Self consistent, absolute calibration technique for photon number resolving detectors

A. Avella,1,2 G. Brida,1 I. P. Degiovanni,1 M. Genovese,1 M. Gramegna,1 L. Lolli,1 E. Monticone,1 C. Portesi,1 M. Rajteri,1,∗ M. L. Rastello,1 E. Taralli,1 P. Traina,1 and M. White1,3

1INRIM, Strada delle Cacce 91, Torino 10135, Italy
2 Dipartimento di Fisica Teorica, Università degli Studi di Torino, Via P. Giuria 1, Torino 10125, Italy
3 NPL, National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, UK
∗m.rajteri@inrim.it

Abstract: Well characterized photon number resolving detectors are a requirement for many applications ranging from quantum information and quantum metrology to the foundations of quantum mechanics. This prompts the necessity for reliable calibration techniques at the single photon level. In this paper we propose an innovative absolute calibration technique for photon number resolving detectors, using a pulsed heralded photon source based on parametric down conversion. The technique, being absolute, does not require reference standards and is independent upon the performances of the heralding detector. The method provides the results of quantum efficiency for the heralded detector as a function of detected photon numbers. Furthermore, we prove its validity by performing the calibration of a Transition Edge Sensor based detector, a real photon number resolving detector that has recently demonstrated its effectiveness in various quantum information protocols.

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OCIS codes: (270.5570) Quantum detectors; (030.5260) Photon counting; (030.5630) Radiometry.

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53. Incidentally, if one wants to provide a precise estimate of the naked TES based detector quantum efficiency $\eta$ it is necessary a careful estimation of the optical transmittance $\tau$, accounting for the coupling efficiency in the optical fiber and the optical losses in the non-linear crystal. According to the results of Ref.s [S.V. Polyakov, A.L. Migdall, Opt. Express 15, 1390 (2007); J. Y. Cheung et al., Appl. Opt. (submitted)], one could provide an estimate of this parameter with a less than 1% uncertainty.

1. Introduction

Photon number resolving (PNR) detectors are a fundamental tool in many different fields of optical science and technology [1,2] such as quantum metrology (redefinition of the SI candela unit [3]), super-resolution [4], foundations of quantum mechanics [5], quantum imaging [6] and quantum information [7,8,9].

Unfortunately, most conventional single-photon detectors can only distinguish between zero photons detected (“no-click”) and one or more photons detected (“click”). Photon number resolution can be achieved by spatially [10,11] or temporally [12,13] multiplexing these click / no-click detectors. True PNR detection can be achieved only by exploiting detectors intrinsically able to produce a pulse proportional to the number of absorbed photons. However, detectors with this intrinsic PNR ability are few [1,2], for example photo-multiplier tubes [14] [15] [16] and hybrid photo-detectors [17]. At the moment, because of their high detection efficiency, the most promising PNR detectors are the visible light photon counters [18,19] and transition edge sensors (TESs) [20].

TESs are based on a superconducting thin film working as a very sensitive thermometer. They are able to discriminate up to tens of photons per pulse. TESs have recently found important application to quantum information experiments [21] [22] [23], demonstrating their huge potential in this field. For practical application of these detectors it is fundamental they are appropriately characterised. In particular, one of the most important figures of merit to be characterised is the detection efficiency, defined as the overall probability of detecting a single photon impinging
on the detector.

For measuring detection efficiency in the photon counting regime, where conventional standards are cumbersome, an efficient solution is given by Klyshko’s absolute calibration technique \[\text{[24, 25, 26]}\], which exploits parametric down conversion (PDC) as a source of heralded single photons. Despite this technique being suggested in the seventies \[\text{[27, 28]}\], only in recent years has it developed from demonstrational experiments to more accurate calibrations \[\text{[29, 30, 31, 32]}\]. Nowadays, it has been added to the toolbox of primary radiometric techniques for detector calibration, even though it has only been deeply studied in the case of single-photon click / no-click detectors \[\text{[33, 34, 35, 36, 37]}\].

Recently, other techniques for detector calibration, exploiting PDC in the high gain regime, have been proposed both for the case of analog detectors \[\text{[38, 39]}\] and CCDs \[\text{[40]}\]. Furthermore, a new technique for the calibration of single photon detectors was proposed exploiting bright PDC light \[\text{[41]}\]. This technique, strongly based on the assumption of a specific detection model, can in principle be more accurate than the version of Klyshko, but it is important to underline that the Klyshko’s technique, properly developed by the radiometric community, has been proven accurate at the level of parts in \[10^{-3}\] \[\text{[36, 37]}\], i.e. one order of magnitude more accurate than discussed in Ref. \[\text{[41]}\].

We note that the extension of Klyshko’s technique to the PNR detection system is quite straightforward when considering the PNR as a click / no-click single-photon detector. Nevertheless, this simple application of Klyshko’s method is detrimental to the peculiar property of the PNR detector, i.e. its PNR ability.

By contrast, in this paper we propose and demonstrate an absolute technique for measuring quantum efficiency, based also on a PDC heralded single photon source, but exploiting all the information obtained from the output of the PNR detector. As the technique is absolute no reference standards are required.

We also note this represents the first quantum efficiency measurement of a TES detector exploiting an absolute technique. Other researchers \[\text{[42, 43]}\] have demonstrated a substitution method \[\text{[44]}\] employing a laser beam, calibrated optical attenuators and calibrated reference standard detectors.

In particular in section 2 we present the theory of our calibration method, while in section 3 we present the experimental setup and the results.

2. Our method

We used a pulsed PDC based heralded single photon source to illuminate our TES detector. The typical output of a PNR detector is an histogram representing the relative frequency of detection events of a certain number of photons. Specifically, we performed two separate measurements, one in the presence of and one in the absence of heralded photons, obtaining two data histograms. Starting from these histograms we estimate the probabilities of observing \(i\) photons per heralding count in the presence and in the absence of the heralded photon, \(P(i)\) and \(P'(i)\) respectively. Furthermore, we account for the presence of false heralding counts due to stray light and dark counts. As \(\xi\) is the probability of having a true heralding count (i.e. not due to stray light and dark counts), the probability of observing no photons on the PNR detector is the sum of the probability of non-detection of the heralded photons multiplied by the probability of having no accidental counts in the presence of a true heralding count and the probability of having no accidental counts in the presence of a heralding count due to stray light or dark counts:

\[
P(0) = \xi(1-\gamma)P'(0) + (1-\xi)P(0),
\]

hereafter \(\gamma\) is the TES “total” quantum efficiency, i.e. \(\gamma = \tau\eta\) where \(\tau\) is the optical and coupling losses from the crystal to the fibre end ((a) in Fig. 1) , and \(\eta\) is the quantum efficiency of the
TES detector. According to Fig. 1, we consider the TES detector as the system from the fibre end (b) to the sensitive area, since this represents the real detector for applications. This means that \( \eta \) accounts also for the losses of the fibre in the fridge and the geometrical coupling of the light from the fibre to the TES sensitive area.

Analogously, the probability of observing \( i \) counts is

\[
P(i) = \xi [(1 - \gamma) P(i) + \gamma P(i - 1)] + (1 - \xi) P(i),
\]

with \( i=1,2,... \), i.e. the sum of the joint probability of non-detection of the heralded photons and the probability of having \( i \) accidental counts, and the joint probability of detection of the heralded photons and the probability of having \( i - 1 \) accidental counts both in the presence of a true heralding count, and the probability of having \( i \) accidental counts in the presence of a heralding count due to stray light or dark counts.

From Eq. (1) the efficiency can be estimated as

\[
\gamma_0 = \frac{P(0) - P(0)}{\xi P(0)},
\]

while from Eq. (2)

\[
\gamma = \frac{P(i) - P(i)}{\xi (P(i - 1) - P(i))}.
\]

It is noteworthy to observe that the set of hypotheses in the context of this calibration technique is similar to the one in Klyshko’s technique, i.e. multiphoton PDC events in the time interval of the order of DET1 temporal resolution (jitter) should be absolutely negligible. Furthermore, in our case for each value of \( i \) we obtain an estimation for \( \gamma \) allowing a test of consistency for the estimation model.

3. Method implementation and discussion

The PNR detector for implementing the proposed calibration technique is a TES based detector, suitable for broadband response. The TES sensor consists of a superconducting Ti film proximised by an Au layer [45]. Such detectors have been thermally and electrically characterised by impedance measurements [46]. The transition temperature of the TES is \( T_c = 121 \) mK with \( \Delta T_c = 2 \) mK. It is voltage biased [47] and mounted inside a dilution refrigerator at a bath temperature of 40 mK. The TES active area is 20 \( \mu \)m x 20 \( \mu \)m and is illuminated with a single mode, 9.5 \( \mu \)m core, optical fibre. The fibre is aligned on the TES using a stereomicroscope [48]. The distance between the fibre tip and the detector is approximately 150 \( \mu \)m. The read out is based on a dc-SQUID array [49], mounted close to the detector, coupled to a digital oscilloscope for signal analysis. The obtained energy resolution is \( \Delta E_{FWHM} = 0.4 \) eV (64 zJ), with a response time of 10.4 \( \mu \)s [48].

The calibration is performed using an heralded single photon source based on pulsed non-collinear degenerate PDC [24, 25, 26] (Fig. 1). The heralding photon at 812 nm, emitted at 3\(^\circ\) with respect to the pump propagation direction, is spectrally selected by means of an interference filter 1 nm FWHM (IF1) and detected by a single photon detector DET1 (Perkin-Elmer SPCM-AQR-14). The heralding signal from DET1 announces the presence of the conjugated photon that is coupled into the single mode optical fibre and sent towards the TES detector (DET2) after spectral filtering (IF2 centered at 812 nm with 10 nm FWHM). As usual in quantum efficiency measurement based on heralding single photon source, the spectral selection is determined by the trigger detector, while the filter in front of the detector under-test should not reject heralded photons but it is just inserted to reduce the background counts [24–37].
Fig. 1. Experimental setup: the heralded single photon sources based on non-collinear degenerate PDC pumped by 406 nm pulsed laser. The heralding signal from DET1 announces the presence of the conjugated photon that is coupled in the single mode optical fibre and sent towards the TES based detector (DET2, identified by the dotted line) starting from the fibre end (b).

The pulsed PDC is realised by pumping a type I BBO crystal with a 406 nm laser, electrically driven by a train of 80 ns wide pulses with a repetition rate of 40 kHz. This low repetition rate is required to avoid pile up effect in the statistics of the measured counts. In fact it is necessary to use a pulsed heralded single-photon source with a period longer than the pulse duration of the detector, in order to avoid unwanted photons impinging on the TES surface before the end of the pulse. If it does not happen, the end effect would be a pile up of the signal on the tail of the previous detection event with a subsequent extension of the pulse tail (that can be, somehow, considered the extended dead time of the detector [50]).

Despite the pump laser pulse being quite long (80 ns), we note that it is shorter than the temporal resolution of TESs (time jitter larger than 100 ns). Furthermore, the poor temporal resolution does not allow the use of small coincidence temporal windows such as the ones used in the typical coincidence experiments exploiting, for example, Time-to-Amplitude-Converter circuits. One of the advantages of using a pulsed heralded single photon source is the possibility of evaluating the events counted by the TES in the presence and absence of an heralding signal, providing an estimate of the probabilities $P(i)$ and $\mathcal{P}(i)$ in terms of events $C(i)$ and $\mathcal{C}(i)$ counted by the TES. In particular $C(i)$ ($\mathcal{C}(i)$) is the number of events observed by the TES counting $i$ photons in the presence (absence) of the heralding photon, where $P(i) = C(i)/\sum_i C(i)$ and $\mathcal{P}(i) = \mathcal{C}(i)/\sum_i \mathcal{C}(i)$.

In Fig. 2 typical traces of the TES detected events observed by the oscilloscope are shown. The oscilloscope readout is triggered only when both the pump laser trigger and the heralding detector DET1 clicks are present. The time base is set in order to record on the trace two subsequent laser pulses. In such a way we are able to measure, on the same trace of the DET2 pulses, the events containing the heralded photon announced by the contemporary two trigger signal, i.e. the one corresponding to the laser pulse and the one from DET1 (left pulses in Fig. 2), and the subsequent ones not containing the heralded photon (right pulses in Fig. 2). By measuring the amplitude of the pulses in this trace we could generate an histogram where
the peaks identify the different number of detected photons corresponding to the two kind of pulses of Fig. 2. The insets (a) and (b) are the histograms of the amplitudes of the pulses in the presence and in the absence of heralding photons, respectively. The histogram is fitted with gaussian curves \( \sum_{i=0}^{2} A_i \exp\left[-\frac{(x - x_i)^2}{2\sigma_i^2}\right] \), where the fit parameters are the areas \( A_i \), the centres \( x_i \) and the widths \( \sigma_i \) of the Gaussian curves. The agreement between the experimental data and the fitting is excellent, as stated from the ratio between the reduced \( \chi^2 \)-square value and the reduced total sum of square that is lower than \( 10^{-4} \). The integrals of the gaussian curves fitted to the histogram peaks provide an estimate for the parameters \( C(i) \) and \( C'(i) \). The probability of having true heralding counts \( \xi = 0.98793 \pm 0.00007 \) is obtained as \( \xi = 1 - n_{OFF}/n_{ON} \), where \( n_{ON} \) and \( n_{OFF} \) are the number of events triggered by the laser pulses and counted by DET1 in the presence and in the absence of PDC emission, respectively. They correspond in one case to true heralded counts, or stray light and dark counts, while in the other case only to stray light and dark counts and they are obtained by means of pump polarization rotation. The PDC extinction provided by the pump polarization rotation was almost perfect at our pump regime. The measured value for stray light and dark counts on DET1, are compatible with the values measured with the pump laser blocked before the crystal. The uncertainty on \( \xi \) is evaluated by standard uncertainty propagation on the measured counts in the presence and in the absence of PDC.

According to Eqs. 3 and 4, the different estimated values for the “total” quantum efficiencies are \( \gamma_0 = (0.709 \pm 0.003)\% \), \( \gamma_1 = (0.709 \pm 0.003)\% \), and \( \gamma_2 = (0.65 \pm 0.05)\% \). In Table 1 can be found the full analysis of the uncertainty contributions [51]. All the uncertainties are given with coverage factor \( k = 1 \), obtained from six repeated measurements, each measurement being five hours long, corresponding to approximately \( 11 \times 10^6 \) heralding counts. The system was very stable during this long run of measurements. We note that the large uncertainty (derived from standard uncertainty propagation) in the estimation of \( \gamma_2 \) is essentially due to the poor statistics. For the same reason, i.e. negligible amount of counted events, it was impossible
to obtain estimates of $\gamma$ for $i > 2$. Nevertheless, within its large uncertainty $\gamma_2$ is compatible with $\gamma_0$ and $\gamma_1$ estimates, which are themselves within very good agreement. This is consistent with the fact that $\gamma_0 = \gamma_1 = \gamma_2$ is expected, since the TES detector has been recently proved to be a linear detector \cite{52}, as generally believed \cite{1, 2}. The averaged results for the efficiency is $(0.709 \pm 0.002)\%$, from a standard weighted mean, where the uncertainty is calculated accordingly.

Table 1. Uncertainty contributions in the measurement of $\gamma_0$, $\gamma_1$ and $\gamma_2$. The uncertainty contributions are calculated according to the well known gaussian propagation of uncertainty formula \cite{51}, where the correlations are accounted for.

| Quantity | Value  | Standard Uncertainty | Unc. Contrib. to $\gamma_0$ (%) | Unc. Contrib. to $\gamma_1$ (%) | Unc. Contrib. to $\gamma_2$ (%) |
|----------|--------|----------------------|---------------------------------|---------------------------------|---------------------------------|
| $C_0$    | 5.069  | $10^6$               | 1.4 $10^4$                      | -0.003                          | -0.003                          |
| $C_1$    | 5.0200 | $10^4$               | 200                             | 0.004                           | -4 $10^{-5}$                    |
| $C_2$    | 118    |                      | 6                               | 2 $10^{-4}$                     | -2 $10^{-6}$                    |
| $\zeta_0$| 5.103  | $10^6$               | 1.4 $10^4$                      | 8 $10^{-4}$                     | 0.003                           |
| $\zeta_1$| 1.4600 | $10^4$               | 150                             | -0.003                          | -0.007                          |
| $\zeta_2$| 23.9   |                      | 1.5                             | -3 $10^{-5}$                    | 3 $10^{-7}$                     |
| $\xi$    | 0.98794|                      | 7 $10^{-5}$                     | -6 $10^{-5}$                    | -5 $10^{-5}$                    |
| $\gamma_0$ (%) | 0.709 |                      | 0.003                           |                                 |                                 |
| $\gamma_1$ (%) | 0.709 |                      | 0.003                           |                                 |                                 |
| $\gamma_2$ (%) | 0.65  |                      |                                 | 0.05                            |                                 |

In order to validate the proposed technique we compared the efficiencies obtained with those obtained following the well developed Klyshko’s technique \cite{28}. We point out that the extension of Klyshko’s technique to a TES detector is absolutely straightforward. In fact the PNR ability of the TES detector can be disregarded, it being considered as a click / no-click detector. Along the guidelines of Ref.s \cite{36, 37} and from the same experimental data used for the evaluation of the $\gamma_i$’s we evaluate the “total” efficiency in the case of the Klyshko’s technique, obtaining $\gamma_{Klyshko} = (0.707 \pm 0.003)\%$. The result is in perfect agreement with that obtained from the proposed new technique as implemented in the work reported here.

The evaluation of the total efficiency $\gamma$, instead of $\eta$, allows us a better comparison between the results obtained from the two techniques, as the additional independent measurement of $\tau$ is common to the two techniques. For this reason, in the context of the comparison, it only provides an additional and somewhat misleading common uncertainty contribution \cite{53}.

We notice that the value of the measured efficiency is rather small with respect to results presented in the literature, e.g. \cite{42, 43}. However, the measured values are absolutely consistent within the context of our experimental setup. Note that the TES sensitive area is not optimised for detection efficiency at a specific wavelength. On the basis of the material used the expected efficiency of the TES is approximately 49%, while the parameter $\tau$ is estimated to be 10%. The geometrical and optical losses inside the refrigerator contribute to lower the value of $\eta$ to 7%.

4. Conclusions

In conclusion, we have proposed and demonstrated a new absolute calibration technique, applicable to TES detectors, with an estimated relative uncertainty of $10^{-3}$, that does not rely on reference standards. Considering the importance of PNR detectors in advancing quantum
technologies, this result represents an important step in their precise characterisation, paving the way to metrological applications of this absolute method.

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