Timing jitter characterization of the SFQ coincidence circuit by optically time-controlled signals from SSPDs

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***Abstract*—We report on the timing jitter characterization of the superconducting single flux quantum (SFQ) coincidence circuit, which is an essential component of the superconducting coincidence photon counter. Two superconducting nanowire single photon detectors (SSPDs), each of which is irradiated with optically time-controlled photons, are connected to the SFQ coincidence circuit, and the timing jitter of the SFQ circuit is evaluated by changing the relative time delay between two input ports for the SFQ comparator unit. We successfully observe the transition curve of the probability of obtaining the signal from the SFQ coincidence circuit by sweeping photon arrival time to each SSPD and confirm that this curve shifts temporally upon changing the bias current to the Josephson transmission line (JTL) in the SFQ circuit. A systematic investigation reveals that the relation between time delay and the bias current to JTL can be estimated. The full width half maximum timing jitter of the SFQ circuit is 1.1 ps, which is sufficiently low so that it does not influence the entire timing jitter of the coincidence photon counter.**

***Index Terms*—Superconducting nanowire single photon detector, superconducting single quantum flux circuit, coincidence photon counter, timing jitter**

I. Introduction

SUPERCONDUCTING nanowire single photon detectors (abbreviated as SNSPDs or SSPDs; hereinafter, represented as SSPDs [1]) offer the benefits of high efficiency, low dark count rate, and low timing jitter. These advantages are extremely suitable for various applications such as laser ranging [2], free space optical communications [3], and photonic quantum technologies [4-6]. In particular, the application of SSPDs to observe the Hong–Ou–Mandel (HOM) interference between indistinguishable photons is a promising approach to realize high visibility interference, which underpins a range of components and protocols in photonic quantum technologies [4-6]. In addition, the HOM interference of heralded photons prepared from a continuous-wave-pumped spontaneous parametric down conversion can be observed if the timing jitter contribution of the photon counters is smaller than the coherence time of photons; in such a case, a pulsed laser source is not required, and hence, the system configuration becomes much simpler.

Recently, we developed a superconducting coincidence photon counter with short timing jitter for the observations of HOM interference [7]. This counter consists of two superconducting nanowire single photon detectors (SSPDs) and a coincidence circuit comprising a superconducting single flux quantum (SFQ) circuit [8]. In our previous work, we demonstrated the observation of HOM interference with a weak coherent pulse, and the timing jitter of an entire coincidence photon counter system was evaluated as 32.3 ps, which is clearly smaller than the values obtained using low noise amplifiers located at room temperature (LNA 545, RF Bay, Inc.) and the standard TCSPC module (Hydra harp 400, PicoQuant GmbH) [7]. The low timing jitter was achieved because of the reduction in the external contributions to jitter other than those due to the two SSPDs. Meanwhile, the timing jitter of the SSPD (j_{SSPD}) was estimated as 14.8 ps by extracting the contribution from other factors, implying that the external jitter contribution still exists [8]. For further suppression of these external contributions, it is important to clarify the exact contributions from various factors such as the magnetically coupled DC/SFQ (MC-DC/SFQ) converters ($j_{\mathrm{MC\text{-}DC/SFQ}}$) that convert electrical signals to SFQ pulses [9] and internal timing jitter in the SFQ circuit (j_{SFQ}).

In this work, we focus on the experimental characterization of j_{SFQ} in our superconducting coincidence photon counter. So far, we have evaluated the j_{SFQ} but only based on the calculation of the delay time in the Josephson transmission lines (JTL) by using Josephson integrated circuit simulator [10,11]. In contrast, in this work, we evaluated the j_{SFQ} by using two SSPDs

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connected to the SFQ coincidence circuit that is irradiated with optically time-controlled photons at a time resolution of 0.01 ps.

II. Experimental Setup and Operation Check of the SFQ Circuit

Figure 1 shows the schematic diagram of the superconducting photon coincidence counter and the experimental setup for characterizing the timing jitter of the SFQ circuit. The SFQ coincidence circuit is identical to that reported in [10] and mainly consists of MC-DC/SFQ converters, confluence buffers, a splitter, and a variable delay line comprised of JTLs, a comparator circuit, and a voltage driver. The circuit has two input ports, namely, START and STOP, each of which are connected to the fiber-coupled NbTiN SSPD [11]. The output signals from the SSPDs are converted into SFQ pulses by the MC-DC/SFQ converters, and the SFQ pulses are propagated through JTLs (JTL1 and JTL2) to the SFQ comparator circuit to differentiate the relative timing of the input pulses between START′ and STOP′. An output SFQ pulse appears from the SFQ comparator only when an SFQ pulse arrives at the STOP′ port within 800 ps after an SFQ pulse has arrived at the START′ port of the SFQ comparator. In other words, the SFQ comparator acts as a coincidence circuit with a time window of 800 ps. The time window was set to be relatively long in this experiment to facilitate adjustment of the timing of the START and STOP signals. However, it can be arbitrarily set within a range of values by adjusting the time delay determined by the length of JTLs. For detecting room temperature electronics, the output SFQ pulses were then converted to rectangular pulses with an amplitude of ~2.0 mV and a duration of ~1.6 ns by means of the voltage driver circuit.

Two fiber-coupled NbTiN-SSPDs and SFQ coincidence circuit were installed in a 0.1-W GM cryocooler system operating at 2.4 K. The incident light from a mode-locked pulsed fiber laser with ~0.1-ps pulse width, wavelength of 1550nm, and 10-MHz repetition frequency (Calmer laser, Inc) was attenuated to a single photon level and split into two optical paths by using a 1 × 2 fiber splitter. The incident photons from each optical path entered the respective SSPDs through the variable optical delay line ranging from 0 to 400 ps with 0.01 ps resolution which can control the arrival timing of incident photons to the SSPDs, and the polarization controller to optimize the polarization conditions to achieve the maximum counts in the SSPDs.

Note that the circuit has TEST port to check the operation of the SFQ circuit. The input electrical pulses from the TEST port are converted to SFQ pulses, and then, they enter the splitter that splits into two SFQ pulses. These two pulses are then sent to JTL1 and JTL2 through SFQ merger and entered to START′ and STOP′ in the SFQ comparator circuit, respectively. Since the propagating speed of an SFQ pulse along JTL1 can be varied by controlling the independent bias current (I_{delay}), the transition of the output probability can be observed by sweeping the I_{delay}. We connected the TEST port to a pulse pattern generator and input the electrical pulses with a duration of 10 ns and a repletion frequency of 10 MHz, allowing 10^7 trials per second. The output pulses were amplified by a low-noise amplifier and were counted by a pulse counter while sweeping I_{delay}. As result, the transition caused by the time differentiation was clearly observed, as shown in Fig. 2.

III. Timing Jitter Evaluation of the SFQ Circuit

The probability of an output pulse being generated by the SFQ coincidence circuit is determined by the arrival time differentiation of the SFQ input pulses between START′ and STOP′. Therefore, by sweeping the relative photon arrival time between two SSPDs, we can observe the transition of the output probability. We swept the photon arrival time to the SSPD on the START input port by using the variable optical delay line and recorded the number of the output counts from the SFQ circuit for fixed values of the arrival time of incident photons at the STOP input port of the SSPD and the variable delay line in the SFQ circuit. Furthermore, since the arrival time at START′ can also be changed by changing I_{delay}, the timing points on the transition curve obtained by sweeping the photon arrival time vary with I_{delay}. Figure 3 shows the output count number as a

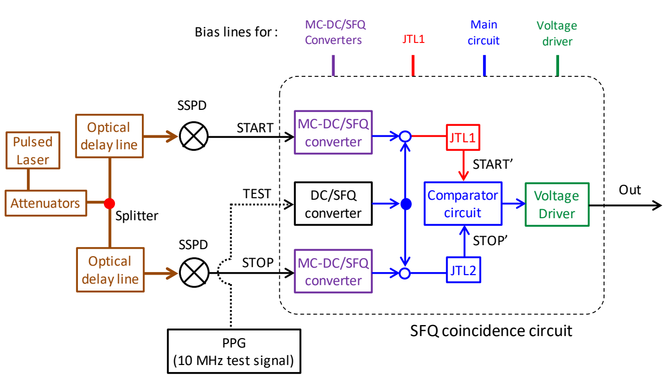

Fig. 1. Schematic diagram of the single flux quantum (SFQ) coincidence circuit and the experimental setup for timing jitter characterization. The uncolored and solid circles indicate SFQ pulse merger and SFQ pulse splitter, respectively. Each component of the SFQ circuit and its corresponding bias line are indicated by the same color.

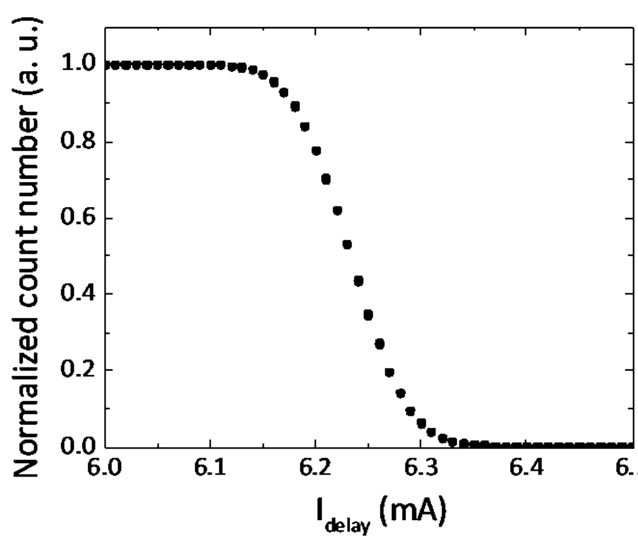

Fig. 2. Transition curve of the output probability as a function of I_{delay} for the input signal from the TEST port.

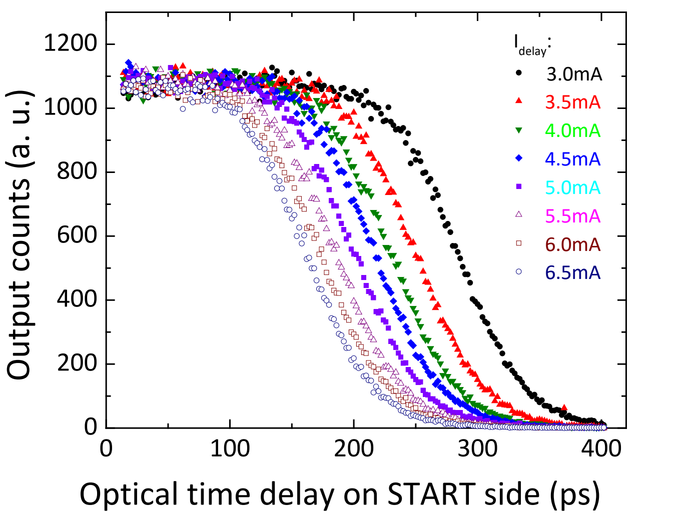

Fig. 3. Output count number as a function of the time delay in photon arrival on the START side under different I_{delay} conditions.

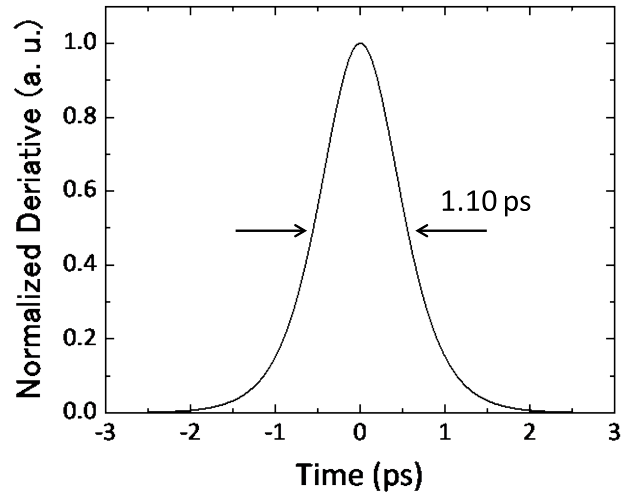

Fig. 5. Timing jitter characteristic of single flux quantum (SFQ) coincidence circuit. The contributions from the magnetically coupled DC/SFQ (MC-DC/SFQ) converters are not included.

function of photon arrival time on the START input port for different values of I_{delay}. The derivatives of these transition curves reflect the convolution of the entire timing jitter of coincidence photon counter [8]. As shown in the figure, clear transitions were observed for all the I_{delay} conditions, and the transition curves undergo a shift upon changing I_{delay}, as expected. The relation between the time shift of the transition curves and I_{delay} is plotted in Fig. 4, where the time shift were determined from the peak position of derivative curves derived from the transition curves in Fig. 3. In Fig. 3, the red curve shows polynomial fit for the obtained plots and according to this fitting curve, the I_{delay} in Fig. 2 was converted into the time delay of JTL1. The derivative curve of the transition curve in Fig. 2 with relative time delay on the x-axis is shown in Fig. 5. The histogram reflects the j_{SFQ} and the full width half maximum (FWHM) timing jitter was estimated as 1.10 ps. The possible physical source of the timing jitter in the SFQ circuit is the

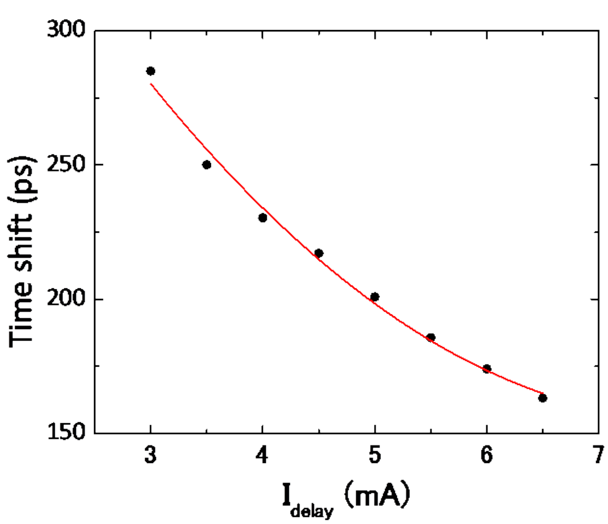

Fig. 4. Relation between the time shift of the transition curves and I_{delay} (from Fig. 3). The red curve is fitted by polynomial fitting method.

Johnson noise from a shunt resistor connected in parallel to the Josephson junction, and the timing jitter is estimated to be in the order of 1 ps both for the JTL consisting of 100 Josephson junctions and the comparator [12, 13], which is comparable with the observed jitter of 1.1 ps and sufficiently low to realize a high time-resolved superconducting coincidence photon counter.

IV. Conclusion

Reduction of possible contributions to the jitter in superconducting coincidence photon counters is necessary for reducing the entire timing jitter. This is an important step toward realizing high time-resolved coincidence photon counters. In this work, we experimentally investigated the characterization of j_{SFQ}, and the FWHM of j_{SFQ} was evaluated as 1.1 ps. This value is sufficiently low and does not significantly affect the timing jitter of the coincidence photon counter. Therefore, other contribution such as j_{SSPD} and $j_{MC\text{-}DC/SFQ}$ have to be reduced. Extremely low timing jitter (<3 ps) of SSPDs was recently realized although accompanied with the decrease in detection efficiency [14], expecting further reduction of j_{SSPD} in the coincidence photon counter. It is also important to reduce $j_{MC\text{-}DC/SFQ}$, and we believe that the reduction of $j_{MC\text{-}DC/SFQ}$ is also feasible by optimizing the design parameter and fabrication process of the SFQ circuit. Subsequently, it would be possible to realize coincidence photon counters with time resolution higher than the coherence time of photons ~30 ps at bandwidth of 0.1 nm [15]; such devices will make it possible to observe the HOM interference with a continuous-wave-pumped source.

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