EDP2-9

Energy Consumption of Half Flux Quantum Circuits Using π-Shifted Josephson Junctions

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We investigate energy consumption of the low-energy logic circuits called half flux quantum (HFQ) circuits, where half of a magnetic flux quantum ($\frac{1}{2}\Phi_0$) is used for the binary operation [1]. The HFQ circuits are made up of 0-π SQUIDs, which are composed of pairs of π-shifted Josephson junction (π-junction) and conventional Josephson junction (0-junction) with the same critical currents (I_c). In a 0-π SQUID, the π-junction, such as ferromagnetic Josephson junction, serves as both switching element and superconductor phase shift element. The HFQ circuits can also be implemented using SQUIDs composed of three π-junctions (π-π-π SQUIDs) or SQUIDs composed of two 0-junctions and one π-junction (0-0-π SQUIDs) instead of 0-π SQUIDs, where one π-junction is used for a non-switching, phase shift element and the other junctions are used for switching elements. Recently we successfully fabricated Nb/PdNi/Nb magnetic Josephson junctions on a four-layer Nb/AlO_x/Nb integrated circuit chips and obtained 0-0-π SQUIDs toward demonstration of HFQ circuits [2].

In the HFQ circuits, a SQUIDs act as Josephson junctions with an extremely small I_c if the SQUID loop inductance (L) is small, and lead to lower energy operation. In this study, we evaluate the energy consumption of HFQ circuits using numerical analysis and analog circuit simulation [3]. Fig. (a) shows a transmission line, basic wiring element of HFQ circuits composed of 0-π SQUIDs. The SQUID has two stable states where the loop current flows in clockwise or counterclockwise. The transmission line propagates a flip of the state in each SQUID. A π-leap in superconductor phase is observed at each single switching event, and dynamic energy (E_d) is consumed. We need the energy greater than the potential barrier between two states (ΔE) to switch a 0-π SQUID, and about twice the energy of ΔE is consumed under the optimal bias condition that maximizes the operating margin. The E_d corresponds to the product of $\frac{1}{2}\Phi_0$ and bias currents and is reduced below 0.1 aJ when $LI_c/\Phi_0 < 0.5$ using 100-μA junctions, as show in Fig. (b). We will report a comparison of energy consumption of HFQ circuits made up of the different type of SQUIDs.

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Acknowledgments: This work was supported by the JSPS KAKENHI, Grant Numbers JP18H05211, JP18H01498, and JP19H05615, and JST MIRAI JPMJMI18E1.

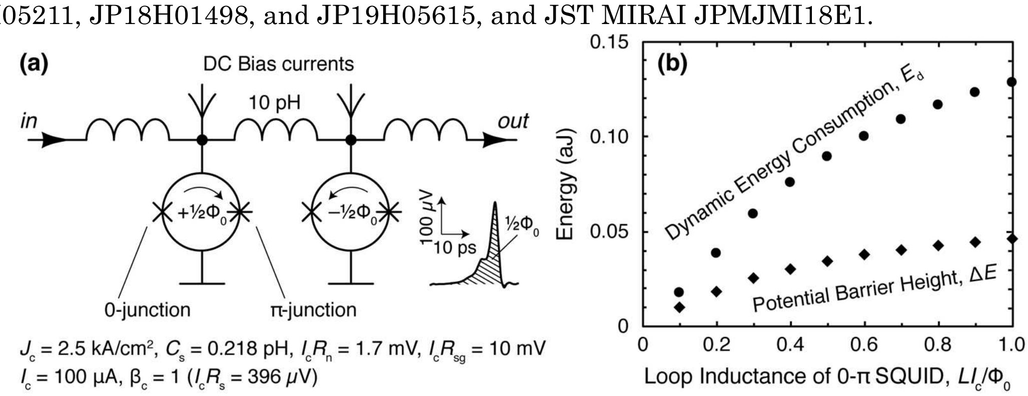

Fig. (a) Schematic diagram of HFQ transmission line, (b) loop inductance dependency of dynamic energy consumption and potential barrier height of a 0-π SQUID.

Keywords: Low-energy logic circuits, Ferromagnetic Josephson junction, π-shifted Josephson junction , Half flux quantum