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Proposal of Single-Flux-Quantum Logic Device

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***Abstract*—A new type of logic gate that can be designed using a nonhysteretic Josephson weak link is proposed. The basic component of the proposed device is a one-junction interferometer, and a logic state is represented by either a zero or a single-flux-quantum. In contrast to the "Parametric Quantron," this device is designed to operate without a three-phase clock and the dependence of the junction critical current on magnetic field is not used. The switching behavior of the device was simulated by computer and an analytical expression for the switching delay has been obtained.**

I. Introduction

At least two types of Josephson-junction devices for digital use have been reported. One uses the voltage change of the Josephson junction to represent logic state and the other uses trapping or untrapping of a single-flux-quantum to represent binary states.

One type of the device in the latter group is the "Parametric Quantron" proposed by Likharev [1]. The "Parametric Quantron" uses the magnetic sensitivity of the critical current of Josephson junctions and is driven by three-phase control current.

Here, we propose a new type of single-flux-quantum logic device, which is designed to operate in a mode that allows only a zero-to-one transition followed by a resetting of the logic network. The device does not use magnetically sensitive junctions or a three-phase clock. Its logical operation by computer simulation and an analytical study of its switching characteristics are presented.

II. Principle of Logic Operation

Consider the circuit of Fig. 1(a), which is a one-junction interferometer. If the inductance of the interferometer L and the critical current I_c are chosen so that $L \cdot I_c \sim \Phi_0$, a flux quantum, the flux in the interferometer is quantized in two stable states which correspond to a zero-flux-quantum mode and a one-flux-quantum mode, as shown in Fig. 1(b). The zero-flux-quantum mode can be taken as a logical "0" state and the one-flux-quantum mode as a logical "1" state.

Two methods can be used for switching the interferometer from the logical "0" state to the "1" state. One is to hold the bias flux $\Phi_b = LI_b$, where I_b is the bias current as shown in Fig. 1(a), fixed and to reduce the critical flux Φ_c, which is the maximum bias flux that leaves the interferometer in the logical "0" state as shown in Fig. 1(b), to less than Φ_b by reducing the critical current I_c. The other is to hold Φ_c fixed, i.e., I_c fixed, and to increase Φ_b to larger than Φ_c by adding a small magnetic flux to Φ_b. This will be called "flux switching" hereafter. To switch back the interferometer in the logical "1" state to the logical "0" state, the interferometer should be reset by reducing the bias flux Φ_b below some critical value. This is similar to the resetting commonly used in Josephson-tunneling logic gate.

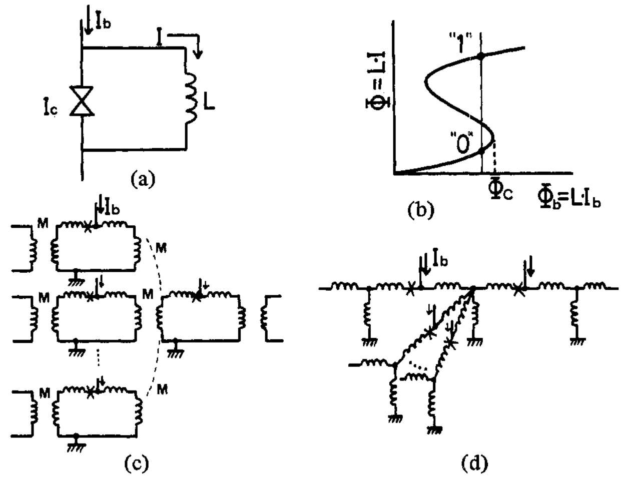

Fig. 1. (a) Schematic drawing of the one-junction interferometer. I_b is the bias current, L is the inductance of the interferometer, I is the current in the inductance, and I_c is the critical current of the Josephson junction. (b) Internal flux versus applied flux relation for the interferometer of Fig. 1(a). (c) A configuration of the proposed single-flux-quantum logic. The coupling between the interferometer is accomplished by mutual inductance. (d) The other coupling scheme in which mutual inductance is not required.

The key idea of the design for flux-switching logic is shown schematically in Fig. 1(c). One-junction interferometers are coupled to each other by mutual inductances. If the currents of the preceding interferometers generate a magnetic flux to make the total magnetic flux coupled to the next interferometer larger than Φ_c, the next interferometer will be switched from the "0" state to the "1" state and latched in the "1" state. Then, in the same manner, the next interferometer triggers the interferometer after the next. The preceding interferometers still remain in the state "1" because of their latching property. This latching property ensures the unilateral propagation of signals in the same manner as "Domino Toppling." The direction of the propagation is determined by the positions of the interferometers which are first triggered, and a three-phase clock is not required to determine the direction. After each logic cycle, the interferometers are reset to "0" in the same manner as conventional Josephson-tunneling logic gate. The basic operation, AND, OR, and NOT can be realized using this logic scheme, and confirmed by numerical calculations. Fig. 1(d) shows an alternative coupling scheme, called the current injection scheme, which does not require the mutual inductance. Fig. 2 shows the result of the computer simulation of an AND gate using the current injection scheme. The parameters of the interferometers used in the simulation are listed in the figure caption.

III. Calculation of Switching Delay

To analyze the switching delay of the proposed device, it is useful to replace Josephson weak links by their resistively shunted-junction model in the limit of heavy damping. The resulting circuit equations for the circuit shown in Fig. 1(a) can be written

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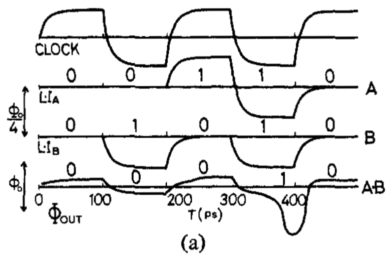
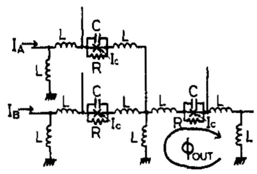


(a)



(b)

Fig. 2. (a) Simulation of the time dependence of the flux in the interferometers forming AND gate illustrated in Fig. 2(b). The parameter values are: $L = 0.33$ pH, R the normal resistance of the junction (0.2 Ω), C the capacitance of the junction (0.1 pF), and I_c the critical current (1 mA). The total inductance of an interferometer L_T is 4 L and $2\pi L_T I_c$ is equal to $4.0\Phi_0$ in this case. The bias current of each interferometer is clocked by a bipolar trapezoidal signal. (b) The configuration of the AND gate used for simulation.

$$(1/R)(d\Phi/dt) = [\Phi_b - \{\Phi + LI_c \sin(2\pi\Phi/\Phi_0)\}]/L \quad (1)$$

and

$$\Phi = (\Phi_0/2\pi)\,\theta. \quad (2)$$

Here, θ is the quantum phase change across the junction and R is the normal resistance. The switching delay τ for $\Phi_b(t < 0) = \Phi_c - \Delta\Phi$ and $\Phi_b(t > 0) = \Phi_c + \Delta\Phi$ is expressed by the following equation:

$$\tau = \int_{\Phi(t=0)}^{\Phi(t\to\infty)\times 0.9} \frac{dt}{d\Phi}\, d\Phi = \frac{L}{R}\int_{\Phi(t=0)}^{\Phi(t\to\infty)\times 0.9} \cdot \frac{d\Phi}{\Phi_b - \{\Phi - LI_c \sin(2\pi\Phi/\Phi_0)\}}. \quad (3)$$

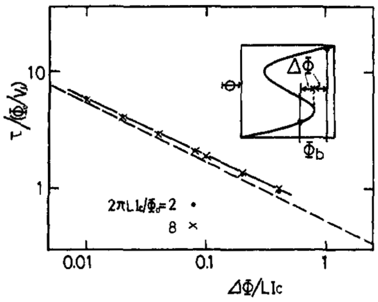


Fig. 3. Switching delay versus overdrive for the interferometer of Fig. 1(a). Solid line: numerical calculations. Dashed line: (4). Equation (4) agrees with the numerical calculation of (3) within about 15 percent for overdrives $\Delta\Phi/LI_c$ below about 20 percent, and for values of LI_c ranging from about $0.3\Phi_0$ to $1.3\Phi_0$.

This can be well approximated by

$$\tau = (3/4\sqrt{2})\,(\Phi_0/V_J)\,(\Delta\Phi/LI_c)^{-1/2} \quad (4)$$

where $V_J = R \cdot I_c$. In Fig. 3, the turn-on delay obtained from the numerical calculation of (3) and the delay calculated from (4) are indicated by a solid-line curve and a dashed-line curve, respectively. It can be seen that the result calculated from (4) agrees with the numerical calculation of (3) within about 15 percent for overdrives $\Delta\Phi/LI_c$ below about 20 percent, and for values of LI_c ranging from about $0.3\Phi_0$ to $1.3\Phi_0$.

If the Josephson junction with $V_J = 0.3$ mV is used and $\Delta\Phi/LI_c = 0.1$, about 10 ps is obtained for τ from (4).

IV. Conclusion

We have proposed a new single-flux-quantum Josephson-logic device. Magnetic sensitivity of the critical current of Josephson junctions is not required in this logic device. It is predicted theoretically that a switching delay of about 10 ps is feasible.

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