

Extending Single-Photon Optimized Superconducting Transition Edge Sensors Beyond the Single-Photon Counting Regime

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Photon number resolving transition-edge sensors (TES) are the cutting-edge enabling technology for high quantum efficiency photon number counting. The TES developed at NIST reliably show system detection efficiencies of more than 95%, and even approach 99% for individual detectors [1]. Recently, efforts to directly tying existing optical power measurements to measurements at the single-photon level are being considered by some metrology institutions around the world with the goal of better uncertainties. An initial step in this direction would be to explore how far existing detectors can be extended beyond their usual operating regimes. One promising candidate under consideration for connecting these two regions is the TES, as it functions as a microcalorimeter and is therefore able, in principle, to measure optical powers from the single-photon-regime to picowatt levels.

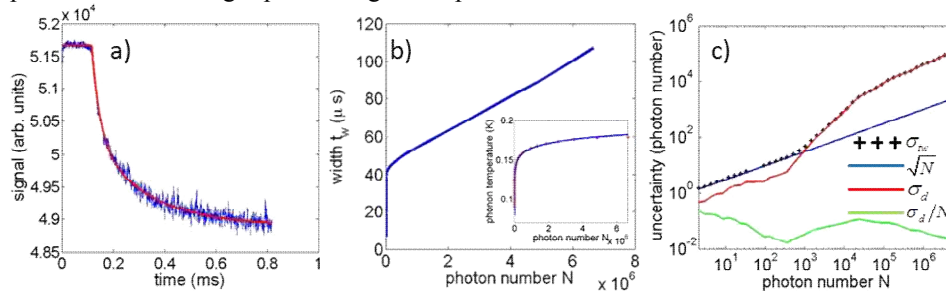


Fig. 1. a) TES temporal response after absorbing 10^6 photons. b) Fitted saturation time (temporal width) vs. input mean photon number; inset: phonon bath temperature as a function of input mean photon number. c) Uncertainties vs. input mean photon number; black crosses: total measured uncertainty; blue solid line: input state uncertainty; red solid line: inferred readout and detector uncertainty; green solid line: relative readout and detector uncertainty (σ_d/N)

We have tested a TES designed for single-photon counting in the regime far beyond the single-photon saturation point of the detector, *e.g.* $> 7 \cdot 10^6$ photons or 0.9 pJ in a single pulse of coherent laser light. The laser pulse repetition rate is 1 kHz. The detection efficiency of this detector is 94 %, optimized for a wavelength of 1550 nm. After ~ 10 photons, the TES passes from the superconducting-normal transition region where single-photons are resolved to the normal resistance regime. At this point, all the current is diverted through the shunt resistor in our SQUID readout electronics and a constant voltage output is observed for a time t_w until the TES re-enters the transition region due thermal coupling of the electron system to the phonon system. t_w strongly depends on the amount of deposited energy, *i.e.* number of photons absorbed by the device. A typical TES trace after absorbing $\sim 5 \cdot 10^6$ photons is shown in fig. 1a. We fit the temporal response to a double-exponential whose decay is delayed by t_w (red solid line) [2]. When fitting all traces as function of input mean photon number (N), we find that t_w linearly depends on N , as can be seen in fig. 1b. We calculate that the electron system is heated to about 30 K after absorbing $7 \cdot 10^6$ photons. Due to the hot electron system and the long thermal decay of the phonon system, the phonon system experiences a cumulative increase in temperature. This is equivalent to raising the thermal bath temperature for the electron system. The phonon temperature rises steadily as a function of N until it reaches the electron superconducting transition temperature of ~ 180 mK at $\sim 7 \cdot 10^6$ photons. The inset in fig. 1b shows the inferred phonon temperature as a function of N . The dependence of the phonon temperature with respect to the laser pulse energy is: $T_{ph} = 0.009 \cdot \ln[2E/\gamma V] + 0.12$, where E is the energy absorbed by the TES, γ is the electron specific heat capacity and V is the TES volume. Figure 1c shows the uncertainty of t_w as a function of N . The uncertainty is given in units of photon number. The black crosses correspond to the standard deviation of t_w (σ_{tw}) obtained when fitting 20,000 individual traces to our model. Since, we use a coherent state input, the input state shot noise scales as \sqrt{N} (solid blue line). After quadrature subtracting the input state shot noise from σ_{tw} , we obtain the readout plus detector uncertainty σ_d (solid red line). σ_d is below the input state shot noise up to $N \sim 1000$. Throughout the entire input state range, the relative uncertainty (σ_d/N) is below 10 % for the single-shot measurements (solid green curve).

We conclude that this technique can be very powerful when optical powers from the single-photon regime to the picowatt regime are used. The measured width depends linearly on N and the relative single-shot uncertainty remains below 10 % and can certainly be reduced by averaging traces.

References

1. Lita, A.E., A.J. Miller, and S.W. Nam, Opt. Express, 2008. **16**(5): p. 3032-3040.
2. Bennett, D.A., et al., Applied Physics Letters, 2010. **97**(10): p. 102504-3.