An Operand Routing Network for an SFQ Reconfigurable Data-Paths Processor

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Outline

- Architectures of the Operand Routing Network
  - NDRO-based ORN
  - Crossbar-based ORN

- A crossbar switch with a multicasting function

- Experimental results
  - Crossbar switches
  - A 1-to-2 ORN prototype

- Conclusion
Reconfigurable Data-path processor
an architecture suitable for SFQ implementation

- two-dimensional array of Floating Point Units
- connected using Operand Routing network
- ORN is reconfigured to fit a DFG
Requirements for the Operand Routing Network

- each FPU can be connected to one or more FPUs in the next row
- connections are established between the FPUs in the immediate vicinity of each other
- number of the connections, N, is odd
- one FPU’s output can be connected to either or both inputs of an FPU in the next stage
NDRO-based Operand Routing Network

“+”:
- $2 \times M \times N$ NDRO cells
- small number of Josephson junctions

“-”:
- irregular non-pipelined structure
- with the increase of the complexity becomes cumbersome
Crossbar-based Operand Routing Network

- “+”: scalable, pipelined, easily re-designed for any number of $N$ and $M$
- “-”: large number of Josephson junctions, $M - \frac{1}{2} CB$ and $(2 \times M+1)(N-1)/2 - CB$
### Comparison of the ORN architectures

#### NDRO-based ORN

<table>
<thead>
<tr>
<th>ORN complexity</th>
<th>latency, ps</th>
<th>minimum interval</th>
<th>number of control lines</th>
<th>bias current, A</th>
<th>power, mW</th>
<th>number of JJ (including control block)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N=2, M=4)</td>
<td>200</td>
<td>(n_r+200)ps</td>
<td>32</td>
<td>0.2</td>
<td>0.5</td>
<td>1710</td>
</tr>
<tr>
<td>(N=3, M=8)</td>
<td>288</td>
<td>(n_r+288)ps</td>
<td>96</td>
<td>0.7</td>
<td>1.75</td>
<td>6840</td>
</tr>
<tr>
<td>(N=5, M=10)</td>
<td></td>
<td></td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N=9, M=32)</td>
<td></td>
<td></td>
<td>1152</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of JJs of NDRO-based ORN in a table is an estimation based on a design of the switch for RDP prototype \((N=3, M=4)\) that consisted of 3420 JJs (Iwasaki, not published yet).

#### Crossbar-based ORN

<table>
<thead>
<tr>
<th>ORN complexity</th>
<th>latency, clocks</th>
<th>minimum interval</th>
<th>number of control lines</th>
<th>bias current, A</th>
<th>power, mW</th>
<th>number of JJ</th>
<th>number of JJ (including control block)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N=2, M=4)</td>
<td>6</td>
<td>(n_r)</td>
<td>48</td>
<td>0.3</td>
<td>0.75</td>
<td>3000</td>
<td>4020</td>
</tr>
<tr>
<td>(N=3, M=8)</td>
<td>6</td>
<td>(n_r)</td>
<td>100</td>
<td>0.63</td>
<td>1.575</td>
<td>6230</td>
<td>7684</td>
</tr>
<tr>
<td>(N=5, M=10)</td>
<td>10</td>
<td>(n_r)</td>
<td>208</td>
<td>1.41</td>
<td>3.525</td>
<td>13930</td>
<td>14954</td>
</tr>
<tr>
<td>(N=9, M=32)</td>
<td>18</td>
<td>(n_r)</td>
<td>1168</td>
<td>8.28</td>
<td>20.7</td>
<td>77440</td>
<td>99088</td>
</tr>
</tbody>
</table>

A crossbar switch with broadcasting function: 296 JJs
Crossbar switch with a multicasting function, ver.1

- 788 JJs
- Area – 1.28mm × 1mm
- Bias current – 87 mA
- Clock frequency – 27 GHz
- 4 pipeline stages
Crossbar switch with a multicasting function, ver. 2

- 296 JJs
- 30 mA
- 62% reduction of the number of JJs
- 2 pipeline stages instead of 4

- 141 JJs
- 14 mA
- 70% reduction of the number of JJs
- 2 pipeline stages instead of 4

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>01</td>
<td>01</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>
Experimental results

Circuits tested:

- crossbar switch with a multicasting function, *ver.1*
- \( \frac{1}{2} \) crossbar switch with a multicasting function, *ver.1*
- 1-to-2 ORN prototype
Cross-bar switch with a multicasting function, ver.1

- 788 JJs
- area – 1.28mm × 1mm
- bias current – 87 mA
- clock frequency – 27 GHz

Total:
- 1484 JJs
- bias current – 172 mA

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Bias current</th>
<th>Lower margin, %</th>
<th>Upper margin, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>bias1</td>
<td>-13.450</td>
<td>4.213</td>
</tr>
<tr>
<td></td>
<td>bias2</td>
<td>-4.702</td>
<td>15.014</td>
</tr>
<tr>
<td>01</td>
<td>bias1</td>
<td>-13.450</td>
<td>7.745</td>
</tr>
<tr>
<td></td>
<td>bias2</td>
<td>-7.989</td>
<td>5.156</td>
</tr>
<tr>
<td>10</td>
<td>bias1</td>
<td>-15.217</td>
<td>7.745</td>
</tr>
<tr>
<td></td>
<td>bias2</td>
<td>-4.702</td>
<td>5.156</td>
</tr>
<tr>
<td>11</td>
<td>bias1</td>
<td>-13.450</td>
<td>4.213</td>
</tr>
<tr>
<td></td>
<td>bias2</td>
<td>-4.702</td>
<td>11.728</td>
</tr>
</tbody>
</table>
½ cross-bar switch with a multicasting function, ver.1

- 455 JJs
- area – 1mm × 0.52mm
- bias current – 50 mA
- clock frequency – 27 GHz

Total:
- 1066 JJs
- bias current – 127 mA

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Bias current lower margin, %</th>
<th>Bias current upper margin, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>2.402</td>
<td>15.512</td>
</tr>
<tr>
<td>01</td>
<td>2.7</td>
<td>17.797</td>
</tr>
<tr>
<td>10</td>
<td>1.011</td>
<td>18.293</td>
</tr>
</tbody>
</table>

Tested at the frequencies: 22 ÷ 36 GHz
1-to-2 ORN: low frequency test

- completely functional, exhaustive test
- bias_kern0 = -14.6/5.3 % does not depend on the pattern
- bias_kern1 = -16.1/18.3 % for din0 -> dout11, dout12
- bias_kern2 = -20.7/12.6 % for din0 -> dout11, dout12 minimum!
- bias_kern1 = -40.3/17.2% for din1 -> dout01
- bias_kern2 = -38/12.6% for din2 -> dout02, dout12 maximum!

- Total 2031 JJs
- Total bias current 224.4 mA

open466, no. 4 chip F2 example:

din0 -> dout01, dout02, dout12
control pattern: CBT0 "10", CBT1 "01", CBT2 "10"

- bias_kern0 = -14.6/5.3 %
- bias_kern1 = -23/17.2%
- bias_kern2 = -23/12.6%
1-to-2 ORN: high frequency test and bias margins frequency dependence

open466, no. 4 chip F2 example:
din0 -> dout11
control pattern: CBT0 “00”, CBT1 “00”

- bias_kern0 margins were frequency independent
- measured at the frequencies up to 23.5 GHz
Conclusion

- we have proposed two different architectures of an ORN:
  - NDRO-based
  - crossbar-based

- complexity comparison has been done and crossbar-based ORN is considered a better option due to its scalability and pipelined structure

- a new version of the crossbar switch has been designed

- two versions of a crossbar with a multicasting function have been designed for 2.5 kA/cm² process and successfully tested at the frequencies up to 28 GHz

- a 1-to-2 ORN has been designed and successfully tested at the frequencies up to 23.5 GHz