Extending Single-Photon Optimized Superconducting Transition Edge Sensors beyond the single-photon counting regime

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Abstract: We illuminate a photon-number-resolving transition edge sensor with strong pulses of light containing up to 6.7 million photons (0.85 pJ per pulse). These bright pulses heat the sensor far beyond its transition edge into the normal resistance regime. We show that the sensor operates from the single-photon-counting regime to picowatt levels of light and that the detection noise is below shot-noise for up to 1000 photons.
OCIS codes: (040.3780) Low light level; (270.5570) Quantum detectors

1. Introduction

Photon-number-resolving transition-edge sensors (TESs) are an enabling technology for high detection efficiency photon counting when the number of photons of an input state needs to be determined. The TESs developed at NIST reliably shows system detection efficiencies of more than 95%, and even approach 99% for individual detectors [1]. There have been recent efforts to directly tie existing optical power measurements to measurements at the single-photon level by some metrology institutions around the world with the goal of lower uncertainties. A promising candidate for connecting these two measurement regions is the TES, as it functions as a microcalorimeter and is therefore able to measure optical powers from the single-photon regime to picowatt levels.

2. Experimental Results

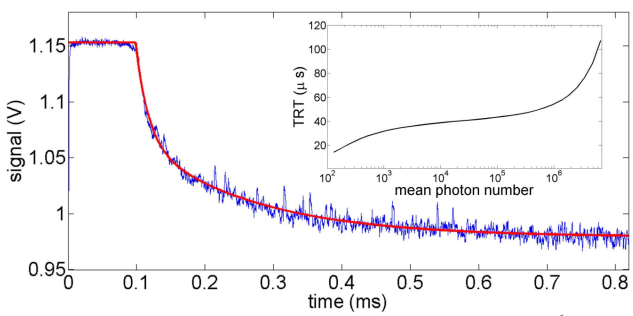

Fig. 1. TES output signal time trace after illumination with a coherent laser pulse, containing $4.8\cdot10^6$ photons. The blue line shows the data. The red line is a fit to a double-exponential function with a delayed onset. The inset shows the thermal relaxation time (TRT) of the TES as a function of mean input photon number.

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.* $6.7\cdot10^6$ photons or 0.85 pJ in a single pulse of coherent laser light. The laser pulse repetition rate is 1 kHz. The system detection efficiency of this detector was 91 %, optimized for a wavelength of 1550 nm. After $\approx$ 15 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 until the TES re-enters the transition region due to thermal coupling of the electron system to the phonon system and thermal bath. This thermal relaxation time (TRT) strongly depends on the amount of energy deposited, *i.e.* the number of photons absorbed by the device. A typical TES trace after absorbing $4.8\cdot10^6$ photons is shown in Fig. 1. We fit the trailing edge of the temporal response to a double-exponential whose decay is delayed (red solid line). We also fit the leading edge of the onset of the temporal response to another delayed double-exponential function. We found that the system can be well described by using two delayed double exponentials. From these two fits we determine the full width at the 70 % value of the maximum. We define this width as the TRT. When fitting all traces as function of mean input photon number ($\bar{N}$), we find that the TRT monotonically increases with $\bar{N}$, as can be seen in the inset of Fig. 1. By fitting this behavior to a thermal model based on an electron-phonon-phonon 3 body system we find that the results agree well with the theory. Also, according to this model, the electron system is heated to 18K after absorbing the maximum of $6.7 \cdot 10^6$ photons.

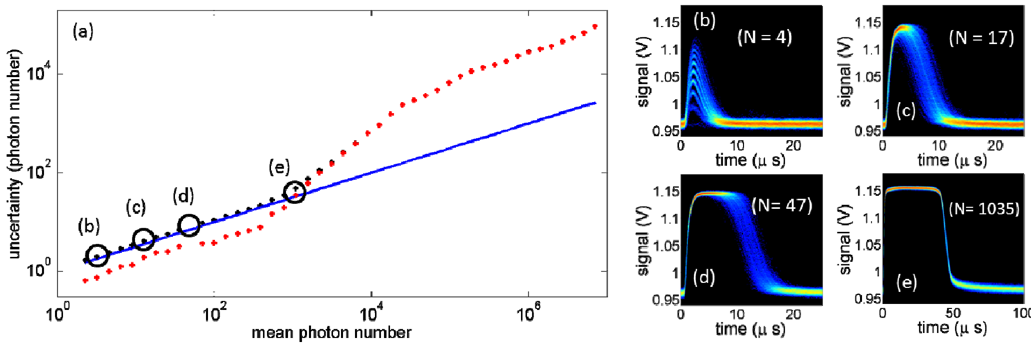

Fig. 2. (a) Measured uncertainty as a function of mean input photon number. The black datapoints correspond to the total measured uncertainty. The blue solid line shows the input state shot noise. The red datapoints represents the actual detection (read-out plus detector) uncertainty. (b)-(e) show raw TES output signal persistence traces for different mean input photon numbers. (b) $\bar{N} = 4$; (c) $\bar{N} = 17$; (d) $\bar{N} = 47$; (e) $N = 1035$.

Figure 2(a) shows the uncertainty as a function of $\bar{N}$ in photon number. We determined this measurement uncertainty for $\bar{N} < 35$ by applying matched filtering to each of the individual output traces [1]. For $\bar{N} > 70$ we used the fitting routine described above. For $35 < \bar{N} < 70$, neither the fitting nor the optimum filter technique worked. A more general model mating the two regimes needs to be developed in the future. The black datapoints show the total uncertainty, σ. This uncertainty is equal to the standard deviation of the thermal relaxation time obtained from 20480 individual fits for $\bar{N} > 70$. The blue solid line shows the uncertainty inherent in the input optical state that scales as $\bar{N}^{1/2}$. This is the shot noise limit originating from the coherent laser pulse source. The total uncertainty is the quadrature sum of both, the uncertainty due to the detection σ_d and the input state uncertainty. We can calculate the uncertainty due to the detection via: $\sigma_d^2 = \sigma^2 - \bar{N}$. However, as we assume a perfect coherent state, this calculation only yields an upper bound for the detection uncertainty, as excess noise from the source will further degrade the total measurement uncertainty. The red datapoints in Fig. 2(a) show the upper bound estimate of the detection uncertainty. The estimates show sub-shot-noise detection for $\bar{N} < 1000$. At 100 photons, the uncertainty is about 3 photons. For $\bar{N} > 1000$, the detection uncertainty becomes larger than the uncertainty due to input state and increases dramatically for $\bar{N} > 10000$. The reason for this upturn is the low sensitivity of the TRT to the absorbed number of photons in that range. This sensitivity is ≈ 5000 times smaller than that in the region for $\bar{N} < 1000$. Figures 2(b)-(e) show 1,024 raw output signal traces for different $\bar{N}$. Figure 2(b) shows typical TES output traces for $\bar{N} = 4$. The photon-number-resolving capability in the low photon-number regime is demonstrated here. Figure 2(c) shows the output signal trace for $\bar{N} = 17$. In this regime the TES is at the upper edge of its transition region and starts to enter the normal-resistance regime. Partial photon-number resolution can still be observed. Figures 2(b) and 2(c) show examples where we used the optimum filter method to determine the measurement uncertainty. Figure 2(d) shows the output signal traces for $\bar{N} = 47$. In this regime none of our models works well. Due to the input state uncertainty, the TES remains inside the transition region for some photon numbers and enters the normal-resistance region for other photon numbers; some individual photons numbers can still be resolved. Figure 2(e) shows TES responses after illumination with $\bar{N} = 1035$. At this point the TES measurement is no longer shot-noise limited, and photon-number resolution is no longer present.

3. Conclusion

In conclusion, we have demonstrated the operation of a photon-number-resolving transition edge sensor beyond the single-photon counting regime up to 6.7 million photons, corresponding to an absorbed average power of 780 pW. Our results show that the intrinsic energy resolution and single photon sensitivity of the TES provides a route connecting bright light level (picowatts) photo detection with single photon counting.

4. References

[1] Lita, A.E., A.J. Miller, and S.W. Nam, *Counting near-infrared single-photons with 95% efficiency.* Opt. Express, 2008. **16**(5): p. 3032-3040.