Understanding Correlated-Photon Based Efficiency Calibration of Photon Counting Detectors

The demand for detectors with photon counting capability grows rapidly. This is driven by advances in optical technologies, biophotonics and astronomy, or for example by novel quantum information applications. The requirement for simple, but precise, characterization of the photon-counting detectors goes hand in hand with this progress.

Conventional approach:

All traditional routes to efficiency measurements of detectors rely on comparison with externally calibrated reference sources or detectors. They always involve (i) establishing the primary source or primary detector standards, which define the radiometric scales at discrete wavelengths, (ii) extending the radiometric scales to a spectral continuum by characterizing intermediate standards, and (iii) dissemination of the scales to users.

The multistep procedure from establishing high-accuracy primary radiometric quantities to comparison of a tested device with the working standards is complex, not flexible, and resource-demanding, making the final costs for the user relatively high. Every step adds a calibration uncertainty into the entire procedure and thus a very high initial accuracy of the primary radiometric quantities is inevitably lost in the transfer chain of standards. The situation is even more complicated, because the present radiometric standards are precise at a power range well above the operating levels of photon counting detectors. Therefore, one needs calibrated attenuators, rendering the conventional calibration methods of photon counting detectors impractical and barely usable at all.

Correlated two-photon approach:

The working principle of this new attractive calibration method is based on a fundamental property of spontaneous parametric downconversion (SPDC) – the two-photon correlated emission. In SPDC, the photons from a pump laser beam spontaneously convert in a nonlinear crystal into a “train” of photon pairs. Since the photons are generated at random times in pairs like twins, the detection of one photon heralds, with certainty, the existence of the other. Not only the existence, but also the wavelength and the propagation direction of the other photon from a pair are accurately known due to restrictions of energy and momentum conservation,

$$\boldsymbol{k}_{\mathrm{p}} = \boldsymbol{k}_1 + \boldsymbol{k}_2, \quad \omega_{\mathrm{p}} = \omega_1 + \omega_2,$$

where ω and $\boldsymbol{k}$ are the photon frequencies and wave vectors and the subscripts $\mathrm{p}, 1$ and 2 refer to the pump and the two down-conversion photons, respectively.

The correlated nature of the two-photon light emitted from the SPDC offers a unique resource for absolute optical measurements of detector efficiency. The basic arrangement of the method is sketched in the figure 1. A pair of photon-counting detectors, a trigger detector (TRIG) and a device under test (DUT), are positioned behind the nonlinear crystal along the propagation directions of correlated photon pairs with given wavelengths. Whenever the TRIG registers a photon, the DUT should have ideally seen, in coincidence, one as well. But due to the finite detection efficiency of the DUT detector, only a fraction of TRIG detections is accompanied by a coincident detection at the DUT. It is just this fraction, which defines the efficiency of the DUT detector (assuming the detectors fire only due to correlated photon pairs and the DUT channel path from the point of SPDC emission to the detector is lossless).

Quantitatively, if N is the total number of correlated photon pairs emitted by SPDC in some

SPDC Emission Characteristics

The emission pattern of SPDC is formed by the cones which imprint characteristic rings in a plane perpendicular to the pump-beam direction. Each cone corresponds to a different down-conversion wavelength. If the nonlinear process is tuned to a spectral degeneracy, the photons of a pair are always located on the opposite sides of the same cone. In the case of spectral non-degeneracy the photons belong to different cones, yet they must be located on their opposite sides to obey the momentum conservation rule.

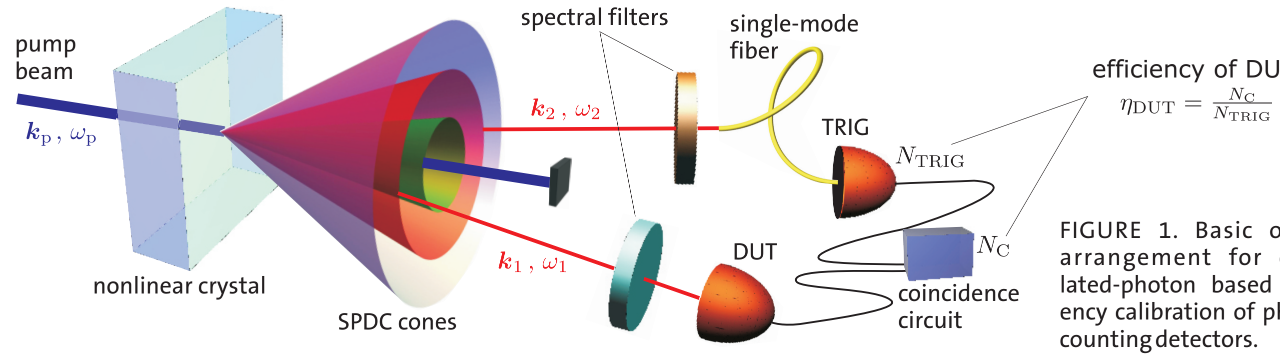

FIGURE 1. Basic optical arrangement for correlated-photon based efficiency calibration of photon-counting detectors.

arbitrary time unit, then the mean photon numbers N_{TRIG} and N_{DUT} registered by the two detectors and the number of detections N_{C} registered in coincidence are given by:

$$\begin{aligned} N_{\mathrm{TRIG}} &= \eta_{\mathrm{TRIG}} N, \\ N_{\mathrm{DUT}} &= \eta_{\mathrm{DUT}} N, \\ N_{\mathrm{C}} &= \eta_{\mathrm{TRIG}} \eta_{\mathrm{DUT}} N, \end{aligned}$$

where η_{TRIG} and η_{DUT} are the efficiencies of the detectors. As a result, the absolute value of η_{DUT} is simply detemined by:

$$\eta_{\mathrm{DUT}} = \frac{N_{\mathrm{C}}}{N_{\mathrm{TRIG}}}.$$

Remarkably, to determine the efficiency η_{DUT} of the DUT detector, the efficiency η_{TRIG} of the trigger detector need not be known! This makes the method inherently absolute. To highlight this point, one could even think of a measurement system where the DUT holds a role of its own trigger. In this measurement scenario the mutually delayed photons of a pair would be incident on the tested detector, whose time-resolved output reveals the efficiency in the same way as with a separate trigger detector.

Additional benefit comes from the spectral correlation of SPDC photons: The calibration wavelength can be defined by spectral selectivity components (with unknown transmission) put into the trigger arm. This allows the calibration regime to be transferred from some difficult spectral region to a more convenient one (e.g. from the infrared to visible by using detectors operating at widely separated spectral ranges).

Despite the advantages, there are several potentially problematic issues, which must be carefully considered, in order to turn the operation principle of the correlated-photon method into an accurate metrological measurement of detector efficiency. The issues are:

1. Any darkcount or count due to back-ground photons of the trigger detector falsely heralds the arrival of the correlated photon at the DUT detector. Therefore, the number N_{TRIG} of TRIG detections has to be subtractively corrected for the dark- and background-count rate, which can be easily measured.

2. As with false trigger events, a small fraction of coincidence detections is not due to correlated photons, but rather due to noise of detectors or background light. Thus, independent measurement has to be performed to determine the number of accidental coincidences.

3. The efficiency η_{DUT} given by the ratio of trigger-to-coincidence events includes all the losses of the DUT channel from the point of SPDC emission to the point of detection. Thus, in principle, the correlation method measures the efficiency of the entire DUT channel! The losses in the DUT path include the finite transmittance of the nonlinear crystal from the emission point, the transmittance of any pump-blocking filter and focusing optics and incomplete collection of the correlated photons. To extract the accurate efficiency of the detector DUT, all the losses have to be individually determined, and appropriate corrections performed.

System design considerations

To minimize the calibration uncertainties, ideally all the photons correlated to those recorded by the trigger detector should reach the DUT detector. To this end, one adopts an unbalanced setup geometry, in which all the spectral and spatial filtering is concentrated into the trigger channel (see fig. 1). Practically, this is realized by inserting a narrow-band spectral filter and the single-mode fiber into the trigger channel, whereas only a pump-blocking filter (with a high transmission over the entire spectral band correlated to that defined by the narrowband filter) and a large collection aperture (letting pass all the correlated photons through, while restricting the number of uncorrelated photons) is used in the DUT channel.