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Measurement of quantum efficiency using correlated photon pairs and a single-detector technique

A. Czitrovszky, A. Sergienko, P. Jani and A. Nagy

Abstract. A new approach is proposed to the calibration of photodetectors and the determination of the absolute value of the quantum efficiency of photon-counting photomultipliers using entangled-photon pairs. It is based on a new single-photodetector technique and a special modulation of the entangled-photon flux. The absolute values of the quantum efficiency have been determined for several photon-counting photomultipliers.

1. Introduction

The most important tasks in quantum optics measurements include the detection of the arrival time of single photons, their time distribution, coincidences and statistical parameters. The measurement result often depends critically on the absolute value of the quantum efficiency of the photodetector. It is known that for the experimental demonstration of quantum state teleportation and for the conversion of quadrature-squeezed light into amplitude-squeezed light, the absolute value of the quantum efficiency must exceed a given threshold [1-7]. Another important problem, which cannot be solved using conventional avalanche photodiodes or photomultipliers, is the ability to distinguish between the detection of single and double photons [8-12]. The traditional approach to the calibration of the quantum efficiency of a detector is based on the use of an optical standard. This is usually a specially designed source of optical radiation, whose intensity can be evaluated from the basic physical principles, temperature, and geometry of the device.

In this paper we demonstrate the measurement of the quantum efficiency of a photon-counting photomultiplier using the entangled two-photon technique. This approach is based on the unique correlation between entangled photons generated in the non-linear process of spontaneous parametric down-conversion (SPDC) and is realized by using two photon-counting detectors and a coincidence circuit [13-17]. We report on the first practical realization of a new quantum efficiency measurement scheme that requires the use of only one photodetector. The absolute value of the quantum efficiency for the photon-counting photomultiplier is derived, based on its capacity to distinguish between single-photon and double-photon events. This information can be evaluated by measuring the pulse-height distribution.

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2. Principle of operation

The proposed technique for calibration of quantum efficiency works best for photodetectors in the photon-counting regime, as non-classical properties of light in this process are revealed with better contrast for single photons [18-21]. The photodetection process is usually characterized by the quantum efficiency value, η, that can be used as a measure of successful conversion of optical quanta into macroscopic electrical signals. If the average intensity of the photon flux (number of photons) arriving at the surface of a photodetector in a unit of time is $\langle N \rangle$, then the number of successful photodetection events will be determined by $P_1 = \eta \langle N \rangle$. The number of events when no detection occurred will, obviously, be defined by the complementary value $P_0 = (1 - \eta) \langle N \rangle$.

The principle of this technique is based on the existing strong correlation between two entangled photons in space and time, which distinguishes this effect from other processes of non-linear optics and light scattering. The presence of optical radiation consisting of rigorously correlated photon pairs with continuous distribution in a broad spectral and angular range – as a result of the non-linear parametric interaction of laser pump radiation with the non-linear crystal – makes it possible to determine the spectral distribution of the measured quantities of photodetectors.

A distinctive characteristic of the two-photon field emitted during the SPDC process from ordinary optical radiation is the fact that all photons are generated in pairs. This means that the average number of pairs $\langle N_{\rm pair}\rangle$ per unit of time is equal to the number of either the signal $\langle N_{\rm s}\rangle$ or the idler $\langle N_{\rm i}\rangle$ photons: $\langle N_{\rm s}\rangle = \langle N_{\rm i}\rangle = \langle N_{\rm pair}\rangle$.

In the case of an ideal photodetector, which can perfectly separate single- and double-photon detection events by the height of the corresponding electrical pulse, this non-classical feature of SPDC light would allow the design of a simple technique for the measurement of quantum efficiency. From the theory of photodetection, the number of double-photon events (number of double-electron pulses) will be

$$P_2 = \eta^2 \langle N_{\rm pair}\rangle.$$

The probability of observing a single-photon detection event and a single-electron pulse will apparently involve the loss of one photon from a pair. As this can occur in two different ways for every pair, the total number of single-photon detections will be

$$P_1 = 2\,\eta\,(1-\eta)\,\langle N_{\rm pair}\rangle.$$

One concludes immediately that the quantum efficiency value can be evaluated using the following formula:

$$\eta = (1 + P_1/2\,P_2)^{-1}.$$

However, the gain fluctuation and thermal noise in real photodetectors usually result in a very broad pulse-height distribution that corresponds to single- and double-photon detection events. This has stimulated the development of a more realistic version of this technique that would be efficient, robust, and insensitive to such imperfections of real photon-counting detectors.

In order to eliminate the influence of the broad pulse-height distribution, we can use a simple comparison between the numbers of registered detection events (regardless of their amplitude) counted in two special cases: (i) when the photodetector is exposed to a pair of entangled photons; and (ii) when it is exposed to signal (or idler) photons only. The total number of detections when pairs of entangled photons are arriving at the photocathode will consist of the superposition of P_1 and P_2:

$$P_{\rm pair} = P_1 + P_2 = 2\,\eta\,(1-\eta)\,\langle N_{\rm pair}\rangle + \eta^2\,\langle N_{\rm pair}\rangle.$$

The number of detections in the case of exposure to signal (or idler) photons only will be

$$P_{\rm single} = \eta\,\langle N_{\rm s}\rangle = \eta\,\langle N_{\rm i}\rangle = \eta\,\langle N_{\rm pair}\rangle.$$

The absolute value of the quantum efficiency can be evaluated based on the results of these two measurements:

$$\eta = 2 - P_{\rm pair}/P_{\rm single}.$$

A thorough study of possible sources of thermal noise in the photodetector is required in order to improve the accuracy of our measurement technique. This has been accomplished by using the special measurement procedure outlined below.

3. Measurement

The correlated photon pairs were generated by parametric down-conversion in a potassium dihydrogen phosphate (KDP) crystal pumped by an ultraviolet line

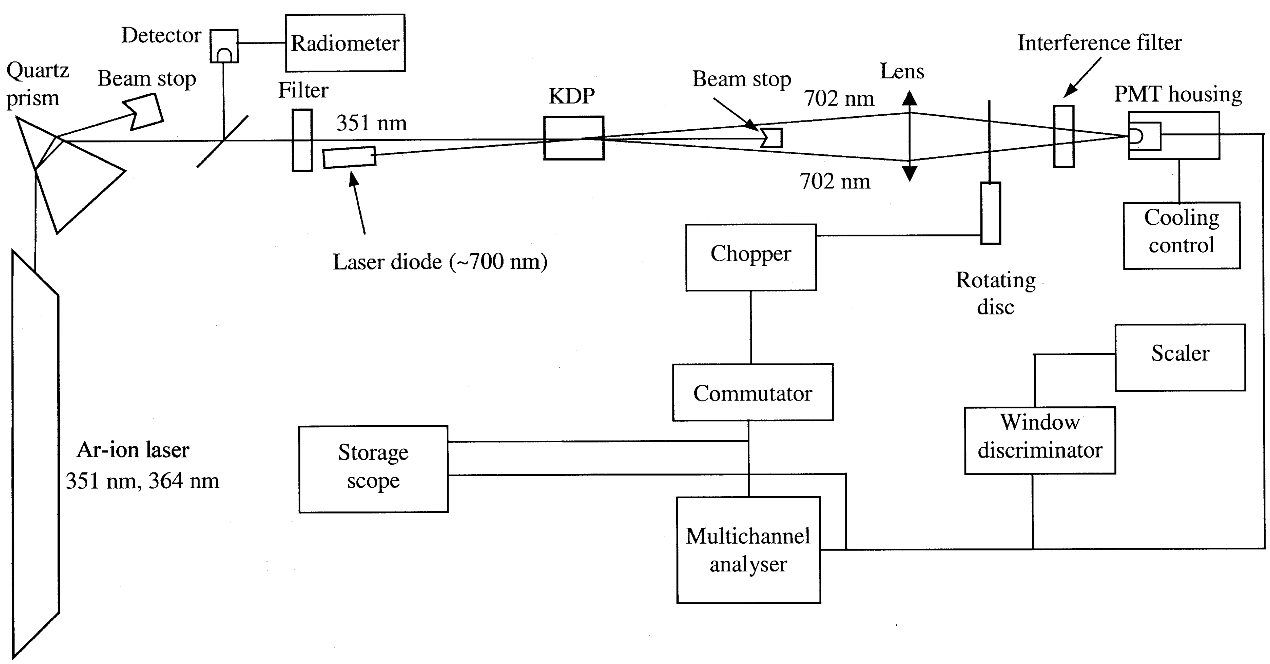

Figure 1. Experimental set-up for the measurement of quantum efficiency using a single photodetector.

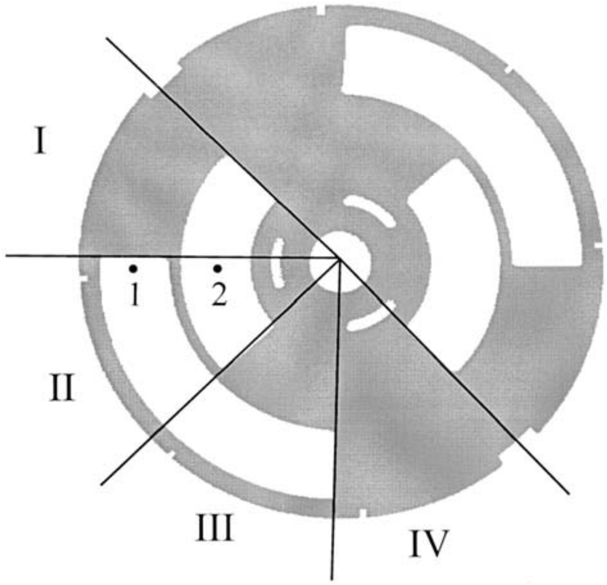

Figure 2. Rotating disc. 1: signal beam; 2: idler beam.

of an argon laser at 351 nm [16, 17] (see Figure 1). The crystal was cut at the type-I phase-matching angle (53° relative to the optical axis) to produce entangled photons of the same polarization.

The non-collinear photon pairs of the same wavelength (702 nm) were selected using two diaphragms and a narrowband interference filter. In order to reduce the level of dark counts, the photomultiplier tubes (PMTs) were placed in a Peltier cooling housing with temperature stabilization. The measurements were carried out at –10 °C.

To ensure separate registration of single and double photons arriving at the photocathode of the PMT, we performed a special modulation of the signal and idler beams using an SR540-type Stanford Research Systems chopper.

The rotating disc placed between the focusing lens and the interference filter in front of the photocathode was divided into four quadrants (see Figure 2). A special synchronous commutation of memory sectors of our 16 000-channel multichannel analyser (MCA) allows all contributions of photons from signal and idler beams separately, from the joint detection of two photons, and from noise, to be registered in different memory sectors.

The quantum efficiency value can be evaluated using the ratio between the single- and double-photon peaks in pulse-height distribution [17].

4. Results

Figure 3 shows the amplitude distribution corresponding to the detection of single- and double-electron events using the MCA.

The single-electron peak is well pronounced and the double-electron peak is also observable. In preparation for calculations of the quantum efficiency, we define the following terms: $M\,(\mathrm{i}+\mathrm{b})$ is the total number of counts in sector I (Figure 2), $M\,(\mathrm{i}+\mathrm{s}+\mathrm{si}+\mathrm{b})$ is the total number of counts in sector II, $M\,(\mathrm{s}+\mathrm{b})$ is the total number of counts in sector III, $M\,(\mathrm{b})$ is the total number of counts in sector IV (background), where i and s correspond to the single-photon rates of the idler and signal beam, respectively, b the background count rate, and si the rate of two photons detected. Statistically, in the case of good alignment, $M\,(\mathrm{i}+\mathrm{b}) = M\,(\mathrm{s}+\mathrm{b})$. The number of single counts in sector I is $\langle N_{\mathrm{i}}\rangle\eta = \langle N_{\mathrm{pair}}\rangle\,\eta$, where $\langle N_{\mathrm{pair}}\rangle$ is the photon-pair rate and η is the quantum efficiency. The number of single-photon counts in sector II is $2\,\langle N_{\mathrm{pair}}\rangle\,\eta\,(1-\eta)$, and the number of two-photon counts in the same sector is $\langle N_{\mathrm{pair}}\rangle\,\eta^2$. The number of counts in sector III is consequently $\langle N_{\mathrm{s}}\rangle\,\eta = \langle N_{\mathrm{pair}}\rangle\,\eta$. In this case, the estimator of the expectation value $M\,(\mathrm{i}+\mathrm{s}+\mathrm{si}+\mathrm{b}) - M\,(\mathrm{b}) = 2\,\langle N_{\mathrm{pair}}\rangle\,\eta\,(1-\eta) + \langle N_{\mathrm{pair}}\rangle\,\eta^2$ and $M\,(\mathrm{i}+\mathrm{b}) - M\,(\mathrm{b}) = \langle N_{\mathrm{pair}}\rangle\,\eta$. Using these two equations, the quantum efficiency value can be calculated from the following formula:

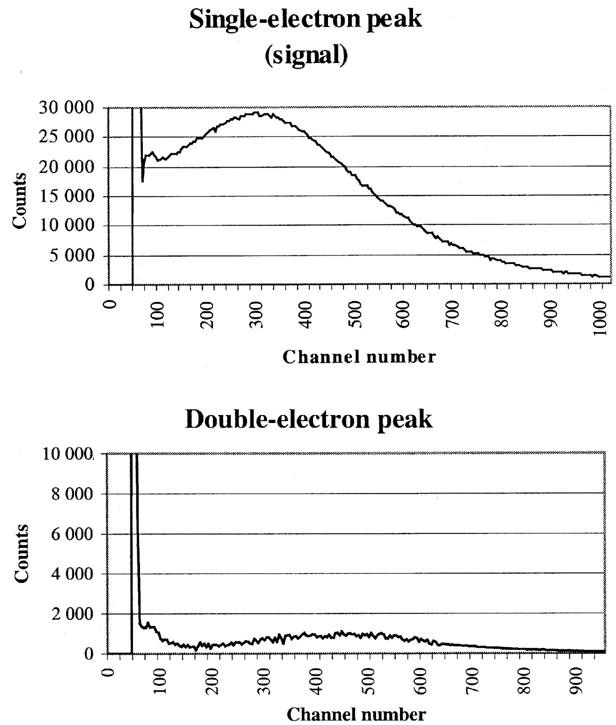

Figure 3. Amplitude distribution corresponding to single- and double-photon peak.

$$\eta = 2 - [M\,(\mathrm{i}+\mathrm{s}+\mathrm{si}+\mathrm{b}) - M\,(\mathrm{b})]\,/\,[M\,(\mathrm{i}+\mathrm{b}) - M\,(\mathrm{b})],$$

where on the right-hand side we find only the values that can be measured. This also prevents thermal background noise from contributing to the result.

During one measurement cycle, data were accumulated during 25 000 periods containing four different sectors (100 000 measurements) making the statistical variation of the measured distribution less than 1 %.

The uncertainties caused by the electronics may arise from the fluctuation of the amplitude of electrical pulses in the photomultiplier because of the short-term and long-term instability of the high-voltage (HV) source, fluctuation of the amplification of the signal in the photomultiplier, and uncertainty caused by the electronic signal evaluation. The errors caused by the instability of HV in our measurements can be neglected because the HV is stabilized to 0.1 %. This makes a much lower contribution to the pulse amplitude fluctuation than other sources. The amplification process inside the photomultiplier gives rise to a Poisson variation in the pulse height. The non-linearity of the amplifier is less than 0.1 %, the gain temperature instability is $< 50 \times 10^{-6}$/°C, the dc level stability is < 50 µV/°C, the integral linearity of the MCA is ± 0.08 %, the differential linearity is ± 0.8 %, and the temperature stability 50×10^{-6}/°C. As we calculated, the total contribution of these sources to the measurement results is less than 0.5 %. The cumulative uncertainty of the reported measurement is less than 5 %.

The quantum efficiency of two photomultipliers, types EMI 9863B/350 and EMI 9882B, has been measured to be 3 % and 2 %, respectively, at the 702 nm wavelength.

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