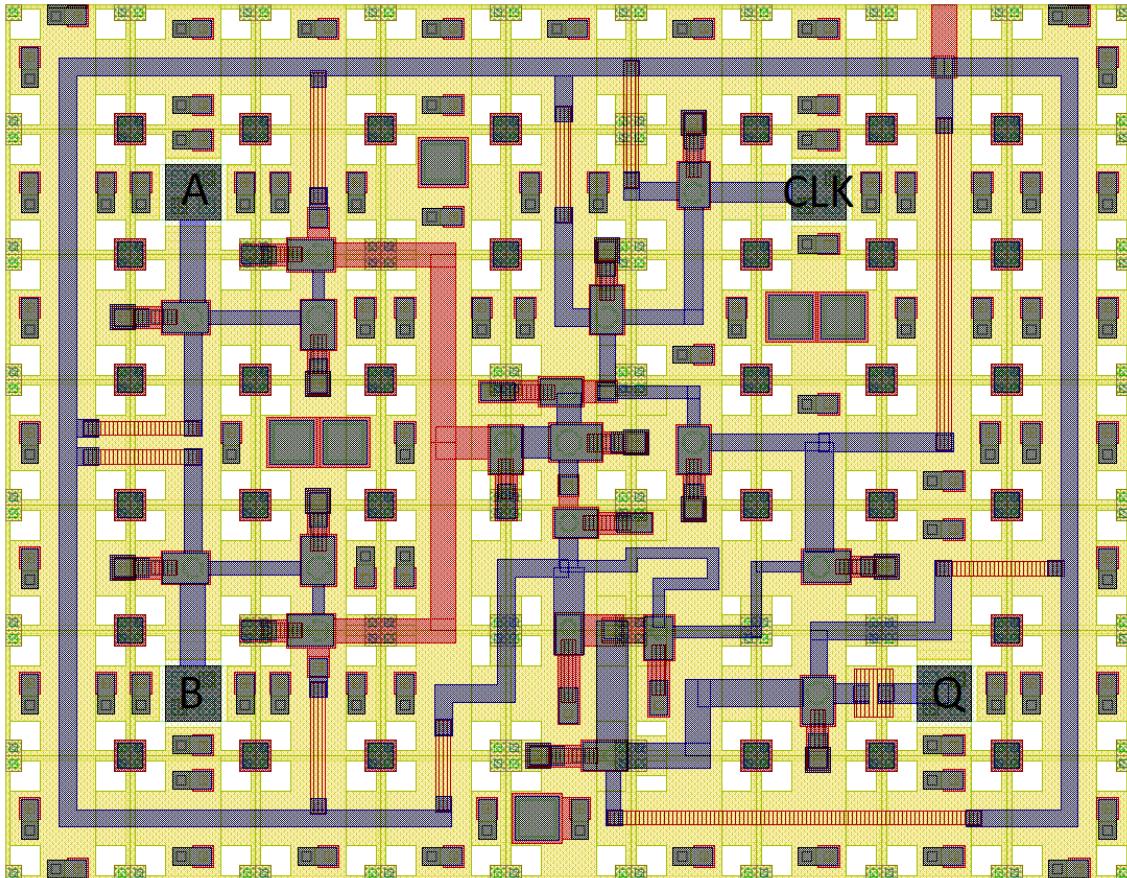
#### Schematic



**Figure 3.50:** Schematic of RSFQ XNORT.

## Layout

The physical layout for the RSFQ XNORT is shown in Fig. 3.51. The layout height is  $70 \mu\text{m}$  and the width is  $90 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.51:** RSFQ XNORT Layout.

## Analog model

```

1  * Author: L. Schindler
2  * Version: 2.1
3  * Last modification date: 7 June 2021
4  * Last modification by: L. Schindler
5
6  *$Ports a b clk q
7 .subckt LSMITLL_XNORT a b clk q
8 .model jjmit jj(rtype=1, vg=2.8mV, cap
  ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA
  ↪ )
9 .param Phi0=2.067833848E-15
10 .param B0=1
11 .param Ic0=0.0001
12 .param IcRs=100u*6.859904418
13 .param B0Rs=IcRs/Ic0*B0
14 .param Rsheet=2
15 .param Lsheet=1.13e-12
16 .param LP=0.2p
17 .param IC=2.5
18 .param Lptl=2p
19 .param LB=2p
20 .param BiasCoef=0.7
21
22 .param B1=2.0
23 .param B2=2.74
24 .param B3=2.23
25 .param B4=B1
26 .param B5=B2
27 .param B6=B3
28 .param B7=2.40
29 .param B8=3.29
30 .param B9=2.0
31 .param B10=2.42
32 .param B11=1.36
33 .param B12=2.40
34 .param B13=2.28
35 .param B14=1.75
36 .param B15=1.07
37 .param B16=1.54
38 .param B17=1.64
39 .param B18=2.5
40
41 .param IB1=195E-6
42 .param IB2=168E-6
43 .param IB3=IB1
44 .param IB4=IB2
45 .param IB5=175E-6
46 .param IB6=195E-6
47 .param IB7=60E-6
48 .param IB8=262E-6
49 .param IB9=53E-6
50 .param IB10=175E-6
51
52 .param L1=Lptl
53 .param L2=2.10e-12
54 .param L3=1p
55 .param L4=4.12e-12
56 .param L5=L1
57 .param L6=L2
58 .param L7=L3
59 .param L8=L4
60 .param L9=1p
61 .param L10=Lptl
62 .param L11=3.11e-12
63 .param L12=1.07E-12
64 .param L13=1.01E-12
65 .param L14=2.45e-12
66 .param L15=1.83e-12
67 .param L16=1.12e-12
68 .param L17=4.32e-12
69 .param L18=1.6p
70 .param L20=1.06E-12
71 .param L21=0.55E-12
72 .param L22=5.40e-12
73 .param L23=1.18e-12
74 .param L24=2.78e-12
75 .param L25=Lptl
76
77 .param RD=1.36
78
79 .param RB1=B0Rs/B1
80 .param RB2=B0Rs/B2
81 .param RB3=B0Rs/B3
82 .param RB4=B0Rs/B4
83 .param RB5=B0Rs/B5
84 .param RB6=B0Rs/B6
85 .param RB7=B0Rs/B7
86 .param RB8=B0Rs/B8
87 .param RB9=B0Rs/B9
88 .param RB10=B0Rs/B10
89 .param RB11=B0Rs/B11
90 .param RB12=B0Rs/B12
91 .param RB13=B0Rs/B13
92 .param RB14=B0Rs/B14
93 .param RB15=B0Rs/B15
94 .param RB16=B0Rs/B16
95 .param RB17=B0Rs/B17
96 .param RB18=B0Rs/B18
97 .param LRB1=(RB1/Rsheet)*Lsheet
98 .param LRB2=(RB2/Rsheet)*Lsheet
99 .param LRB3=(RB3/Rsheet)*Lsheet
100 .param LRB4=(RB4/Rsheet)*Lsheet
101 .param LRB5=(RB5/Rsheet)*Lsheet
102 .param LRB6=(RB6/Rsheet)*Lsheet
103 .param LRB7=(RB7/Rsheet)*Lsheet
104 .param LRB8=(RB8/Rsheet)*Lsheet
105 .param LRB9=(RB9/Rsheet)*Lsheet
106 .param LRB10=(RB10/Rsheet)*Lsheet
107 .param LRB11=(RB11/Rsheet)*Lsheet
108 .param LRB12=(RB12/Rsheet)*Lsheet
109 .param LRB13=(RB13/Rsheet)*Lsheet
110 .param LRB14=(RB14/Rsheet)*Lsheet
111 .param LRB15=(RB15/Rsheet)*Lsheet
112 .param LRB16=(RB16/Rsheet)*Lsheet
113 .param LRB17=(RB17/Rsheet)*Lsheet
114 .param LRB18=(RB18/Rsheet)*Lsheet
115
116 B1 1 2 jjmit area=B1
117 B2 3 4 jjmit area=B2
118 B3 5 6 jjmit area=B3
119 B4 8 9 jjmit area=B4
120 B5 10 11 jjmit area=B5
121 B6 12 13 jjmit area=B6
122 B7 14 15 jjmit area=B7
123 B8 15 16 jjmit area=B8
124 B9 17 18 jjmit area=B9
125 B10 19 20 jjmit area=B10
126 B11 22 15 jjmit area=B11
127 B12 23 24 jjmit area=B12
128 B13 26 27 jjmit area=B13
129 B14 29 34 jjmit area=B14
130 B15 34 31 jjmit area=B15

```

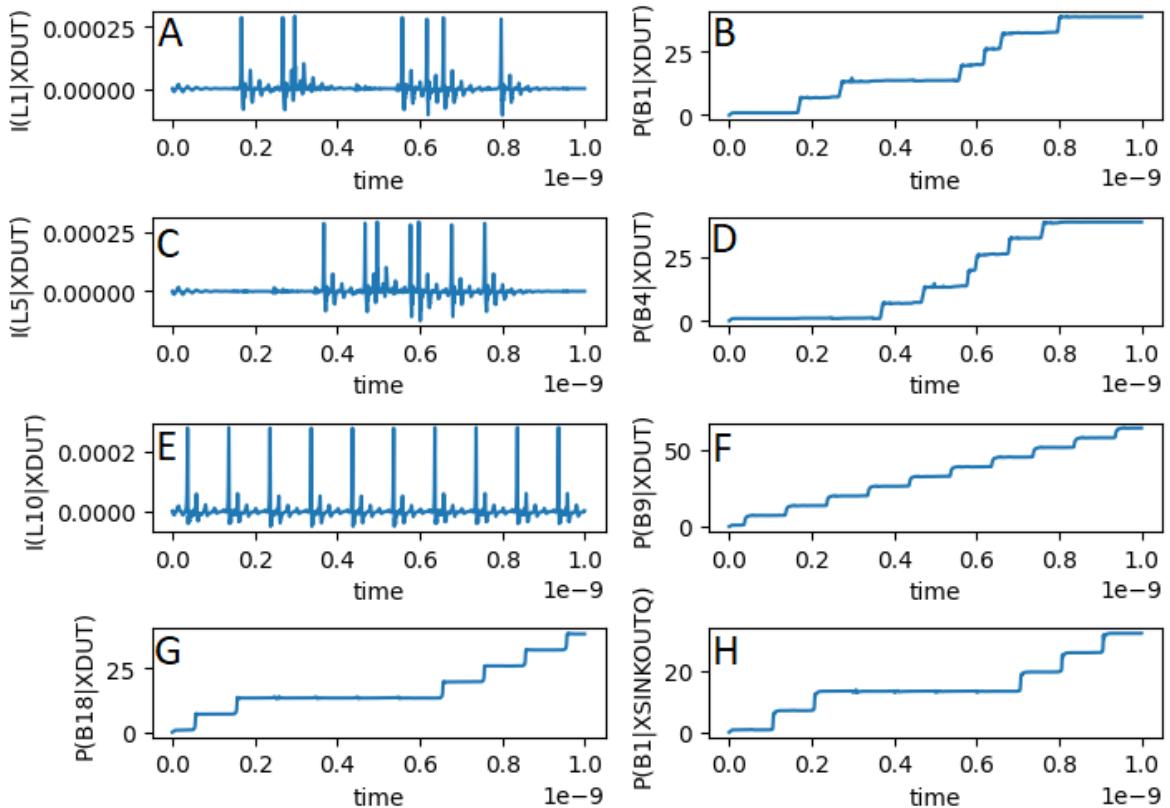
131	B16 28 33 jjmit area=B16	177	L21 33 32 L21
132	B17 35 36 jjmit area=B17	178	L22 34 28 L22
133	B18 37 38 jjmit area=B18	179	L23 32 35 L23
134		180	L24 35 37 L24
135	LP1 2 0 LP	181	L25 37 39 L25
136	LP2 4 0 LP	182	RD 39 q RD
137	LP4 9 0 LP	183	
138	LP5 11 0 LP	184	RB1 1 101 RB1
139	LP8 16 0 LP	185	LRB1 101 0 LRB1
140	LP9 18 0 LP	186	RB2 3 103 RB2
141	LP10 20 0 LP	187	LRB2 103 0 LRB2
142	LP12 24 0 LP	188	RB3 5 105 RB3
143	LP13 27 0 LP	189	LRB3 105 6 LRB3
144	LP17 36 0 LP	190	RB4 8 108 RB4
145	LP18 38 0 LP	191	LRB4 108 0 LRB4
146		192	RB5 10 110 RB5
147	IB1 0 1 pwl(0 0 5p IB1)	193	LRB5 110 0 LRB5
148	IB2 0 6 pwl(0 0 5p IB2)	194	RB6 12 112 RB6
149	IB3 0 8 pwl(0 0 5p IB3)	195	LRB6 112 13 LRB6
150	IB4 0 13 pwl(0 0 5p IB4)	196	RB7 14 114 RB7
151	IB5 0 17 pwl(0 0 5p IB5)	197	LRB7 114 15 LRB7
152	IB6 0 19 pwl(0 0 5p IB6)	198	RB8 15 115 RB8
153	IB7 0 25 pwl(0 0 5p IB7)	199	LRB8 115 0 LRB8
154	IB8 0 34 pwl(0 0 5p IB8)	200	RB9 17 117 RB9
155	IB9 0 35 pwl(0 0 5p IB9)	201	LRB9 117 0 LRB9
156	IB10 0 37 pwl(0 0 5p IB10)	202	RB10 19 119 RB10
157		203	LRB10 119 0 LRB10
158	L1 a 1 L1	204	RB11 22 122 RB11
159	L2 1 3 L2	205	LRB11 122 15 LRB11
160	L3 3 5 L3	206	RB12 23 123 RB12
161	L4 6 7 L4	207	LRB12 123 0 LRB12
162	L5 b 8 L5	208	RB13 26 126 RB13
163	L6 8 10 L6	209	LRB13 126 0 LRB13
164	L7 10 12 L7	210	RB14 29 129 RB14
165	L8 13 7 L8	211	LRB14 129 34 LRB14
166	L9 7 14 L9	212	RB15 34 130 RB15
167	L10 clk 17 L10	213	LRB15 130 31 LRB15
168	L11 17 19 L11	214	RB16 28 128 RB16
169	L12 19 21 L12	215	LRB16 128 33 LRB16
170	L13 21 22 L13	216	RB17 35 135 RB17
171	L14 21 23 L14	217	LRB17 135 0 LRB17
172	L15 23 25 L15	218	RB18 37 137 RB18
173	L16 25 26 L16	219	LRB18 137 0 LRB18
174	L17 26 28 L17	220	.ends
175	L18 15 29 L18		
176	L20 31 32 L20		

**Listing 3.27:** RSFQ XNORT JoSIM netlist.**Table 3.23:** RSFQ XNORT pin list.

Pin	Description
<b>a</b>	Data input
<b>b</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ XNORT using JoSIM is shown in Fig. 3.52. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b**,
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.



**Figure 3.52:** RSFQ XNORT analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 4 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 'timescale 1ps/100fs
16 module LSmitll_XNORT_v2p1_optimized (a, b, clk, q);
17
18 input
19   a, b, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state0_clk_q = 19.0,
29   ct_state0_clk_a = 6.0,
30   ct_state0_clk_b = 6.0,
31   ct_state0_clk_clk = 30.0,
32   ct_state1_b_a = 11.3,
33   ct_state1_b_b = 7.5,
34   ct_state1_b_clk = 18.1,
35   ct_state1_clk_a = 12.5,
36   ct_state1_clk_b = 7.6,
37   ct_state2_a_a = 7.5,
38   ct_state2_a_b = 11.3,
39   ct_state2_a_clk = 18.1,
40   ct_state2_clk_a = 7.6,
41   ct_state2_clk_b = 12.5;
42
43 reg
44   errorsignal_a,
45   errorsignal_b,
46   errorsignal_clk;
47
48 integer
49   outfile,
50   cell_state; // internal state of the cell
51
52 initial
53 begin
54   errorsignal_a = 0;
55   errorsignal_b = 0;
56   errorsignal_clk = 0;
57   cell_state = 0; // Startup state
58   q = 0; // All outputs start at 0
59 end
60
61 always @(posedge a or negedge a) // execute at positive and negative edges of input
62 begin
63   if ($time>4) // arbitrary steady-state time)
64   begin
65     if (errorsignal_a == 1'b1) // A critical timing is active for this input
66     begin
67       outfile = $fopen("errors.txt", "a");

```

```

68         $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
69             ↪ ", $stime);
70         $fclose(outfile);
71         q <= 1'bX; // Set all outputs to unknown
72     end
73     if (errorsignal_a == 0)
74     begin
75         case (cell_state)
76             0: begin
77                 cell_state = 1; // Blocking statement -- immediately
78             end
79             1: begin
80                 end
81             2: begin
82                 cell_state = 0; // Blocking statement -- immediately
83                 errorsignal_a = 1; // Critical timing on this input; assign
84                     ↪ immediately
85                 errorsignal_a <= #(ct_state2_a_a) 0; // Clear error signal
86                     ↪ after critical timing expires
87                 errorsignal_b = 1; // Critical timing on this input; assign
88                     ↪ immediately
89                 errorsignal_b <= #(ct_state2_a_b) 0; // Clear error signal
90                     ↪ after critical timing expires
91                 errorsignal_clk = 1; // Critical timing on this input; assign
92                     ↪ immediately
93                 errorsignal_clk <= #(ct_state2_a_clk) 0; // Clear error signal
94                     ↪ after critical timing expires
95             end
96         endcase
97     end
98
99     always @(posedge b or negedge b) // execute at positive and negative edges of input
100    begin
101        if ($time>4) // arbitrary steady-state time)
102        begin
103            if (errorsignal_b == 1'b1) // A critical timing is active for this input
104            begin
105                outfile = $fopen("errors.txt", "a");
106                $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
107                    ↪ ", $stime);
108                $fclose(outfile);
109                q <= 1'bX; // Set all outputs to unknown
110            end
111            if (errorsignal_b == 0)
112            begin
113                case (cell_state)
114                    0: begin
115                        cell_state = 2; // Blocking statement -- immediately
116                    end
117                    1: begin
118                        cell_state = 0; // Blocking statement -- immediately
119                        errorsignal_a = 1; // Critical timing on this input; assign
120                            ↪ immediately
121                        errorsignal_a <= #(ct_state1_b_a) 0; // Clear error signal
122                            ↪ after critical timing expires
123                        errorsignal_b = 1; // Critical timing on this input; assign
124                            ↪ immediately
125                        errorsignal_b <= #(ct_state1_b_b) 0; // Clear error signal
126                            ↪ after critical timing expires
127                        errorsignal_clk = 1; // Critical timing on this input; assign
128                            ↪ immediately
129                        errorsignal_clk <= #(ct_state1_b_clk) 0; // Clear error signal
130                            ↪ after critical timing expires
131                    end
132                    2: begin
133                        end
134                endcase
135            end
136        end

```

```

124         end
125     end
126
127     always @(posedge clk or negedge clk) // execute at positive and negative edges of input
128     begin
129         if ($time>4) // arbitrary steady-state time)
130             begin
131                 if (errorsignal_clk == 1'b1) // A critical timing is active for this input
132                     begin
133                         outfile = $fopen("errors.txt", "a");
134                         $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;,%0d_ps.\n"
135                                     ↪ ", $stime);
136                         $fclose(outfile);
137                         q <= 1'bX; // Set all outputs to unknown
138                     end
139                 if (errorsignal_clk == 0)
140                     begin
141                         case (cell_state)
142                             0: begin
143                                 q <= #(delay_state0_clk_q) !q;
144                                 errorsignal_a = 1; // Critical timing on this input; assign
145                                     ↪ immediately
146                                 errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
147                                     ↪ after critical timing expires
148                                 errorsignal_b = 1; // Critical timing on this input; assign
149                                     ↪ immediately
150                                 errorsignal_b <= #(ct_state0_clk_b) 0; // Clear error signal
151                                     ↪ after critical timing expires
152                                 errorsignal_clk = 1; // Critical timing on this input; assign
153                                     ↪ immediately
154                                 errorsignal_clk <= #(ct_state0_clk_clk) 0; // Clear error
155                                     ↪ signal after critical timing expires
156                             end
157                             1: begin
158                                 cell_state = 0; // Blocking statement -- immediately
159                                 errorsignal_a = 1; // Critical timing on this input; assign
160                                     ↪ immediately
161                                 errorsignal_a <= #(ct_state1_clk_a) 0; // Clear error signal
162                                     ↪ after critical timing expires
163                                 errorsignal_b = 1; // Critical timing on this input; assign
164                                     ↪ immediately
165                                 errorsignal_b <= #(ct_state1_clk_b) 0; // Clear error signal
166                                     ↪ after critical timing expires
167                             end
168                         endcase
169                     end
170                 end
171             end
172         end
173     endmodule

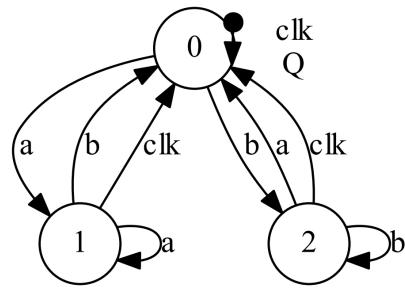
```

Listing 3.28: RSFQ XNORT verilog model.

The digital simulation results for the RSFQ XNORT is shown in Fig. 3.53 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.54.



**Figure 3.53:** RSFQ XNORT digital simulation results.



**Figure 3.54:** RSFQ XNORT Mealy finite state machine diagram.

## Power Consumption

**Table 3.24:** RSFQ XNORT power consumption.

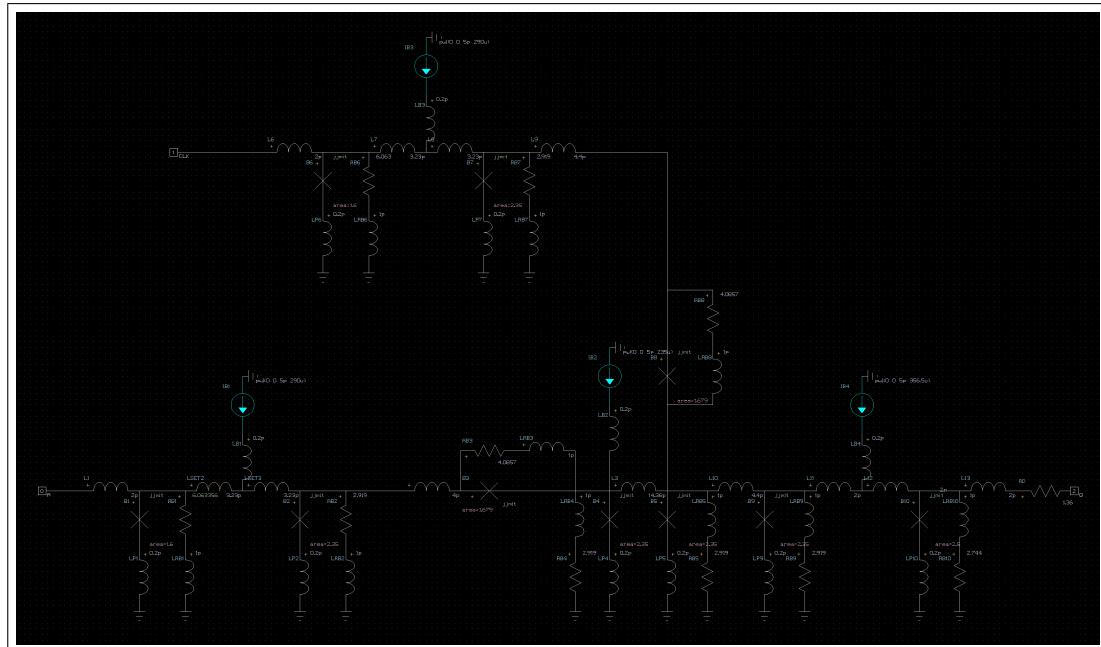
Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	4280	7.98
2	4280	16.0
5	4280	39.9
10	4280	79.8
20	4280	160
50	4280	399

## 3.3 Buffers

### 3.3.1 DFFT

The RSFQ DFFT, D flip-flop, is a multi-state device used to transmit an input set pulse synchronised with a reset (typically clock) signal. The DFFT is designed with integrated PTL transmitters and receivers and is intended to connect directly to PTLs.

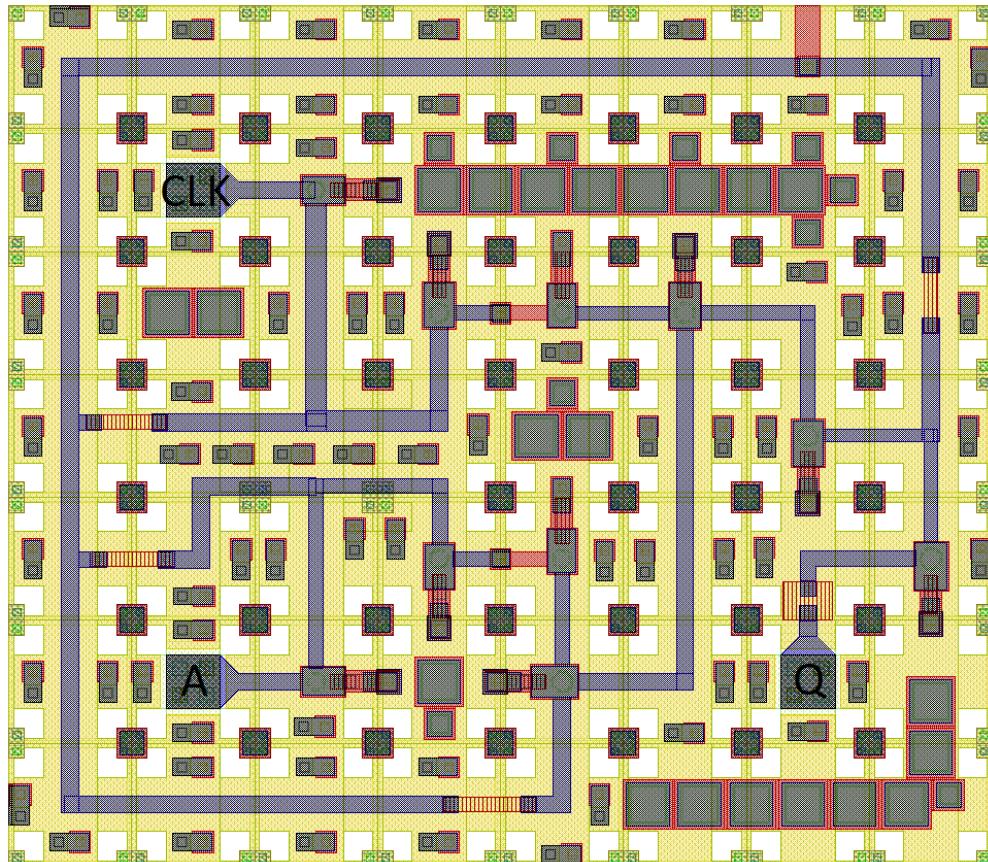
#### Schematic



**Figure 3.55:** Schematic of RSFQ DFFT.

## Layout

The physical layout for the RSFQ DFFT is shown in Fig. 3.56. The layout height is  $70 \mu\text{m}$  and the width is  $80 \mu\text{m}$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.56:** RSFQ DFFT Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param RB10=B0Rs/B10
2   ↪ by InductEx v.6.0.4 on 27-4-21.          65  .param LRB1=(RB1/Rsheet)*Lsheet+LP
3  * Author: L. Schindler                      66  .param LRB2=(RB2/Rsheet)*Lsheet+LP
4  * Version: 2.1                               67  .param LRB3=(RB3/Rsheet)*Lsheet+LP
5  * Last modification date: 8 June 2021       68  .param LRB4=(RB4/Rsheet)*Lsheet+LP
6  * Last modification by: L. Schindler        69  .param LRB5=(RB5/Rsheet)*Lsheet+LP
7  *$Ports a clk q                           70  .param LRB6=(RB6/Rsheet)*Lsheet+LP
8  .subckt LSMITLL_DFFT a clk q             71  .param LRB7=(RB7/Rsheet)*Lsheet+LP
9  .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param LRB8=(RB8/Rsheet)*Lsheet+LP
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA     73  .param LRB9=(RB9/Rsheet)*Lsheet+LP
   ↪ )                                         74  .param LRB10=(RB10/Rsheet)*Lsheet+LP
10 .param Phi0=2.067833848E-15                75  .param LP1=LP
11 .param B0=1                                 76  .param LP2=LP
12 .param Ic0=0.0001                            77  .param LP4=LP
13 .param IcRs=100u*6.859904418                 78  .param LP5=LP
14 .param B0Rs=IcRs/Ic0*B0                     79  .param LP6=LP
15 .param Rsheet=2                             80  .param LP7=LP
16 .param Lsheet=1.13e-12                       81  .param LP9=LP
17 .param LP=0.2p                             82  .param LP10=LP
18 .param IC=2.5                             83  .param LB1=LB
19 .param ICreceive=2.0                        84  .param LB2=LB
20 .param ICtrans=2.5                          85  .param LB3=LB
21 .param Lptl=2p                            86  .param LB4=LB
22 .param LB=2p                             87  IB1 0 5 pwl(0 0 5p IB1)
23 .param BiasCoef=0.7                         88  IB2 0 11 pwl(0 0 5p IB2)
24 .param RD=1.36                            89  IB3 0 18 pwl(0 0 5p IB3)
25 .param B1=1.62                            90  IB4 0 25 pwl(0 0 5p IB4)
26 .param B2=1.89                            91  B1 2 3 jjmit area=B1
27 .param B3=1.72                            92  B2 6 7 jjmit area=B2
28 .param B4=2.32                            93  B3 8 9 jjmit area=B3
29 .param B5=2.12                            94  B4 9 10 jjmit area=B4
30 .param B6=1.62                            95  B5 12 13 jjmit area=B5
31 .param B7=1.98                            96  B6 15 16 jjmit area=B6
32 .param B8=1.71                            97  B7 19 20 jjmit area=B7
33 .param B9=2.12                            98  B8 21 12 jjmit area=B8
34 .param B10=2.5                           99  B9 22 23 jjmit area=B9
35 .param B10=2.5                           100 B10 26 27 jjmit area=B10
36 .param IB1=276u                           101 L1 a 2 1.587E-12
37 .param IB2=235u                           102 L2 2 4 3.253E-12
38 .param IB3=284u                           103 L3 4 6 3.304E-12
39 .param IB4=312u                           104 L4 6 8 3.979E-12
40 .param L1=Lptl                           105 L5 9 12 7.521E-12
41 .param L2=(Phi0/(2*B1*Ic0))/2           106 L6 clk 15 1.6E-12
42 .param L3=(Phi0/(2*B1*Ic0))/2           107 L7 15 17 3.042E-12
43 .param L4=(Phi0/(2*B2*Ic0))              108 L8 17 19 3.045E-12
44 .param L5=Phi0/(B4*Ic0)                  109 L9 19 21 4.21E-12
45 .param L6=Lptl                           110 L10 12 22 4.022E-12
46 .param L7=(Phi0/(2*B6*Ic0))/2           111 L11 22 24 2.164E-12
47 .param L8=(Phi0/(2*B6*Ic0))/2           112 L12 24 26 2.183E-12
48 .param L9=Phi0/(2*B7*Ic0)                113 L13 26 28 2.536E-12
49 .param L10=Phi0/(2*B5*Ic0)               114 LP1 3 0 5.021E-13
50 .param L11=(Phi0/(2*B9*Ic0))/2           115 LP2 7 0 5.102E-13
51 .param L12=(Phi0/(2*B9*Ic0))/2           116 LP4 10 0 5.275E-13
52 .param L13=Lptl                           117 LP5 13 0 5.37E-13
53 .param RB1=B0Rs/B1                      118 LP6 16 0 5.005E-13
54 .param RB2=B0Rs/B2                      119 LP7 20 0 5.161E-13
55 .param RB3=B0Rs/B3                      120 LP9 23 0 5.212E-13
56 .param RB4=B0Rs/B4                      121 LP10 27 0 5.039E-13
57 .param RB5=B0Rs/B5                      122 LB1 4 5 3.559E-12
58 .param RB6=B0Rs/B6                      123 LB2 9 11 2.45E-12
59 .param RB7=B0Rs/B7                      124 LB3 17 18 2.72E-12
60 .param RB8=B0Rs/B8                      125 LB4 24 25 1.988E-12
61 .param RB9=B0Rs/B9                      126 RB1 2 102 RB1
62 .param RB10=B0Rs/B10                     127 RB2 6 106 RB2
63 .param RB11=B0Rs/B11                     128 RB3 8 108 RB3
64 .param RB12=B0Rs/B12                     129 RB4 9 109 RB4

```

```

130 | RB5 12 112 RB5
131 | RB6 15 115 RB6
132 | RB7 19 119 RB7
133 | RB8 21 121 RB8
134 | RB9 22 122 RB9
135 | RB10 26 126 RB10
136 | LRB1 102 0 LRB1
137 | LRB2 106 0 LRB2
138 | LRB3 108 9 LRB3
139 | LRB4 109 0 LRB4
140 | LRB5 112 0 LRB5
141 | LRB6 115 0 LRB6
142 | LRB7 119 0 LRB7
143 | LRB8 121 12 LRB8
144 | LRB9 122 0 LRB9
145 | LRB10 126 0 LRB10
146 | RD 28 q RD
147 | .ends

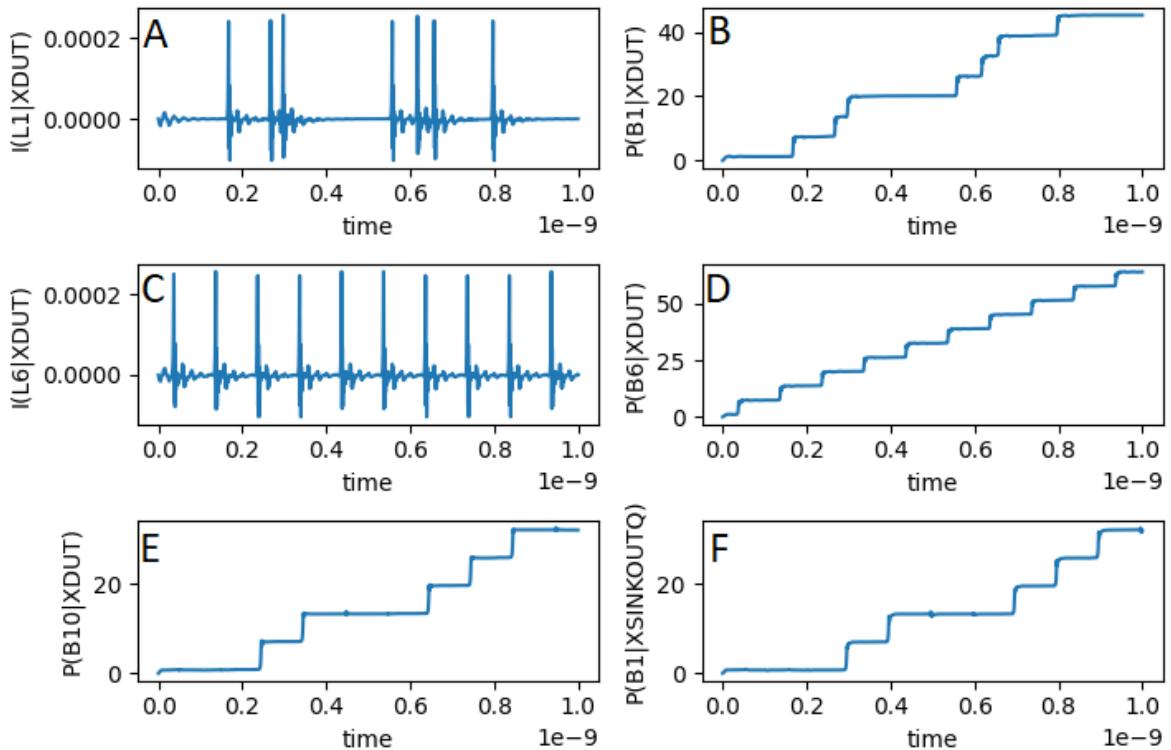
```

**Listing 3.29:** RSFQ DFFT JoSIM netlist.**Table 3.25:** RSFQ DFFT pin list.

<b>Pin</b>	Description
<b>a</b>	Data input
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ DFFT using JoSIM is shown in Fig. 3.57. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **clk**,
- (d) the phase over the input JJ of pin **clk**,
- (e) the phase over the output JJ of pin **q**, and
- (f) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.



**Figure 3.57:** RSFQ DFFT analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 8 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 // -----
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 // -----
15 `timescale 1ps/100fs
16 module LSmitll_DFFT_v2p1_optimized (a, clk, q);
17
18 input
19   a, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state1_clk_q = 8.5,
29   ct_state0_clk_a = 1.8,
30   ct_state1_a_clk = 1.8;
31
32 reg
33   errorsignal_a,
34   errorsignal_clk;
35
36 integer
37   outfile,
38   cell_state; // internal state of the cell
39
40 initial
41 begin
42   errorsignal_a = 0;
43   errorsignal_clk = 0;
44   cell_state = 0; // Startup state
45   q = 0; // All outputs start at 0
46 end
47
48 always @ (posedge a or negedge a) // execute at positive and negative edges of input
49 begin
50   if ($time>4) // arbitrary steady-state time)
51     begin
52       if (errorsignal_a == 1'b1) // A critical timing is active for this input
53         begin
54           outfile = $fopen("errors.txt", "a");
55           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
56           ↪ ", $stime);
57           $fclose(outfile);
58           q <= 1'bX; // Set all outputs to unknown
59         end
60       if (errorsignal_a == 0)
61         begin
62           case (cell_state)
63             0: begin
64               cell_state = 1; // Blocking statement -- immediately
65             end
66             1: begin
67               errorsignal_clk = 1; // Critical timing on this input; assign

```

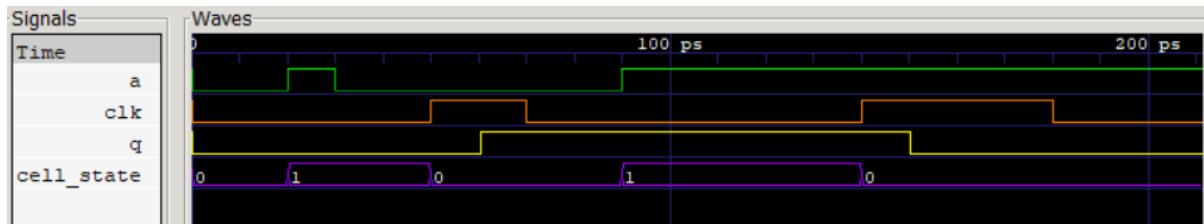
```

67           ↪ immediately
68           errorsignal_clk <= #(ct_state1_a_clk) 0; // Clear error signal
69           ↪ after critical timing expires
70       end
71   endcase
72 end
73
74 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
75 begin
76     if ($time>4) // arbitrary steady-state time)
77     begin
78         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
79         begin
80             outfile = $fopen("errors.txt", "a");
81             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
82             ↪ ", $stime);
83             $fclose(outfile);
84             q <= 1'bX; // Set all outputs to unknown
85         end
86         if (errorsignal_clk == 0)
87         begin
88             case (cell_state)
89             0: begin
90                 errorsignal_a = 1; // Critical timing on this input; assign
91                 ↪ immediately
92                 errorsignal_a <= #(ct_state0_clk_a) 0; // Clear error signal
93                 ↪ after critical timing expires
94             end
95             1: begin
96                 q <= #(delay_state1_clk_q) !q;
97                 cell_state = 0; // Blocking statement -- immediately
98             end
99         endcase
100    end
101 endmodule

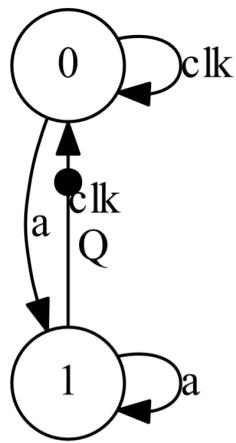
```

Listing 3.30: RSFQ DFFT verilog model.

The digital simulation results for the RSFQ DFFT is shown in Fig. 3.58 and the Mealy finite state machine diagram, extracted using *TimEx*, is shown in Fig. 3.59.



**Figure 3.58:** RSFQ DFFT digital simulation results.



**Figure 3.59:** RSFQ DFFT Mealy finite state machine diagram.

## Power Consumption

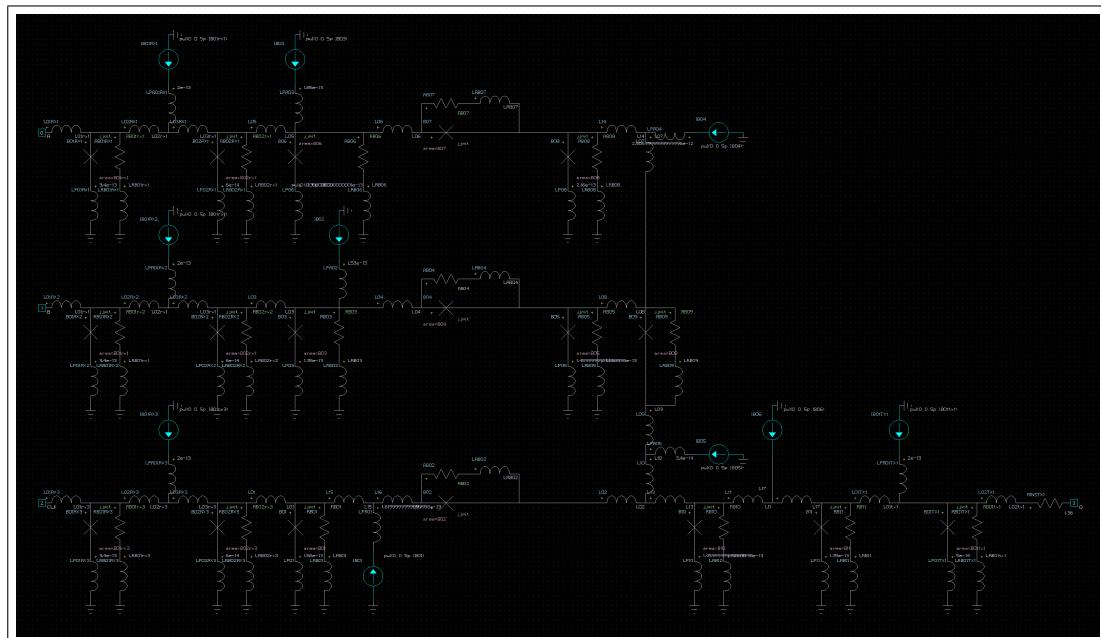
**Table 3.26:** RSFQ DFFT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	2878	4.05
2	2878	8.11
5	2878	20.3
10	2878	40.5
20	2878	81.1
50	2878	203

### 3.3.2 NDROT

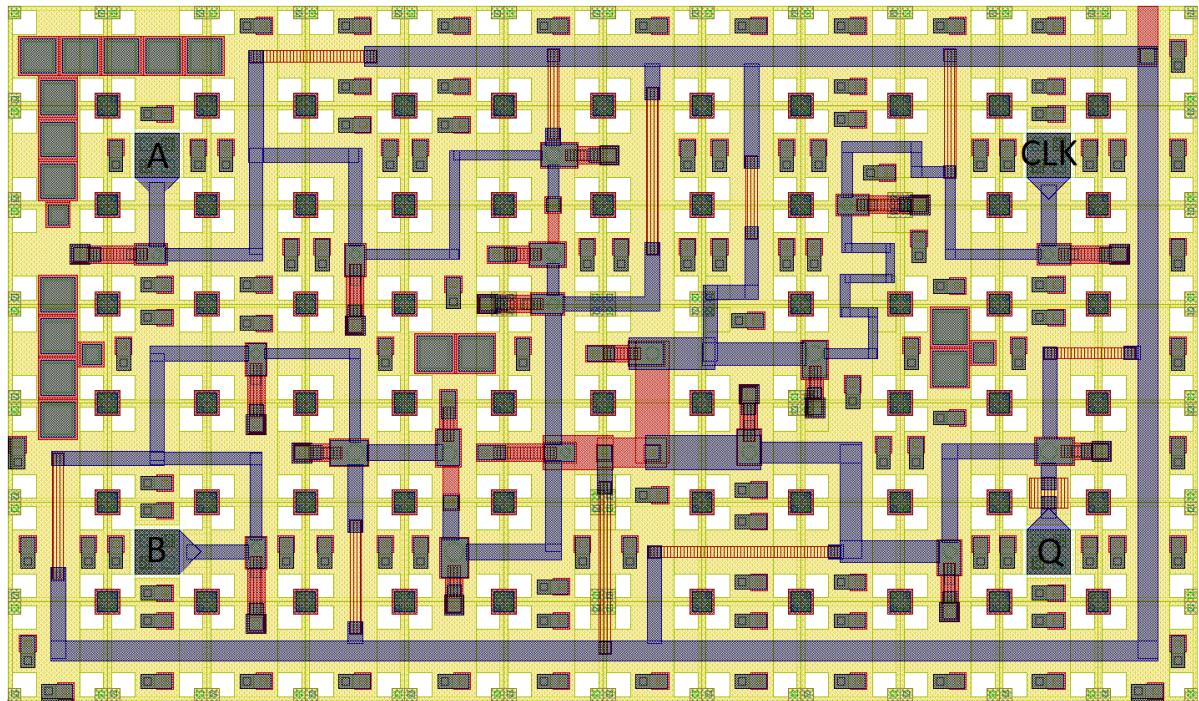
The NDROT, non-destructive readout, cell is a memory device controlled by a set, reset and clock input signal. When an input set signal is received, the NDROT will generate an output pulse after each clock signal until an input reset signal is received. The NDROT is designed with integrated PTL transmitters and receivers and is intended to connect directly to PTLs.

#### Schematic



## Layout

The physical layout for the RSFQ NDROT is shown in Fig. 3.61. The layout height is  $70 \mu m$  and the width is  $120 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.61:** RSFQ NDROT Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param L16=3.926p
2  	↳ by InductEx v.6.0.4 on 29-4-21.          65  .param L17=7.5833p
3  * Author: L. Schindler                      66  .param L18=1.2875p
4  * Version: 2.1                               67  .param L19=1.0678p
5  * Last modification date: 29 April 2021     68  .param L21=0.37382p
6  * Last modification by: L. Schindler        69  .param L22=0.52995p
7  *$Ports a b clk q                         70  .param L23=0.95137p
8 .subckt LSmitll_NDROT a b clk q           71  .param L24=2.5089p
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    72  .param L25=1.2791p
   ↳ =0.07pF, r0=160, rn=16, icrit=0.1mA    73  .param L26=3.5427p
   ↳ )                                         74  .param L27=Lptl
10 .param B0=1                                 75
11 .param Ic0=0.0001                           76  .param RB1=B0Rs/B1
12 .param IcRs=100u*6.859904418                77  .param RB2=B0Rs/B2
13 .param B0Rs=IcRs/Ic0*B0                     78  .param RB3=B0Rs/B3
14 .param Rsheet=2                            79  .param RB4=B0Rs/B4
15 .param Lsheet=1.13e-12                      80  .param RB5=B0Rs/B5
16 .param Lptl=2p                             81  .param RB6=B0Rs/B6
17 .param LB=2p                               82  .param RB7=B0Rs/B7
18 .param LP=0.2p                            83  .param RB8=B0Rs/B8
19
20 .param B1=0.86                            84  .param RB9=B0Rs/B9
21 .param B2=1.00                            85  .param RB10=B0Rs/B10
22 .param B3=1.91                            86  .param RB11=B0Rs/B11
23 .param B4=1.78                            87  .param RB12=B0Rs/B12
24 .param B5=1.16                            88  .param RB13=B0Rs/B13
25 .param B6=0.86                            89  .param RB14=B0Rs/B14
26 .param B7=1.00                            90  .param RB15=B0Rs/B15
27 .param B8=2.35                            91  .param RB16=B0Rs/B16
28 .param B9=1.96                            92  .param RB17=B0Rs/B17
29 .param B10=2.84                           93  .param RB18=B0Rs/B18
30 .param B11=0.78                           94
31 .param B12=0.99                           95  .param LRB1=(RB1/Rsheet)*Lsheet
32 .param B13=0.94                           96  .param LRB2=(RB2/Rsheet)*Lsheet
33 .param B14=2.18                           97  .param LRB3=(RB3/Rsheet)*Lsheet
34 .param B15=1.66                           98  .param LRB4=(RB4/Rsheet)*Lsheet
35 .param B16=1.63                           99  .param LRB5=(RB5/Rsheet)*Lsheet
36 .param B17=1.51                           100 .param LRB6=(RB6/Rsheet)*Lsheet
37 .param B18=2.36                           101 .param LRB7=(RB7/Rsheet)*Lsheet
38
39 .param IB1=134u                           102 .param LRB8=(RB8/Rsheet)*Lsheet
40 .param IB2=198u                           103 .param LRB9=(RB9/Rsheet)*Lsheet
41 .param IB3=99u                            104 .param LRB10=(RB10/Rsheet)*Lsheet
42 .param IB4=134u                           105 .param LRB11=(RB11/Rsheet)*Lsheet
43 .param IB5=152u                           106 .param LRB12=(RB12/Rsheet)*Lsheet
44 .param IB6=132u                           107 .param LRB13=(RB13/Rsheet)*Lsheet
45 .param IB7=224u                           108 .param LRB14=(RB14/Rsheet)*Lsheet
46 .param IB8=95u                            109 .param LRB15=(RB15/Rsheet)*Lsheet
47 .param IB9=64u                            110 .param LRB16=(RB16/Rsheet)*Lsheet
48 .param IB10=196u                           111 .param LRB17=(RB17/Rsheet)*Lsheet
49
50 .param L1=Lptl                           112 .param LRB18=(RB18/Rsheet)*Lsheet
51 .param L2=4.0481p                          113
52 .param L3=3.6036p                          114 .param LB1=LB
53 .param L4=7.2183p                          115 .param LB2=LB
54 .param L5=3.0677p                          116 .param LB3=LB
55 .param L7=2.5596p                          117 .param LB4=LB
56 .param L8=Lptl                           118 .param LB5=LB
57 .param L9=4.0481p                          119 .param LB6=LB
58 .param L10=3.6036p                         120 .param LB7=LB
59 .param L11=4.3879p                         121 .param LB8=LB
60 .param L12=3.217p                          122 .param LB9=LB
61 .param L13=3.2439p                         123 .param LB10=LB
62 .param L14=Lptl                           124
63 .param L15=4.3135p                         125 .param LP1=LP
64
65
66
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74
75
76
77
78
79
80
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82
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```

```

130 | .param LP7=LP          197 | L2 2 4 4.036E-12
131 | .param LP8=LP          198 | L3 4 6 3.595E-12
132 | .param LP10=LP         199 | L4 6 8 7.246E-12
133 | .param LP12=LP         200 | L5 8 11 3.06E-12
134 | .param LP13=LP         201 | L7 12 29 2.546E-12
135 | .param LP14=LP         202 | L8 b 17 1.572E-12
136 | .param LP16=LP         203 | L9 17 19 4.01E-12
137 | .param LP17=LP         204 | L10 19 21 3.596E-12
138 | .param LP18=LP         205 | L11 21 23 4.373E-12
139 |
140 | B1 2 3 jjmit area=B1  206 | L12 23 26 3.223E-12
141 | B2 6 7 jjmit area=B2  207 | L13 27 29 3.265E-12
142 | B3 8 9 jjmit area=B3  208 | L14 clk 34 1.573E-12
143 | B4 11 12 jjmit area=B4 209 | L15 34 36 4.349E-12
144 | B5 12 13 jjmit area=B5 210 | L16 36 38 3.941E-12
145 | B6 17 18 jjmit area=B6 211 | L17 38 40 7.501E-12
146 | B7 21 22 jjmit area=B7 212 | L18 40 42 1.301E-12
147 | B8 23 24 jjmit area=B8 213 | L19 42 44 1.505E-12
148 | B9 26 27 jjmit area=B9 214 | L21 30 31 5.791E-13
149 | B10 27 28 jjmit area=B10 215 | L22 31 46 5.223E-13
150 | B11 29 30 jjmit area=B11 216 | L23 46 47 1.048E-12
151 | B12 34 35 jjmit area=B12 217 | L24 47 49 2.514E-12
152 | B13 38 39 jjmit area=B13 218 | L25 49 51 1.269E-12
153 | B14 40 41 jjmit area=B14 219 | L26 51 53 3.539E-12
154 | B15 44 46 jjmit area=B15 220 | L27 53 56 6.608E-13
155 | B16 47 48 jjmit area=B16 221 |
156 | B17 51 52 jjmit area=B17 222 | RD 56 q 1.36
157 | B18 53 54 jjmit area=B18 223 |
158 |
159 | IB1 0 5 pwl(0 0 5p IB1) 224 | RB1 2 102 RB1
160 | IB2 0 10 pwl(0 0 5p IB2) 225 | LRB1 102 0 LRB1
161 | IB3 0 15 pwl(0 0 5p IB3) 226 | RB2 6 106 RB2
162 | IB4 0 20 pwl(0 0 5p IB4) 227 | LRB2 106 0 LRB2
163 | IB5 0 25 pwl(0 0 5p IB5) 228 | RB3 8 108 RB3
164 | IB6 0 37 pwl(0 0 5p IB6) 229 | LRB3 108 0 LRB3
165 | IB7 0 43 pwl(0 0 5p IB7) 230 | RB4 11 111 RB4
166 | IB8 0 32 pwl(0 0 5p IB8) 231 | LRB4 111 12 LRB4
167 | IB9 0 50 pwl(0 0 5p IB9) 232 | RB5 12 112 RB5
168 | IB10 0 55 pwl(0 0 5p IB10) 233 | LRB5 112 0 LRB5
169 |
170 | LB1 4 5 2.101E-12      234 | RB6 17 117 RB6
171 | LB2 8 10 4.183E-13    235 | LRB6 117 0 LRB6
172 | LB3 12 15 2.907E-12   236 | RB7 21 121 RB7
173 | LB4 19 20 2.228E-12   237 | LRB7 121 0 LRB7
174 | LB5 23 25 1.461E-12   238 | RB8 23 123 RB8
175 | LB6 36 37 2.777E-13   239 | LRB8 123 0 LRB8
176 | LB7 42 43 3.002E-12   240 | RB9 26 126 RB9
177 | LB8 31 32 9.476E-13   241 | LRB9 126 27 LRB9
178 | LB9 49 50 5.108E-13   242 | RB10 27 127 RB10
179 | LB10 53 55 2.133E-12  243 | LRB10 127 0 LRB10
180 |
181 | LP1 3 0 5.398E-13     244 | RB11 29 129 RB11
182 | LP2 7 0 5.963E-13     245 | LRB11 129 30 LRB11
183 | LP3 9 0 4.237E-13     246 | RB12 34 134 RB12
184 | LP5 13 0 6.003E-13     247 | LRB12 134 0 LRB12
185 | LP6 18 0 5.045E-13     248 | RB13 38 138 RB13
186 | LP7 22 0 5.781E-13     249 | LRB13 138 0 LRB13
187 | LP8 24 0 4.931E-13     250 | RB14 40 140 RB14
188 | LP10 28 0 4.784E-13    251 | LRB14 140 0 LRB14
189 | LP12 35 0 5.289E-13    252 | RB15 44 144 RB15
190 | LP13 39 0 5.509E-13    253 | LRB15 144 46 LRB15
191 | LP14 41 0 4.982E-13    254 | RB16 47 147 RB16
192 | LP16 48 0 5.004E-13    255 | LRB16 147 0 LRB16
193 | LP17 52 0 5.204E-13    256 | RB17 51 151 RB17
194 | LP18 54 0 4.135E-13    257 | LRB17 151 0 LRB17
195 | L1 a 2 1.51E-12       258 | RB18 53 153 RB18
196 |                           259 | LRB18 153 0 LRB18
                                260 | .ends

```

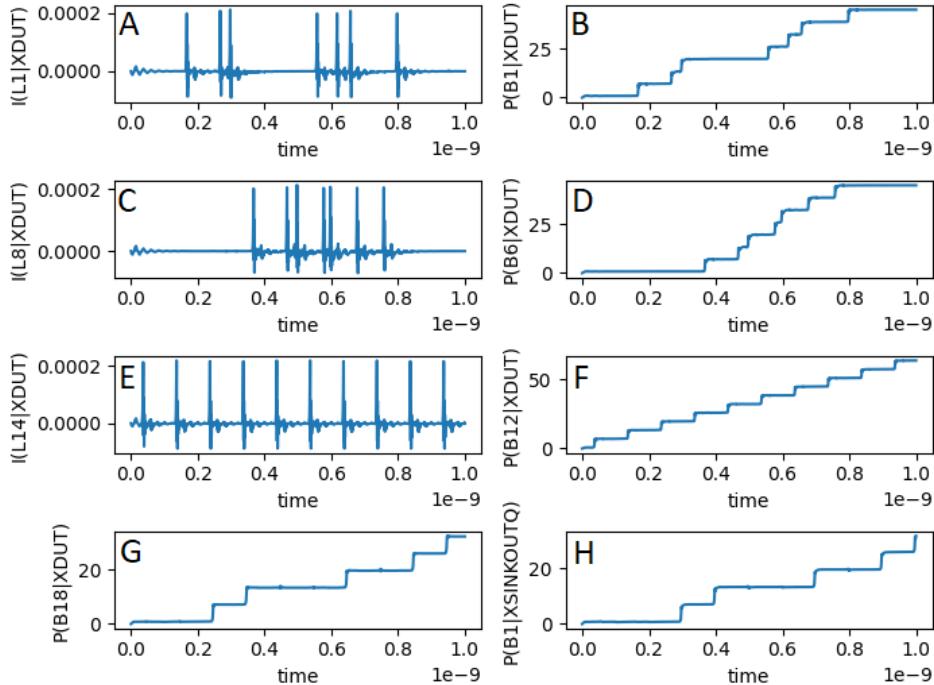
**Listing 3.31:** RSFQ NDROT JoSIM netlist.

**Table 3.27:** RSFQ NDROT pin list.

Pin	Description
<b>a</b>	Data input (set signal)
<b>b</b>	Data input (reset signal)
<b>clk</b>	Clock input
<b>q</b>	Data output

The simulation results for the RSFQ NDROT using JoSIM is shown in Fig. 3.62. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a** (set signal),
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the input inductor connected to pin **b** (reset signal),
- (d) the phase over the input JJ of pin **b**,
- (e) the current through the input inductor connected to pin **clk**,
- (f) the phase over the input JJ of pin **clk**,
- (g) the phase over the output JJ of pin **q**, and
- (h) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.

**Figure 3.62:** RSFQ NDROT analog simulation results.

## Digital model

```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 3 June 2021
5 // Last modification by: L. Schindler
6 // -----
7 //
8 // Automatically extracted verilog file, created with TimEx v2.05
9 // Timing description and structural design for IARPA-BAA-14-03 via
10 // U.S. Air Force Research Laboratory contract FA8750-15-C-0203 and
11 // IARPA-BAA-16-03 via U.S. Army Research Office grant W911NF-17-1-0120.
12 // For questions about TimEx, contact CJ Fourie, coenrad@sun.ac.za
13 // (c) 2016-2018 Stellenbosch University
14 //
15 'timescale 1ps/100fs
16 module LSmitll_NDROT_v2p1_optimized (a, b, clk, q);
17
18 input
19   a, b, clk;
20
21 output
22   q;
23
24 reg
25   q;
26
27 real
28   delay_state1_clk_q = 9.0,
29   ct_state0_b_a = 5.0,
30   ct_state1_a_b = 2.2,
31   ct_state1_clk_clk = 10.1;
32
33 reg
34   errorsignal_a,
35   errorsignal_b,
36   errorsignal_clk;
37
38 integer
39   outfile,
40   cell_state; // internal state of the cell
41
42 initial
43 begin
44   errorsignal_a = 0;
45   errorsignal_b = 0;
46   errorsignal_clk = 0;
47   cell_state = 0; // Startup state
48   q = 0; // All outputs start at 0
49 end
50
51 always @ (posedge a or negedge a) // execute at positive and negative edges of input
52 begin
53   if ($time > 4) // arbitrary steady-state time)
54     begin
55       if (errorsignal_a == 1'b1) // A critical timing is active for this input
56         begin
57           outfile = $fopen("errors.txt", "a");
58           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
59             ↪ ", $stime);
60           $fclose(outfile);
61           q <= 1'bX; // Set all outputs to unknown
62         end
63       if (errorsignal_a == 0)
64         begin
65           case (cell_state)
66             0: begin
67               cell_state = 1; // Blocking statement -- immediately

```

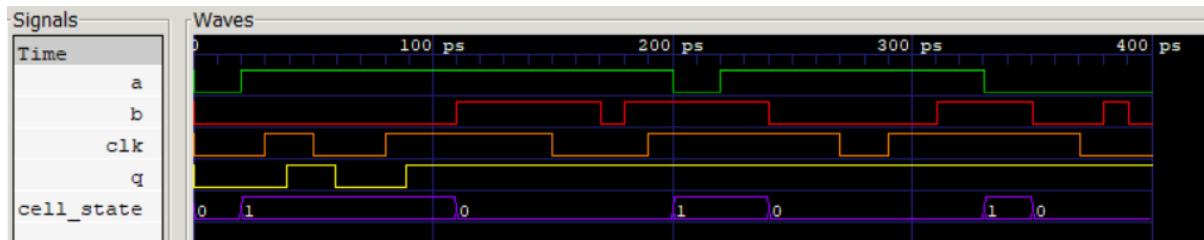
```

67          end
68      1: begin
69          errorsignal_b = 1; // Critical timing on this input; assign
70          // immediately
71          errorsignal_b <= #(ct_state1_a_b) 0; // Clear error signal
72          // after critical timing expires
73      end
74  endcase
75 end
76 always @(posedge b or negedge b) // execute at positive and negative edges of input
77 begin
78     if ($time>4) // arbitrary steady-state time)
79     begin
80         if (errorsignal_b == 1'b1) // A critical timing is active for this input
81         begin
82             outfile = $fopen("errors.txt", "a");
83             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n
84             ", $stime);
85             $fclose(outfile);
86             q <= 1'bX; // Set all outputs to unknown
87         end
88         if (errorsignal_b == 0)
89         begin
90             case (cell_state)
91                 0: begin
92                     errorsignal_a = 1; // Critical timing on this input; assign
93                     // immediately
94                     errorsignal_a <= #(ct_state0_b_a) 0; // Clear error signal
95                     // after critical timing expires
96                 end
97                 1: begin
98                     cell_state = 0; // Blocking statement -- immediately
99                 end
100            endcase
101        end
102    end
103 always @(posedge clk or negedge clk) // execute at positive and negative edges of input
104 begin
105     if ($time>4) // arbitrary steady-state time)
106     begin
107         if (errorsignal_clk == 1'b1) // A critical timing is active for this input
108         begin
109             outfile = $fopen("errors.txt", "a");
110             $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n
111             ", $stime);
112             $fclose(outfile);
113             q <= 1'bX; // Set all outputs to unknown
114         end
115         if (errorsignal_clk == 0)
116         begin
117             case (cell_state)
118                 0: begin
119                     errorsignal_clk = 1; // Critical timing on this input; assign
120                     // immediately
121                     errorsignal_clk <= #(ct_state1_clk_clk) 0; // Clear error
122                     // signal after critical timing expires
123                 end
124             endcase
125         end
126     end
127 endmodule

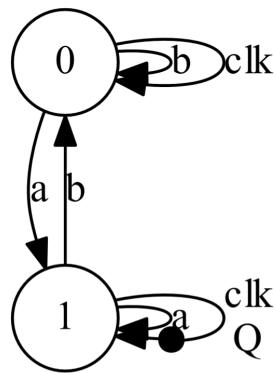
```

Listing 3.32: RSFQ NDROT verilog model.

The digital simulation results for the RSFQ NDROT is shown in Fig. 3.63 and the Mealy finite state diagram, extracted using *TimEx*, is shown in Fig. 3.64.



**Figure 3.63:** RSFQ NDROT digital simulation results.



**Figure 3.64:** RSFQ NDROT Mealy finite state machine diagram.

## Power Consumption

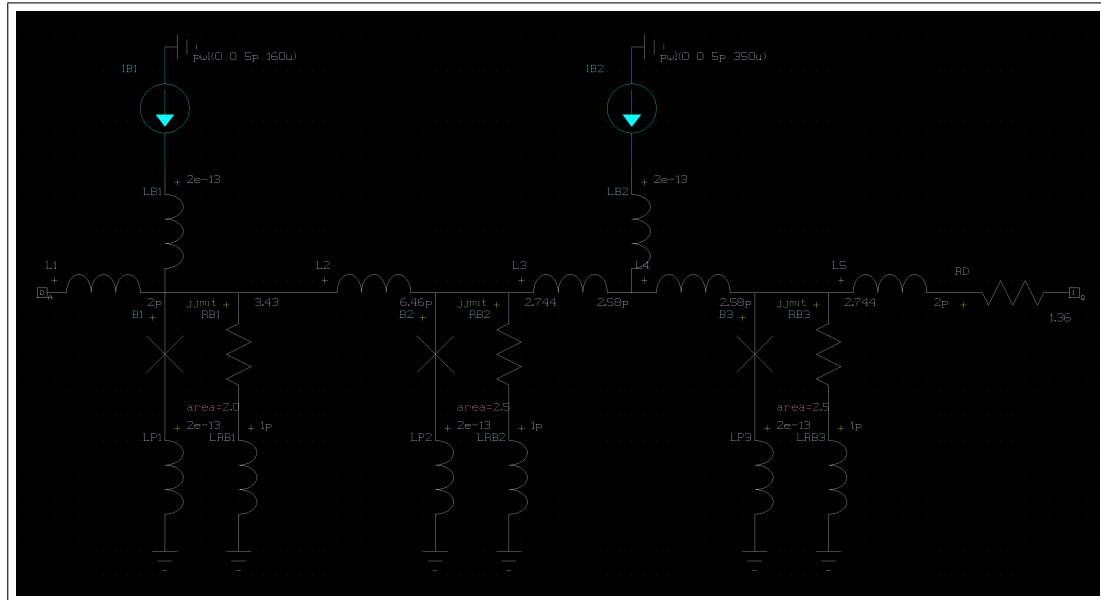
**Table 3.28:** RSFQ NDROT power consumption.

Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	3713	5.74
2	3713	11.5
5	3713	28.7
10	3713	57.4
20	3713	115
50	3713	287

### 3.3.3 BUFFT

The RSFQ BUFFT cell is a buffer cell intended for clock balancing. It is designed to have the same a-to-q delay as the SPLITT cell. The BUFFT is designed with integrated PTL drivers and receivers and is intended to be connected directly to PTLs.

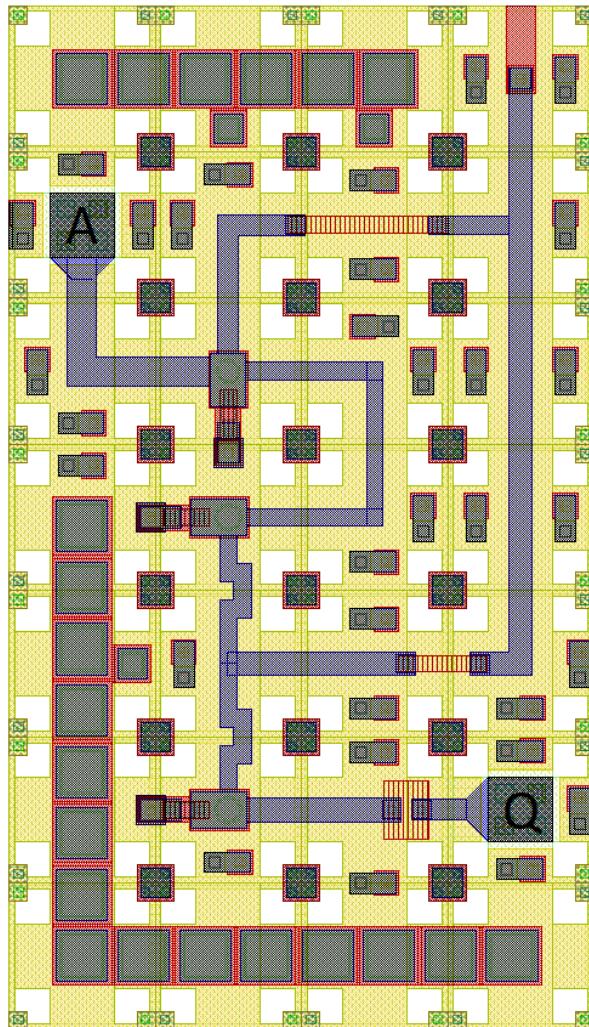
#### Schematic



**Figure 3.65:** Schematic of RSFQ BUFFT.

## Layout

The physical layout for the RSFQ BUFFT is shown in Fig. 3.66. The layout height is  $70 \mu m$  and the width is  $40 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.66:** RSFQ BUFFT Layout.

## Analog model

```

1  * Back-annotated simulation file written      33 | .param LP1=LP
2   ↪ by InductEx v.6.0.4 on 30-4-21.          34 | .param LP2=LP
3  * Author: L. Schindler                      35 | .param LP3=LP
4  * Version: 2.1                               36 | .param RB1=B0Rs/B1
5  * Last modification date: 11 June 2021       37 | .param RB2=B0Rs/B2
6  * Last modification by: L. Schindler        38 | .param RB3=B0Rs/B3
7  *$Ports a q                                39 | .param LRB1=(RB1/Rsheet)*Lsheet
8 .subckt LSmitll_bufft a q                   40 | .param LRB2=(RB2/Rsheet)*Lsheet
9 .model jjmit jj(rtype=1, vg=2.8mV, cap     41 | .param LRB3=(RB3/Rsheet)*Lsheet
10    ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    42
11    ↪ )
12 .param B0=1.0                               43 | B1 2 3 jjmit area=B1
13 .param Ic0=0.0001                           44 | B2 6 7 jjmit area=B2
14 .param IcRs=100u*6.859904418                45 | B3 11 12 jjmit area=B3
15 .param B0Rs=IcRs/Ic0*B0                     46 | IB1 0 5 pwl(0 0 5p IB1)
16 .param Rsheet=2                            47 | IB2 0 10 pwl(0 0 5p IB2)
17 .param Lsheet=1.13e-12                      48 | L1 a 2 2.727E-12
18 .param RD=1.36                            49 | L2 2 6 6.22E-12
19 .param LB=0.2p                            50 | L3 6 9 2.06E-12
20 .param Lpt1=2p                            51 | L4 9 11 2.051E-12
21 .param LP=0.2p                            52 | L5 11 14 2.041E-12
22 .param B1=2.0                             53 | RD 14 q RD
23 .param B2=2.5                             54 | LP1 3 0 5.275E-13
24 .param B3=2.5                             55 | LP2 7 0 5.212E-13
25 .param IB1=168u                           56 | LP3 12 0 5.126E-13
26 .param IB2=340u                           57 | RB1 2 4 RB1
27 .param LB1=LB                            58 | RB2 6 8 RB2
28 .param L1=Lpt1                           59 | RB3 11 13 RB3
29 .param L2=6.2p                           60 | LRB1 4 0 LRB1
30 .param L3=2.07p                           61 | LRB2 8 0 LRB2
31 .param L4=2.07p                           62 | LRB3 13 0 LRB3
32 .param L5=Lpt1                           63 | LB1 2 5 2.883E-12
                                         64 | LB2 9 10 2.393E-12
                                         65 | .ends

```

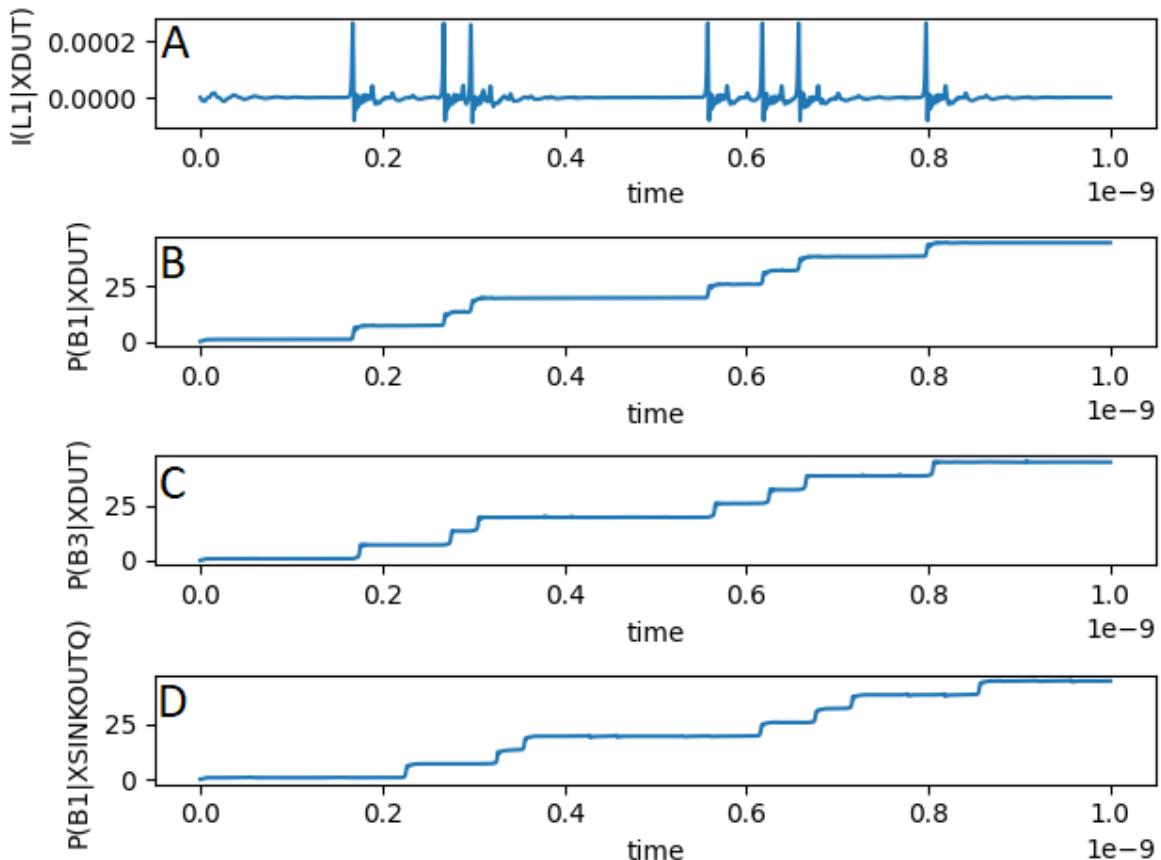
**Listing 3.33:** RSFQ BUFFT JoSIM netlist.

**Table 3.29:** RSFQ BUFFT pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ BUFFT using JoSIM is shown in Fig. 3.67. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the phase over the output JJ of pin **q**, and
- (d) the phase over the input JJ of the load circuit connected via a PTL to pin **q**.



**Figure 3.67:** RSFQ BUFFT analog simulation results.

## Digital model

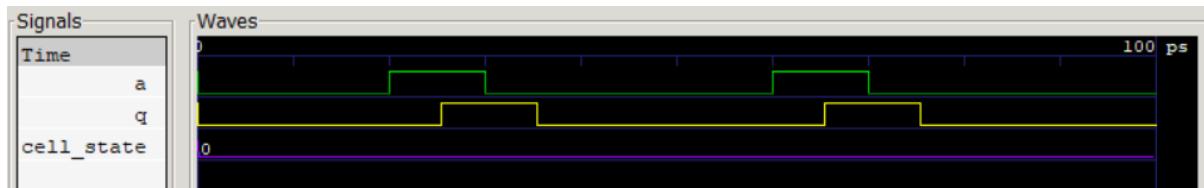
```

1 // -----
2 // Author: L. Schindler
3 // Version: 2.1
4 // Last modification date: 11 June 2021
5 // Last modification by: L. Schindler
6 //
7 'timescale 1ps/100fs
8 module LSmit11_BUFFT_v2p1_annotated (a, q);
9
10 input
11   a;
12
13 output
14   q;
15
16 reg
17   q;
18
19 real
20   delay_state0_a_q = 7.3,
21   ct_state0_a_a = 7.9;
22
23 reg
24   errorsignal_a;
25
26 integerc
27   outfile,
28   cell_state; // internal state of the cell
29
30 initial
31 begin
32   errorsignal_a = 0;
33   cell_state = 0; // Startup state
34   q = 0; // All outputs start at 0
35 end
36
37 always @(posedge a or negedge a) // execute at positive and negative edges of input
38 begin
39   if ($time>4) // arbitrary steady-state time)
40     begin
41       if (errorsignal_a == 1'b1) // A critical timing is active for this input
42         begin
43           outfile = $fopen("errors.txt", "a");
44           $fdisplay(outfile, "Violation_of_critical_timing_in_module_%m;_%0d_ps.\n"
45           ↪ ", $stime);
46           $fclose(outfile);
47           q <= 1'bX; // Set all outputs to unknown
48         end
49       if (errorsignal_a == 0)
50         begin
51           case (cell_state)
52             0: begin
53               q <= #(delay_state0_a_q) !q;
54               errorsignal_a = 1; // Critical timing on this input; assign
55               ↪ immediately
56               errorsignal_a <= #(ct_state0_a_a) 0; // Clear error signal
57               ↪ after critical timing expires
58             end
59           endcase
60         end
61     end
62   end
63 endmodule

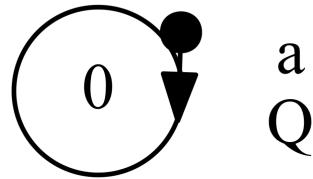
```

**Listing 3.34:** RSFQ BUFFT verilog model.

The digital simulation results for the RSFQ BUFFT is shown in Fig. 3.68 and the Mealy finite state machine diagram, extracted using *TimEx*, is shown in Fig. 3.69.



**Figure 3.68:** RSFQ BUFFT digital simulation results.



**Figure 3.69:** RSFQ BUFFT Mealy finite state machine diagram.

## Power Consumption

**Table 3.30:** RSFQ BUFFT power consumption.

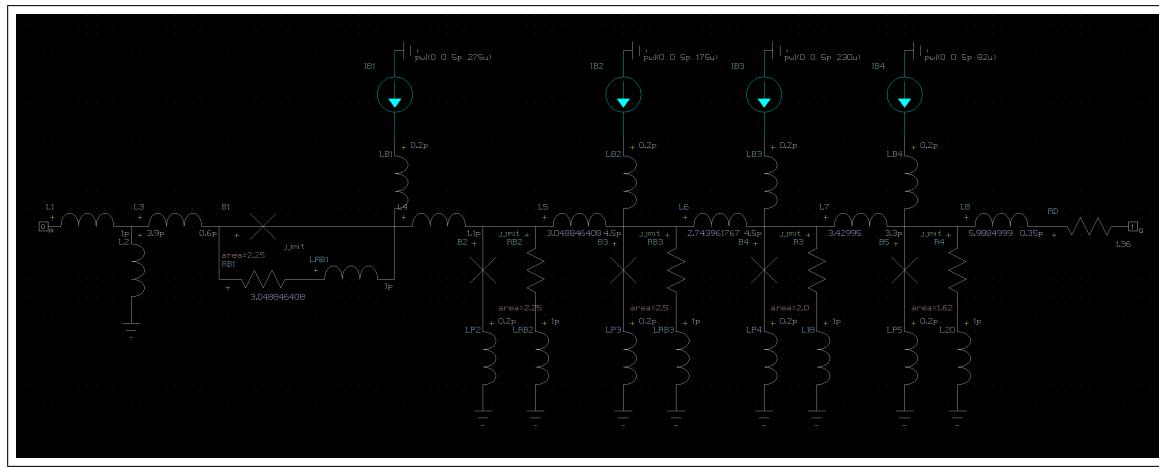
Clock rate (GHz)	Static power (nW)	Dynamic power (nW)
1	1321	1.45
2	1321	2.89
5	1321	7.24
10	1321	14.5
20	1321	28.9
50	1321	72.4

## 3.4 Interface cells

### 3.4.1 DCSFQ-PTLTX

The RSFQ DCSFQ-PTLTX is an interface cell designed to convert input voltage pulses into SFQ pulses. The DCSFQ-PTLTX has an integrated PTL transmitter and is intended to connect directly to a PTL output.

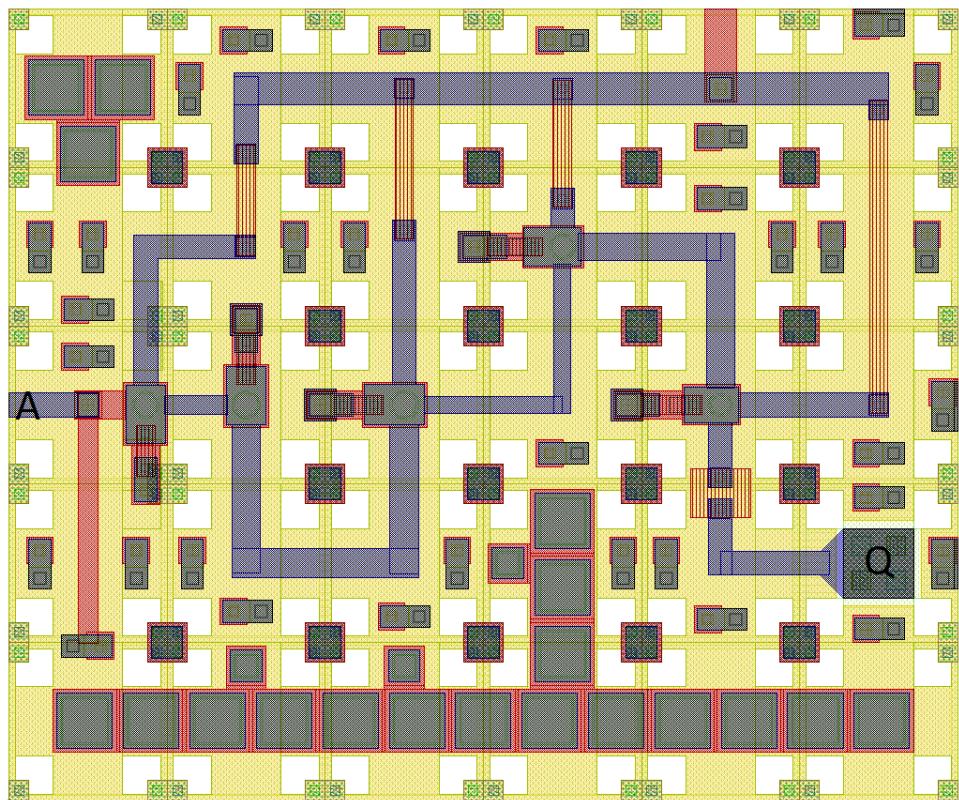
#### Schematic



**Figure 3.70:** Schematic of RSFQ DCSFQ-PTLTX.

## Layout

The physical layout for the RSFQ DCSFQ-PTLTX is shown in Fig. 3.71. The layout height is  $50 \mu m$  and the width is  $60 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.71:** RSFQ DCSFQ-PTLTX Layout.

## Analog model

```

1  * Back-annotated simulation file written      43 | .param LRB3=(RB3/Rsheet)*Lsheet
2  *   ↪ by InductEx v.6.0.4 on 2-6-21.          44 | .param LRB4=(RB4/Rsheet)*Lsheet
3  * Author: L. Schindler                      45 | .param LRB5=(RB5/Rsheet)*Lsheet
4  * Version: 2.1                                46 |
5  * Last modification date: 2 June 2021        47 | B1 2 3 jjmit area=B1
6  * Last modification by: L. Schindler         48 | B2 6 7 jjmit area=B2
7  *$Ports a q                                  49 | B3 9 10 jjmit area=B3
8  .subckt LSmitll_DCSFQ_PTLTX a q            50 | B4 13 14 jjmit area=B4
9  .model jjmit jj(rtype=1, vg=2.8mV, cap     51 | B5 17 18 jjmit area=B5
   ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA      52 | IB1 0 5 pwl(0 0 5p IB1)
   ↪ )                                         53 | IB2 0 12 pwl(0 0 5p IB2)
10 .param B0=1                                    54 | IB3 0 16 pwl(0 0 5p IB3)
11 .param Ic0=0.0001                            55 | IB4 0 20 pwl(0 0 5p IB4)
12 .param IcRs=100u*6.859904418                 56 | LB1 5 3 3.122E-12
13 .param B0Rs=IcRs/Ic0*B0                     57 | LB2 12 9 2.229E-12
14 .param Rsheet=2                             58 | LB3 16 13 6.294E-13
15 .param Lsheet=1.13e-12                      59 | LB4 20 17 2.139E-12
16 .param LB=0.2p                               60 | L1 a 1 1.293E-12
17 .param LP=0.2p                               61 | L2 1 0 3.9E-12
18 .param B1=2.25                             62 | L3 1 2 5.991E-13
19 .param B2=2.25                             63 | L4 3 6 1.088E-12
20 .param B3=2.5                               64 | L5 6 9 4.514E-12
21 .param B4=2                                65 | L6 9 13 4.542E-12
22 .param B5=1.62                            66 | L7 13 17 3.272E-12
23 .param IB1=275u                           67 | L8 17 21 1.009E-12
24 .param IB2=175u                           68 | LP2 7 0 5.238E-13
25 .param IB3=230u                           69 | LP3 10 0 5.263E-13
26 .param IB4=82u                            70 | LP4 14 0 4.571E-13
27 .param L1=1p                               71 | LP5 18 0 4.763E-13
28 .param L2=3.9p                            72 | LRB1 2 4 LRB1
29 .param L3=0.6p                            73 | LRB2 8 0 LRB2
30 .param L4=1.1p                            74 | LRB3 11 0 LRB3
31 .param L5=4.5p                            75 | LRB4 15 0 LRB4
32 .param L6=4.5p                            76 | LRB5 19 0 LRB5
33 .param L7=3.3p                            77 | RB1 4 3 RB1
34 .param L8=0.35p                           78 | RB2 6 8 RB2
35 .param RD=1.36                           79 | RB3 9 11 RB3
36 .param RB1=B0Rs/B1                      80 | RB4 13 15 RB4
37 .param RB2=B0Rs/B2                      81 | RB5 17 19 RB5
38 .param RB3=B0Rs/B3                      82 | RD 21 q RD
39 .param RB4=B0Rs/B4                      83 | .ends
40 .param RB5=B0Rs/B5                      83 |
41 .param LRB1=(RB1/Rsheet)*Lsheet
42 .param LRB2=(RB2/Rsheet)*Lsheet

```

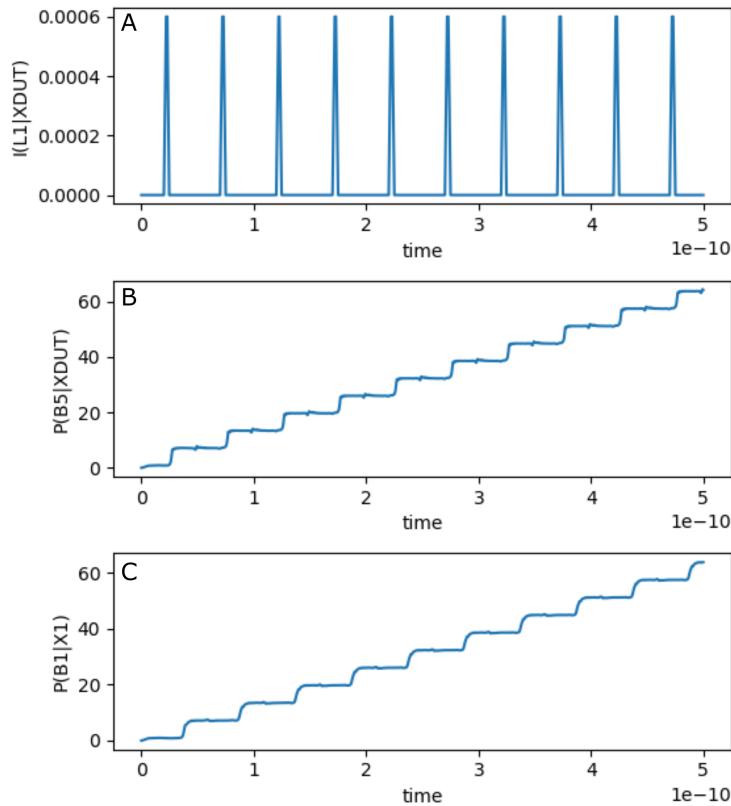
**Listing 3.35:** RSFQ DCSFQ-PTLTX JoSIM netlist.

**Table 3.31:** RSFQ DCSFQ-PTLTX pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ DCSFQ-PTLTX using JoSIM is shown in Fig. 3.72. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the output JJ of pin **q**, and
- (c) the phase over the input JJ of the load circuit connected through a PTL to pin **q**.

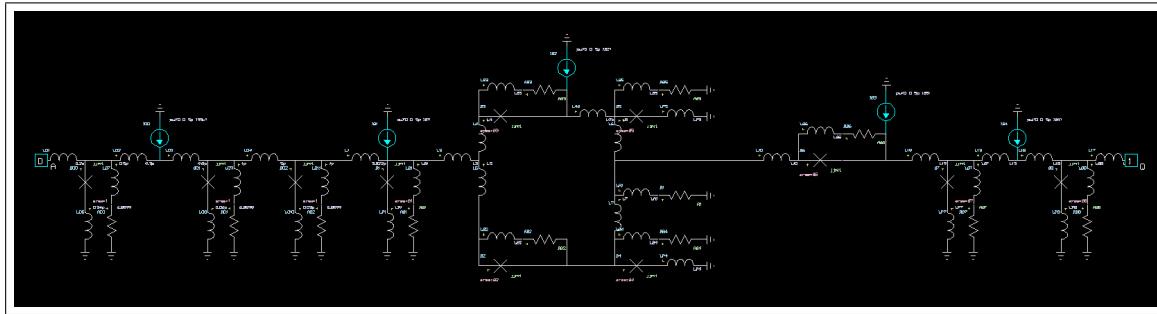


**Figure 3.72:** RSFQ DCSFQ-PTLTX analog simulation results.

### 3.4.2 PTLRX-SFQDC

The RSFQ PTLRX-SFQDC is an interface cell designed to convert SFQ pulses to an output voltage level which can be measured by standard equipment. The PTLRX-SFQDC has an integrated PTL receiver and is intended to be connected directly to a PTL input.

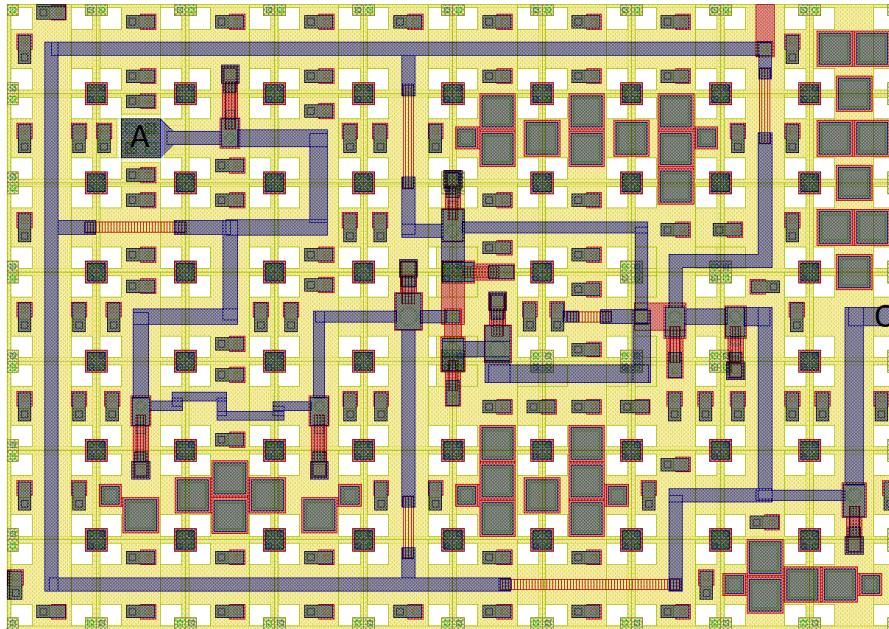
#### Schematic



**Figure 3.73:** Schematic of RSFQ PTLRX-SFQDC.

#### Layout

The physical layout for the RSFQ PTLRX-SFQDC is shown in Fig. 3.74. The layout height is  $70 \mu m$  and the width is  $100 \mu m$ . The bias line is located on M5 at the top right of the cell.



**Figure 3.74:** RSFQ PTLRX-SFQDC Layout.

## Analog model

```

1  * Back-annotated simulation file written      64  .param LRB10=(RB10/Rsheet)*Lsheet
2   ↪ by InductEx v.6.0.4 on 27-4-21.          65  .param LRB11=(RB11/Rsheet)*Lsheet
3  * Author: L. Schindler                      66
4  * Version: 2.1                               67  .param R1=5.74
5  * Last modification date: 26 April 2021     68
6  * Last modification by: L. Schindler        69
7  *$Ports a q                                70  B1 2 3 jjmit area=B1
8 .subckt LSmitll_PTLRX_SFQDC a q           71  B2 6 7 jjmit area=B2
9 .model jjmit jj(rtype=1, vg=2.8mV, cap    72  B3 8 9 jjmit area=B3
10  ↪ =0.07pF, r0=160, rn=16, icrit=0.1mA    73  B4 10 11 jjmit area=B4
11  ↪ )                                         74  B5 13 14 jjmit area=B5
12 .param B0=1                                 75  B6 15 16 jjmit area=B6
13 .param Ic0=0.0001                           76  B7 19 20 jjmit area=B7
14 .param IcRs=100u*6.859904418                77  B8 20 21 jjmit area=B8
15 .param B0Rs=IcRs/Ic0*B0                     78  B9 23 24 jjmit area=B9
16 .param Rsheet=2                            79  B10 26 27 jjmit area=B10
17 .param Lsheet=1.13e-12                      80  B11 30 31 jjmit area=B11
18 .param LB=2p                               81
19 .param LP=0.2p                             82  LP1 3 0 5.068E-13
20 .param B1=1                                83  LP2 7 0 6.182E-13
21 .param B2=1                                84  LP3 9 0 6.097E-13
22 .param B3=1                                85  LP4 11 0 4.785E-13
23 .param B4=3.25                            86  LP6 16 0 4.984E-13
24 .param B5=1.50                            87  LP8 21 0 4.692E-13
25 .param B6=1.75                            88  LP10 27 0 5.018E-13
26 .param B7=2.00                            89  LP11 31 0 5.645E-13
27 .param B8=3.00                            90
28 .param B9=1.50                            91  IB1 0 5 pwl(0 0 5p IB1)
29 .param B10=1.50                           92  IB2 0 12 pwl(0 0 5p IB2)
30 .param B11=2.00                           93  IB3 0 17 pwl(0 0 5p IB3)
31 .param IB1=155u                           94  IB4 0 25 pwl(0 0 5p IB4)
32 .param IB2=280u                           95  IB5 0 29 pwl(0 0 5p IB5)
33 .param IB3=150u                           96
34 .param IB4=220u                           97  LB1 4 5 1.284E-12
35 .param IB5=80u                            98  LB2 10 12 3.934E-12
36 .param LB1=LB                            99  LB3 15 17 1.916E-12
37 .param LB2=LB                            100 LB4 24 25 5.378E-12
38 .param LB3=LB                            101 LB5 28 29 3.797E-12
39 .param LB4=LB                            102
40 .param LB5=LB                            103 L1 a 2 1.524E-12
41 .param RB1=B0Rs/B1                      104 L2 2 4 4.301E-12
42 .param RB2=B0Rs/B2                      105 L3 4 6 4.612E-12
43 .param RB3=B0Rs/B3                      106 L4 6 8 5.035E-12
44 .param RB4=B0Rs/B4                      107 L5 8 10 3.791E-12
45 .param RB5=B0Rs/B5                      108 L6 10 13 8.316E-13
46 .param RB6=B0Rs/B6                      109 L7 14 15 1.167E-12
47 .param RB7=B0Rs/B7                      110 L9 15 18 5.964E-12
48 .param RB8=B0Rs/B8                      111 L10 13 19 1.104E-12
49 .param RB9=B0Rs/B9                      112 L11 20 18 3.24E-12
50 .param RB10=B0Rs/B10                     113 L12 18 22 8.87E-13
51 .param RB11=B0Rs/B11                     114 L14 18 23 5.769E-13
52 .param LRB1=(RB1/Rsheet)*Lsheet         115 L15 24 26 9.383E-13
53 .param LRB2=(RB2/Rsheet)*Lsheet         116 L16 26 28 3.701E-12
54 .param LRB3=(RB3/Rsheet)*Lsheet         117 L17 28 30 2.06E-12
55 .param LRB4=(RB4/Rsheet)*Lsheet         118 L18 30 q 4.08E-12
56 .param LRB5=(RB5/Rsheet)*Lsheet         119
57 .param LRB6=(RB6/Rsheet)*Lsheet         120 R1 22 0 R1
58 .param LRB7=(RB7/Rsheet)*Lsheet         121
59 .param LRB8=(RB8/Rsheet)*Lsheet         122 RB1 2 102 RB1
60 .param LRB9=(RB9/Rsheet)*Lsheet         123 LRB1 102 0 LRB1
61 .param LRB10=(RB10/Rsheet)*Lsheet        124 RB2 6 106 RB2
62 .param LRB11=(RB11/Rsheet)*Lsheet        125 LRB2 106 0 LRB2
63 .param LRB12=(RB12/Rsheet)*Lsheet        126 RB3 8 108 RB3
64 .param LRB13=(RB13/Rsheet)*Lsheet        127 LRB3 108 0 LRB3
65 .param LRB14=(RB14/Rsheet)*Lsheet        128 RB4 10 110 RB4
66 .param LRB15=(RB15/Rsheet)*Lsheet        129 LRB4 110 0 LRB4

```

130	RB5 13 113 RB5	139	LRB9 123 24 LRB9
131	LRB5 113 14 LRB5	140	RB10 26 126 RB10
132	RB6 15 115 RB6	141	LRB10 126 0 LRB10
133	LRB6 115 0 LRB6	142	RB11 30 130 RB11
134	RB7 19 119 RB7	143	LRB11 130 0 LRB11
135	LRB7 119 20 LRB7	144	.ends
136	RB8 20 120 RB8		
137	LRB8 120 0 LRB8		
138	RB9 23 123 RB9		

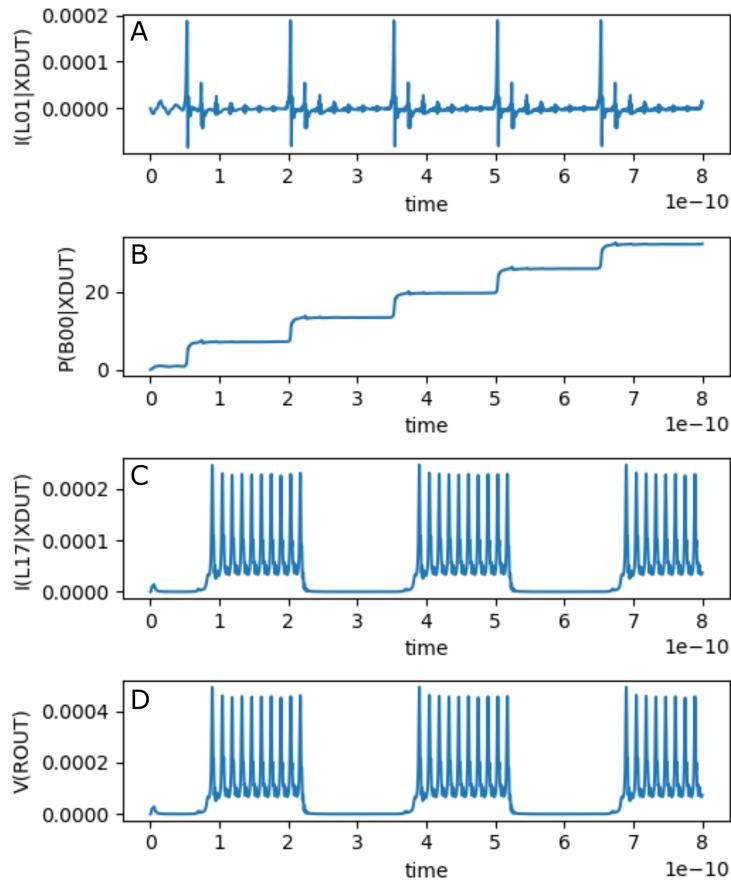
**Listing 3.36:** RSFQ PTLRX-SFQDC JoSIM netlist.

**Table 3.32:** RSFQ PTLRX-SFQDC pin list.

Pin	Description
a	Data input
q	Data output

The simulation results for the RSFQ PTLRX-SFQDC using JoSIM is shown in Fig. 3.75. The figure shows the graph for:

- (a) the current through the input inductor connected to pin **a**,
- (b) the phase over the input JJ of pin **a**,
- (c) the current through the output inductor connected to pin **q**, and
- (c) the voltage over the load resistor connected to pin **q**.



**Figure 3.75:** RSFQ PTLRX-SFQDC analog simulation results.

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