

Direct observation of photon-induced vortices in superconducting films

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Nucleation of vortex-antivortex pairs (VAPs) is believed to play a central role in the photon detection mechanism of superconducting detectors; however, their direct dynamic observation has remained challenging. Here, we report the direct observation of photon-induced VAP dynamics in a current-carrying superconductor as quantized voltage signals following photon absorption. The observed signals are interpreted as discrete phase-slip events, where each vortex traversal induces a 2π phase change of the superconducting order parameter, resulting in a quantized voltage pulse whose time integral is given by the magnetic flux quantum Φ_0 . We analyze the resulting quantized signals as a function of bias current, base temperature, and input photon-number states and find that the number of VAPs generated per absorbed photon becomes effectively stabilized under specific conditions. Under these conditions, we demonstrate photon-number-resolving capability by directly counting phase-slip-induced voltage quanta. Our results reveal a detection mechanism governed by phase dynamics rather than conventional resistive transitions and represent the first demonstration of photon-number resolution based on VAP counting, enabling fast multi-photon-resolving superconducting detectors for quantum optics.

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I. INTRODUCTION

The detection of single photons using superconducting devices is a key technology for quantum information, sensing, and optical communication. Conventional superconducting photon detectors, such as transition-edge sensors (TESs) [1,2] and superconducting nanowire single-photon detectors (SNSPDs) [3–5], rely on photon-induced suppression of superconductivity and the resulting resistive response.

In these detectors, photon absorption creates a non-equilibrium region in which the superconducting order parameter is locally suppressed. This process is commonly described by hotspot-based models, including early theoretical descriptions [6,7] and subsequent refinements and analyses [8–11]. Under a bias current, such nonequilibrium regions facilitate the generation of multiple vortex-antivortex pairs (VAPs), whose motion leads to Joule heating and can trigger the formation of a normal conducting domain.

In particular, vortex-based descriptions have been proposed, where photon absorption induces VAP nucleation

through the temporal suppression and recovery of the superconducting order parameter [8,12,13]. The number of such events is expected to depend on the ratio between the strip width and the superconducting coherence length [8]. In conventional SNSPDs with relatively narrow strips, multiple VAPs are generated, and their motion results in the formation of a resistive region. The detection signal is therefore governed by the resulting resistive transition, which depends on the bias current, thermal relaxation, and circuit conditions.

In addition, photon-number-resolving capabilities have also been actively explored in superconducting nanowire detectors [14]. In contrast to these conventional approaches, the present work focuses on the nonequilibrium phase dynamics associated with photon absorption in a current-carrying superconductor. Rather than relying on the formation of a macroscopic resistive state, we investigate the regime in which only a small number of vortex-antivortex pairs are generated and their dynamics can be directly resolved. The conceptual difference between these two detection mechanisms is illustrated schematically in Fig. 1.

Photon absorption locally suppresses the superconducting order parameter, forming a transient nonequilibrium region (hotspot-like region). This region should not be confused with the normal core of a vortex; rather, it represents a temporary reduction of the superconducting condensate. Under bias current, the nonuniform current

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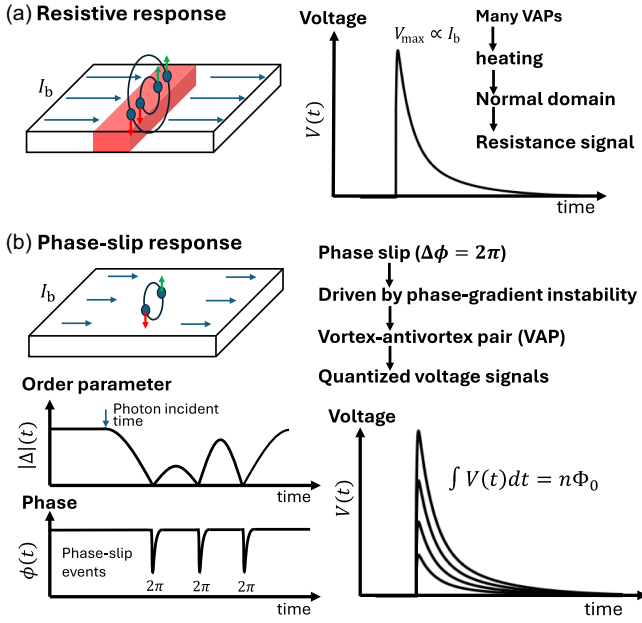


FIG. 1. Schematic illustration of photon detection mechanisms: (a) conventional resistive detection, in which photon absorption generates many vortex-antivortex pairs, resulting in heating, normal-domain formation, and a resistive response; and (b) VAP-mediated phase-slip detection (VBD in this work), in which only a few VAPs are generated and directly detected as quantized voltage pulses. The lower panels illustrate the transient suppression and recovery of the superconducting order parameter $\Delta(t)$ and the corresponding phase evolution $\phi(t)$ associated with discrete phase-slip events.

distribution leads to an instability in the phase gradient of the superconducting order parameter. This instability is released through the nucleation of vortex-antivortex pairs, which corresponds to discrete phase-slip events.

When a vortex traverses the superconducting strip, the superconducting phase undergoes a 2π change. According to the Josephson relation,

$$V = \frac{\hbar}{2e} \frac{d\phi}{dt},$$

each phase-slip event produces a voltage pulse whose time integral satisfies

$$\int V(t)dt = \Phi_0,$$

where $\Phi_0 = h/2e$ is the flux quantum. Thus, the observed voltage pulses directly reflect the underlying phase evolution associated with vortex motion.

In this work, we demonstrate the direct observation of photon-induced vortex-antivortex dynamics through quantized voltage signals. By resolving the number of phase-slip events occurring after photon absorption, we show that

the number of VAPs generated per absorbed photon remains approximately constant under specific bias current and temperature conditions. This enables photon-number resolution based on VAP counting, providing a detection paradigm fundamentally different from conventional amplitude-based or resistive detection schemes.

The key distinction of this approach is that the detection signal is governed by discrete phase-slip events rather than by a continuous resistive transition. While the peak amplitude of the voltage signal depends on the readout circuit and bias current, the time-integrated voltage is determined solely by the phase change and remains quantized in units of Φ_0 . This allows direct access to the number of phase-slip events induced by photon absorption. In the following, we refer to this device as a vortex-based detector (VBD).

The remainder of this paper is organized as follows. We first describe the device structure and measurement setup and then present experimental observations of quantized voltage pulses. Finally, we analyze the dependence of the phase-slip dynamics on bias current, temperature, and photon number and discuss the implications for photon-number-resolving detection.

II. EXPERIMENT

A. Experimental methods

The VBD used in the experiment consisted of a bilayer superconducting film composed of titanium and gold with thicknesses of 20 and 10 nm, respectively. This bilayer film was patterned into a square strip measuring $8 \mu\text{m} \times 8 \mu\text{m}$. The substrate of this device was a Si wafer. To enhance the detection efficiency, a Ti (5 nm)/Au (50 nm)/Ti (5 nm) was sputtered to form an Au mirror, and a SiO_2 layer was subsequently deposited on top of the Au mirror to electrically insulate the active area. The titanium layers in this trilayer served as an adhesion layer. The Ti/Au bilayer was then deposited on the SiO_2 layer, and an additional five-layer $\text{SiO}_2/\text{Si}_3\text{N}_4$ stacks were sputtered to form an antireflection layer. Niobium superconducting leads were fabricated on opposite sides of the square to read the VBD response signal. The superconducting properties of the VBD were measured in a dilution refrigerator and are summarized in Table I. The device performance is comparable to previously reported low- T_c optical TES devices [15].

Based on the measured superconducting parameters, we estimated $\xi_{\text{GL}}(0) = 62.5 \text{ nm}$ for $T_c = 128 \text{ mK}$ and $D = 1.67 \text{ cm}^2/\text{s}$ [1,16]. The coherence length was not directly measured from magnetic-field-dependent measurements but estimated from the diffusion constant using standard relations. Thus, the ratio $w/\xi_{\text{GL}}(0) \approx 128$ for our VBD. In contrast to conventional narrow SNSPDs, where rapid formation of extended resistive regions can dominate the response depending on the bias current, this large ratio places the device in a regime in which only a limited

TABLE I. Performance of the superconducting device in the ETF-TES mode.

Material		Ti (20 nm)/Au (10 nm)
Size		$8\ \mu\text{m} \times 8\ \mu\text{m}$
Critical temperature	T_c	128 mK
Effective time constant	τ_{eff}	$4.82\ \mu\text{s}$ ($T_b = 6\ \text{mK}$) $29.1\ \mu\text{s}$ ($T_b = 117\ \text{mK}$)
Normal resistance	R_n	$2.87\ \Omega$
Detection efficiency	η	76%
Critical current	$I_c(T \rightarrow 0)$	$7.36\ \mu\text{A}$ (extrapolated)

number of vortex-antivortex pairs are generated, enabling direct observation of discrete phase-slip events.

Figure 2(a) shows the readout circuit for the VBD, where the VBD and an inductor with inductance L are shunted by a resistor R_s . A bias current I_b is supplied to the VBD from an external current source. The VBD is cooled to a base temperature $T_b < T_c$ so that under equilibrium conditions, almost all of I_b flows through the VBD. The VBD is optically coupled to a fiber, and a laser pulse with an average photon number μ_{in} is delivered to it through the fiber. The wavelength of the incident photons was 1526 nm. After photon absorption in the VBD, a voltage signal $\Delta v(t)$ results from either the formation of resistance or the induced electromotive force due to the VAP motion, which is read out by the current amplifier of a superconducting quantum interference device (SQUID). From the observed current change $\Delta I(t)$ at the SQUID output, we obtain

$$\Delta v(t) = R_s \times \Delta I(t)$$

with a bandwidth of $0.35/\tau_{\text{el}}$, where we define the electrical time constant $\tau_{\text{el}} = L/R_s$.

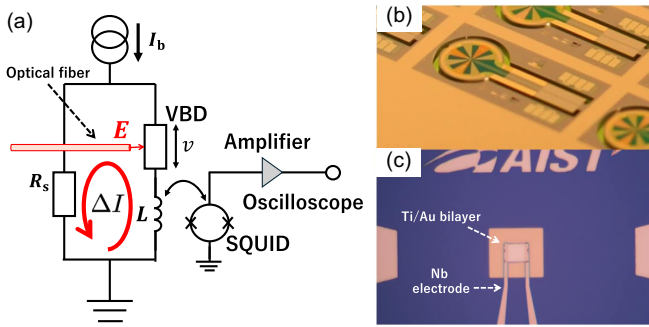


FIG. 2. (a) Readout circuit for the VBD. The rectangle with an arrow represents the VBD as the photon detection device. R_s , shunt resistance; I_b , bias current; L , kinetic inductance; ΔI , change in current flowing through this readout circuit. (b) VBD fabricated on a key-shaped Si substrate to improve alignment between the optical fiber and the VBD. (c) Active area of the VBD. This active area consists of the Ti (20 nm)/Au (10 nm) bilayer, and the electrodes are made of niobium.

For reference, the device can also exhibit a resistive response similar to electrothermal-feedback-based TES detection. However, in the present work, we focus on a regime where the device remains superconducting and the detection signal arises from discrete phase-slip events associated with vortex motion. Figure 2(b) illustrates the VBD structure fabricated on a key-shaped Si substrate, and Fig. 2(c) shows the Ti/Au active area of the VBD together with the niobium electrodes. Table I summarizes representative ETF-TES-mode performance metrics for reference. To determine the appropriate operating conditions for the VBD mode, in particular the bias current relative to the critical current, we first investigated the dependence of the critical current I_c on the base temperature T_b by applying a triangular-shaped current to the VBD. The critical current I_c was defined as the current at which the resistance of the VBD exceeded $3\ \text{m}\Omega$. The temperature dependence of I_c is shown in Fig. 3(a). At lower values of T_b , $I_c(T)$ is almost constant. We evaluated $I_c(0) = 7.36\ \mu\text{A}$ by extrapolating the data obtained in the range $30\ \text{mK} < T_b < 50\ \text{mK}$. $I_c(T)$ gradually vanishes as T_b approaches T_c .

B. Photon response of the VBD

To evaluate the photon response, we irradiated the VBD with photons while applying a bias current $I_b < I_c$, ensuring that the device remained in its superconducting equilibrium state. This condition closely resembles the standard operating mode of SSPDs. Figure 3(b) shows the signals observed under $I_b = 5.0\ \mu\text{A}$, $T_b = 6\ \text{mK}$, $R_s = 21.4\ \text{m}\Omega$, and $\mu_{\text{in}} = 10$ photons/pulse. Here, μ_{in} denotes the average number of incident photons per pulse. The corresponding average number of detected photons is given by $\eta\mu_{\text{in}}$, where η is the detection efficiency. The pulse heights are quantized into discrete voltage steps in response to the incident laser pulses, a behavior fundamentally different from that of SSPDs.

The measured time constant was 445 ns, approximately 10 times faster than that in the ETF-TES mode (see Table I). To clarify whether quantization originates from resistance or voltage changes, we measured the dependence of Δv on I_b and T_b . If Δv is caused by a resistance change ΔR , it will scale proportionally with I_b because ΔR remains nearly constant at a fixed T_b . Likewise, for a constant I_b , Δv will vary with T_b because the heat capacity of the VBD changes with the temperature T_b .

Figure 4 shows the pulse-height distribution for $\mu_{\text{in}} = 5$ photons/pulse, including markers for the peak positions and an overlaid envelope curve. Figures 4(a) and 4(b), obtained at $T_b = 6\ \text{mK}$, demonstrate that increasing I_b from 4 to 6 μA produces additional peaks, even at the same photon input. Similarly, for a constant I_b , the peak index increases as T_b rises from 63 to 91 mK. Across all conditions, the voltage pulses remain quantized at intervals

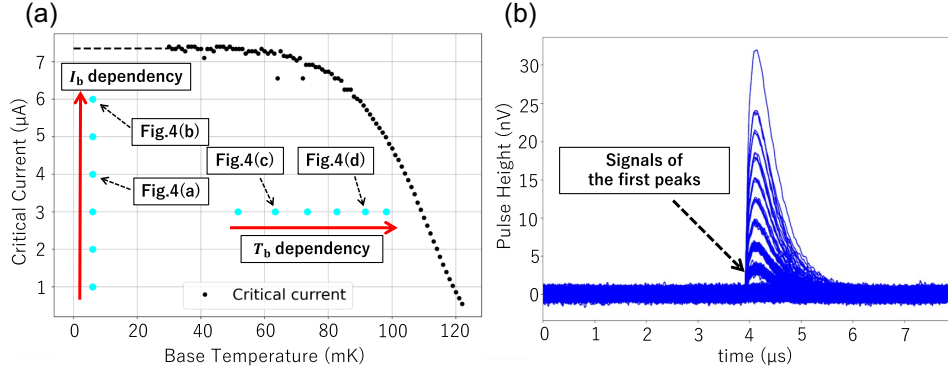


FIG. 3. (a) Experimental data showing the dependence of the critical current on the base temperature. These experimental data of the critical current are obtained from the current-voltage characteristics, and the dotted line is extrapolated to determine $I_c(T = 0 \text{ mK})$. (b) Recorded signals at $I_b = 5.0 \text{ } \mu\text{A}$, $T_b = 6 \text{ mK}$, $R_s = 21.4 \text{ m}\Omega$, and $\mu_{\text{in}} = 10 \text{ photons/pulse}$. Under this condition, the time constant of the VBD is $\tau = 445 \text{ ns}$.

of approximately 0.45 nV , forming discrete peaks regardless of I_b or T_b .

In Fig. 4(d), pulses with amplitudes exceeding 8 nV are not observed. When the pulse height at a single peak is 0.45 nV , the current diverted to the shunt resistor is approximately $0.2 \text{ } \mu\text{A}$. Thus, the number of pulse peaks is determined by the bias current. Therefore, the pulse heights in Fig. 4(d) are truncated at around 8 nV because $I_b = 3 \text{ } \mu\text{A}$. Furthermore, the minimum peak amplitude in Fig. 3(b) is approximately an order of magnitude smaller

than that in Fig. 4. This difference is attributed to the change in the electrical time constant resulting from the different value of R_s . These results indicate that photon detection in a VBD is governed by a mechanism fundamentally distinct from that of resistance variation. Notably, Figs. 4(b) and 4(d), where I_b or T_b is close to I_c or T_c , respectively, exhibit periodic modulations of the peak counts. These modulations are evident from the envelope formed by connecting the peak maxima in the figure. This behavior indicates enhanced fluctuations in the number of

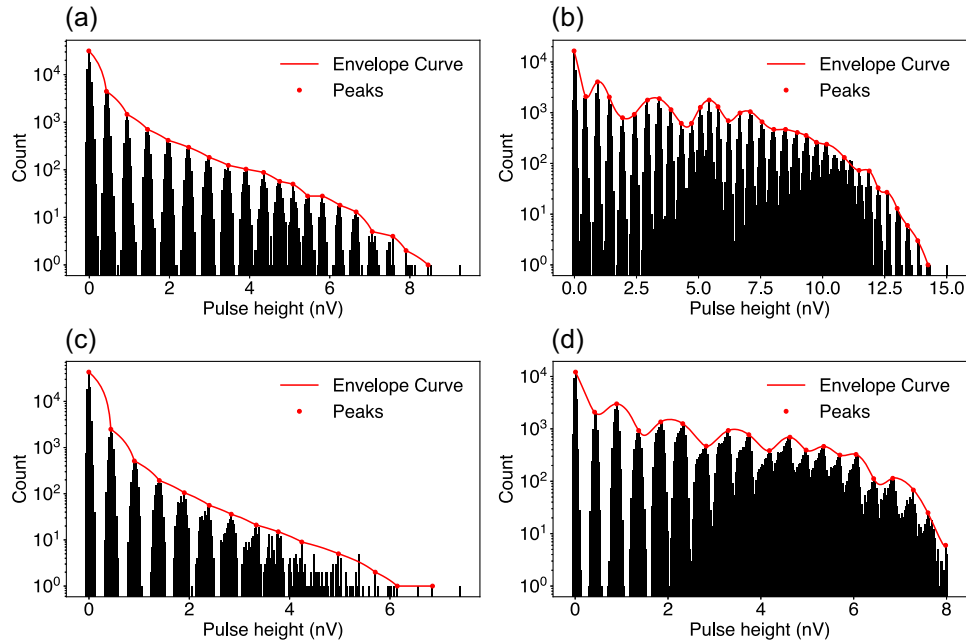


FIG. 4. Pulse-height distributions under four different experimental conditions, where the peak positions are marked. The envelope curves are included only as visual guides for peak evolution and do not represent a theoretical model. (a) $I_b = 4.0 \text{ } \mu\text{A}$, $T_b = 6 \text{ mK}$, $\mu_{\text{in}} = 5 \text{ photons/pulse}$; (b) $I_b = 6.0 \text{ } \mu\text{A}$, $T_b = 6 \text{ mK}$, $\mu_{\text{in}} = 5 \text{ photons/pulse}$; (c) $I_b = 3.0 \text{ } \mu\text{A}$, $T_b = 63 \text{ mK}$, $\mu_{\text{in}} = 5 \text{ photons/pulse}$; (d) $I_b = 3.0 \text{ } \mu\text{A}$, $T_b = 91 \text{ mK}$, $\mu_{\text{in}} = 5 \text{ photons/pulse}$. In all cases, discrete peaks are observed, where each peak corresponds to the number of phase-slip events. The peak structure depends on both bias current I_b and base temperature T_b , indicating that the number of generated VAPs varies systematically with the operating conditions.

VAP events under these operating conditions, suggesting that the VAP generation process is not fully stabilized and motivating the statistical analysis presented in Sec. III.

III. PHOTON DETECTION MECHANISM BASED ON PHASE-SLIP DYNAMICS

A. Quantization of signal waveforms in units of magnetic flux quantum

As discussed in the previous section, the observed signal in the VBD mode does not primarily originate from the generation of resistance following photon absorption because the minimum pulse integral remains independent of both I_b and T_b . Instead, we interpret the observed voltage in terms of the phase evolution of the superconducting order parameter. According to the Josephson relation,

$$V(t) = \frac{\hbar}{2e} \frac{d\phi}{dt}, \quad (1)$$

where ϕ is the superconducting phase. When a vortex traverses the superconducting strip, the phase changes by 2π , and therefore the time-integrated voltage satisfies

$$\int V(t)dt = \frac{\hbar}{2e} \Delta\phi = n_{\text{VAP}}\Phi_0, \quad (2)$$

where n_{VAP} denotes the number of phase-slip events (or equivalently the number of traversing VAPs) and $\Phi_0 = h/2e$ is the flux quantum.

From this point of view, we obtained the voltage-time integral in Eq. (2) for the minimum-amplitude pulses under different experimental conditions involving I_b and T_b . Figures 5(a) and 5(b) show the dependence of

this quantity on the bias current and base temperature, respectively. In Fig. 4, the voltage pulses remain quantized with a constant interval of approximately 0.45 nV. Therefore, we extracted the waveform corresponding to the first peak index and calculated its voltage-time integral to discuss its dependence on I_b and T_b . At $T_b = 98$ mK, the first-peak statistics were insufficient, so we instead used the waveform corresponding to peak index 3 and divided the resulting integral by the peak index to compare with the single-event value.

For all experimental conditions, the minimum pulse integral remains almost constant and close to the magnetic flux quantum $\Phi_0 = 2.07 \times 10^{-15}$ Wb. The value does not depend on R_s . These results show that the minimum-amplitude voltage pulse corresponds to a single phase-slip event, i.e., $n_{\text{VAP}} = 1$.

Here, we assume that the quantized pulse shape originates from the quantum number n_{VAP} and examine the dependence of Φ on n_{VAP} . Figure 6(a) shows the results under two different experimental conditions with respect to I_b and T_b . Specifically, we define case 1 as $I_b = 6$ μ A and $T_b = 6$ mK, and case 2 as $I_b = 3$ μ A and $T_b = 98$ mK. For case 1, the value of Φ is proportional to n_{VAP} up to approximately 17, which clearly indicates that the observed signals in Fig. 3(b) are quantized according to n_{VAP} . However, for $n_{\text{VAP}} > 17$, this proportionality is no longer valid. Under the conditions of case 2, the value of Φ significantly exceeds Φ_0 even for small values of n_{VAP} . To investigate this, we focus on the pulse shape of the observed voltage signals. Figure 6(b) shows an example of the averaged pulse shape used for the decomposition analysis. Apparently, the signal shape consists of two exponential components with distinct time constants, which is completely different from the shape shown in Fig. 3(b).

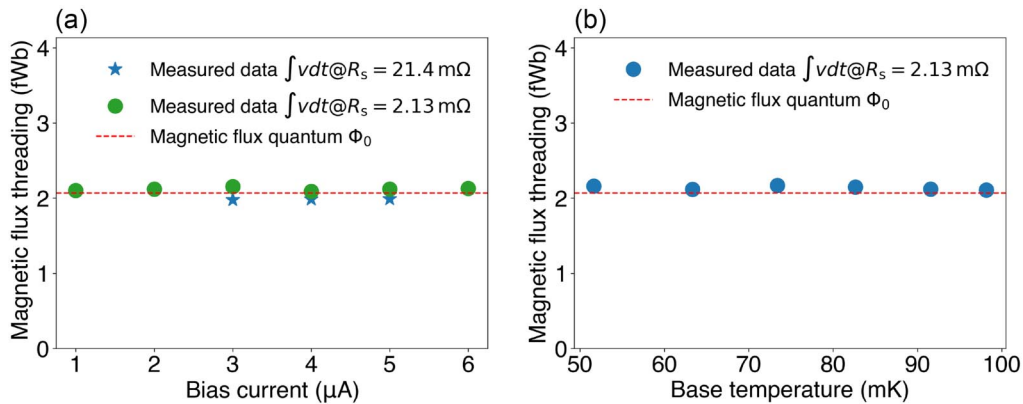


FIG. 5. (a) Relationship between voltage-time integral at each bias current and magnetic flux quantum. We obtained these data from $I_b = 1$ μ A to 6 μ A at $T_b = 6$ mK, following the I_b dependency in Fig. 3(a). (b) Relationship between voltage-time integral at each base temperature and magnetic flux quantum. The data were obtained from $T_b = 52$ mK to 98 mK (52, 63, 73, 83, 92, and 98 mK) at $I_b = 3$ μ A, following the T_b dependency in Fig. 3(a). At $T_b = 98$ mK, the voltage-time integral is calculated from the time constant of the first stage in the averaged pulse.

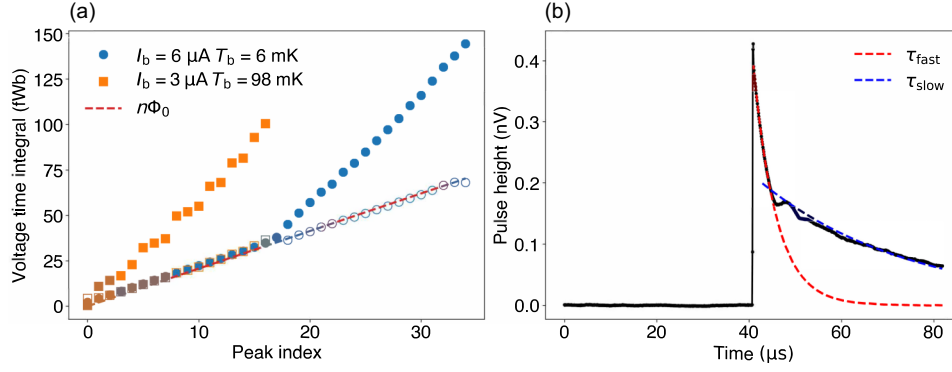


FIG. 6. (a) Dependence of the voltage-time integral of individual pulse peaks on the peak index. Closed circles and rectangles represent $\int v dt$ of the obtained average pulse, whereas the results obtained by integrating the τ_{fast} component of the separated signals are replotted as open circles or rectangles. The open symbols exhibit good consistency with the straight line having a slope of Φ_0 . (b) Averaged pulse obtained from the VBD at $T_b = 98 \text{ mK}$. The time constant of this waveform appears to increase in the later part owing to Joule heating.

To separate the two components, we fit the signal with

$$f(t) = a \exp(-t/\tau_{\text{fast}}) + b \exp(-t/\tau_{\text{slow}}), \quad (3)$$

which gives $a = 0.397 \text{ nV}$, $b = 0.207 \text{ nV}$, $\tau_{\text{fast}} = 5.06 \mu\text{s}$, and $\tau_{\text{slow}} = 32.4 \mu\text{s}$. We performed this separation for the other signals for each n_{VAP} , and the results obtained by integrating the τ_{fast} component of the separated signals are replotted in Fig. 6(a) as open circles or rectangles.

In this case, all the values are proportional to Φ_0 with n_{VAP} , which shows that the first component of Eq. (3) can be attributed to the traversal of the magnetic flux quanta, consistent with the expected phase-slip dynamics.

In addition, τ_{slow} in the slow component of Eq. (3) is close to the ETF-TES time constant $\tau_{\text{ETF}} = 29.1 \mu\text{s}$, measured at $T_b = 117 \text{ mK}$, as shown in Table I. In the ETF-TES operation, the effective time constant increases as the base temperature approaches the critical temperature. Therefore, the slow component can be attributed to the generation of a resistive change in the transition region after the traversal of magnetic flux quanta.

B. Signal response speed

In the VBD operation mode, the signal response time is in the order of $\tau \sim w/v$, where w and v denote the strip width of the superconducting film and traversing velocity of the VAPs, respectively. The velocity v for the titanium/gold superconducting film is not known; however, previous research reports that the velocity for an NbC superconductor is approximately 10^4 m/s [17]. Assuming this estimation holds for the Ti/Au film, the signal response time can be approximated as $\tau \sim 800 \text{ ps}$ for $w = 8 \mu\text{m}$. Consequently, the VBD mode is expected to exhibit a substantially faster response when compared with that of the ETF mode. Nevertheless, the observed time constant in Fig. 3(b) is restricted to $\tau = 445 \text{ ns}$. This limitation arises from the bandwidth of the bias circuit depicted in Fig. 2,

where the signal response is governed by the electrical time constant $\tau_{\text{elc}} = L/R_s$. We estimated $L = 9.8 \text{ nH}$ by measuring the noise spectrum of the VBD, which yields $\tau_{\text{elc}} = 458 \text{ ns}$ for $R_s = 21.4 \text{ m}\Omega$. This value is in good agreement with the time constant of the observed signals. Therefore, a wide-bandwidth readout is crucial for achieving an intrinsically faster signal response in the VBD.

C. PNR capability

As discussed in the previous section, the response signal is quantized according to the number of phase-slip events. This quantization enables photon-number resolution by directly counting VAP events. To quantitatively evaluate this behavior, we introduce the average number of traversing VAPs per absorbed photon, denoted as n_{VAP} , which refers to the average number of traversing VAPs per absorbed photon as defined in Eq. (4). This quantity provides a measure of the conversion between absorbed photons and the resulting phase-slip events.

The average number of traversing VAPs is obtained from the observed distribution of phase-slip events using the following equation:

$$n_{\text{VAP}} = \frac{1}{\eta \mu_{\text{in}}} \sum_{n=0} n P(n), \quad (4)$$

where $P(n)$ represents the probability of observing n magnetic flux quanta, and η is the detection efficiency.

To identify the operating conditions under which fluctuations of n_{VAP} are suppressed, we evaluate the second-order correlation function $g_{\text{VAP}}^{(2)}$, defined from the number of VAP events observed per pulse, as a function of bias current and base temperature, as shown in Fig. 7.

Figure 7(a) shows the dependence of $g_{\text{VAP}}^{(2)}$ on the bias current at $T_b = 97 \text{ mK}$, while Fig. 7(b) shows its dependence on the base temperature at $I_b = 3 \mu\text{A}$. We find

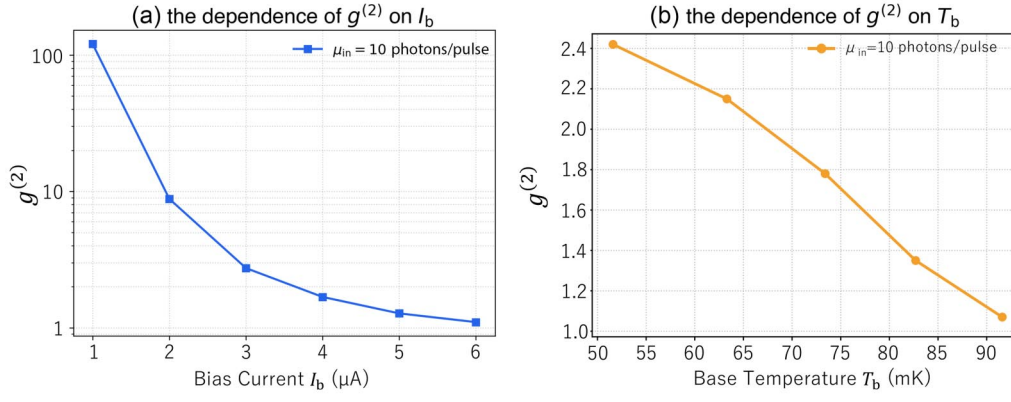


FIG. 7. (a) Dependence of the second-order correlation function $g_{\text{VAP}}^{(2)}$, calculated from the number of observed VAP events per pulse, on the bias current I_b at a base temperature of $T_b = 97 \text{ mK}$. (b) Dependence of $g_{\text{VAP}}^{(2)}$ on the base temperature T_b at a fixed bias current of $I_b = 3 \mu\text{A}$. In both cases, $g_{\text{VAP}}^{(2)}$ approaches unity with increasing I_b or T_b , corresponding to the Poisson limit. These results indicate that fluctuations in the number of VAP events per pulse are suppressed, identifying the operating conditions under which the VAP generation process becomes effectively stabilized.

that $g_{\text{VAP}}^{(2)}$ approaches unity under specific combinations of I_b and T_b , indicating that fluctuations in the number of VAP events per pulse are suppressed. Using these operating conditions, we examine the photon-number-resolving (PNR) behavior under $T_b = 98 \text{ mK}$ and $I_b = 3 \mu\text{A}$, with $\mu_{\text{in}} = 1$ photon/pulse.

Under these conditions, we directly evaluate the statistical distributions of the detected events to verify the emergence of photon-number-resolving behavior. The bars in Fig. 8(a) show the distribution of the individual magnetic quantum peaks under these conditions. The total number of events is $N_{\text{all}} = 10^5$. From this distribution, we obtained n_{VAP} using Eq. (4), which yields $n_{\text{VAP}} = 3.22 \Phi_0/\text{photon}$.

In addition to this method, we applied a multi-Gaussian fitting to the distribution to determine n_{VAP} . The fitting function is expressed as

$$f(x) = \frac{N_{\text{all}}}{\sqrt{2\pi}} \sum_{n=0} \frac{P_{\text{photon}}(n)}{\sigma_n} \exp \left[-\frac{(x - b_n)^2}{2\sigma_n^2} \right], \quad (5)$$

where N_{all} is the total number of events, $P_{\text{photon}}(n)$ is the probability of the n -photon state, b_n is the center position of the n th peak, and σ_n is its standard deviation. After fitting, we obtained $n_{\text{VAP}} = \sum b_n / \sum n = 3.18$, which agrees well with the value obtained by the previous method in Eq. (4). The bars in Fig. 8(b) show the probability of the photon-number states $P_{\text{photon}}(n)$ determined by the fitting.

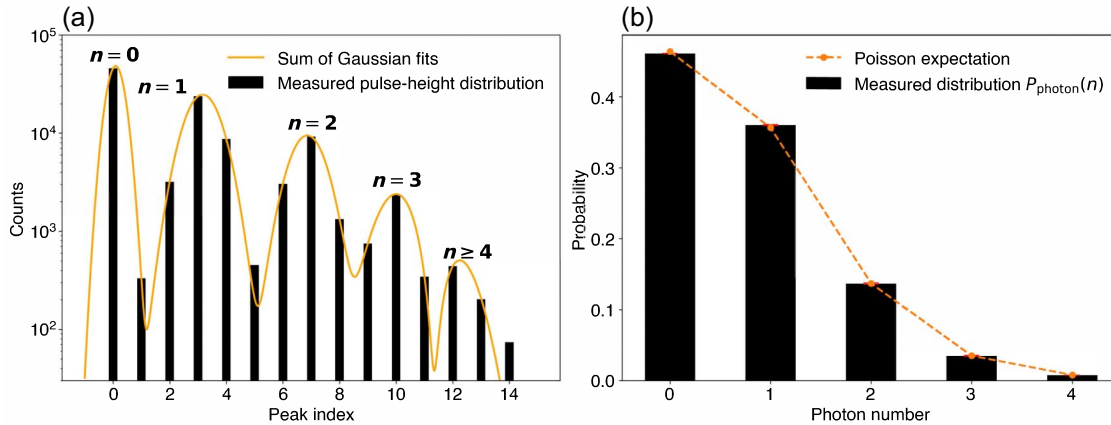


FIG. 8. Photon-number-resolving behavior measured under operating conditions identified in Fig. 7, where $g_{\text{VAP}}^{(2)} \approx 1$ (at $T_b = 97 \text{ mK}$), indicating stabilized VAP generation. (a) Distribution of the number of observed VAP events per pulse. (b) Corresponding photon-number distribution inferred from the VAP counts. Under these conditions, both distributions follow Poisson statistics. The second-order correlation function evaluated from the photon-number distribution, $g_{\text{photon}}^{(2)} \approx 1$, is consistent with Poissonian photon statistics. These results demonstrate that the Poissonian nature of the VAP statistics ($g_{\text{VAP}}^{(2)} \approx 1$) is directly transferred to the photon-number statistics, enabling photon-number-resolving behavior.

The dotted line represents the Poisson distribution under the same condition, with an average photon number of $\eta\mu_{\text{in}} = 0.77$. We conducted a χ^2 test on the datasets, and the results revealed no significant differences among the conditions ($\chi^2 = 3.41$, $p = 0.333$).

Moreover, the second-order correlation function $g_{\text{photon}}^{(2)}$ for photons was evaluated to be $g_{\text{photon}}^{(2)} = 0.972$, consistent with Poissonian photon statistics. This result demonstrates that the Poissonian nature of the VAP statistics ($g_{\text{VAP}}^{(2)} \approx 1$) is directly transferred to the photon-number statistics. It should be noted that these measurements are performed under specific operating conditions identified through the $g_{\text{VAP}}^{(2)}$ analysis, in contrast to the general response shown in Fig. 4, where the VAP number fluctuates and does not directly reflect photon statistics.

To compare the experimentally obtained value with a simple energy-scale estimate, we introduce the kinetic-inductive energy scale associated with a 2π phase-slip event,

$$E_{\Phi_0} = \frac{\Phi_0^2}{2L_k}, \quad (6)$$

where L_k is the kinetic inductance of our device. Using the estimated kinetic inductance under $T_b = 98$ mK, $I_b = 3$ μ A, and an input wavelength of 1526 nm, we obtain $E_\gamma/E_{\Phi_0} \approx 2.88$, which is in reasonable agreement with the experimentally obtained value. We emphasize that this estimate is not a rigorous prediction of the number of VAPs; rather, it provides an order-of-magnitude consistency check, since the actual number of events is governed by nonequilibrium phase-slip dynamics under the given bias and thermal conditions.

IV. CONCLUSION

In summary, we experimentally demonstrated the direct observation of photon-induced VAP dynamics in superconducting films operated in a vortex-based detection mode. By analyzing the quantized voltage signals associated with phase-slip events, we confirmed that the observed response associated with phase-slip events (i.e., magnetic flux quanta traversing the superconducting strip) rather than the resistance changes in the transition region. The voltage-time integrals exhibit clear quantization in units of the magnetic flux quantum, establishing a direct link between the signal amplitude and the number of VAPs. Furthermore, we identified that the measured response time is limited by the readout circuit bandwidth, suggesting that sub-nanosecond intrinsic timescales are achievable through circuit optimization.

Notably, we demonstrated the PNR capability based on the correlation between the number of absorbed photons and the number of traversing VAPs. The reconstructed photon-number distribution agrees with the Poisson

statistics, confirming the feasibility of multi-photon resolution in this detection scheme. These findings represent the first experimental evidence of VAP-mediated photon detection and provide a pathway toward fast, high-efficiency, multi-photon-resolving superconducting detectors. Such detectors could play a crucial role in quantum optics and quantum information processing, where precise photon-number discrimination and ultrafast response are essential. These results demonstrate that photon detection can be governed by phase-slip dynamics rather than conventional resistive transitions.

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D. F. contributed equally to this work. F. H., T. T., and T. K. led the discussion and interpretation of the results.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

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