**Photon number and timing resolution of a near-infrared continuous-wave source with a transition edge sensor**

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Abstract- The Transition Edge Sensor (TES) is a calorimetric spectrometer that have near unit efficiency and is photon-number resolving [1]. Slow recovery time, on the order of microseconds, limits the number resolving and timing accuracy for high photon-flux detection. This is usually resolved by pulsing the light source or discarding overlapping signals, thereby limiting its applicability. In this work, we analyze the output signal when detecting a continuous wave source, and show a procedure to determine amplitude and timing of overlapping pulses. As a direct application, we measure the arrival-time difference distribution of a coherent source in a single spatial mode using a single detector.

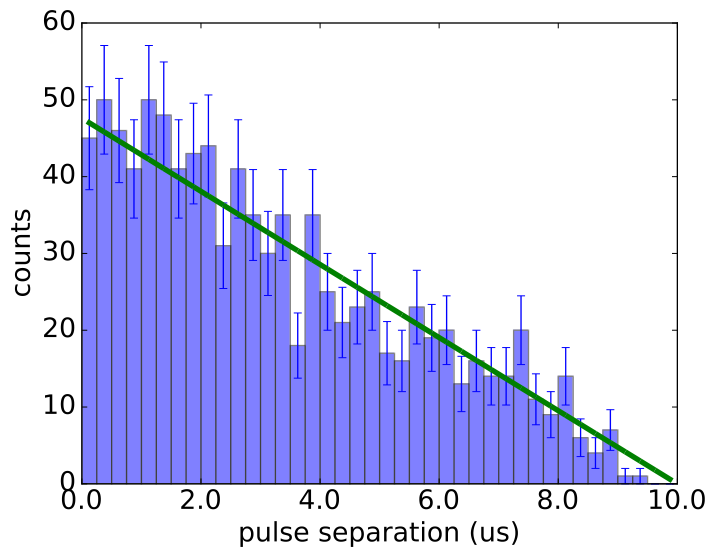
When a photon is absorbed by a TES, it produces a pulse with a fast rising edge of tens of nanoseconds, and a decay time of several microseconds. A straightforward way of obtaining its arrival time is by the time when it crosses a predefined threshold. The same method will not work when two pulses are overlapped, as the rising edge of the second pulse is obscured.

It was recently demonstrated [2] that by low-pass filtering and differentiating the pulse, we can estimate the arrival time of the second pulse. In the case of NIR photons, where we have lower signal-to-noise ratios, the differentiated signal could identify noise instead of the onset of a photon. Applying a low-pass filter to circumvent this, decreases timing resolution.

Instead, we fit the TES output to a linear superposition of single-photon models. To obtain the TES response model to a 810nm single photon, we drive a LD centred at 810 nm with 4 ns pulses, containing an average photon number of 1, at a repetition rate of 100kHz. As the photon number distribution is Poissonian, it will contain not just single photon events. We use the pulse integral to distinguish single photon pulses, and average them to obtain our model.

We obtain the arrival-times and amplitudes of overlapping pulses in the following way: First, we estimate and remove the baseline offset in every trace. Second, we identify the number of photons in the trace by integrating only regions corresponding to photon detection. Next, we low-pass filter and differentiate the signal to estimate the arrival-time of the underlying photons. If the pulses are sufficiently separated, two distinct arrival-times can be identified in this way, and we use these times to initialise a least-squares fit on the unfiltered trace. Otherwise, we perform a Monte-Carlo Markov Chain fit over the pulses, using also the expected amplitude distribution as priors. In this way, arrival-time differences of 200 ns can be estimated with an accuracy of ~60 ns.

We apply this procedure to 2-photon traces, 10 us long, collected from a free-running LD. We obtain an arrival-time difference distribution that agrees well with our prediction (see Figure 1).

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**Fig 1.** Arrival-time separation histogram of a continuously running LD. Bin size = 250~ns. Error bars indicate Poissonian standard deviation. Green line: Theoretical prediction. Due to the finite duration of our oscilloscope traces, the coincidence probability of two photons decreases with increasing separation.

**References**

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2. J. W. Fowler et al., "Microcalorimeter spectroscopy at high pulse rates: a multi-pulse fitting technique," ApJS 219, 35, August 2015.