Nanosecond-scale timing jitter in transition edge sensors at telecom and visible wavelengths

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Transition edge sensors (TES) have the highest reported efficiencies (> 98%) for detection of single photons in the visible and near infrared. Experiments in quantum information and foundations of physics that rely critically on this efficiency have started incorporating these detectors into conventional quantum optics setups. However, their range of applicability has been hindered by slow operation both in recovery time and timing jitter. We show here how a conventional tungsten-TES can be operated with jitter times of ≤ 4 ns, well within the timing resolution necessary for MHz clocking of experiments, and providing an important practical simplification for experiments that rely on the simultaneous closing of both efficiency and locality loopholes.

For any timing pulse signal, the jitter or timing uncertainty for crossing a threshold is determined by the noise and the underlying slope of the signal at the point of crossing (see fig. 1).

\[ \Delta t_\sigma = \frac{\sigma}{A_{\text{rise}}} \approx \frac{\sigma}{A_{\text{rise}}} \tau_{\text{rise}}, \]  

where \( A \) represents the amplitude of the signal, \( \sigma \) its standard deviation and \( \tau_{\text{rise}} \) the rise time. The approximation in equation 1 holds for a linear rise of the pulse, and we will use this expression as a guide to the expected jitter performance. For a TES, we can calculate the expected RMS (root mean square) noise and amplitude of the current signal produced by the arrival of a photon [8]. Assuming instant thermalization, no damping inductance and for an ideal voltage bias, the change in current is given [2] by

\[ \Delta I \approx \sqrt{\frac{P_0}{R_0} \frac{\eta h \nu}{C T_0 (1 + \beta)}}, \]  

where \( P_0 \) is the equilibrium power dissipation of the device, \( R_0 \) is the resistance of the device at the operating point, \( C \) is the device heat capacity, \( \eta \) is the energy collection fraction, \( T_0 \) and \( T_0 \) are the temperature and current at the operation point, \( \alpha = \frac{P_0}{R_0} \frac{\partial R}{\partial T} \) and \( \beta = \frac{P_0}{R_0} \frac{\partial R}{\partial I} \) are related to the shape of the superconducting to normal transition, and \( h \nu \) is the absorbed photon energy.

The main contribution to the noise in the TES signal is a combination of Johnson noise in the device and thermal
fluctuations between the device and the bath,
\[ \tau_{\text{rise}} = \sqrt{\tau_{\text{el}}^2 + \tau_{\text{ext}}^2}, \]
where \( \tau_{\text{el}} \) is the intrinsic rise time of the photon detection pulse and \( \tau_{\text{ext}} \) is the rise time of the external amplifier.

where the rise time of the external amplifier is related to the bandwidth as \( \tau_{\text{ext}} \approx 0.35/\Delta f \). Combining these expressions and with the additional simplifying assumptions of a noiseless amplifier, operation at the superconducting transition temperature and low base temperature, we arrive at a final expression for the jitter
\[ \Delta t_{\text{FWHM}} \approx \frac{2\sqrt{2\ln 2} I_{\text{RMS}} \tau_{\text{rise}}}{\Delta f} \approx \frac{2\sqrt{2\ln 2} I_{\text{RMS}} \tau_{\text{rise}}}{\Delta f} \times \frac{\gamma}{\alpha \eta h \nu} \times \sqrt{\frac{R_0 V k_B}{L \Sigma}} \times \sqrt{\tau_{\text{ext}}^2 + \frac{L^2}{R_0^2 (1 + \beta)^2}}, \]
where \( \Sigma \) and \( \gamma \) are material parameters and \( V \) is the volume.

The device under test is a W-TES optimized for detection of near-IR photons at a wavelength of approximately 800 nm. The physical parameters and material characteristics of this particular TES-SQUID system are listed in Table I.

We measure the W-TES in a dilution refrigerator at a base temperature of 30 mK. Critically to the timing performance, the TES is electrically connected to a low input inductance SQUID amplifier via Al bond wires. Room temperature electronics perform the last amplification stage at a nominal bandwidth of 20 MHz.

The test light signal consists of a pulsed diode laser at a wavelength of 1550 nm, a pulse duration of 1 ns and the repetition rate is kept at 100 kHz, well below the recovery time of the TES, for convenience in the analysis. The signal was captured by a digitizing oscilloscope at a sampling rate of 1.25 GS/s and 8 bit dynamic range.

We chose the input optical power level to see a significant number of 1, 2, and 3 photon events to allow independent jitter analysis for different photon numbers. The SQUID and W-TES bias point were chosen manually to minimize the rise time and maximize amplitude of the pulses.

Figure 2 shows a histogram of the areas of each pulse after a postprocessing digital matched filter. The peaks corresponding to 0, 1, 2, 3 and 4 photons are clearly visible, as is a strong non-linearity in the peak separation between consecutive photon numbers. This non-linearity is dominated by the SQUID response in open-loop operation, which we use for optimum bandwidth. The non-linear response complicates the determination of the energy resolution, as it varies strongly depending on the

| Parameter | Value |
|-----------|-------|
| \( T_0 \) | 150 mK |
| \( R_0 \) | 1 Ω |
| \( \tau_{\text{ext}} \) | 17.5 ns |
| \( V \) | 12.5 μm² |
| \( M_j \) | 1.5-3.5 |
| \( \Sigma \) | 0.4 nW μm⁻³ K⁻¹ |
| \( L \) | 24 ± 5 nH |
| \( \alpha \) | 150-800 |
| \( \gamma \) | 340.2 nJ μm⁻³ K⁻¹ |
| \( \beta \) | 0.8-2.2 |

Combining these expressions and with the additional simplifying assumptions of a noiseless amplifier, operation at the superconducting transition temperature and low base temperature, we arrive at a final expression for the jitter.

![Jitter dependence on noise and slope for a simulated Gaussian pulse with random noise.](trigger_level.png)
The inter-peak separation is highly non-linear as a consequence of an open loop operation of the SQUID amplifier/SQUID/wiring system. The parameters associated with the shape of the average pulse and its rise time, there is an optimal choice of the term \( 1/e \). As expected from eq. 6, the jitter improves with the local steepness of the signal, which in the case of TES pulses is right at the onset, i.e. at lower threshold levels. For 1550 nm single photons, the fitted FWHM values of the timing uncertainty vary between 4.1 ns and 10.5 ns. For the 2-photon signal, or equivalently for single photons at 775 nm, the times are between 2.3 ns and 7.9 ns, and become shorter as higher photon signals are considered. In all cases, the jitter is well within the 12 ns limiting case for operation with an 80 MHz repetition laser.

These numbers are roughly consistent with what is expected from eq. 6 and the TES-SQUID parameters. In particular, the SQUID input noise needs to be less than \( \approx 1 \ pA/\sqrt{Hz} \) for our assumption of negligible SQUID noise contribution and the resulting expression to be valid. Some of the physical and material parameters listed in table III are known within a relatively small error. However, the parameters associated with the shape of the transition, \( \alpha \) and \( \beta \), and excess noise terms, \( M_J \), are only approximately known for this device. Given these constraints, eq. 6 predicts a wide range of possible values of \( \Delta t_{FWHM} \). It is worth noting that, in the regime where the room temperature amplifier limits the rise time, there is an optimal choice of the term

\[
\frac{t}{\kappa_0(1+\beta)} = \tau_{el}
\]

In our case, we believe our measured value.
FIG. 4: Timing uncertainty. The histogram of crossing times is fitted to a convolution of a Gaussian and an exponential decay. The figure shows an example of these fits for 1-photon signals at threshold levels of 10%, 30%, 50%, 70% and 90%. The fits for other threshold levels and for the 2 and 3 photon signals are of similar quality.

FIG. 5: Timing uncertainty. Thresholding at different levels provides the simplest method for measuring the time of arrival of a pulse and its associated uncertainty. The three curves show results for 1, 2 and 3 photon pulses (0.8 eV, 1.6 eV and 2.4 eV respectively).

FIG. 6: Expected jitter for 1550 nm photons. The two extremal curves are the highest and lowest values of jitter calculated for the range of parameters values in our devices. The data points correspond to the measured FWHM of the timing distributions for different trigger levels. Note that our measured value for the effective inductance ($L = 24$ nH), is close to optimal.

In conclusion, optical TES have demonstrated extremely good photon number discrimination and close to unity quantum efficiency. However, they lag behind other detector technologies in their timing performance, both in the jitter or “time of arrival” and in their recovery times. In this paper we have shown how the jitter in these devices can be made significantly smaller than is ordinarily reported by using reduced input inductance SQUID amplifiers [10], achieving values as low as 4.1 ns for 1550 nm single photons and 2.3 ns for 775 nm. These values are an order of magnitude smaller than previously reported and well below the technologically important 12 ns threshold associated with 80 MHz repetition Ti:Sa lasers.

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