

Towards Quantum Based Metrology for Photonic Technologies

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Quantum optical information technologies such as key distribution systems for secure communications, which are based on the discrete and quantum properties of photons, are now commercial products. Market take-up of these and other developing quantum technologies will be compromised unless there are traceable measurements to validate the performance of these devices. We highlight some ongoing collaborative research that will provide the required high accuracy techniques for the few and single photon regime, including operation at telecom wavelengths.

This overview of ongoing collaborative research to develop a metrological infrastructure for quantum optical technologies addresses the fact that these technologies are based on the discrete and quantum properties of photons. We discuss progress in developing a technique for calibrating photon-counting detectors, the measurement of the uniformity and linearity of such detectors, and the development and characterisation of a new source of correlated photons operating in the telecom band. These topics also illustrate the mixture of ‘classical’ and ‘quantum’ techniques required to develop metrology for this field.

Measurement of detector quantum efficiency

NPL has been developing a technique which can provide an absolute calibration of detector quantum efficiency (q.e.) in the photon counting regime, using correlated photons produced via spontaneous parametric down conversion (SPDC) in non-linear media¹. The uncertainty with which the technique is currently realized is believed to be better than 1%^{2,3}.

NPL is collaborating with the Czech Metrology Institute (CMI) to measure the detection efficiency of a photon counting detector using a conventional trap detector and a CMI/NPL–developed switched integration amplifier (SIA)⁴. This will enable a comparison to be made with the correlated photon technique. The trap detector has been calibrated against the current, conventional primary standard for optical radiation, the cryogenic radiometer.

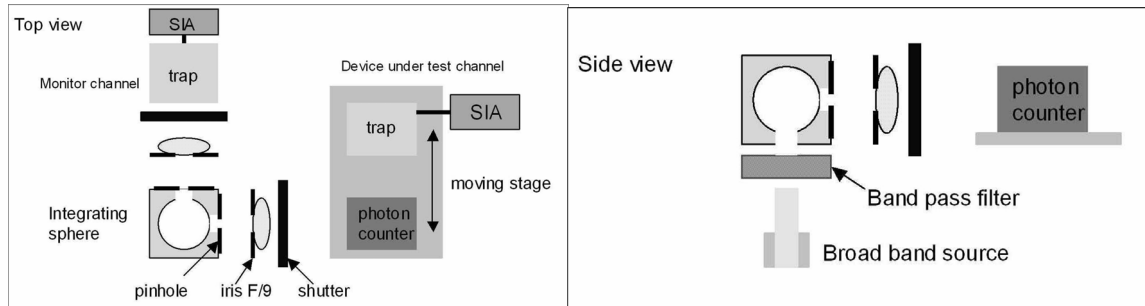


Figure 1 – set-up for ‘classical’ measurement of quantum efficiency

The trap detector has close to 100% external detection efficiency and near unity spatial uniformity. It also has a large active area, being comprised of three ~ 10 mm square photodiodes. It is typically used with a transimpedance amplifier (TIA) and allows high accuracy measurements in the high photon flux regime, typically 10^{12} photons s^{-1} (mW). The noise floor (~ 60 fA at amplifier gain 10^9 V/A) of this combination limits its use to the high power regime.

The SIA offers a number of significant advantages over the TIA for operation with large capacitances at low power levels and high gain above $\sim 10^7$. There is no Johnson noise from a large feedback resistor, and noise due to the shunt resistance of the detector is averaged over many integration cycles. In addition, for detectors

such as large area silicon photodiodes (~ 18 mm square) and trap detectors which have a high capacitance, the SIA does not have the susceptibility to oscillation that the TIA exhibits. The high gain ($10^9 - 10^{12}$), low noise (<10 fA at amplifier gain 10^{11} V/A) performance of the SIA enables a reference trap detector to be used at low power levels (50,000 cps).

In preparation for this comparison, we have investigated the noise characteristics of a cooled trap detector with an SIA. The objective is to improve the ability of the trap detector to measure a low photon flux by reducing the dark current. Two trap detectors were temperature stabilized and the dark current was measured at a range of temperatures. The temperature stability of the diodes was better than 0.1 K, measured using a Tinsley bridge and Rh-Fe connection to the trap photodiodes. The temperature stabilization minimizes the signal long-term drift and this can be critically important for low photon measurements.

The dark current measurements were carried out overnight in an enclosure to shield the traps and SIAs from variations in the lab temperature. Figures 2 and 3 show the expected exponential temperature dependence of the dark current (Hamamatsu data sheet⁵). In figure 3 we can see the saturation level of the trap and SIA combination due to the high gain setting of 10^{11} .

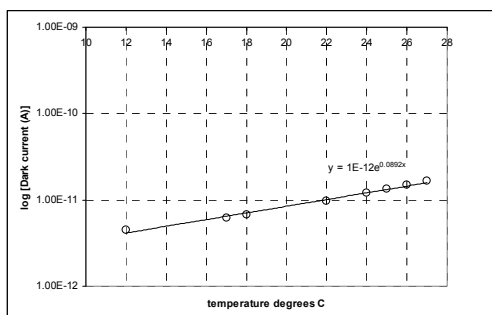


Figure 2 : Temperature dependence of trap1 with SIA gain 10^9

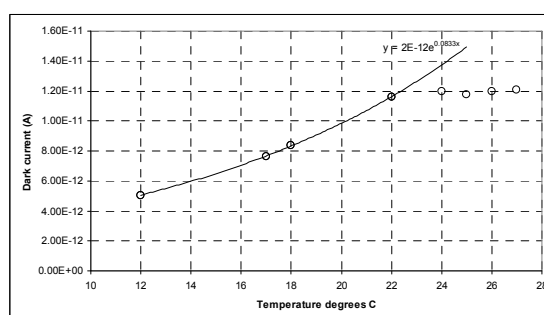


Figure 3: Temperature dependence of trap2 with SIA gain 10^{11}

The noise floor of the detectors was also measured at the different temperatures. The noise floor was determined by taking a moving standard deviation over the dark current data over an interval window of ~ 10 minutes. The results (not shown) demonstrated that the noise, ~ 10 fA, did not vary significantly with temperature. This could be due to the fact that noise due to the shunt resistance of the detector is averaged over many integration cycles, i.e. any change is averaged out, or because the SIA is the dominant noise source. In the latter case the most likely causes are temperature fluctuations causing changes in the integrating capacitor and/or bias current. The change in voltage across the shunt resistance when switching from readout to integration mode may also have some effect. Further investigations are planned.

The results of the conventional calibration, and any further characterisation of the SIAs, will be reported.

Measurement of detector uniformity and linearity

The spatial non-uniformity is a critical aspect of the cross validation as we cannot be sure that we are irradiating the same area of the detector in the two techniques. The linearity of a detector must be measured to assess the true photon flux arriving at the detector.

The NPL spatial uniformity and linearity facility has recently been upgraded to allow operation in current mode and photon-counting mode. The facility uses aluminium coated reflective optics (OAP mirrors), which allow it to operate at wavelengths down to 200 nm. Wavelength selection is by narrow bandpass interference filters. The longest wavelength it can currently operate at is 20 μm . This limitation is only due to the bandpass filters being used. Pinholes whose diameters range from 22 μm to 2 mm are being used to generate spots of identical diameters on the active area of the test detector. The probe spot is progressively moved on the active area of the test detector so the responsivity of the detector is sequentially mapped. The linearity capability incorporates the use of a double-aperture system. The operation of the facility is fully automated and has been used to evaluate the spatial uniformity of response of various types of detectors before selecting the best detector samples.

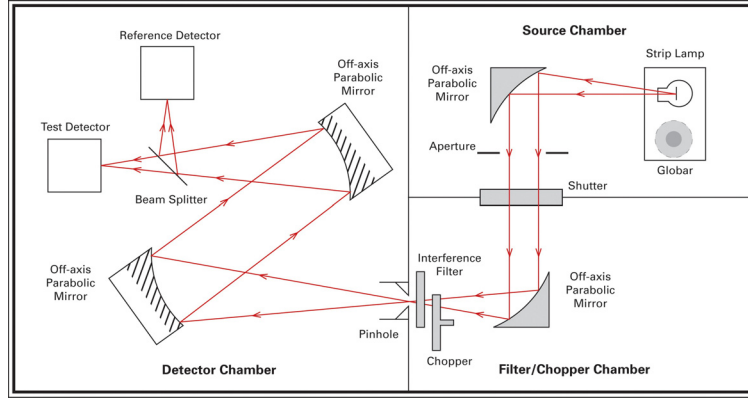


Figure 4 : NPL Spatial uniformity of response measurement facility

The figures below are examples of spatial uniformity maps of two off-the-shelf photon counting detectors with active areas of 5 mm diameter and 200 μm diameter respectively, carried out at 633 nm.

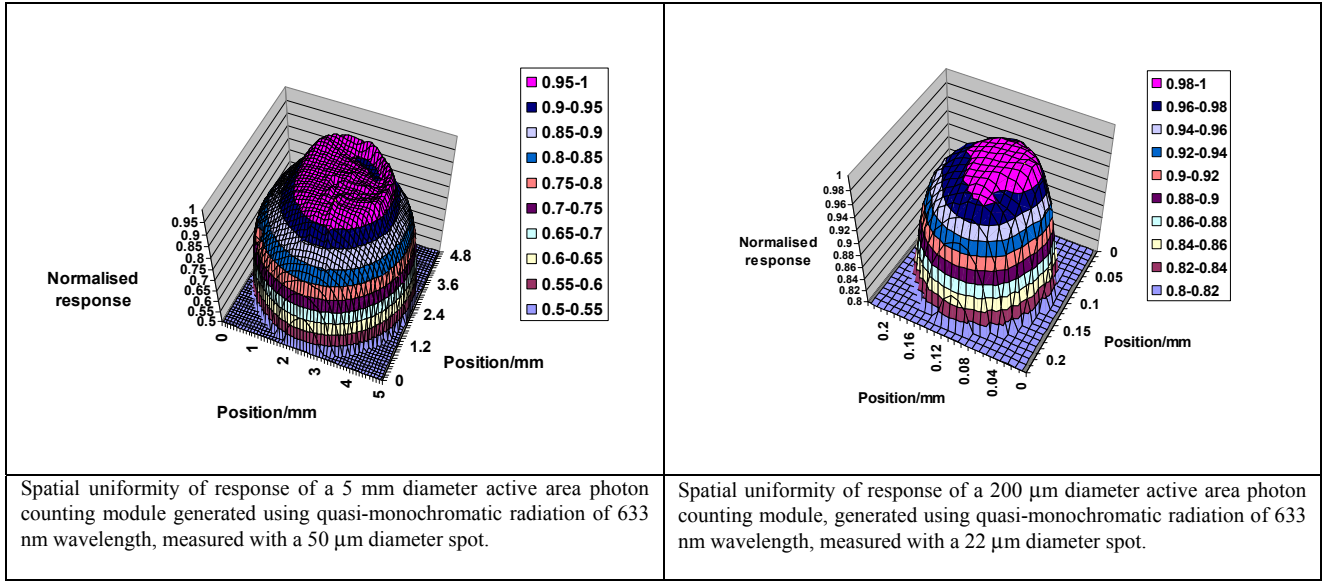


Figure 5: NPL Spatial uniformity of response measurement facility

The facility is currently being used to assess the uniformity and linearity of infrared photon counting detectors operating in the 1064 nm region, and these results will be presented at the conference.

A new source of correlated photons for the telecom wavelength region

Most of the work with SPDC sources has been in the visible/near-infrared region because of the high performance of silicon avalanche photodiode detectors. There is, however, a demand for telecoms wavelength correlated photon sources for use in quantum schemes using distributed fibre networks, and improvements in detectors for this spectral region are making telecoms wavelength experiments more tractable.

In collaboration with the University of St. Andrews, an optical resonator pump-enhanced high-flux source of correlated photons in the telecoms region has been built using periodically-poled potassium titanyl phosphate (ppKTP) as the downconversion medium. Degenerate, orthogonally polarized photons pairs produced at 1584 nm can be coupled into a single spatial fibre optic mode at a rate estimated to be $\sim 6.2 \times 10^4 \text{ s}^{-1} \text{ mW}^{-1}$ pump power using the optical cavity, giving an order of magnitude improvement on the generation efficiency relative to the non pump-enhanced setup.

A half-wave plate was used to rotate the polarization of one of the pair photons, and Hong-Ou-Mandel (HOM) interferometry⁶ was used to characterize the indistinguishability of the resulting photon pairs. The measured HOM dip visibility was $(77.8 \pm 1)\%$ when the interferometer was sourced by pump-enhanced generated photons and $(77.1 \pm 6)\%$ for the photons generated in the absence of the cavity. The HOM measurements suggests that the inclusion of the pump enhancement cavity does not degrade the suitability of the correlated

photons for quantum mechanical experiments. The design and characterisation of the source will be further described. Work is currently under way to incorporate of the source into a device that generates polarisation entangled photons.

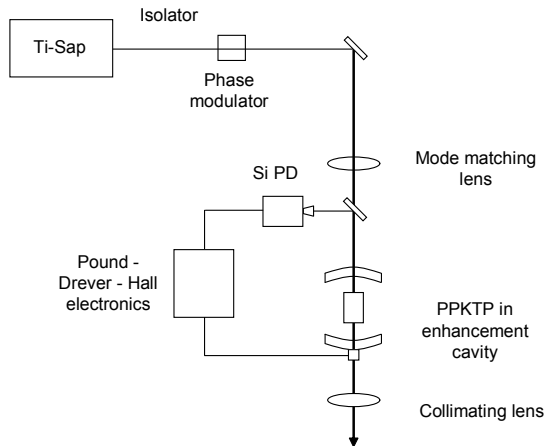


Figure 6. Schematic of pump enhanced source

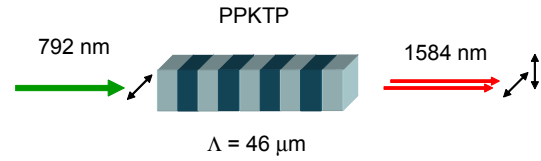


Figure 7. Phase-matching configuration for pump enhanced source

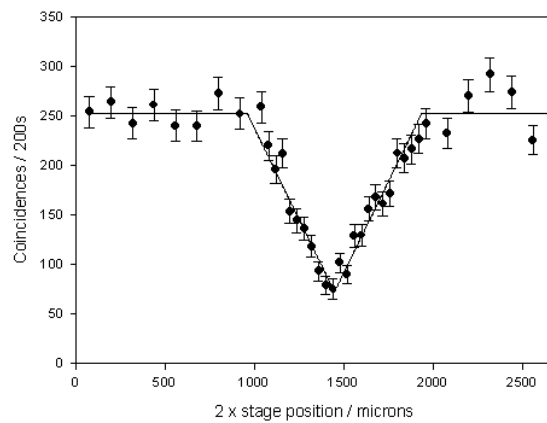


Figure 8. Measured HOM interference from pump enhanced source

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Acknowledgements

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