Ultrafast reset time of superconducting single photon detectors


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We have measured the ultrafast reset time of NbN superconducting single photon detectors (SSPDs) based on a design consisting of $N$ parallel superconducting stripes. Compared to a standard SSPD of identical active area, the parallel SSPD displays a similar detection efficiency and a kinetic inductance, which is divided by $N^2$. For $N=12$, the duration of the voltage detection pulse is reduced by nearly two orders of magnitude down to 200 ps. The timing jitter associated with the rising front is only 16 ps. These results open a way to efficient detectors with ultrahigh counting rate exceeding 1 GHz. © 2008 American Institute of Physics. [DOI: 10.1063/1.2945277]

Single photon detection has many applications in various domains of fundamental research as well as in characterization and measurement applications. Among them, one can cite quantum cryptography and more generally quantum information processing, singlet oxygen detection for cancerology, III-V semiconductor characterization, photon counting optical time domain reflectometry including light detection and ranging, or low photon flux astronomy. In most of these applications, the timing characteristics (dead time and jitter) of the detector are key parameters. The dead time, which is the minimum time allowed between two consecutive detections, limits the maximum count rate of the detector. The timing jitter, i.e., the uncertainty on the time delay between the photon arrival and the detector response, plays a crucial role in photon correlation experiments involving the delay between the photon arrival and the detector response.

Superconducting single photon photodetectors (SSPDs) offer an appealing alternative to traditional photon counting, especially in the near infrared where they outperform photomultiplier tubes and avalanche photodiodes. The SSPDs are made of a superconducting thin stripe (typically 4 nm) biased just below the critical current. The absorption of a photon generates a small, out of equilibrium, resistive area—the so-called hotspot—which in turn leads to a breakdown of superconductivity on a whole stripe section. A voltage builds up through the device and vanishes after a few tens of picoseconds, when the superconductive state is spontaneously restored. This mechanism allows for efficient and fast photon counting in the visible and in the near infrared, including the 1.3 and 1.55 μm telecommunication wavelength. Practical detectors come generally with a meander shaped stripe integrated in a 10×10 μm² pixel, a size adapted to the core diameter of a single-mode telecommunication optical fiber. In these devices, the detector timings are no longer limited by the intrinsic hotspot mechanism. As shown in Ref. 11, the voltage pulse duration is directly proportional to the kinetic inductance $L_k$ of the superconducting stripe. Given the $l=500$ μm stripe length and its 100 nm width, mandatory to optimize the detection efficiency, $L_k$ commonly reaches 500 nH. As a consequence, efficient detectors display a voltage pulse duration in the $L_k/50\,\Omega=10$ ns range, severely limiting the photon counting rate down to below 100 MHz.

In this letter, we show that this limitation can be overcome using a parallel structure design allowing for ultrafast timing characteristics while preserving a high quantum efficiency. Figure 1 details the equivalent electrical circuit of a detector whose superconducting stripe is decomposed into $N$ parallel sections of length $l/N$. For a given total meander length $l$, corresponding to a kinetic inductance $L_k$ for a standard detector, this parallel design leads to a total kinetic inductance $L_k/N^2$. Since the total stripe length remains unchanged ($l=500$ μm), the parallel wiring does not affect the detection efficiency. When a section absorbs a photon, the current flowing in this section drops and is redirected toward the high-frequency line and in the remaining $N-1$ superconducting sections. The kinetic inductance of each section prevents a bypass of the high-frequency line. However, experiments showed that this simple design is subject to afterpulsing caused by the appearance of superconducting loops. The problem was solved adding a series resistor $R_0=10$ Ω in each section. Interestingly enough, this design also allows for photon number resolution.

Figure 2 precises the geometry of the detectors. They were made from 4.0 nm thin NbN epitaxial films grown by
dc magnetron sputtering over a sapphire substrate. A first electron-beam lithography step and subsequent etching form a $10 \times 10 \mu m^2$ pixel with $N$ sections having a meander structure. Here, the stripe width is 120 nm and the pixel filling factor is 60%. After the etching, the devices display a superconducting transition temperature of 10.9 K very close to the one of the unprocessed film (within 0.1 K), indicating that superconducting properties are preserved by the process. At 4.2 K, each section has a critical current in the 20 $\mu A$ range. A second lithography step then defines the Ti:Au resistors. Finally, the detector is connected to an on-chip 50 $\Omega$ coplanar waveguide to efficiently extract the high-frequency voltage signal.

The SSPDs were operated in a liquid helium cryostat featuring a broadband electronic setup. The detector is illuminated, via a single mode optical fiber, by an attenuated Ti:sapphire laser that produces 1 ps pulses with a repetition rate of 80 MHz at a wavelength of 950 nm. Electrical contacts on the sample are taken using a microwave probe connected to a cryogenic microwave coaxial line. Outside the cryostat, the coaxial cable reaches a bias tee whose dc port is connected to an adjustable low noise voltage source and a cryostat, the coaxial cable reaches a bias tee whose dc port is connected to a low noise, broadband, 35 dB microwave amplifier. The ac port is connected to an adjustable low noise voltage source and a cryostat, the coaxial cable reaches a bias tee whose dc port is connected to a low noise, broadband, 35 dB microwave amplifier and the signal can be either recorded with a HP 54120 digital sampling oscilloscope or fed to a pulse counting system.

The bandwidth of the high-frequency acquisition line is 0.1–20 GHz, and special care was taken to avoid parasitic reflections. The bandwidth of the high-frequency acquisition line is 0.1–20 GHz, and special care was taken to avoid parasitic reflections. The inset shows the jitter measurement of a 12-section SSPD. (b) Characteristic falltime $\tau_{\text{fall}}$ vs. the number of sections $N$. The solid line is the theoretical falltime deduced from the electrical model presented in Fig. 1. Inset: voltage pulse of a 12-section detector plotted in a log scale.

In the present work, the detectors’ bias points are chosen to maximize the detection efficiency while maintaining a dark count rate below 10 Hz. The optical power in the fiber is in the 1 $\mu W$ range. The light spot on the sample has a diameter of 1 mm due to divergence at the output of the fiber. The quantum efficiency of all the detectors investigated in this work was measured around 0.01%. This leads to a count rate of about $10^2$ Hz. Figure 3(a) shows voltage pulses resulting from the absorption of a single photon by parallel structures and illustrates the dramatic decrease of the pulse duration as the number of section increases. Indeed, the pulse duration (measured at half maximum) of a 12-section SSPD is 200 ps, more than 40 times smaller than the 8.5 ns achieved with the standard design. As shown in the inset in Fig. 3(b), the voltage pulse can be roughly decomposed into three main parts: (i) a rapidly rising edge associated with the appearance and growing of the resistive region, (ii) a plateau, which corresponds to a progressive saturation of the resistive region size and whose end corresponds to its disappearance, and (iii) an exponential decay with a characteristic falltime $\tau_{\text{fall}}$. For standard devices, the pulse duration is largely dominated by $\tau_{\text{fall}}$. As shown in Fig. 3(b), this time can be divided by two orders of magnitude with the parallel design. Experimental points compare very well to the value $\tau_{\text{fall}} = L_i/(R_i N^2)$ deduced from the electrical equivalent circuit given in Fig. 1. In this expression, $L_i$ is the total inductance corresponding to the standard design ($N=1$) and $R_i = 50 \Omega$ is the impedance of the microwave line. $L_i = 415$ nH is immediately deduced from the falltime of a one-section device. On another hand, the leading edge of the voltage pulse is also significantly shortened by the parallel design, but not so dramatically as the falling edge. The pulse risetime, measured between levels at 10% and 90% of the pulse amplitude, decreases while $N$ changes from 1 to 7, but remains constant for $N \geq 7$. The value of 50 ps obtained in these cases may reflect a limit arising from the physics of the resistive state formation. Anyway, such a high commutation speed is a strong advantage in terms of temporal resolution on the photon arrival. Indeed, the timing jitter corresponding to a $N=12$ device was measured to be as low as 16 ps [inset in Fig. 3(a)]. As $N$ increases, the impedance associated to the parallel sections decreases. For $N$ exceeding 12, the shunt of the rf line limits the output voltage pulse and the investigation of highly parallel detectors will certainly require a very low noise experimental setup with cryogenic amplification.
static electrotherm domains (hotpots).\textsuperscript{16} In this approach, the resistive region is formed due to interaction of the initial resistive area with the current flowing into the stripe; its dynamics should be controlled by the interplay between the hotspot thermalization and heating by Joule effect. This depends on the circuit temporal response; our preliminary calculations predict that the resistive region lifetime should be of the order of 50 ps for a total device inductance of 5 nH.

The resistive state nature is still not completely understood, and alternative models exist, involving photoinduced vortex-antivortex pair unbinding process.\textsuperscript{17} Using the qualitative formula for the vortex velocity $v_{vortex} = \rho v E^2 / 2 \pi \Phi_0$, with $\Phi_0$ the flux quantum, one can estimate the corresponding characteristic lifetime as $\tau = w / v_{vortex} = 15$ ps, where $w$ is the width of the stripe.\textsuperscript{18} This time may be prolonged due to vortex interactions with pinning centers and quasiparticles. At present, further investigation in the ultrafast detection dynamics is required to elucidate this point.

In conclusion, we have introduced a parallel structure design of SSPD, which allows for ultrashort detection response while maintaining a high quantum efficiency. This breakthrough opens the way to count rates over 1 GHz and makes SSPDs very appealing detectors, especially for long range telecommunications secured by quantum cryptography.

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