

Measurement of quantum efficiency using the correlated photon technique

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Abstract. Correlated photons offer a direct means of calibrating detector quantum efficiency in the photon counting regime. This paper describes the facility being developed at the National Physical Laboratory for calibrating such detectors using this technique. An uncertainty budget for the measurements currently achievable with the technique is presented, and the related effects of after-pulsing and spatial uniformity are also discussed. Progress on an intercomparison of the correlated photon technique with that traceable to cryogenic radiometry is also reported. The facility currently operates in the visible part of the spectrum, and plans to cover the key telecommunication wavelengths in the infrared will be discussed.

Low light measurements

Detectors operating in the photon counting regime are being developed for a wide variety of applications, such as quantum information processing, astronomy and biotechnology. The main challenge of low light level measurement is in the development of detector technology to meet the requirements of the user. Detector properties such as quantum efficiency (q.e.), spatial uniformity, dead time, jitter, after pulsing, photon number resolving capabilities, room temperature operation and robustness in harsh conditions need to be improved. In addition, high accuracy metrology techniques are required to quantify these properties. Correlated photon metrology is currently

being developed to meet the metrology challenges.

Correlated photon metrology

Spontaneously produced correlated photons can be used to measure the absolute quantum efficiency of photon counting detectors while those produced via stimulated downconversion can be used to measure source radiance. The technique is direct, requiring no calibration chain, and absolute ¹. The technique relies on the process of optical parametric downconversion. A high-energy photon (pump) entering a non-linear crystal will spontaneously decay ² into two lower energy photons (signal, idler) which are fundamentally related by the laws of conservation and momentum. Detection of an idler photon indicates that its twin signal photon must exist. Moreover the emission time, direction, wavelength and polarisation of the signal and idler photons are correlated, i.e. given the values for the idler, those of the signal can be inferred.

Figure 1 is a schematic of the correlated photon setup, used to measure the q.e. of a detector at 702 nm. When the trigger (TRIG) registers a photon it heralds the arrival of its twin at the device under test (DUT). Photons lost due to optical elements in the trigger channel are of no concern, what is crucial is whether the DUT captures every twin of every photon detected by the trigger. Rearranging the equations in figure 1 shows that the q.e. of the DUT channel can be expressed as $\eta_{DUT} = N_c / N_{TRIG}$ and is the q.e. from the point of downconversion in the crystal.

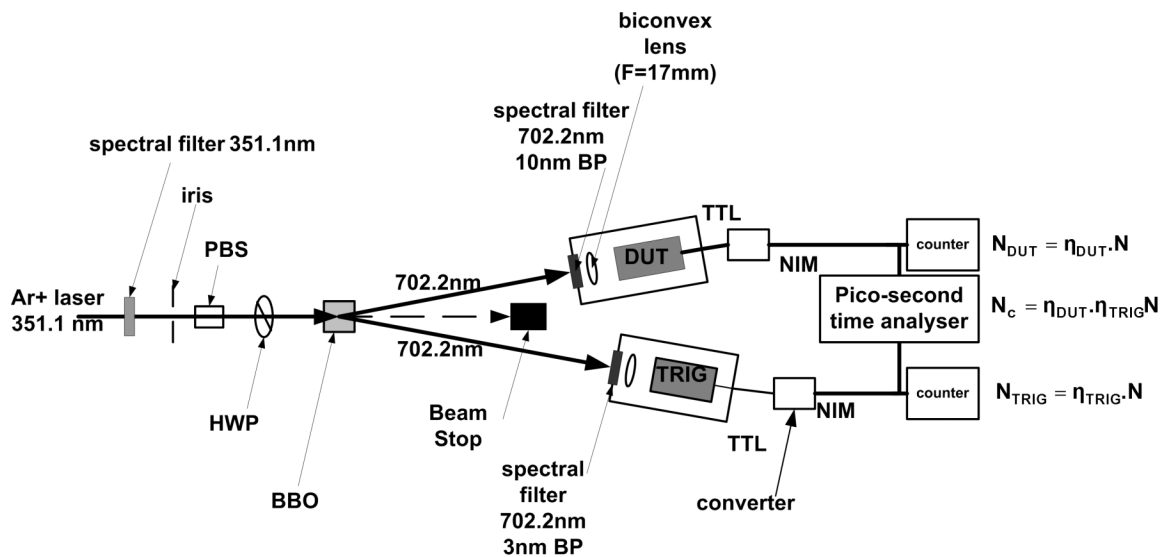


Figure 1. Schematic of q.e. measurement using the correlated photon technique, N_{DUT} and N_{TRIG} = the number of photons counted on each detector, N = the number of photons pairs emitted by the crystal, N_c = number of coincident photons measured by time-analyser, BBO = barium beta borate downconversion crystal, HWP = half-wave plate, PBS = polarising beamsplitter. When a photon is detected the detectors output a TTL pulse which is converted into a NIM pulse to be compatible with the counting electronics. In this diagram, degenerate downconversion, i.e. signal and idler photons having same wavelength, is being used.

The following represents a calculation of the quantum efficiency of the detector:

$$\eta_{DUT} = \frac{N_C - A_C}{T_{DUT}(N_{TRIGGER} - D_{TRIGGER})} \quad (1)$$

N_C is the number of coincidences, A_C the number of accidental coincidences, T_{DUT} the transmittance losses in DUT channel, $N_{TRIGGER}$ the number of photons detected by the trigger, $D_{TRIGGER}$ the number of false triggers.

The transmittance T_{DUT} includes the transmittance of the downconversion medium, focussing optics, filter, and losses due to misalignment or aperturing, as well as losses in the electronic chain³⁻¹⁰. All of these components can be measured with high accuracy using existing facilities at NPL^{6,7,11}.

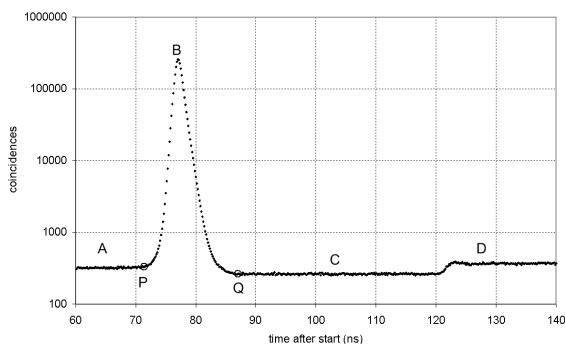


Figure 2. Histogram of coincidence counts versus time interval between trigger and DUT pulses. The DUT pulses are artificially delayed by 74 ns to compensate for the timer deadtime.

Figure 2 shows a typical histogram of coincidences. The evaluation of the true number of coincidences as given by the numerator of equation (1) requires a detailed analysis of this curve, and involves effects such as detector after-pulsing, and detector and timer deadtime⁷.

Taking into account the optical and electronic uncertainties, at the time of writing the technique has an overall uncertainty of 0.36% with the dominant uncertainty being that due to the non-uniformity of the transmittance losses of the crystal. An overall uncertainty of 0.06% should be achievable with current capabilities if a downconversion medium with better uniformity could be used, and work is in progress to investigate this.

Current and future work

Work for an in-house comparison against measurements traceable to the NPL cryogenic radiometer is currently underway and progress will be reported at the meeting. The spatial uniformity of any detector used in such a comparison is a critical component. Figure 3 shows the uniformity in one example of a Perkin-Elmer SPCM detector. The variation of around 0.5% in the central region may limit the level at which a comparison can currently be carried out, even if the techniques are

expected to have a higher accuracy.

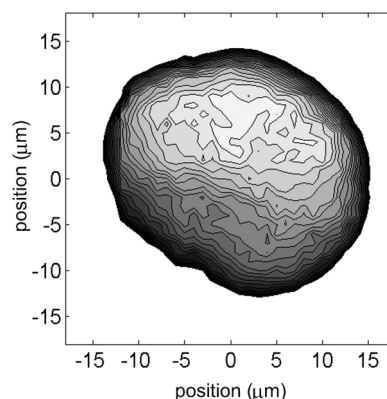


Figure 3. Contour plot of response of a photon-counting detector over the central region where the normalized response varies between 0.95 and 1.0. Each contour corresponds to 0.0025 units.

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