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Study on the optical input interface for Nb single-flux-quantum logic circuits

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The authors have studied the optical input interface for Nb single-flux-quantum (SFQ) circuits and demonstrated its operation using photomixing technique. Two tunable lasers of C band were used for photomixing. We adopted a multistage toggle flip-flop (TFF) circuit as the main part of the test circuit. As the first trial, we used lasers with wavelength difference of 0.044 nm at around 1550 nm, which corresponds to the laser beat frequency of 5.5 GHz. The output signals from the 13- and 14-stage TFFs were observed and it showed the input SFQ frequency of 5.5 GHz. Thus, the authors demonstrated the conversion of the optical signal to SFQ signal and succeeded in driving the SFQ circuit. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2410216]

Single-flux-quantum (SFQ) circuits have the feature of high-speed operation above 100 GHz with very low power consumption. Recent developments in the SFQ circuit technology are remarkable. For example, a 50 GHz cross-bar switch[1] and an 18 GHz microprocessor[2] have been demonstrated. Recently, an 8 bit shift resistor was demonstrated to operate at 120 GHz,[3] which is very promising for further improvement of the SFQ circuit technology. As the operation speed increases, an interface between the SFQ circuits and the conventional electric systems is becoming a problem because of large signal losses and impedance mismatches. For such high-speed operation, an optical-SFQ interface is the most promising candidate to solve the above-mentioned problems. However, only a few groups have reported the conversion of optical pulses to SFQ pulses.[4] As for circuit operations other than simple Josephson transmission lines, Bulzacchelli *et al.* reported the operation of toggle flip-flop (TFF) up to 1.3 GHz. They used high-frequency optical pulses by multiplying the pulse rate using an optical arrangement of beam splitters, mirrors, and half-wave plates.[5]

On the other hand, Tonouchi *et al.* have proposed to use the photomixing technology and photodiodes such as unitraveling-carrier photodiode to construct an ultrafast optical input-interface for SFQ circuit.[6] Up to now, we have reported fundamental researches on optical interfaces, for example, flux flow transistor,[7] high-frequency signal injection to the Josephson junction using the photomixing technique,[8] and so on. Furthermore, we also reported our work on an optical input interface using $YBa_2Cu_3O_x$ (YBCO) thin films.[9] In this letter, we introduce another research for the ultrafast optical input interface, where we use a SFQ circuit with Nb Josephson junctions and photomixing technique in a wavelength region of optical communication.

Figure 1 shows the schematic diagram of the experimental setup for the optical input interface. Two tunable lasers of C band are used to produce optical signals. They are set to operate at frequencies f_1 and f_2, which are slightly different. Coupling of these laser lights at a coupler generates laser beats with a frequency corresponding to the difference of f_1 and f_2, i.e., $\Delta f = |f_1 - f_2|$, by photomixing. Laser beats with a frequency of several tens of gigahertz and more can be generated by this method. Such laser beats are introduced to a photoconductive device and converted into current modulation, which is introduced to the SFQ circuit. The entire optical system was constructed using optical fibers. Thus, this system can be handled easily.

In the SFQ circuit, the input current signals are first converted to the SFQ pulses at a dc/SFQ converter and then delivered to the succeeding SFQ main circuit. We adopted a circuit shown in Fig. 2 for this test circuit. The main part is an N-stage TFF circuit. The output of a single TFF "toggles" with each input SFQ pulses. Thus, the output pulse train has

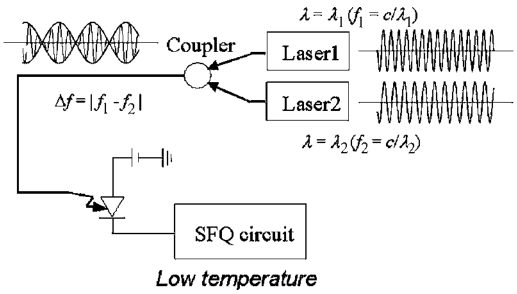

FIG. 1. Schematic diagram of the experimental setup.

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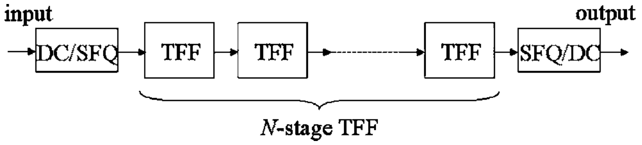

FIG. 2. Test SFQ circuit adopted for the demonstration of the optical-SFQ interface using Nb junctions.

a frequency of half that of the input. Chaining N TFFs together in series creates a frequency divider, and the output signal frequency of the N-stage TFF is $1/2^N$ of that of the input signal. The output is observed at the SFQ/dc converter. If $N=10$ and the input signal frequency is 10 GHz, which is too high for direct observation, the output signal frequency is about 10 MHz, which can be observed using an oscilloscope. When output taps are added in the series of TFFs, outputs from different stages can be observed using the same circuit. In this experiment, we prepared this test circuit with output taps for $N=10-14$, which enabled us to observe the outputs of different stages at the same time.

Before using the optical input, we checked the operation of the test TFF circuit by electrical methods. First, square-wave electrical signals were introduced to the input port of the dc/SFQ at a slow rate, and we measured the output of ten-stage TFF. We observed that the output of the ten-stage TFF toggled after 1024 ($=2^{10}$) pulses were added. Thus, the correct operation of this TFF up to $N=10$ was confirmed. Then, we checked the TFF stages from the 11th to the 14th, utilizing the oscillation at the dc/SFQ, which produces SFQ pulses, by adjusting the bias current for the dc/SFQ. We could observe that each stage toggles its output every two input signals. Thus we confirmed the correct operation of the test TFF circuit up to $N=14$.

As the first trial, we used a photodiode as the photoconductive device. It is desirable that the photoconductive device is placed near the SFQ circuit at low temperature. However, in this trial, we put the photodiode at room temperature for utilizing our conventional circuit measuring system. We used lasers with frequencies of 1549.924 and 1549.968 nm. The wavelength difference is 0.044 nm, which corresponds to the laser beat frequency of 5.5 GHz. It was the limitation of the cable connecting the photodiode and the SFQ circuit.

The output signals from the 13- and 14-stage TFF were observed as shown in Fig. 3. We can observe periodical output wave forms. Input SFQ frequency can be calculated from the output frequency. The SFQ frequency after 13-stage TFF is 0.673 MHz. This value suggests the input SFQ signal frequency of 5.5 GHz. It corresponds to the laser beat frequency. The periodic time for the 14-stage TFF is twice that of the 13-stage TFF, which is normal operation of this circuit. The input SFQ frequency was also calculated from the result for 14-stage TFF and resulted in the same value as that calculated for 13-stage TFF. Thus, we demonstrated the conversion of the optical signal to SFQ signal and succeeded in driving the SFQ circuit by the converted SFQ signal.

In conclusion, we investigated the optical input interface for Nb SFQ circuit and demonstrated its operation using the photomixing technique. The frequency of the optical signal was 5.5 GHz. We were able to show that the input optical signal was converted to SFQ signals correctly and succeeded in driving the TFF circuit using the optical input signal at 5.5 GHz. Though the frequency of the input signal is not so high in this letter compared with the ability of the SFQ circuit, higher frequencies can be expected by improving the measurement setup. The photomixing produces high-frequency optical signal, making it an important technique for testing the optical interface. In addition, the frequency is determined by the laser wavelengths correctly with high accuracy. Thus the optical input interface using the photomixing technique is expected to be applicable to the stable clocking system with low jitter for ultrafast SFQ circuits.

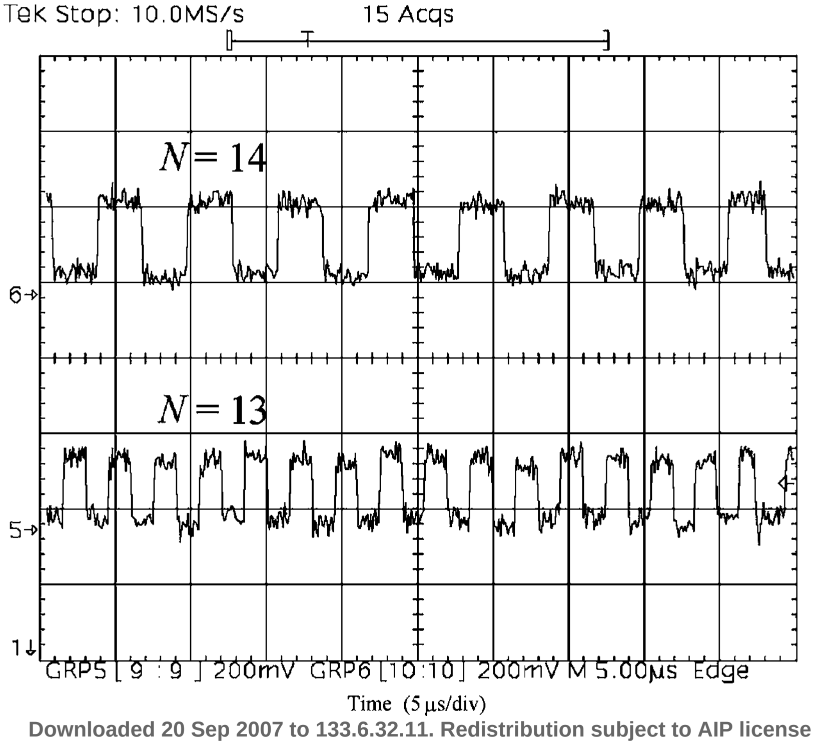

FIG. 3. Output signals of the 13- and 14-stage TFF test circuits measured after SFQ/dc.

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