Superconducting optical switch based on a Josephson vortex flow transistor

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INTRODUCTION

Ultrafast optical switches with very low power consumption are strongly desired to process large-capacity data-traffic on expanding information networks. Some attractive optical devices using semiconductors operative in terahertz region are realized, however, the power consumption become quite large in such a high frequency region. On the other hand superconducting devices are expected to operate at over hundred GHz with 10^{-3} times lower power consumption than semiconductor devices. Josephson vortex flow transistors (JVFTs) based on the motion of vortices in Josephson junctions had been expected as high-speed three-terminal devices for superconducting circuits. However, few studies on JVFTs have been performed in recent years. The main reason for this fact is that it is difficult to achieve both a significant signal gain and a high operation speed. Recently, we have considered applying JVFTs to an input interface for SFQ logic circuits, which converts electrical or optical signals to flux quanta [1-3]. In this case, high-speed operation over the several tens GHz is required. However, the large power gain is not necessary for this type of interface. Up to now, we have examined the characteristics of JVFTs with DC and AC current as the input signals [4]. In this report, we have irradiated femtosecond laser pulses to vortex flow channel, and the responses of flow voltage were observed.

EXPERIMENTAL SETUP

Figure 1 shows a schematic illustration of an optical input interface based on JFVT. Josephson junctions were prepared using c-axis oriented 160 nm thick \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \) (YBCO) thin films grown on 24° bi-crystal MgO (100) substrates. Au layer was deposited by RF sputtering as contact pads and a protection layer from the laser irradiation. The patterning of the JVFTs was performed by conventional photolithography and Ar ion beam etching.

The JVFTs typically consist of a vortex flow channel and a control line for applying a magnetic field. The vortices are generated in the channel and the density of vortices is controlled by an applied magnetic field via control current \( I_{co} \), which flows through the control line located near the channel. The flow voltage \( V_f \) along the channel is induced by the flowing vortices droved by the Lorentz force in Josephson junctions. Thus \( V_f \) can be controlled by \( I_{co} \). The YBCO thin film is covered by the Au film except for the flux flow channel consist of parallel array of Josephson junctions. The width of Josephson junctions is 3 \( \mu \text{m} \), and each loop area is 10 × 8 \( \mu \text{m}^2 \). The center dashed line indicates the grain boundary of the MgO substrate, and the Josephson junctions are located on this line. The control current line with the width of 25 \( \mu \text{m} \) is located 5 \( \mu \text{m} \) apart from the edge of the channel.

The mode locked Ti:sapphire laser that provided 100 fs-pulses with 800 nm wavelength at a 82 MHz repetition rate, was used for laser irradiation. The white dashed circle in Fig. 1 shows the laser spot and includes the flux flow channel and the control line, however, only the center 25 \( \mu \text{m} \) region was irradiated. The input square pulse current with the amplitude of 3.5 mA, and the response of the flow voltage to the input pulse current are shown in Fig. 2.

![Fig. 1](image1.png)  
A schematic illustration of JFVT based optical interface.

![Fig. 2](image2.png)  
(a) Input square pulse current with the amplitude of 3.5 mA, and (b) the response of the flow voltage to the input pulse current.
RESULTS AND DISCUSSION

The response of the flow voltage to the square pulse current with the amplitude of 3.5 mA was observed as shown in Fig. 2 (a) and (b). The flow voltage $V_f$ responded to the control current $I_{co}$, however, the waveform of output signal $V_f$ was distorted. The result does not mean the poor performance of the JVFT in high frequency region. Since the output signals were detected via the amplifier with 1 MHz bandwidth, the high frequency component of output signals above 1 MHz were not detected. Moreover, impedance mismatch between the output terminals and measurement system caused the signal reflection.

Figure 3 shows the response of the flow voltage $V_f$ under the irradiation of laser pulses with the power of 7 mW and the chopping rate of 4 kHz. The bias current and the control current are 5.2 mA and 3.0 mA, respectively. The modulation of $V_f$ at 2 kHz was clearly observed. The amplitude of the modulation was $12 \sim 15 \mu V$ and nearly corresponds to increases in the flow voltage by the irradiation for $I_B = 5.2$ mA as shown in the inserted $I_{co}$ - $V_f$ curve in the Fig. 3. The result indicates that the device have feasibility to operate above several hundreds GHz. However the influence of thermal effect may restrict the operation speed, and additional researches with a high-speed measurement system in terahertz range are necessary to elucidate an optical responses of JVFT.

In Fig. 4, thick line shows the response of the voltage to the square pulse current with the amplitude of 3.5 mA, and the thin line shows the modulation of flow voltage under the simultaneous input of pulse current and laser pulse irradiation. This result shows output signals of JVFT based optical switch can be controlled by both of electrical signals and optical signals, the device can operate as not only an optical switch but also simple logic circuits.

REFERENCES