XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

TOWARDS THE IMPLEMENTATION OF A SINGLE-PHOTON DETECTOR ABSOLUTE CALIBRATION SYSTEM WITH CORRELATED PHOTON-PAIRS

T. Ferreira da Silva [1*], I. B. Couceiro [1], H. P. H. Grieneisen [1], J. P. von der Weid [2]

[1] National Institute of Metrology, Standardization and Industrial Quality, Duque de Caxias, Brazil,
[2] Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil
[*] tfsilva@inmetro.gov.br

Abstract − An experimental system using correlated photon pairs for absolute measurements of single-photon detectors quantum efficiency has been set up at the Brazilian National Institute of Metrology (INMETRO). The establishment of this methodology is of special significance for the absolute calibration of detectors, especially for near infrared range as an alternative to the conventional radiometric methods. This paper describes the preliminary implementation of this absolute calibration method. Our first experimental results are reported and the optimization of the system is pointed out for obtaining further improvements the near future.

Keywords: single-photon detectors absolute calibration, time-correlated photon pair source, type-I parametric down-conversion.

1. INTRODUCTION

The capability of detecting a single-photon is an attractive possibility not only for the field of metrology [1] but also for quantum communications and photonic-based quantum computation [2]. In this way, single-photon detectors have been extensively studied in the last decades, with especial interest on the single-photon avalanche detectors (SPAD) [3] which are commercially available.The process of spontaneous parametric down-conversion in nonlinear bulk crystals has been explored for optical measurements, such as for calibration of optical radiation sources and quantum efficiency of photodetectors without the need of a reference to any other calibration standard [4-9]. Such techniques rely on the time-correlation property of the photons in pair generation within the crystal, such as β-Barium Borate (BBO). In this process, the detection of one photon indicates not only the existence of the other photon but also its direction and energy, as the pairs obey conditions of energy and momentum conservation. It is this particular property which allows for the determination of the absolute detector quantum efficiency.

With the value of this parameter it is possible to calibrate classical photodetector in a comparative measurement. It represents an alternative to traditional methods like the cryogenic radiometer [10].

2. PARAMETRIC DOWN-CONVERSION

Parametric down-conversion (PDC) is obtained from the nonlinear interaction of light from a pump beam within a nonlinear crystal like a BBO, KTP or periodically-poled $LiNO_3$. Depending on the relative polarization between the pump beam and the optical axis of the crystal, some pump photons can be absorbed and a pair of photons emitted, obeying the phase-matching condition. The photon pair is generated agreeing with the energy conservation

$$\omega_s + \omega_i = \omega_p \qquad (1)$$

where ω_s, ω_I and ω_p, are the frequencies of the signal and idler photons and of the pump beam, respectively.

In type-I PDC, the pump beam is focused into a $\chi^{(2)}$ medium with its polarization parallel to the plane containing the direction of propagation and the crystal axis. The down-converted photons exit the crystal with orthogonal polarization in respect to the pump.

For this work the BBO crystal was cut in such way that both photons generated have the same frequency (degenerated case).

3. TIME-CORRELATED PHOTON-PAIRS SOURCE

3.1. Experimental setup

As already reported by other institutes and research centers [4-9], photon pairs are generated by a heralded photon source, in which a photon from a time-correlated pair heralds the presence of the other, as shown in Fig. 1.

A cw-laser diode at 406 nm (LD) with 30 mW is focused into a β-Barium Borate crystal (BBO) by a 30 mm doublet achromatic lens (L_1) after passing through a 1 mm aperture iris and two plane mirrors (M_1 and M_2). A half-wave plate (HWP) is inserted between the laser and the crystal allowing by rotation to switch on or off the parametric down-conversion. The crystal of 10x10x5 mm³ size (width, high, length) has its optical axis cut at 28.9º (θ) and is provided with an anti-reflective coating for 406 and 812 nm at both input and output ports.

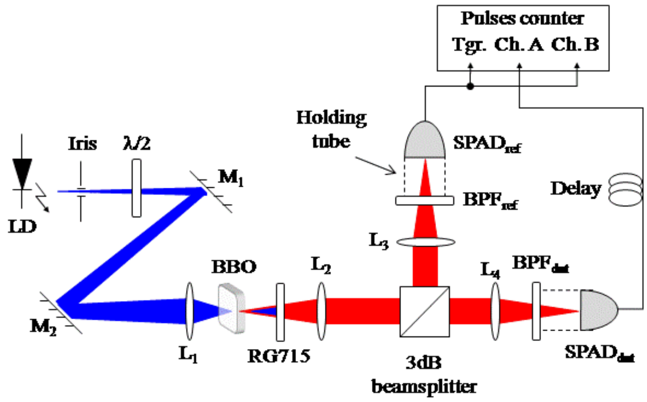

Fig. 1. SPAD quantum efficiency absolute calibration system.

At the BBO output, the pump beam signal is absorbed by a colored glass high-pass filter (RG715) and the collinearly generated 812 nm degenerated photons are collimated by a 40 mm doublet achromatic lens with an anti-reflection coating for 700-1000 nm (L_2). As the emerging PDC cone has a very small aperture angle, we chose to use a 3 dB beam splitter (BS) in order to separate the twin photons probabilistically. At each output port, the photon is focused by lenses identical to L_2 (L_3 and L_4) into a silicon single-photon avalanche detector, after passing through a bandpass interference filter (BPF) centered at 810 nm. These filters are mounted to the detectors with supporting light tight tubes, minimizing the stray light. The filters, BPF_1 and BPF_2, have been characterized, transmission of 0.695 and 0.53 with a full width at half maximum of 9.32 nm and 21.26 nm, respectively. The reference ($SPAD_{ref}$) and device-under-test ($SPAD_{DUT}$) single-photon avalanche detectors, which operate in the free-running mode, have an active area with a diameter of 170 µm. Their typical dark counts rates are 32 and 130 Hz, with a dead time of approximately 46.3 and 49.0 ns, respectively. The electrical pulses are delivered to a pulse counting module. The electrical pulses generated by the detector under test are delayed by ~40 ns with a delay line. In this way, a detection pulse by the reference detector triggers channel 1, opening a measurement window with 8 ns width at channel 2, inside which the time-correlated DUT detection pulse should fall. The delay line allow the pulse counter to set an internal relative time delay of channel 1 (DUT) to channel 2 (reference) be internally swept by the equipment. Coincidences and DUT photon counts are thus recorded.

Photography of the implemented system is shown in Fig. 2.

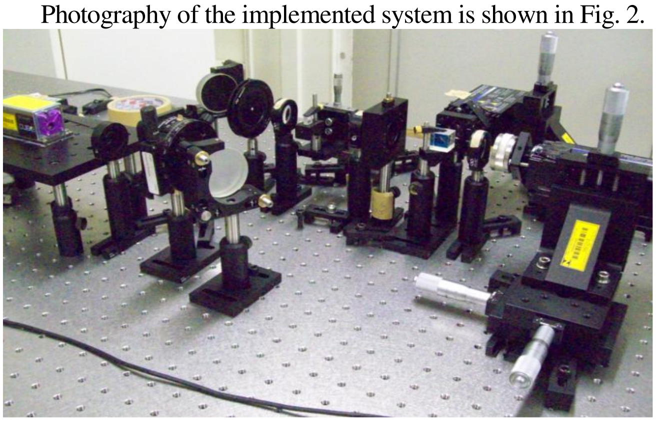
Fig. 2. Photography of the system.

3.2. Calibration method

As the photons are generated in pairs, we can correlate the existence of a probe photon to the detection of its twin at the reference SPAD. Once the reference photon is detected at the reflected output of the beam splitter, the other one will have the probability of being routed to the DUT detector ideally given by the BS transmittance. However, the loss through its optical path, due to the devices, especially the filter (BPF_1) [8] and misalignment, could erase such photon before it reaches the detector. In order to estimate such loss, two ways can be taken. One of them consists on calibrating the devices transmittances (or applying their datasheet values) as follows.

The mean numbers photon number detected at reference and at the DUT (N_1 and N_2 respectively) in a given time interval are given by

$$N_{DUT} = N\eta_{DUT}T_{BS}T_1 \tag{2}$$

$$N_{ref} = N\eta_{ref}R_{BS}T_2 \tag{3}$$

where N is the total number of photon pairs down converted by the crystal in the same time interval, η_{DUT} and η_{REF} are the quantum efficiencies of the SPADs and T_1 and T_2 represent the transmittances of the optical paths at the system branches.

As the mean number of coincident counts (N_c) is given by

$$N_c = N\eta_{DUT}T_{BS}T_1\eta_{ref}R_{BS}T_2 \tag{4}$$

one can, applying eq. (3), obtain the detector under test efficiency independently of the reference SPAD, resulting in

$$\eta_{DUT} = \frac{N_c}{N_{ref}}\frac{1}{T_{BS}T_1} \qquad (5).$$

On the other hand, the second method consists of a relative measurement, in which one branch of the system acts as a reference. The relative optical loss difference between both optical paths of the system after the beamsplitter can be evaluated and further compensated at the calculation by measuring the photon counts after both bandpass filters with the same reference photodetector. Following this, the ratio of the counts, considering the probabilistic effect of the BS, can be account by

$$\frac{N_1}{N_2} = \frac{T_{BS}T_1}{R_{BS}T_2} \tag{6}$$

where η is the efficiency of the photodetector and T_1 and T_2 are the path losses at branches 1 and 2.

Considering that T_2 = 1, the loss at branch 1 can be replaced by

$$T_1 = \frac{N_1 R_{BS}}{N_2 T_{BS}} \quad (7)$$

that, applied to eq. (4), results in

$$\eta_{DUT} = \frac{N_c}{N_{ref}} \frac{N_2}{N_1 R_{BS}} \quad (8)$$

3.3. System adjustment and measurements

Firstly each arm of the system was calibrated by placing the reference detector at the optimum focused position after BPF_1 and BPF_2 to the maximum conversion angle of the HWP. The ratio between counts at the last and the former positions refers to the insertion loss of the testing device optical path to the reference and must be considered in the further measurement results.

With the SPADs optical input covered, the dark counts were measured 60 times for 10 seconds. So, with the laser turned off, the background light was measured at both devices. The HWP was adjusted to the maximum and to the minimum of PDC in order to calculate the conversion extinction rate.

At the maximum conversion rate, the delay between the reference and the DUT detection electric pulses was swept by the pulses counter equipment in order to find the temporal correlation peak. When a photon is counted at the reference, this is registered and triggers the gate of 8 ns width for the DUT detection pulse after a set delay.

Fixing the optimum delay (16 ns from the trigger signal for the delay line used) and gate width (8 ns), there were performed 1000 measurements of 10 s acquisition of the DUT photon counts and the coincidences counts, what allowed to calculate the detector absolute efficiency.

4. RESULTS AND DISCUSSION

The independent conversion extinction rates of the branches 1 and 2 were calculated to be 86.4 and 79.4%, respectively. The coincidence rates between the twin photons according to the electrical detection signals delay are shown in Fig. 2.

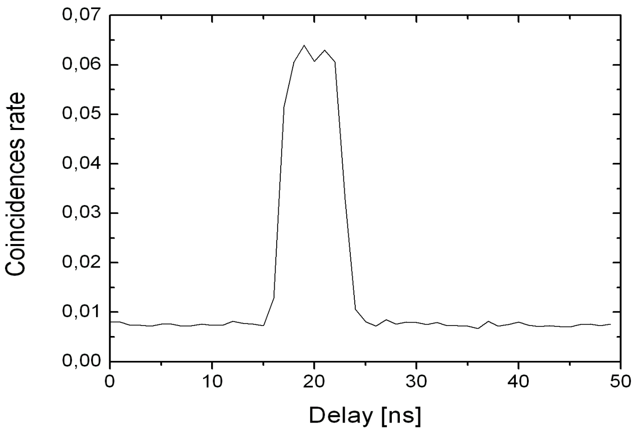

Fig. 2. Coincidence rates between photon detections at $SPAD_{ref}$ and $SPAD_{DUT}$ for different delays.

After setting the delay to match the coincidence peak, it was kept fixed for a series of 1000 measures of 10 s each. Applying eq. (5), the single-photon detector efficiency (η_{dut}) resulted in 24.79%.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

We have described a first step towards the implementation of an absolute time-correlated single-photon detectors efficiency calibration system [4-9]. The obtained SPAD quantum efficiency from measured photon counts leading to a value of 24.79% is overestimated regarding the value of the generic detectors family datasheet of around 35%. A validation measurement is request and will be done soon making use of our cryogenic radiometer is planned [10].

Some improvements are also needed and so the uncertainty budget tailoring to obtain the expanded uncertainty of this system. It is worth to noting that, according to [8], the major uncertainty contribution is due to the optical filters. Improvements concerning the shielding of the apparatus against background light in the laboratory are planned. A careful transmittance calibration of the optical devices (BPF_{DUT}, BPF_{ref}, RG715, L_2, L_3, L_4 and BS), including the BBO will be also performed.

The preliminary measurements reported indicate that the implemented system must be optimized, but still having potential to achieve an accurate result, as stated in [4-9]. Variations of this heralded photon source have applications on optical devices metrology, including fiber optic chromatic dispersion (the wavelengths and the crystal should be reviewed) [11] and optical time-domain reflectometry. SPDC also was also used for calibrate analog detectors in high photon fluxes using stimulated parametric down-conversion [12] and to absolute radiance measurements [13].

A natural evolution of the system consists on entangling the photon pairs in determined degree of freedom. This could be achieved, for example, in polarization, by placing a calcite crystal (birrefringent delay) and another BBO ninety degree rotated after the current crystal and by pumping them with a 45 degree polarization beam related to their axis. In this way, despite each photon in a pair have an indefinite polarization state, they should exhibit a strong correlation (entanglement) in the way that, measuring the polarization state of one of them, the state of the other can be predicted. Such configuration could be used for the same metrological purpose of absolute characterization of single-photon detectors [14], ellipsometry [15] or polarization-dispersion mode measurements [11, 13].

ACKNOWLEDGMENTS

The authors would like to acknowledge G. B. Xavier for helpful discussion. This work has been in part financially supported by CNPq and Finep.

REFERENCES

[1] N. P. Fox, “Primary radiometric quantities and units”, *Metrologia*, vol. 37, pp. 507-513, 2000.

[2] N. Gisin and R. Thew, “Quantum communication”, Nat. Photon., vol. 1, pp.165-171, 2007. [3] S. Cova, M. Ghioni, A. Lacaita, C. Samori and F. Zappa, “Avalanche photodiodes and quenching circuits for single-photon detection”, Appl. Opt., vol. 35, pp.1956-1976, 1996.

[4] A. L. Migdall, R. U. Datla, A. Sergienko,, J. S. Orszak and Y. H. Shih, “Absolute detector quantum-efficiency measurements using correlated photons”, Metrologia, vol. 32, pp. 479-483, 1995.

[5] A. Czitrovszky, A. Sergienko, P. Jani and A. Nagy, “Measurement of quantum efficiency using correlated photon pairs and a single-detector technique”, Metrologia, vol. 37, pp. 617-620, 2000.

[6] S Castelletto, A Godone, C Novero and M L Rastello, “Biphoton fields for quantum-efficiency measurements”, Metrologia, vol. 32, pp. 501-504, 1995.

[7] G Brida, S Castelletto, C Novero and M L Rastello, “Measurement of the quantum efficiency of photodetectors by parametric fluorescence”, Metrologia, vol. 35, pp. 397-401, 1998.

[8] G Brida, S Castelletto, I P Degiovanni, C Novero and M L Rastello, “Quantum efficiency and dead time of single-photon counting photodiodes: a comparison between two measurements techniques”, Metrologia, vol. 37, pp. 625-628, 2000.

[9] J. Y. Cheung, M. P. Vaughan, J. R. Mountford and C. J. Chunnilall, “Correlated photon metrology of detectors and sources“, Proc. of SPIE, vol. 5161, p. 365, 2004.

[10] A Ghazi-Bellouati, A Razet, J Bastie, M E Himbert, I P Degiovanni, S Castelletto and M L Rastello, “Radiometric reference for weak radiations: comparison of methods”, Metrologia, vol. 42, pp. 271-277, 2005.

[11] N. Gisin J. Brendel and H. Zbinden, A. Sergienko and A. Muller, “Twin-photon techniques for fiber measurements”, arXiv:quant-ph/9807063v1, 22 Jul 1998.

[12] G. Brida, M. Chekhova, M. Genovese, A. Penin, M. L. Rastello, I. Ruo-Berchera, “Absolute Calibration of Analog Detectors by Using Parametric Down Conversion”, Instrumentation and Measurement, IEEE Transactions on, vol. 56, Issue 2, April 2007 pp. 275 - 279

[13] A. V. Sergienko, “Quantum metrology with entangled photons”, Proceedings of the International School of Physics “Enrico Fermi”, Course CXLVI, T. J. Quinn, S. Leschiutta and P. Tavella (Eds.), IOS Press, Amsterdam, 2001.

[14] G. Brida, M. Genovese, M. Gramegna, M. L. Rastello, M. Chekhova, and L. Krivitsky, "Single-photon detector calibration by means of conditional polarization rotation ," J. Opt. Soc. Am. B 22, 488-492 (2005)

[15] A. F. Abouraddy, K. C. Toussaint, Jr., A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, " Entangled-photon ellipsometry," J. Opt. Soc. Am. B 19, 656-662 (2002)