Absolute Quantum Efficiency Measurements Using Correlated Photons: Toward a Measurement Protocol

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***Abstract*—Correlated photons can be used to measure the quantum efficiency of photon counting photodetectors without ties to any externally calibrated standards. We present a study of measurement systematics aimed at reducing the measurement uncertainties to the 0.1% level, and developing a robust measurement protocol.**

***Index Terms*—Photodetectors, quantum efficiency, radiometry.**

I. INTRODUCTION

CORRELATED photons have been demonstrated to be useful as tools to make inherently absolute measurements of detector quantum efficiency [1]–[3]. Developing such techniques, that are intrinsically absolute and can thus be considered a primary standard method independent of existing standards, is an important goal of metrological research. As is frequently found in metrology, the implementation of any new method, whether inherently absolute or not, requires a deep understanding of the physical processes and measurement systems involved. Correlated photon-based radiometry is no exception to this rule. In this paper, we explore the measurement technique with the goals of reducing the ultimate measurement uncertainty and developing a robust measurement protocol for making high accuracy measurements. Such a protocol is required to realistically move this technique out of the metrology lab and into the hands of the end user, where its absolute nature can be exploited fully.

II. MEASUREMENT PRINCIPLE

The process of optical parametric downconversion [4], [5] is used to create the correlated pairs of photons that allow one to make absolute determinations of detector quantum efficiency. In this process, a nonlinear crystal allows photons from a pump laser to be converted into pairs of photons under the constraints of energy and momentum conservation (1), (otherwise known as phase matching)

$$\omega_{\mathrm{p}} = \omega_1 + \omega_2 \quad \text{and} \quad \vec{k}_{\mathrm{p}} = \vec{k}_1 + \vec{k}_2 \tag{1}$$

where ω_{p} and $\vec{k}_{\mathrm{p}}$ are the frequency and wave vector (within the crystal) of the pump, and similarly ω_i and $\vec{k}_i$ refer to a pair of down-converted output photons where $i = 1, 2$.

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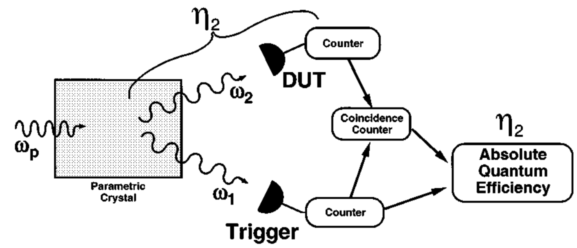

Fig. 1. General quantum efficiency measurement scheme. Downconverted output photons are shown heading for the DUT and the trigger detector. The determined quantum efficiency, η_2 is the efficiency of the entire path from creation of the photon in the crystal to its detection by the detector.

It is the simultaneous creation of two photons that allows absolute measurements to be made without relying on external standards. Since the photons are created in pairs, the detection of one indicates, with absolute certainty, the existence of the other, and because of the phase matching constraints, the directions of each of the photons can be predicted with high certainty also. The quantum efficiency measurement is made by placing a detector to intercept some of the downconverted photons (see Fig. 1). This detector (1) acts as a trigger indicating the existence of the second photon. A second detector (2), the detector-under-test (DUT), is placed so as to collect the photons correlated to those seen by the trigger detector. The absolute detection efficiency of channel 2, η_2 is then simply given by

$$\eta_2 = \frac{N_{\mathrm{Coinc}}}{N_1} \tag{2}$$

where N_{Coinc} and N_1 are the number of coincidences and trigger events (channel 1) recorded in a given time period. These are easily derived from the following definitions:

$$\begin{aligned} N_1 &= \eta_1 N \\ N_2 &= \eta_2 N \\ N_{\mathrm{Coinc}} &= \eta_1 \eta_2 N \end{aligned} \tag{3}$$

where
- N_2 number of counts recorded in channel 2;
- η_1 efficiency of channel 1;
- N number of photon pairs emitted by the crystal.

It is important to realize that (2) yields not the quantum efficiency of the DUT alone (η_{DUT}), but rather the quantum efficiency of the entire detection channel from where the photon is created within the crystal to where the detection is actually recorded. Any losses within the crystal or in the optical collection system are included in η_2 along with the efficiency of the detector to be measured. (Also implicit in the above definition is the assumption that both detectors see photons of the same pairs.) It is the proper handling of this reality that is the key to turning this measurement principle into a truly useful metrological technique.

In addition to effects related to optical collection, there are two other effects that must also be considered—determination of the true trigger rate and determination of what constitutes a coincidence event. We discuss each of these effects and their handling in Section III.

III. Systematic Effects and Their Quantification

"Proper handling" of optical collection is achieved via two tactics. First, the system is designed to maximize the collection of all photons correlated to those seen by the trigger detector. Then, any residual collection losses that cannot be designed out of the system must be carefully measured or estimated. The uncertainty of this residual loss will determine the ultimate limit of the uncertainty of the final detector quantum efficiency.

The collection system losses fall into two categories. They may be conventional transmittance losses, such as those due to reflectance or absorptance of materials or surfaces; or they may be geometric in nature, such as those due to limiting irises or detector areas or positioning. (These losses could alternatively be described by the terms homogenous and nonhomogenous.) The first of these types may be handled straightforwardly; the transmittances of optical components can be measured conventionally with high accuracy, or some losses, like reflective losses of the downconversion crystal, can be calculated with good results. It has been proposed and implemented for a related application, that these transmission losses could even be measured in-situ [6], (although it has yet to be implemented for correlated photon based quantum efficiency measurement). That is, by having two identical sets of collection optics, one could measure individual component transmittances by appropriate swapping of components in the beam path. One must, of course, be careful to do this in such a way that beam paths are not deflected. One benefit of this arrangement, other than the fact that it keeps the whole detector calibration a self contained operation, is that it automatically measures the transmittance of the optical component, in precisely the spectral band of interest for the detector calibration.

The second of the collection loss types, those due to geometry, are somewhat less straightforward to consider. These types of losses arise from two possible causes. First, and most trivially, the detector under test may be misaligned with the center of the path of photons correlated to those seen by the trigger. A second geometric loss can occur because there exists a spread of emission positions and directions of the photons correlated to those seen by the trigger detector. These spreadings occur for several reasons. Since the pump beam and downconversion crystal each have finite extent, the source of the downconversion light has finite extent. So any collection system must be able to collect light from a range of positions in space.

Angular spreading also results from a variety of causes. It turns out, that for a finite downconversion region, the phase-matching equation (1) does not have to be strictly met. That is $\Delta\vec{k} \equiv \vec{k}_1 + \vec{k}_2 - \vec{k}_{\rm p}$ does not have to exactly equal zero. A function $\Phi(\Delta\vec{k})$, can be derived to represent the relative intensity of the downconverted light output as a function of direction, having the value of 1 for $\Delta\vec{k} = 0$ and falling to 0 for large $\Delta\vec{k}$. See [7] for more complete details. In general, the longer the downconversion crystal or the wider the pump beam diameter, the smaller the range of $\Delta\vec{k}$ and associated range of output angles producing significant downconverted output. A second source of angular spreading arises specifically from the pump beam having finite diameter. This finite extent means the pump beam itself has a range of k-vector directions, leading to a smearing of the output light directions.

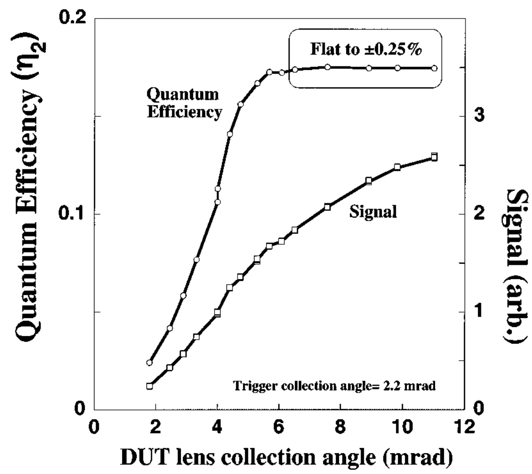

Fig. 2. The apparent quantum efficiency of the DUT and its singles count rate are shown as the DUT collection lens iris is varied with the trigger detector collection angle fixed at 2.2 mrad. The quantum efficiency points are the mean of several individual measurements, with the standard deviations being slightly smaller than the point size shown.

The finite spectral bandwidth of the light seen by the trigger determines the bandwidth of the correlated photons in channel 2 via (1). Thus, it is important to make sure that any frequency selective elements in channel 2 are broad enough to include all correlated frequencies. This finite spread of frequencies also results in a spread of angles that must be collected by the optics system in channel 2. Thus, the finite spectral bandwidth of the trigger channel puts constraints on both the spectral bandwidth and geometric collection parameters of channel 2.

Regardless of their causes, these geometric collection losses must be verified experimentally to ensure that the fraction of correlated photons outside the acceptance angle of the DUT is small and known to the desired level of uncertainty. Fig. 2 shows the results of such a test. In this instance, a collection angle of 6 mrad is required for the quantum efficiency to be determined to within a spread of $\pm 0.25\%$. A complementary measurement can also be made for added verification of this result. By fixing the DUT collection angle at the beginning of the flat region (~ 6.5 mrad), and varying the trigger collection angle, one can see a constant quantum efficiency below 2.2 mrad and falling quantum efficiency for larger trigger collection angles.

It is clear from (2) that an accurate trigger rate is needed to accurately determine quantum efficiency. Since the method depends on trigger detector output pulses indicating the existence

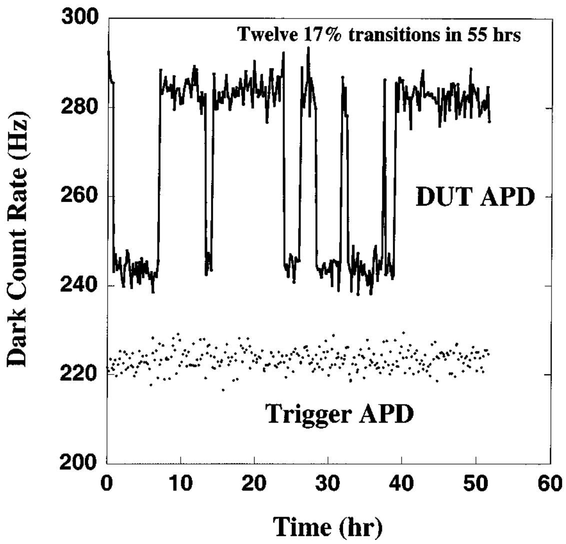

Fig. 3. Stability of the dark count rates of the trigger and DUT APDs. Measurement time per point was 50 s. The DUT shows a bistable level.

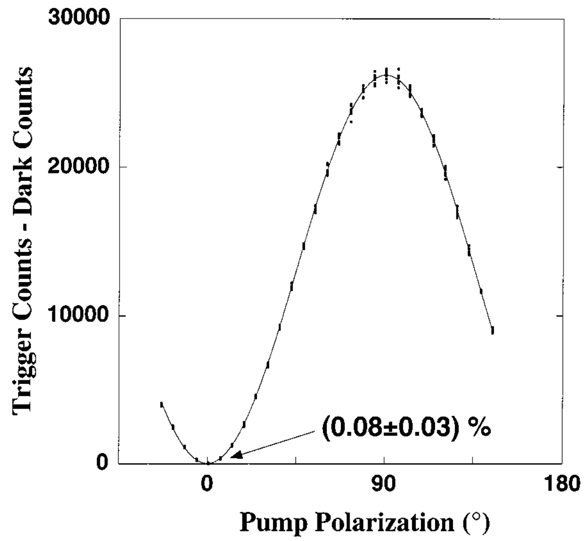

Fig. 4. Optical signal seen by the trigger detector as the pump polarization is rotated. After subtracting the detector dark counts the minimum signal level is $(0.08 \pm 0.03)\%$ $(k = 1)$ of the maximum signal.

of a correlated input photon, we must be able to accurately determine and remove any output pulses not due to the input photons of interest. The most obvious source of these pulses is detector dark counts. These are determined by recording the detector count rate with all light blocked. Fig. 3 shows measurements over an extended period of time of the dark counts of the trigger APD (avalanche photodiode) as well as the DUT. The trigger APD shows a stable value that is easily accounted for. The DUT, in this instance, shows a dark count rate that is bistable with random switches over time. While the dark counts of the DUT are not as critical to the measurement as the trigger dark count rates, it is important to note that such effects are possible with these types of detectors and, thus, the dark count rate should be monitored throughout the measurement period.

This dark count measurement does not determine all false triggers. It is also possible that some false triggers may result from light other than that due to the down conversion process. For example scattered pump laser light may result in a trigger. This could best be tested if one could turn off the downconversion process, while keeping all other light scattering fixed. There are two ways to approximate this condition. First, by blocking the pump beam just before it enters the downconversion crystal. Any upstream light scattering would remain to be measured, but any downstream scattering such as crystal surface scattering would not be measured. A second method allows this additional scattering to be determined. By placing a half-wave plate in the pump beam just before the crystal, it is possible to rotate the pump polarization by $90°$, thus turning off the downconversion, while retaining all other scattering (see Fig. 4). This is possible because the phase matching process, for a given configuration, occurs for only one pump polarization.

The minimum signal level seen in Fig. 4 (0.08% of the maximum signal) shows that it is possible to attain very low levels of unwanted light in the trigger channel. Care must be taken in making this measurement, as it is possible to overestimate the level of scatter. If the purity of the polarization of the pump beam at the waveplate is poor, the downconversion process

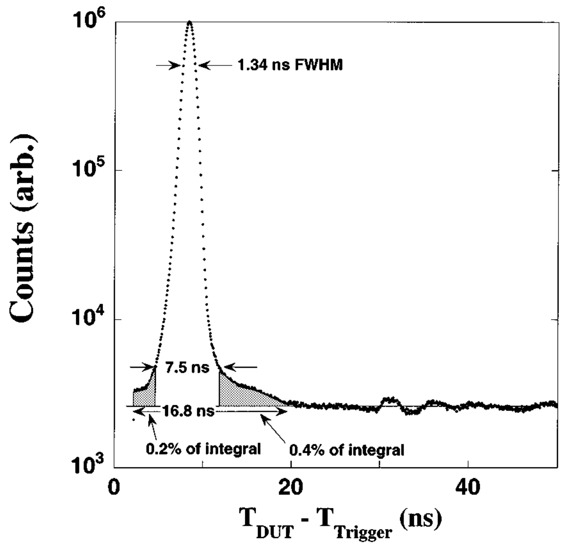

Fig. 5. Histogram of time intervals between firings of the trigger $(T_{trigger})$ and the DUT (T_{DUT}) detectors. Integrals of sections of the tails are given relative to the total integral of the peak.

will not be completely turned off at the minimum point on the curve, raising the minimum level. This can be verified directly by monitoring the coincidence level at this minimum point. In the case of the data of Fig. 4 the minimum coincidence rate was $(0.007 \pm 0.007)\%$ of the maximum rate, indicating high polarization pump purity. This low coincidence rate is not significant for the current measurements.

A second, less obvious systematic effect is due to the electronic determination of the what constitutes the detection of a photon correlated to a trigger photon. This is typically done by sending the two detector outputs to the start and stop inputs of a time-to-amplitude converter (with a fixed delay in the stop channel line for convenience of measurement) and binning the results. Uncorrelated firings of the two detectors result in a flat histogram, while correlated firings produce a peak at some fixed value. Fig. 5 shows a typical histogram of the intervals between counts of the trigger and DUT. It is clear from this semilog display that the correlation peak has long tails (extending for more than ten times the FWHM) requiring careful setting of a coincidence window width. In addition, there can be artifacts in the baseline such as those seen at a delay of about 33 ns. While the origin of those may not be known, their size and contribution to the final uncertainty can be directly determined from the data.

IV. Conclusion

We have presented a number of systematic effects that must be considered to allow this method to achieve its highest accuracy. In addition, we have shown ways to measure the size of each, so that their impact on the final uncertainty can be known with high confidence. (In these instances, uncertainties near 0.2% are verified.) By documenting these types of effects and showing how they can be directly determined (i.e., without resorting to measurements external to the method), we are building toward a protocol that will allow the method to be moved out of the metrology lab and into the user community, where the end user can take maximum advantage of this inherently absolute measurement technique.

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