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Multi-pulse fitting of transition edge sensor signals from a near-infrared continuous-wave source

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Transition-edge sensors (TESs) are photon-number resolving calorimetric spectrometers with near unit efficiency. Their recovery time, which is on the order of microseconds, limits the number resolving ability and timing accuracy in high photon-flux conditions. This is usually addressed by pulsing the light source or discarding overlapping signals, thereby limiting its applicability. We present an approach to assign detection times to overlapping detection events in the regime of low signal-to-noise ratio, as in the case of TES detection of near-infrared radiation. We use a two-level discriminator, inherently robust against noise, to coarsely locate pulses in time and timestamp individual photoevents by fitting to a heuristic model. As an example, we measure the second-order time correlation of a coherent source in a single spatial mode using a single TES detector. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5053834>

I. INTRODUCTION

Transition-edge sensors (TESs) are wideband photon-number resolving light detectors that can be optimized for high quantum efficiency (>98%) and to work in different regions of the electromagnetic spectrum, from gamma-rays to telecom wavelengths.^{1–3} Their high single photon detection efficiency in the optical band was instrumental in one of the recent loophole-free experimental violations of Bell's inequality.⁴ Absorption of a single photon by the TES generates an electric pulse response with a fast (tens of nanoseconds) rising edge and a relaxation with a time constant of a few microseconds.⁵ Photodetection events with time separation shorter than the pulse duration overlap and cannot be reliably identified by threshold crossing. To avoid this problem, TES is often used with pulsed light sources with a repetition rate lower than few tens of kilohertz.⁶ This may exclude the use of TES with superb detection efficiencies from some applications. Therefore, in this work, we investigate the time discrimination for overlapping signal pulses using a continuous-wave (CW) light source.

Similar problems are common in high-energy physics.^{7–11} Fowler *et al.*¹¹ improved time discrimination by considering the time derivative of the signal to locate the steep rising edge of individual photodetection events. In cases with high signal-to-noise ratio, such as in the detection of high-energy photons γ and X-rays (SNR \approx 260, estimated from Ref. 11), this approach is effective also when signals overlap. However, for near-infrared (NIR) photodetection with a TES, it is necessary to filter high frequency noise components to improve the signal-to-noise ratio (SNR \approx 2.4, estimated from Ref. 5) at the expense of a reduced timing accuracy.

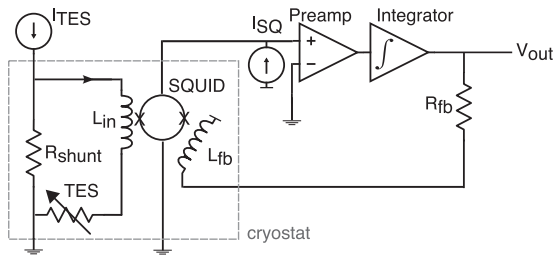
We approach the problem by separating it into two distinct phases: an initial event identification, followed by a more accurate timing discrimination. We identify photodetection events using a two-level discriminator. Its resilience to noise allows us to coarsely locate both isolated and overlapping pulses with a moderate use of filtering, thus retaining some of the high frequency components of the signal, useful to improve the time accuracy of subsequent operations. For monochromatic sources, every detection event has the same energy. We can then estimate the number of photons for every detection region from the total pulse area, identifying the cases of overlapping events. From the number of photons, we calculate a heuristic model function and fit it to the signal to recover the detection-times.

II. ELECTRONICS AND PHOTON DETECTION PULSE

Our tungsten-based TES¹² is kept at a temperature of 75 mK using an adiabatic demagnetization refrigerator cryostat and is voltage biased within its superconducting-to-normal transition in a negative electro-thermal feedback.¹³ The detection signal is inductively picked up and amplified by a SQUID series array, followed by further signal conditioning at room temperature with an overall amplification bandwidth of \approx 6 MHz. A schematic of the TES biasing and readout electronics is shown in Fig. 1. We operate the SQUID in a flux-locked loop¹⁴ to minimize low frequency components of the noise. To characterize the TES response, we use a laser diode centered at 810 nm as a light source, operated in CW mode. We control the average photon flux with a variable attenuator, then launch the light into a fiber (type SMF28e¹⁵) that directs it to the sensitive surface of the TES.

We record 10 μ s long traces with a sampling rate of 5×10^8 s⁻¹ and a 12 bit voltage resolution. For light at 810 nm,

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83 FIG. 1. Schematic of the TES biasing and readout electronics. The TES is
 84 voltage-biased by a constant current source I_{TES} through shunt resistor R_{shunt}
 85 $\ll R_{TES}$. The SQUID array amplifier picks up changes in TES resistance from
 86 L_{in} . The signal is further amplified outside the cryostat. Signal feedback via
 87 R_{fb} and coil L_{fb} linearizes the SQUID response.

88 the signal generated by discrete absorption processes for each
 89 photon after the amplifier chain exhibits a rise time for a single
 90 photon pulse of about 100 ns and an overall pulse duration of
 91 about 2 μ s.

92 We collected a total of 4×10^5 traces with the TES con-
 93 tinuously illuminated by an attenuated laser diode. Despite the
 94 flux-locked loop, we observe a residual voltage offset variation
 95 from trace to trace. Therefore, for every recorded pulse trace
 96 $v_{rec}(t)$, we remove the residual baseline,

$$97 \quad v(t) = v_{rec}(t) - V_M, \quad (1)$$

98 where V_M is the most frequently occurring value of the
 99 discretized signal $v_{rec}(t)$ over the sampling interval.

100 III. PULSE IDENTIFICATION

101 In the first step, we identify the presence of an absorption
 102 process from one or more photons in a trace and distinguish it
 103 from background noise. This is done by a traditional Schmitt
 104 trigger mechanism,¹⁶ implemented via discriminators at two
 105 levels: a qualifier flag is raised when the signal passes threshold
 106 V_{high} [Fig. 2(a), point A] and lowered by the first subsequent
 107 crossing of threshold V_{low} (point B).

108 In order to minimize the number of false events, we esti-
 109 mate V_{high} using a histogram of maximum pulse heights for
 110 4×10^4 traces, as shown in Fig. 3. The distribution has two
 111 distinct peaks, with one around 5 mV corresponding to traces
 112 without any detection event ($n = 0$) and another one starting
 113 from 9.5 mV onwards corresponding to traces with at least
 114 one detection event ($n > 0$). We choose V_{high} to the minimum
 115 between the two peaks (9.5 mV) and V_{low} to 0 mV.

116 We estimate a timing accuracy for single photon events⁵
 117 of $\sigma/(dv/dt) \approx 16$ ns, from the RMS noise $\sigma = 1.75$ mV, and the
 118 steepest slope of the response $dv/dt = 0.11(9)$ mV/ns (from the
 119 average of the 10%-90% transitions of an ensemble of pulses).
 120 However, a simple threshold detection of the leading edge does
 121 not work if pulses start to overlap.

122 More precise timing information of a photodetection event
 123 is obtained from a least square fit to the signal using a dis-
 124 placed standard pulse. To efficiently initialize this fit, we do
 125 not directly use the qualifier window AB for two reasons: first,
 126 it contains only a fraction of the leading edge belonging to
 127 the earlier pulse that contains most of the timing information,
 128 and second, it includes a large portion of the decaying tail

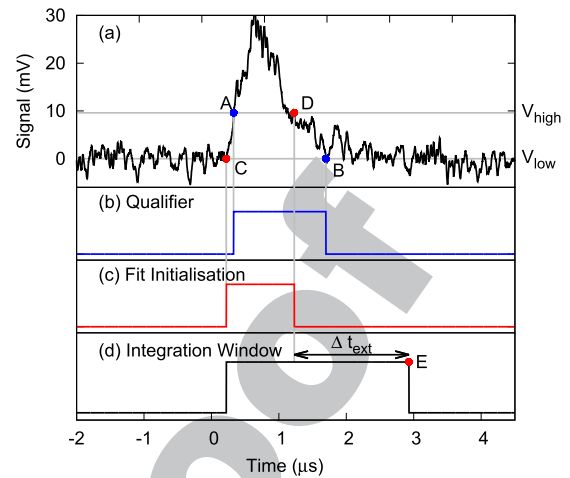


FIG. 2. (a) Typical TES response with overlapping pulses. The horizontal
 lines show the high and low threshold settings of the Schmitt trigger me-
 chanism. (b) Qualifying interval AB identified by the Schmitt trigger. (c) The
 interval CD includes the rising edges of the overlapping pulses and is used to
 initialize a least-square fit. (d) The wider interval CE that includes the rising
 edge and decaying tail is used to estimate the number of photons associated
 with the event. We empirically found a reasonable energy resolution with point
 E obtained by extending interval CD by $\Delta t_{ext} = 1700$ ns.

unassociated with the onset of photodetection. The time win-
 dow CD derived from the same discriminator levels ensures
 the inclusion of the first leading edge and is also shorter.

Similarly, we derive an integration time window from the
 qualifier window to determine the pulse integral, from which
 we extract the photon number of a quasi-monochromatic light
 source. As a starting point, we choose point C for the inte-
 gration to capture the rising slope of a pulse and extend the
 time D by a fixed amount Δt_{ext} to point E to capture the tail
 of the response signal [Fig. 2(d)]. We found that it is more
 reliable to extend point D by a fixed time to capture the tail
 of the signal rather than to reference the end of the integra-
 tion window to point B. This is because the signal-to-noise ratio
 around B is low, leading to a large variation of integration
 times. We empirically find that $\Delta t_{ext} = 1700$ ns gives a good
 signal-to-noise ratio of the pulse integral.

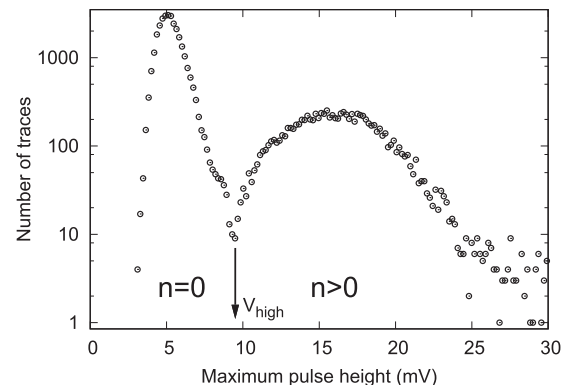


FIG. 3. Histogram of maximum pulse heights for 4×10^5 traces. The two
 distributions correspond to traces with ($n > 0$) and without ($n = 0$) photo-
 detection events. We use the minimum between the two distributions to set the
 threshold V_{high} of the discriminator.

IV. PHOTON NUMBER DISCRIMINATION

To determine the number of photons in each trace, we assume that the detection and subsequent amplification have a linear response so that the integral of each signal is proportional to the absorbed energy,¹⁷ resulting in a discrete distribution of the areas of the signals. This distribution is spread out by noise, and we have to use an algorithm to extract the photon number in presence of this noise.

For this, we first compute the pulse area $a = \int_{t_C}^{t_E} |v(t)|$ for every qualified trace within region CE. Figure 4 shows a histogram of pulse areas from the qualified traces out of all 4×10^5 acquired. The distribution shows three resolved peaks that suggest having been caused by $n = 1, 2, 3$ photons being absorbed by the TES.

One can fit the histogram in Fig. 4 to a sum of three normalized Gaussian peaks $g_n(a; a_n, \sigma_n)$,

$$H(a) = \sum_{n=1}^3 h_n g_n(a|a_n, \sigma_n), \quad (2)$$

where each Gaussian peak is characterized by an average area a_n and width σ_n . The ratio $a_2/a_1 = 1.95$ indicates that the TES response to photon energies of 1 and 2 photons is approximately linear.

We identify thresholds $a_{n-1,n}$ as the values that minimize the overlap between distributions $g_{n-1}(a|a_{n-1}, \sigma_{n-1})$ and $g_n(a|a_n, \sigma_n)$. With this, we assign a number of detected photons n by comparing the area of every trace to thresholds $a_{n-1,n}$ and $a_{n,n+1}$.

The continuous nature of the light source with a fixed power level makes it difficult to assign a number of photons per qualified signal, as the integration window varies from pulse to pulse, and detection events may occur at random times in the respective integration windows. Heuristically, however, one could even replace the individual event numbers h_n in Eq. (2) by a Poisson distribution,

$$h_n = Np(n|\bar{n}), \quad (3)$$

where \bar{n} is an average photon number, $p(n|\bar{n})$ the Poisson coefficient, and N is the total number of traces. For the data shown

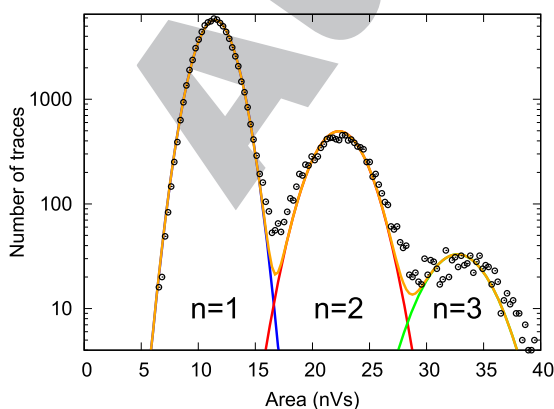


FIG. 4. Distribution of pulse areas $H(a)$. For every trace that triggers, the two-level discriminator, the area is calculated within the region CE. The continuous lines are Gaussian fits for the $n = 1$ (blue), $n = 2$ (red), and $n = 3$ (green) area distributions and their sum (orange).

in Fig. 4, this would lead to an average photon number of $\bar{n} \approx 0.3$ per integration time interval.

V. DETERMINING THE DETECTION-TIMES OF OVERLAPPING PULSES

The difficulty of assigning a photon number to light detected from a CW source can be resolved if one treats the first detection process of light following the paradigm of wideband photodetectors in quantum optics.¹⁸ As TES are sensitive over a relatively wide optical bandwidth, the corresponding time scale of the absorption process is much shorter than the few microseconds of the TES thermal recovery.¹⁹ Then, the signal would correspond to a superposition of responses to individual absorption processes, which may happen at times closer than the characteristic pulse time.

To recover absorption times of individual absorption events in a trace of N overlapping pulses, where N is determined with the pulse area method outlined in Sec. IV, we fit the TES response signal $v(t)$ to a heuristic model $v_N(t)$ of a linear combination of single-photon responses $v_1(t)$,

$$v_N(t|\{t_i, A_i\}) = \sum_{i=1}^N A_i v_1(t - t_i), \quad (4)$$

where A_i is the amplitude and t_i is the detection time of the i th pulse. While the TES response to multi-photon events is not strictly linear, this model will give a reasonably good estimation of the timing for single photon absorption events.

A. Single photon pulse model

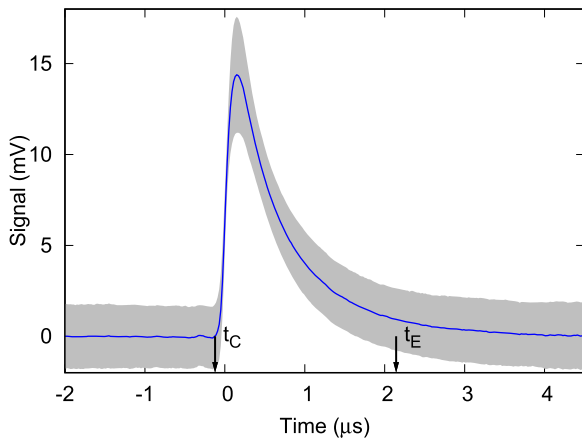
We obtain a model for the single photon response $v_1(t)$ of the TES and its signal amplification chain for the fit in Eq. (4) by selecting $N_1 = 10^4$ single photon traces from the measurement shown in Fig. 4 and averaging over them. The averaging process eliminates the noise from individual traces and retains the detector response.

Signal photon events can happen at any time within the sampling window. It is necessary to align these detection events to average the traces. We assign a detection time to the i th trace $v_1^{(i)}(t)$ by recording the time t_i corresponding to the maximum of $dv_1^{(i)}(t)/dt$. We use a Savitzky-Golay filter (SGF) to reduce the high frequency components;²⁰ the SGF replaces every point with the result of a linear fit to the subset of adjacent 41 points.

We also reject clear outlier traces by limiting the search for t_i to the time interval CD. The remaining N_1 traces are then averaged by synchronizing them according to their respective t_i and to obtain the single-photon response $v_1(t)$,

$$v_1(t) = \frac{1}{N_1} \sum_{i=1}^{N_1} v_1^{(i)}(t + t_i). \quad (5)$$

The result is shown in Fig. 5, together with a noise interval derived from the standard deviation of N_1 single photon traces. The model demonstrates an average rise time of 116 ns from 10% to 90% of its maximum height. The relaxation time ($1/e$) of 635 ns corresponds to detector thermalization.²¹



246 FIG. 5. Solid line: average response of the TES and amplification to a single
247 absorption. We use a Schmitt trigger to identify the region between t_C and t_E .
248 Gray region: one standard deviation in the observed ensemble of $n = 1$ traces.

249 B. Time-tagging via least-square fitting

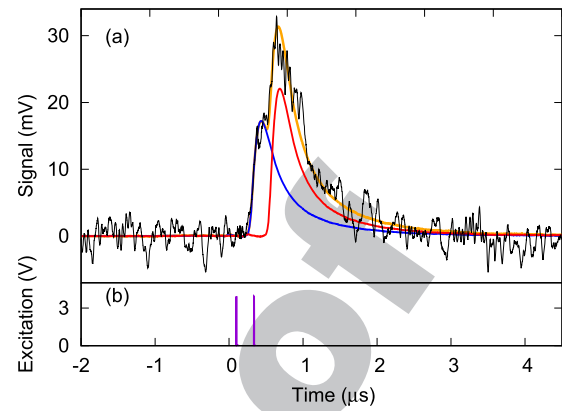
250 For every qualified trace, we assign a number of photons
251 N according to the calculated area, and fit it using Eq. (4). The
252 fit has $2N$ free parameters: detection times t_i and amplitudes
253 A_i , with $i = 1, \dots, N$. We bound t_i to the range CD [Fig. 2(c)]
254 and restrict the sum of A_i to be consistent with the thresholds
255 obtained from the area distribution,

$$256 \frac{a_{N-1,N}}{\int_{t_C}^{t_E} |v_1(\tau)| d\tau} \leq \sum_{i=1}^N A_i \leq \frac{a_{N,N+1}}{\int_{t_C}^{t_E} |v_1(\tau)| d\tau}. \quad (6)$$

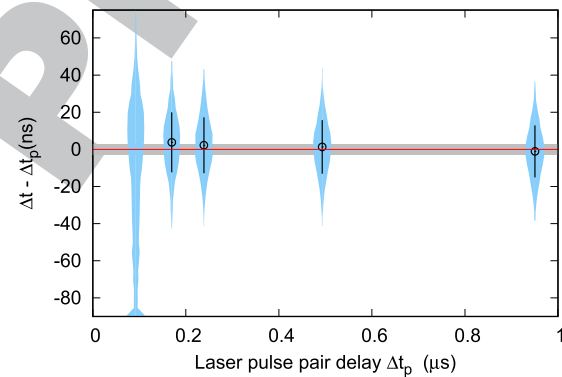
257 The accuracy of the fit depends on the choice of the minimiza-
258 tion algorithm. We used Powell's derivative-free method²²
259 because the presence of noise tends to corrupt gradient
260 estimation.²³

261 To verify the accuracy of the fitting algorithm for $N = 2$,
262 we expose the TES to pairs of short (4 ns) laser pulses with
263 a controlled delay Δt_p . The 100 kHz repetition rate is low
264 enough to isolate the TES response between consecutive laser
265 pulse pairs. Selecting only the traces with two photons, we
266 have two possible cases: (i) a two-photon event generated
267 within one of the 4 ns pulses or (ii) one photon in each pulse.
268 We compared the TES response for five different delays Δt_p :
269 92 ns, 170 ns, 239 ns, 493 ns, and 950 ns. Figure 6 shows an
270 example of a measured trace where the fitting algorithm was
271 able to distinguish between separate photodetection events at
272 $\Delta t_p = 239$ ns even though it appears to be a single event because
273 of the detector noise. For each delay, we collected $\approx 3.5 \times 10^5$
274 traces, and for each trace, we estimate the photodetection times
275 using the least-square method. In Fig. 7, we summarize the
276 distribution of time differences $\Delta t = |t_2 - t_1|$ for each delay.

277 Except for the shortest pulse separation, the time differ-
278 ences have Gaussian distributions with standard deviations of
279 about 16 ns. This matches the time accuracy expected from the
280 simple noise/slope estimation for the leading edge of the single
281 photon pulse (see Sec. III), despite the overlapping pulses. The
282 average separation between the center of the distribution and
283 the expected result, $\Delta t - \Delta t_p$, is 2(2) ns. For $\Delta t_p = 92$ ns,
284 the distribution is clearly skewed toward 0 ns. This multi-
285 modal distribution indicates that the fit procedure is unable to



286 FIG. 6. (a) Fit of a two-photon signal with the heuristic function described in
287 the main text. Black line: measured TES response after removing the vertical
288 offset. Orange line: fit to Eq. (4), with two single photon components separated
289 in time (blue and red lines). (b) Electrical pulse pair separated by 239 ns sent
290 to the LD illuminating the TES.



291 FIG. 7. Difference between the detection-time separations estimated with the
292 fitting technique (Δt) and the delay of laser pulse pairs (Δt_p) for five different
293 delays: 92 ns, 170 ns, 239 ns, 493 ns, and 950 ns. Blue regions: distribution
294 of $\Delta t - \Delta t_p$. Gray region: expected range of separation for 90% of single
295 photon detections for 4 ns long laser pulse pairs. Black circles: mean of the
296 distributions with error bars corresponding to one standard deviation.

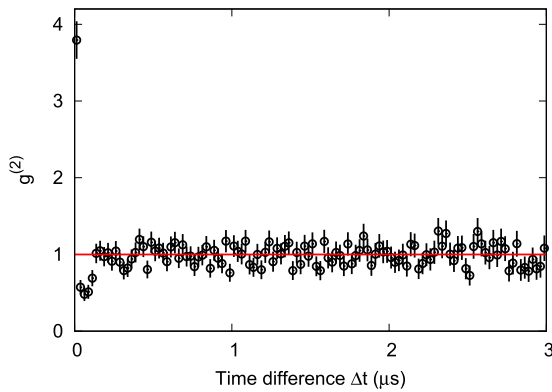
297 distinguish two single-photon events generated by the two sep-
298 arated diode pulses from two-photon events generated within
299 the same diode pulse.

300 VI. DETECTION-TIME SEPARATION 301 FROM COHERENT SOURCE

302 To examine the accuracy of the fitting technique over a
303 continuous range of time differences Δt , we extract the normal-
304 ized second order correlation function $g^{(2)}(\Delta t)$ for detection
305 events recorded with a single TES from a coherent light field.
306 This correlation function should be exactly 1 for all time
307 differences Δt .¹⁸

308 For this, the TES is exposed to light from a continu-
309 ously running laser diode, with an average photon number
310 of about 0.3 per integration interval of around 3 μ s. Again, we
311 select only two-photon traces using the methods described in
312 Sec. IV and fit the traces to the model described by Eq. (4)
313 with $N = 2$.

314 Each fitted trace leads to two time values t_1 and t_2 ,
315 which we sort into a frequency distribution $G^{(2)}(\Delta t)$ of time



316 FIG. 8. Normalized second order correlation function $g^{(2)}(\Delta t)$ for events
 317 recorded with a single TES from a coherent light field. Error bars indicate
 318 one standard deviation assuming Poissonian statistics, the bin size is 25 ns.
 319 Solid line: expected correlation for a coherent field.

320 differences $\Delta t = t_2 - t_1$. We normalize this distribution with
 321 the distribution expected for a Poissonian source, taking into
 322 account the finite time of our acquisition windows. We remove
 323 single-photon traces mis-identified as two-photon traces by
 324 filtering out traces that have a minimum estimated amplitude
 325 smaller than one half of a single photon pulse.

326 The resulting normalized distribution $g^{(2)}(\Delta t)$ is shown in
 327 Fig. 8. For $\Delta t > 150$ ns, the correlation function is compatible
 328 with the expected value of 1. For shorter time differences, the
 329 fit algorithm occasionally locks on the same detection times
 330 t_1 and t_2 , redistributing pair events to $\Delta t = 0$, resulting in a cal-
 331 culated correlation then deviates from the expected behavior,
 332 including the unphysical value $g^{(2)}(\Delta t = 0) > 2$. This insta-
 333 bility region ($\Delta t < 150$ ns) is comparable with the rise time
 334 of the average single-photon pulse and is consistent with the
 335 precision indicated in Fig. 7.

336 VII. CONCLUSION

337 We demonstrated a signal processing method based on a
 338 Schmitt-trigger based data acquisition and a linear algorithm
 339 that can reliably extract both a photon number and photode-
 340 tection times from the signal provided by an optical Transition
 341 Edge Sensor (TES) with an accuracy that is mostly limited by
 342 the detector time jitter.

343 Using this method, we successfully resolved between
 344 $n = 1, 2$, and 3 photons from a CW NIR source, using the
 345 signal integral evaluated in the time interval identified by the
 346 discriminator. The time interval includes a greater fraction of
 347 the photodetection signal than that considered by a single-
 348 threshold discriminator. By considering an optimal fraction of
 349 the pulse profile, we obtained pulse integral distributions that
 350 sufficiently resolve between photon numbers. We note that the
 351 maximum pulse height is unsuitable for photon number dis-
 352 crimination of a CW source since the maximum height depends
 353 on the photodetection times when pulses are overlapped. This
 354 is evident in Fig. 3. By contrast, Fig. 4 shows that $n = 1, 2$,
 355 and 3 photon events are well resolved using the pulse integral,
 356 which does not depend on photodetection times. Although we
 357 do not demonstrate photon number resolution for $n > 3$, tran-
 358 sition edge sensors can resolve $n > 10$ photons from pulsed

359 sources.²⁴ We expect a similar extension to be possible for CW
 360 sources.

361 This technique provides an alternative to photon counting
 362 using edge detection on the differentiated signal¹¹ when the
 363 signal-to-noise ratio is low.

364 The discriminated region is then used to initialize a least-
 365 squares fit of a signal containing two overlapping pulses to
 366 a two-photon model, returning the amplitudes and detection-
 367 times of the individual photons.

368 With the available TES, we can distinguish two photode-
 369 tection events within about 150 ns using this method. The
 370 highest detection rate that can be processed is thus estimated
 371 to be about $6.7 \times 10^6 \text{ s}^{-1}$, compared to about $4.0 \times 10^5 \text{ s}^{-1}$ if
 372 we were to discard overlapping pulses.

373 Potential applications include the measurement of time-
 374 resolved correlation functions using the TES without the need
 375 for the spatial multiplexing of several single-photon non-
 376 photon-number resolving detectors, provided that the coher-
 377 ence time of the light source is larger than the timing resolution
 378 of this technique. The order of the correlation function mea-
 379 sured is limited only by the maximum number of photons
 380 resolvable by the TES.

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389 ¹A. E. Lita, B. Calkins, L. A. Pellouchoud, A. J. Miller, and S. W. Nam, *Proc.*
 390 *SPIE* **7681**, 76810D (2010).

391 ²D. Fukuda, G. Fujii, T. Numata, K. Amemiya, A. Yoshizawa, H. Tsuchida,
 392 H. Fujino, H. Ishii, T. Itatani, S. Inoue, and T. Zama, *Opt. Express* **19**, 870
 (2011).

393 ³S. Hatakeyama, M. Ohno, H. Takahashi, R. M. T. Damayanthi, C. Otani,
 394 T. Yasumune, T. Ohnishi, K. Takasaki, and S. Koyama, *J. Low Temp. Phys.*
 395 **176**, 560 (2014).

396 ⁴M. Giustina, M. A. M. Versteegh, S. Wengerowsky, J. Handsteiner,
 397 A. Hochrainer, K. Phelan, F. Steinlechner, J. Kofler, J.-A. Larsson,
 398 C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, J. Beyer, T. Gerrits,
 399 A. E. Lita, L. K. Shalm, S. W. Nam, T. Scheidl, R. Ursin, B. Wittmann, and
 400 A. Zeilinger, *Phys. Rev. Lett.* **115**, 250401 (2015).

401 ⁵A. Lamas-Linares, B. Calkins, N. A. Tomlin, T. Gerrits, A. E. Lita, J. Beyer,
 402 R. P. Mirin, and S. Nam, *Appl. Phys. Lett.* **102**, 231117 (2013).

403 ⁶Z. H. Levine, T. Gerrits, A. L. Migdall, D. V. Samarov, B. Calkins, A. E. Lita,
 404 and S. W. Nam, *J. Opt. Soc. Am. B* **29**, 2066 (2012).

405 ⁷S. Marrone, E. Berthomieux, F. Beevar, D. Cano-Ott, N. Colonna,
 406 C. Domingo-Pardo, F. Gusing, R. C. Haight, M. Heil, F. Käppler,
 407 M. Krtička, P. Mastinu, A. Mengoni, P. M. Milazzo, J. O'Donnell, R. Plag,
 408 P. Schillebeeckx, G. Tagliente, J. L. Tain, R. Terlizzi, and J. L. Ullmann,
 409 *Nucl. Instrum. Methods Phys. Res., Sect. A* **568**, 904 (2006).

410 ⁸F. Belli, B. Esposito, D. Marocco, M. Riva, Y. Kaschuck, and G. Bonheure,
 411 *Nucl. Instrum. Methods Phys. Res., Sect. A* **595**, 512 (2008).

412 ⁹M. Vencelj, K. Bučar, R. Novak, and H. J. Wörtche, *Nucl. Instrum. Methods*
 413 *Phys. Res., Sect. A* **607**, 581 (2009).

414 ¹⁰G. Tambave, E. Guliyev, M. Kavatsyuk, F. Schreuder, and H. Löhner,
 415 in *IEEE Nuclear Science Symposium Conference Record (IEEE, 2012)*,
 416 p. 2163.

417 ¹¹J. W. Fowler, B. K. Alpert, W. B. Doriese, D. A. Fischer, C. Jaye, Y. I. Joe,
 418 G. C. O'Neil, D. S. Swetz, and J. N. Ullom, *Astrophys. J., Suppl. Ser.* **219**,
 419 35 (2015).

420 ¹²A. E. Lita, A. J. Miller, and S. W. Nam, *Opt. Express* **16**, 3032
421 (2008).
422 ¹³K. D. Irwin, *Appl. Phys. Lett.* **66**, 1998 (1995).
423 ¹⁴D. Drung, C. Assmann, J. Beyer, A. Kirste, M. Peters, F. Ruede, and
424 T. Schurig, *IEEE Trans. Appl. Supercond.* **17**, 699 (2007).
425 ¹⁵Certain commercial equipment, instruments or materials are identified in
426 this report to foster understanding. Such identification does not imply rec-
427 ommendation or endorsement by the National Institute of Standards and
428 Technology, nor does it imply that the materials or equipment are necessarily
429 the best available for the purpose.
430 ¹⁶O. H. Schmitt, *J. Sci. Instrum.* **15**, 24 (1938).
431 ¹⁷B. Cabrera, R. Clarke, A. Miller, S. W. Nam, R. Romani, T. Saab, and
B. Young, *Physica B* **280**, 509 (2000).

¹⁸R. J. Glauber, *Phys. Rev.* **130**, 2529 (1963). 432
¹⁹T. Gerrits, A. E. Lita, B. Calkins, and S. W. Nam, *Superconducting Devices*
in Quantum Optics (Springer International Publishing, Cham, 2016), 433
pp. 31–60. 434
²⁰A. Savitzky and M. Golay, *Anal. Chem.* **36**, 1627 (1964). 435
²¹A. E. Lita, B. Calkins, L. A. Pellouchoud, A. J. Miller, and S. W. Nam, *Proc.*
SPIE **7681**, 76810D (2010). 436
²²M. J. D. Powell, *Comput. J.* **7**, 155 (1964). 437
²³V. P. Plagianakos and M. Vrahatis, *Combinatorial and Global Optimization*
(\blacksquare , 2002), pp. 283–296. 438
²⁴P. C. Humphreys, B. J. Metcalf, T. Gerrits, T. Hiemstra, A. E. Lita, J. Nunn,
S. W. Nam, A. Datta, W. S. Kolthammer, and I. A. Walmsley, *New J. Phys.*
17, 103044 (2015). 439
440
441
442
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