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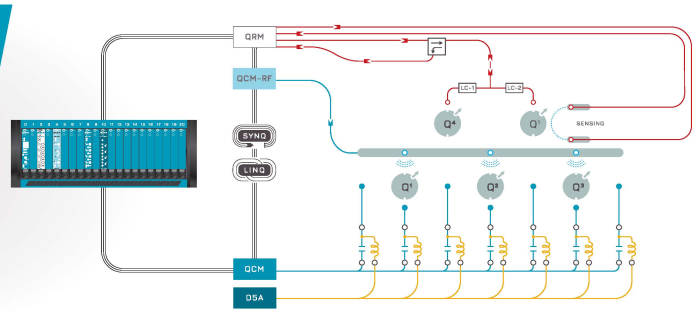

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ABSTRACT

Detector timing jitter is a key parameter in advanced photon counting applications. Superconducting nanowire single-photon detectors offer the fastest timing jitter in the visible to telecom wavelength range and have demonstrated single-photon sensitivity in the mid-infrared spectral region. Here, we report on timing jitter in a NbTiN nanowire device from 1.56 to 3.5 μm wavelength, achieving a FWHM jitter from 13.2 to 30.3 ps. This study has implications for emerging time-correlated single-photon counting applications in the mid-infrared spectral region.

Superconducting nanowire single-photon detectors (SNSPDs) have been developed over the past two decades to become the gold standard for time-resolved photon-counting applications.[1–4] They have demonstrated near unity quantum detection efficiency at 1.55 μm,[5–7] sub-3 ps timing jitter at short wavelengths,[8,9] and sub-Hz dark count rates.[10,11] Recently, there has been growing interest in extending the spectral range of these detectors into the mid-infrared,[12–14] where there is a lack of alternative photon-counting detector technologies.[15] This has been motivated by novel mid-infrared applications such as exoplanet spectroscopy,[16] fluorescence spectroscopy,[17] quantum optics,[18,19] and light detection and ranging (LIDAR).[20–22] The timing resolution of the detector is of particular importance for LIDAR, as it directly impacts the integration time for a given signal-to-noise ratio and for optical quantum information applications such as quantum key distribution where it impacts the quantum bit-error rate and range.[23,24] Moving to the mid-infrared offers potential advantages for these applications due to the presence of atmospheric transparency windows[25] and lower solar background flux[26] when compared to shorter wavelengths. Therefore, development of a low jitter single-photon detector at mid-infrared wavelengths is a task of increasing importance.

Timing jitter, the variation in timing of the output pulse for a periodic source of incident photons, is an important metric in time-correlated single-photon counting (TCSPC)[27,28] and is governed by the experimental setup and device physics.[29] Since the fundamental limits of timing jitter were probed,[8] development of SNSPDs with novel configurations and improved readout electronics has enabled the reduction in the timing jitter to 10 ps in devices with high detection efficiency.[30] The large majority of this work, however, has been performed at wavelengths in the near-infrared or shorter. In our present study, we characterize the timing jitter of a NbTiN SNSPD at wavelengths from 1.56 to 3.5 μm.

The SNSPD chosen for this experiment was a NbTiN nanowire fabricated from a 5 nm thick sputtered NbTiN thin film with R_{sheet} of 880 Ω/sq. and a T_c of 7.0 K. A short straight nanowire with a width of 100 nm and a length of 21 μm was fabricated by electron beam lithography and reactive-ion etch. Short dimensions were chosen to remove the majority of the geometric jitter[31] and increase the chances of constriction-free fabrication. A wide meander section was added after the nanowire to add inductance and prevent latching.[32] The SNSPD was mounted in a ^{4}He sorption refrigerator (Chase Research Cryogenics) and cooled to 900 mK. ZrF_4 mid-infrared optical fiber (single mode from 2.3 to 4.1 μm) was used to couple light from an optical parametric oscillator (OPO, Chromacity Ltd—ps pulses at 110 MHz repetition rate) to the device. The device was flood illuminated by placing the end of the optical fiber 2 cm from the device, thus ensuring even illumination over the active area. As the mid-infrared idler output from the OPO is broadband, narrow bandpass filters were used to select the wavelength of interest. Filters with center wavelengths of 2328 ± 15, 2790 ± 50, 3010 ± 15, and 3500 ± 15 nm were used to pickoff the four wavelengths of interest—more details of this are given in the supplementary material. A sync signal was obtained by using the shorter-wavelength OPO signal output by attenuating it and connecting it to a fast photodiode (Thorlabs DXM30AF). SNSPD output pulses were readout with a cryogenic amplifier (Cosmic Microwave CITLF1) mounted inside the cryostat on the 4K plate and a LNA (RF Bay LNA-1000) at room temperature. Jitter histograms were acquired with a Becker & Hickl TCSPC card (SPC-150NXX).

The photon count rate (PCR) curves were obtained for the SNSPD at all of the wavelengths tested and are shown in Fig. 1. For each wavelength, the output power of the OPO was adjusted by misaligning the output coupler to achieve a count rate of 4 kcps. As can be seen from Fig. 1, saturated internal detection efficiency was observed at all wavelengths. The slight slope in the PCR curves in the saturated region can be attributed to inhomogeneities along the length of the wire, leading to an absorption position-dependent saturation level[33] and photon absorption in the tapered ends of the detector. From the PCR curves, we selected a bias point of 8.6 μA for the jitter measurements where all wavelengths are saturated, as shown in Fig. 1.

Jitter histograms were taken by connecting the output of the SNSPD and amplifier chain to the input of the TCSPC card and the output of the photodiode to the sync channel. As the power level of the OPO signal output (connected to photodiode) changed when the idler wavelength was tuned, a programmable optical attenuator was used to match the photodiode photocurrent for each measurement.

The count rate of the SNSPD was again kept to 4 kcps using the idler output coupler for each measurement. Histograms were integrated for 600 s and the results for the mid-infrared wavelengths are shown in Fig. 2. For each histogram, an exponentially modified Gaussian fitting was performed to account for the non-Gaussian tail observed in the histograms.[34] This provides a good fit to the data for obtaining full-width at half-maximum (FWHM) jitter values although it deviates from the data at longer timescales. This is partially due to detection in the tapered sections of the nanowires (where it transitions to the inductor portion) and partially due to the modified Gaussian

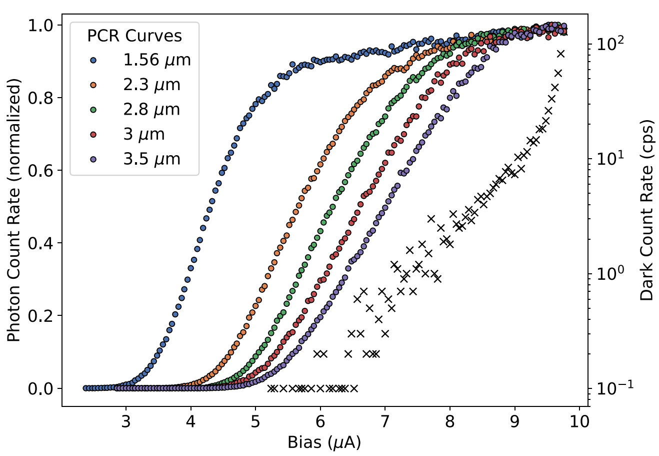

FIG. 1. Normalized photon count rate (PCR) curves for wavelengths of 1.56, 2.3, 2.8, 3, and 3.5 μm. The dark count rate is shown in black ×'s on the right y-axis.

not being expected to fit the true jitter histogram according to current models.[8] FWHM jitter values are obtained from the fitting and give results of 18.3 ps for 2.3 μm photons, 23.0 ps for 2.8 μm photons, 25.4 ps for 3 μm, and 30.3 ps for 3.5 μm photons.

In order to obtain a reference jitter value, a measurement was taken at 1.56 μm with a 1.56 μm fiber laser (0.5 ps pulses at a repetition rate of 50 MHz). This gave a good reference as much of the reported work on SNSPD timing jitter is performed at this wavelength. A FWHM value of 16 ps was observed. It is important to note that the ZrF_4 optical fiber is not single-mode for this wavelength and multimode behavior is expected below 2.3 μm wavelength. It is reasonable to expect that modal dispersion effects will broaden the timing jitter histogram for this wavelength.[35] A comparison measurement was made by swapping the ZrF_4 fiber for the SMF-28 optical fiber. Using this setup, a FWHM jitter value of 13.2 ps was obtained. This is discussed in more detail in the supplementary material.

The jitter histograms shown in Fig. 2 and the FWHM jitter values obtained show an increasing timing jitter as wavelength increases and photon energy decreases. This data is shown in Fig. 3. The scaling of jitter with photon wavelength agrees with other published results.[8,36] The complex nature of the energy downconversion process, however, means that absolute timing jitter is dependent on many factors, such as absolute bias current, fraction of depairing current achieved, and electrical readout characteristics. Therefore, a close comparison of absolute values has limited merit, but the general trend we observe of increasing jitter values at increasing mid-infrared wavelengths continues the trend reported at shorter wavelengths in other work.

Qualitatively, the increase in the timing jitter as photon energy decreases can be explained by Fano fluctuations[37] and the detector latency concept.[29] The energy (E) deposited by the absorbed photon fluctuates as $\sqrt{E}$ due to Fano fluctuations and the escape of high energy phonons during the downconversion process.[37] This variation can be translated into the jitter with the model of an energy-dependent deterministic latency ($\tau_{lat}(E)$). This latency increases as photon energy decreases [see Fig. 7 in Ref. 29 or Fig. 5(b) in Ref. 38], but the shape of the function is dependent on the underlying physics of the detection process. From this function, however, it is evident that fluctuations in E lead to corresponding fluctuations in τ_{lat} and hence jitter. A steep τ_{lat} vs E curve will result in a large variation in τ_{lat} for a small variation in E and hence a large timing jitter value. Determining the exact form of τ_{lat} curve that matches all available experimental data is still an ongoing area of research, but progress has been made in recent years, both experimentally[8] and theoretically.[29,38,39] This work provides additional experimental data points further into the mid-infrared than previously available to aid in model refinement.

The jitter histograms for 2.3, 2.8, and 3 μm shown in Fig. 2 all have an expected shape, that is, a Gaussian with an elongated tail. The 3.5 μm histogram, however, exhibits a secondary peak occurring in the earlier time bins before the main peak. We believe that this is due to an optical reflection within the cavity of the OPO. As we change the cavity length in order to tune the output spectrum (by moving a mirror inside), we observe that this secondary peak shifts in time with respect to the primary peak. This is observable in the full measurement timescales for the 2.8 and 3 μm histograms as well but is sufficiently far away as to be easily gated out for the fitting procedure. For the 3.5 μm wavelength measurement, it is positioned close to the main

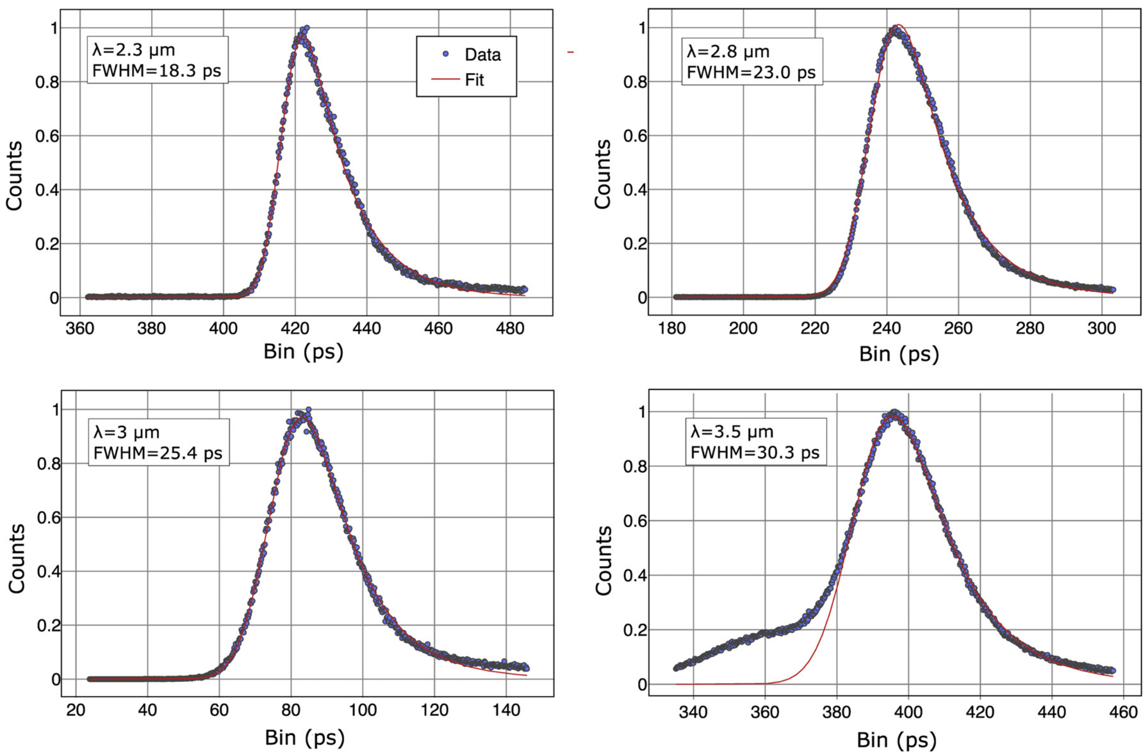

FIG. 2. Normalized timing jitter histograms (instrument response functions) for wavelengths of 2.3, 2.8, 3, and 3.5 μm. The exponentially modified Gaussian fit is shown in red and the FWHM value is derived from this.

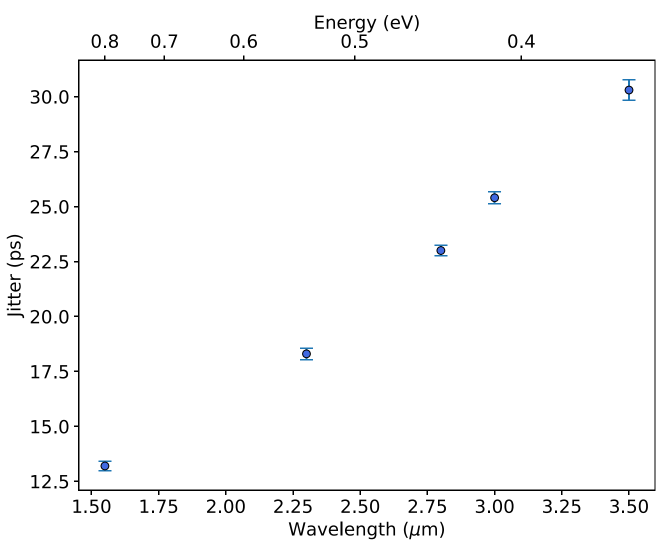

FIG. 3. FWHM jitter against wavelength (bottom y-axis) and photon energy (top y-axis). The measured wavelengths (energies) are 1.56 (0.79 eV), 2.3 (0.53 eV), 2.8 (0.44 eV), 3 (0.41 eV), and 3.5 μm (0.35 eV). The error bars are obtained from the 95% confidence intervals on the exponentially modified Gaussian fit. Note that the 1.56 μm data point was obtained with SMF-28 fiber to account for modal dispersion in the ZrF_4 fiber.

peak but not, we believe, close enough to adversely affect the fitting and extraction of the FWHM jitter values. We have fitted the secondary peak in the 3 μm measurement with an exponentially modified Gaussian to confirm that it is the same shape and comparable FWHM to the main peak. We have observed similar multi-peak effects when stacking optical filters in other experiments.

In this work, we have systematically studied the variation of timing jitter as photon energy decreases into the mid-infrared in a NbTiN SNSPD. By utilizing the same device and electrical readout for each measurement, we were able to directly quantify the effect of photon energy on the timing jitter for a given device. We conclude that low SNSPD timing jitter values are easily obtainable into the mid-infrared. Extrapolating the linear trend we have observed here out to 3.5 μm wavelength, we can infer that it should be possible to achieve jitter in the tens of picoseconds range for photons at even longer wavelengths. As with low-jitter devices at 1.55 μm, ensuring highly uniform fabrication to obtain high fractions of the depairing current[40] and employing architectures, such as differential tapered readout,[30] will ensure that timing jitter is minimized for a given photon energy.

This work is an important milestone in the development of SNSPDs for mid-infrared TCSPC applications. In the future, efficient single-photon detection with low jitter in the mid-infrared will enable a variety of novel applications, such as imaging, sensing, and communications, where alternative single-photon detection technologies cannot currently compete.

See the supplementary material for details and characterization of the optical filters and multi-mode dispersion calculations.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Gregor Gibson Taylor: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Writing – original draft (equal). **Ewan Newell MacKenzie:** Data curation (equal); Formal analysis (equal); Writing – review & editing (equal). **Boris Korzh:** Conceptualization (equal); Resources (equal); Writing – review & editing (equal). **Dmitry V. Morozov:** Data curation (equal); Writing – review & editing (equal). **Bruce Bumble:** Resources (equal). **Andrew Beyer:** Resources (equal); Writing - review & editing (equal). **Jason Allmaras:** Formal analysis (equal); Resources (equal); Writing – review & editing (equal). **Matthew D. Shaw:** Conceptualization (equal); Supervision (equal); Writing – review & editing (equal). **Robert H. Hadfield:** Conceptualization (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data supporting the findings of this study will be available via the University of Glasgow Enlighten research data management online repository.

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