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Reversible logic gate using adiabatic superconducting devices

SUBJECT AREAS:

APPLIED PHYSICS

ELECTRICAL AND ELECTRONIC
ENGINEERING

COMPUTER SCIENCE

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Received
17 June 2014Accepted
26 August 2014Published
15 September 2014Correspondence and
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Reversible computing has been studied since Rolf Landauer advanced the argument that has come to be known as Landauer's principle. This principle states that there is no minimum energy dissipation for logic operations in reversible computing, because it is not accompanied by reductions in information entropy. However, until now, no practical reversible logic gates have been demonstrated. One of the problems is that reversible logic gates must be built by using extremely energy-efficient logic devices. Another difficulty is that reversible logic gates must be both logically and physically reversible. Here we propose the first practical reversible logic gate using adiabatic superconducting devices and experimentally demonstrate the logical and physical reversibility of the gate. Additionally, we estimate the energy dissipation of the gate, and discuss the minimum energy dissipation required for reversible logic operations. It is expected that the results of this study will enable reversible computing to move from the theoretical stage into practical usage.

Energy efficiency has become the most important metric of advancement in modern computer design^{1,2}. One of the most well-known theories regarding the fundamental energy limits in computation is Landauer's principle³, where Rolf Landauer predicted that the erasure of 1-bit information generates heat of more than $k_B T \ln 2$, so that the entropy of the system does not decrease, where k_B is the Boltzmann constant and T is temperature. This principle imposed the Landauer bound of $k_B T \ln 2$ as the minimum energy dissipation on irreversible logic operations, such as AND and OR, because they erase 1-bit information at every logic operation. After long discussions and numerical analyses of this energy bound⁴⁻⁶, some very recent experimental demonstrations that confirmed its validity have been reported^{7,8}. These results indicate that the Landauer bound limits the minimum energy dissipation in modern CMOS-based computers⁹⁻¹², which perform irreversible logic operations. In order to go beyond this bound, Edward Fredkin established a theory of reversible computing¹³, where the entropy of information is conserved during computation to prevent the heat generation resulting from the entropy reduction. He introduced the Fredkin gate¹³ as a 3-in/3-out reversible logic gate, which is logically reversible¹⁴ because its inputs are uniquely determined from its outputs, thereby conserving the entropy during computation. As part of the effort to achieve practical reversible logic gates, several physical models and devices have been proposed¹⁵⁻¹⁸. However, no reversible logic operations have been experimentally demonstrated to date. Thus, discussions on reversible computing remain theoretical, and the question as to whether reversible computing is achievable using practical logic devices has yet to be resolved.

In order to achieve reversible logic gates, an extremely energy-efficient logic device is first necessary because the energy dissipated by the erasure of information is of the order of $k_B T$. The bit energy of conventional logic devices, including CMOS and energy-efficient superconductor logics¹⁹⁻²¹, is at least larger than $\sim 1,000 k_B T$, which is too large to permit their use as reversible logic gates. In contrast, the adiabatic quantum-flux-parametron (AQFP) logic²²⁻²⁵, which is an adiabatic superconducting logic device, is a good candidate for use as a building block of reversible logic gates because its bit energy can go below $k_B T$ due to adiabatic switching operations²⁵. Figure 1a shows the equivalent circuit of an AQFP buffer/NOT gate, which is based on the quantum-flux-parametron (QFP) gate invented by Eiichi Goto^{26,27}. The gate is composed of inductances, L_1 , L_2 , and L_q along with the Josephson junctions, J_1 and J_2 . By applying magnetic fluxes to the gate using an ac excitation current, I_x , either J_1 or J_2 will switch depending on the direction of the input current, I_{in} . As a result, one single-flux-quantum (SFQ) is stored in the loop composed of either L_1 , L_q , and J_1 or L_2 , L_q , and J_2 , generating an output current, I_{out} through a mutual inductance, $M = k_{io}(L_q L_{out})^{0.5}$. During this switching event, the potential energy of the gate changes adiabatically or reversibly from a single-well to a double-well, without a sudden state transition^{22,23}. This means that the switching energy can be much smaller than the energy barrier height, $I_c \Phi_0$, which corresponds to energy dissipation during a non-adiabatic 2π -transition in a current-biased Josephson junction, where I_c is a critical current of Josephson junctions and Φ_0 is an SFQ.

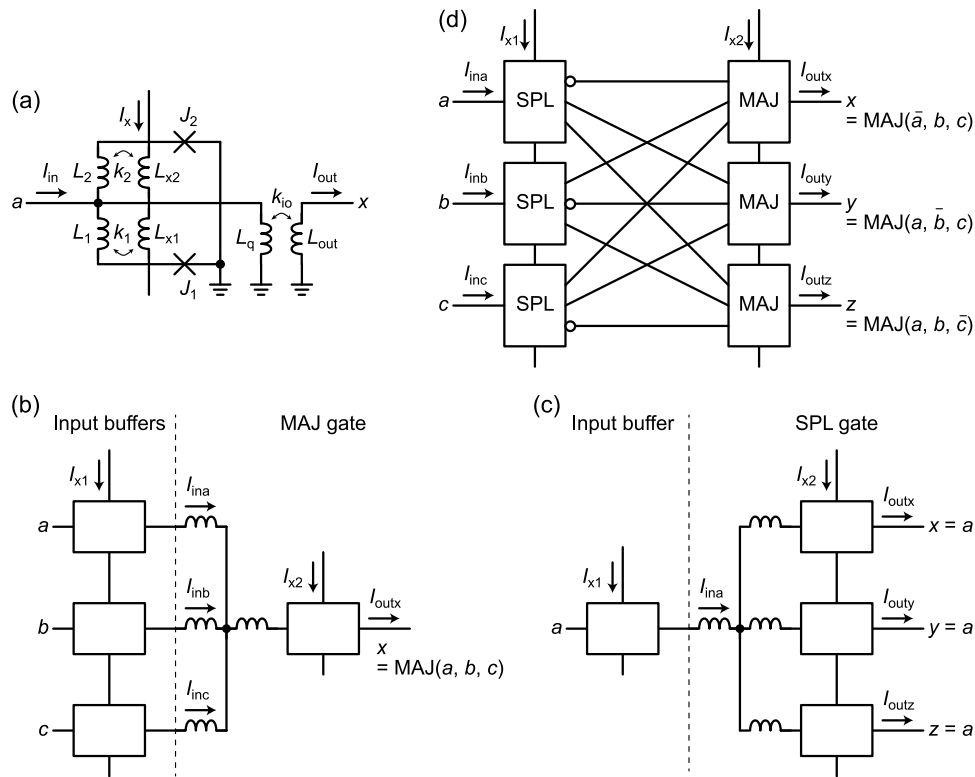


Figure 1 | Circuit schematics of AQFP and RQFP gates. (a) AQFP buffer/NOT gate. The direction of I_{out} defines the logic state of the output port, x ; the state is “1” for $I_{out} > 0$, and “0” for $I_{out} < 0$. For $k_{i0} > 0$, the directions of I_{in} and I_{out} are the same. Therefore this gate operates as a buffer gate. For $k_{i0} < 0$, I_{in} and I_{out} are in the opposite directions and the gate operates as a NOT gate. The circuit parameters were optimized in the previous work²³ as $\phi_x/2\pi = 0.5$, $\beta_L = 0.2$, and $\beta_q = 1.6$, where $\phi_x = 2\pi MI_x/\Phi_0$, $\beta_L = 2\pi LI_c/\Phi_0$, $\beta_q = 2\pi LqI_c/\Phi_0$, $L = L_1 = L_2$, $L_x = L_{x1} = L_{x2}$, $k = k_1 = k_2$ and $M = k(LL_x)^{0.5}$. The critical current, I_c is 50 μA . (b) AQFP 3-in MAJ gate. White blocks correspond to AQFP buffer gates. The state of a MAJ gate is determined by the sum of the three input currents, I_{ina} , I_{inb} , and I_{inc} . Therefore, the state of the output (x) is determined to be $x = MAJ(a, b, c)$. (c) AQFP 3-out SPL gate, whose circuit topology is the same as that of a 3-in MAJ gate. The input current, I_{ina} , is shared by the three buffer gates in a SPL gate, and the states of the outputs (x , y , and z) are determined to be $x = y = z = a$. (d) RQFP gate, which is logically and physically reversible. The circuit topology of the RQFP gate is symmetrical, because those of a 3-in MAJ gate and a 3-out SPL gate are the same.

Results and Discussion

A logic gate is considered to be physically reversible²⁸ if its potential energy changes adiabatically and reversibly. Konstantin K. Likharev argued that physical reversibility is necessary to prevent non-adiabatic energy dissipation during a switching event²⁸, as well as logical reversibility. Bit information in a physically reversible gate can propagate bi-directionally, therefore the circuit topology of a reversible logic gate must be symmetrical in the data flow direction. In this study, we utilize 3-in majority (MAJ) gates and 3-out splitter (SPL) gates as building blocks. Figure 1b shows a block diagram of a 3-in MAJ gate with three input buffers, where a white block corresponds to an AQFP buffer gate. The logic state of the output port, x , is defined as $x = MAJ(a, b, c) = a \cdot b + b \cdot c + c \cdot a$, where a, b, c are the logic states of the three input ports. Figure 1c is the block diagram of a 3-out SPL gate with an input buffer. The logic states of each output port are determined to be $x = y = z = a$. While the 3-in MAJ gate and the 3-out SPL gate have the same circuit topologies, the data flow direction, or the order of the excitation of each gate, is opposite. Figure 1d shows a block diagram of our proposed 3-in and 3-out reversible logic gate, which we have designated as the reversible quantum-flux-parametron (RQFP) gate. The RQFP gate is composed of three 3-in MAJ gates and three 3-out SPL gates, whose function is represented by the following equation:

$$F(a,b,c) = (MAJ(\bar{a},b,c), MAJ(a,\bar{b},c), MAJ(a,b,\bar{c})) = (x,y,z). \tag{1}$$

Table I is the truth table of the RQFP gate. This table clearly shows that the gate is injective and logically reversible by operating the function

two times: $F(F(a, b, c)) = (a, b, c)$. Additionally, the RQFP gate is considered to be a primitive gate in reversible computing, because MAJ, NOT gates and constant inputs constitute a logical primitive. Because a 3-in MAJ gate and a 3-out SPL gate have the same circuit topologies, the topology of the RQFP gate is symmetrical. Data in the RQFP gate can propagate bi-directionally due to this symmetrical circuit topology, depending on the order of excitation. Specifically, if the SPL gates are excited earlier (excitation current, I_{x1} is provided earlier than I_{x2}), the data propagates from the ports, a, b , and c to x, y , and z . If the MAJ gates are excited earlier, the data propagates in the opposite direction. Therefore, the RQFP gate is physically reversible.

To demonstrate logical and physical reversibility of an RQFP gate, we conducted three kinds of experiments, α , β , and γ . The block diagrams of these three experiments are shown in Fig. 2a, where a, b , and c are input ports and x, y , and z are output ports. In the

a	b	c	x	y	z
0	0	0	0	0	0
1	0	0	0	1	1
0	1	0	1	0	1
1	1	0	0	0	1
0	0	1	1	1	0
1	0	1	0	1	0
0	1	1	1	0	0
1	1	1	1	1	1



experiment α , we demonstrate logic operations of an RQFP gate. In β , two RQFP gates are serially connected to demonstrate logical reversibility. Specifically, if $a = a'$, $b = b'$ and $c = c'$, the RQFP gate is injective and proven to be logically reversible. In γ , two RQFP gates are connected but one is physically mirrored to demonstrate physical reversibility. Specifically, if $a = a''$, $b = b''$ and $c = c''$, data can propagate bi-directionally in an RQFP gate, and the gate is proven to be physically reversible. The RQFP gates were designed and fabricated using the Nb Josephson process, the AIST standard process (STP2)²⁹. Figure 2b is a microphotograph of the circuits used in experiment γ , where I_{x1} , I_{x2} , and I_{x3} are three-phase excitation currents. Here, it can be seen that two RQFP gates are serially connected but their physical layouts are horizontally mirrored. Figure 2c shows the measurement results of the experiments α , β , and γ , using trapezoidal excitation currents of 100 kHz at 4.2K. In the experiment α , the correct logic operations were confirmed for the RQFP gate. In β , the obtained outputs (a' , b' , and c') corresponded to the inputs (a , b , and c), which proves the logical reversibility of the RQFP gate. Similarly, the outputs corresponded to the inputs in γ , which proves its physical reversibility. These results confirm that the RQFP gate is logically and physically reversible, and that the RQFP gate is a practical reversible logic gate.

Next, we calculated energy dissipation of the RQFP gate by integrating the product of excitation currents and voltages over time using the Josephson circuit simulator, JSIM³⁰. Figure 3a shows a block diagram for the simulation, where input and output buffers are inserted to avoid the interaction with input and output ports. Figure 3b provides the simulation results and shows the total energy dissipation per clock cycle, including an RQFP gate, input and output buffers, as a function of a rise/fall time of excitation currents. As can be seen in the figure, energy dissipation decreases almost linearly with an increase in the rise/fall time for all input patterns, which indicates that all gates operate adiabatically and reversibly during logic operations^{25,28}. For a rise/fall time of 10,000 ps, the total energy dissipation of the RQFP gate and buffers composed of 69 AQFP gates reaches $\sim 1 \times 10^{-21}$ J/cycle. The bit energy per AQFP gate is $\sim 2 \times 10^{-23}$ J/cycle, which is much smaller than the barrier height, $I_c \Phi_0 \sim 1.0 \times 10^{-19}$ J for $I_c = 50 \mu\text{A}$ and around the same order of magnitude as the Landauer bound at 4.2 K, $k_B T \ln 2 \sim 4.0 \times 10^{-23}$ J. These calculation results show that there is no minimum energy dissipation for reversible logic operations using the RQFP gates.

Conclusions

Based on the above results, we can conclude that the RQFP gate is the first practical reversible logic gate. It is clear that through the use of

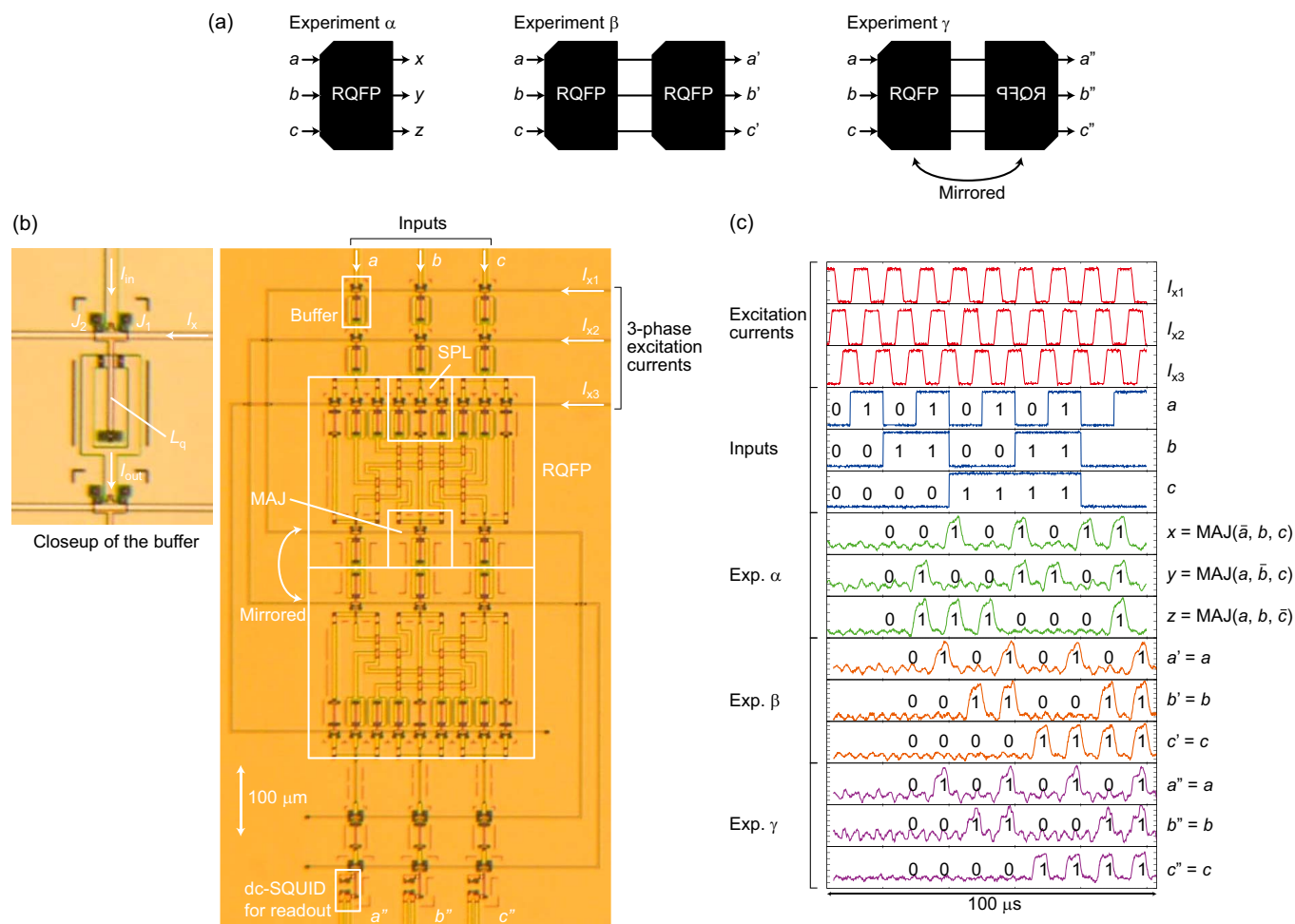


Figure 2 | Demonstration of logical and physical reversibility of the RQFP gate. (a) Block diagrams for experiments α , β , and γ . In α , three inputs (a , b , and c) are externally applied and three outputs (x , y , and z) are observed to confirm its logic operations. In β , two RQFP gates are serially connected to determine if the gate is injective. In γ , two RQFP gates are serially connected but one is mirrored to determine if data can propagate bi-directionally. (b) Micrograph of circuits for the experiment γ . Dc superconducting quantum interference devices (dc-SQUIDS) were used for readout of output ports (a'' , b'' , and c''), which detect output currents of buffer gates. One of the two RQFP gates is physically mirrored. (c) Measurement results, which were conducted at 4.2 K in liquid He. We used three-phase trapezoidal excitation currents of 100 kHz (I_{x1} , I_{x2} , and I_{x3}). Input currents (a , b , and c) were given by using a data-pattern generator. Output voltages were amplified by differential amplifiers.

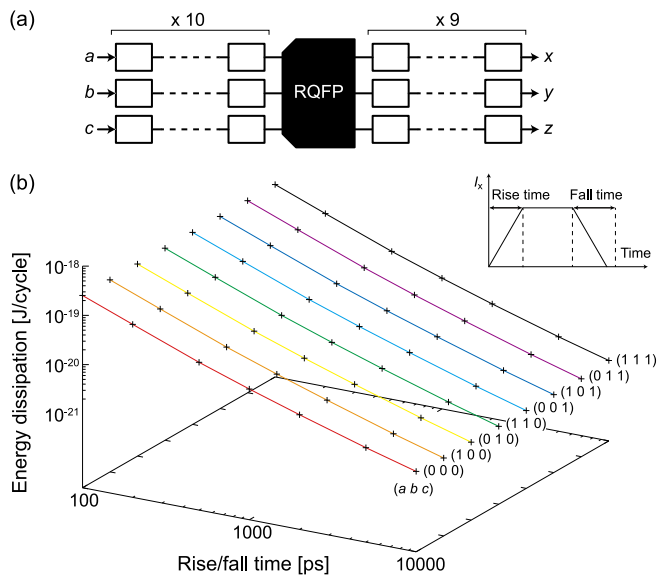


Figure 3 | Energy dissipation of the RQFP gate. (a) Block diagram for simulation. Input and output buffers were inserted to avoid interaction with input and output ports. (b) Simulated energy dissipation, including an RQFP gate, input and output buffers. It was assumed that $L_{out} = L_q$ and $k_{i0} = 0.1$ for AQFP buffer gates, and that each wiring inductance is 10 pH for 3-in MAJ gates and 3-out SPL gates. For all input patterns, energy dissipation decreases almost linearly with an increase of a rise/fall time of excitation currents, which indicates that there is no minimum energy dissipation for reversible logic operations using RQFP gates (see Supplementary Information for energy dissipation of irreversible logic gates). The inset shows the definition of an excitation current.

RQFP gates, detailed discussion and investigations on the energy efficiency of reversible computing will become possible. Although the energy dissipation of the RQFP gate was too small to measure in the low-speed demonstration at 100 kHz, we expect that we will be able to measure it at a higher operation frequency (~ 1 GHz) in future work by using high-speed interface circuits³¹ and the superconducting resonator-based method²⁴. Also, in previous work²⁴, we have confirmed that calculation results of energy dissipation well agree with experimental results using superconducting resonators.

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Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research (S) (No. 22226009) from the Japan Society for the Promotion of Science (JSPS). The circuits were fabricated in the clean room for analog-digital superconductivity (CRAVITY) of National Institute of Advanced Industrial Science and Technology (AIST) with the standard process 2 (STP2). The AIST-STP2 is based on the Nb circuit fabrication process developed in International Superconductivity Technology Center (ISTEC). We would like to thank C. J. Fourie for improving the 3D inductance extractor, InductEx that we used during the layout design of the circuits.

Author contributions

N.T. designed circuits, carried out simulations and experiments, and wrote the paper. Y.Y. and N.Y. supported theoretical aspects and supervised simulations and experiments. All authors discussed the results and commented on the manuscript.

Additional information

Supplementary information accompanies this paper at <http://www.nature.com/scientificreports>

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Takeuchi, N., Yamanashi, Y. & Yoshikawa, N. Reversible logic gate using adiabatic superconducting devices. *Sci. Rep.* **4**, 6354; DOI:10.1038/srep06354 (2014).



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