Research in absolute calibration of single photon detectors by means of correlated photons

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There are two general methods in radiometric calibration of detectors, one is based on radiation sources and the other based on detectors. Because the two methods need to establish a primary standard of high precision and a transfer chain, precision of the standard will be reduced by extension of the chain. A new calibration method of detectors can be realized by using correlated photons generated in spontaneous parametric down-conversion (SPDC) effect of nonlinear crystal, without needing transfer chain. Using 351.1-nm output of a tunable laser to pump β-barium borate (BBO) crystal, an absolute calibration experimental system of single photon detectors based on correlated photons is performed. The quantum efficiency of photomultiplier (PMT) at 702.2 nm is measured by the setup. Advantages of this method over traditional methods are also pointed out by comparison.

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An important aspect of radiometric and photometric research is radiometric calibration. In recent years, because of the requirements in quantitative remote sensing, radiometric calibration of sensors has been becoming a fundamental technique for ensuring precision and availability of data in remote sensing. Up to now, there are two general methods in radiometric calibrations of detectors, one is based on radiation sources and the other based on detectors[1]. The common characteristics of these two methods are that they all need to establish a primary standard of high precision, standards of different precision-classes, and a transfer chain of standard to users. Those are exactly the factors that restrain reproduction of engineering and valid improvements of precision. The precision will be also reduced by extension of transfer chains of standard.

For improving precision, we hope that absolute calibration of radiometric detectors should be established on an objective physical process, which could be reproduced accurately wherever and whenever. It does not depend on certain detector or certain transfer process. Correlated photons generated in spontaneous parametric down-conversion (SPDC) effect of nonlinear crystals make the radiometric calibrations without needing transfer of standard possible.

Since the photons emitted from SPDC are strongly correlated in direction, wavelength, and polarization, the observation of a photon of the pair in a certain direction implies the presence of the other photon in the conjugated direction. An absolute calibration of single photon detectors can be realized by utilizing coincidence measurement for the correlated photons[2]. Figure 1 is the principle sketch of this method.

Using coincidence measurement techniques, characteristics of correlated photons allow absolute calibration of single photon detector without the need for an absolute radiometric reference. Two single photon detectors are placed after the nonlinear crystal, along the propagation directions of the correlated photon pair. If N is the total number of photon pairs emitted from the crystal in a given time interval, N_{s}, N_{i}, and N_{c} are the mean numbers of photons recorded in the same time interval by signal detector, idler detector, and in coincidence measurement, respectively, we have the following relationships

$$N_{\mathrm{s}} = \eta_{\mathrm{s}} N, \quad N_{\mathrm{i}} = \eta_{\mathrm{i}} N, \tag{1}$$

where η_{s} and η_{i} are the quantum efficiencies on signal and idler paths, respectively. Owing to the statistical independence of the two detectors, the number of events in coincidence is

$$N_{\mathrm{c}} = \eta_{\mathrm{s}} \eta_{\mathrm{i}} N. \tag{2}$$

The quantum efficiencies of detectors are easily derived from the above as formulae

$$\eta_{\mathrm{s}} = N_{\mathrm{c}}/N_{\mathrm{i}}, \tag{3}$$

$$\eta_{\mathrm{i}} = N_{\mathrm{c}}/N_{\mathrm{s}}. \tag{4}$$

According to the principle above, we set up a system to calibrate photomultiplier (PMT) in our laboratory. Figure 2 shows the frame of experimental setup. Correlated photons were generated from a β-barium borate crystal (BBO, $6 \times 4 \times 12$ (mm)) pumped with a continuous wave (CW) tunable Ti:sapphire laser at 351.1 nm. The form of phase match in BBO crystal was type I. The angle between optical axis and direction of pumping laser was 36.4°. The wavelengths of down-conversion photons were 702.2 nm.

Two detectors were placed with a distance of 1.0 m from the crystal. In fact, it is very difficult to send

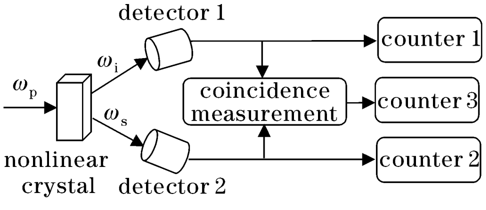

Fig. 1. Principle sketch of absolute calibration of single photon detectors based on correlated photons.

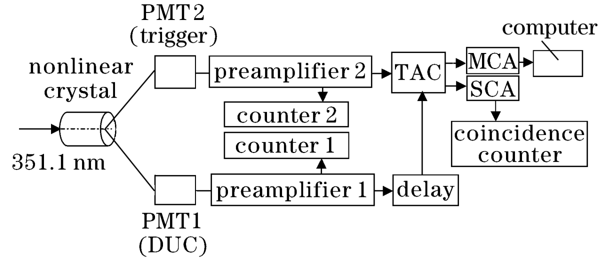

Fig. 2. Frame of the experimental setup.

two fluxes of exactly the same pairs of correlated photons to the sensitive areas of the two detectors[3]. To overcome this difficulty and obtain the needed down converted photons, we handled the two optical paths with interference filters of different bandwidths. An interference filter at 702.2 nm with 10-nm full-width at half-maximum (FWHM) was placed on the so-called trigger path while, on the path of the detector under calibration (DUC), an interference filter with 10-nm FWHM was used only for a first alignment and then removed during measurement. We also employed different irises at trigger path and DUC path. The irises had diameters of 4 and 12 mm, respectively. In such a way, symmetry of the scheme and possibility of simultaneous calibration of the two detectors were all broken. We can only measure the quantum efficiency of PMT1 on the DUC path by correlated photons.

Coincidence measurement was performed with a time-to-amplitude converter (TAC) and a multi-channel analyzer (MCA). The output pulses from two detectors were fed to preamplifiers. The output of the second preamplifier (idler) was directly sent to the "start" input of TAC. After a delay of tens of nanoseconds, the output of the first preamplifier (signal) was sent to the "stop" input of TAC. The TAC produced an output pulse with its height linearly proportional to time interval between "start" and "stop" pulses. This pulse was simultaneously fed to MCA and a single-channel analyzer (SCA). MCA produced a time-correleted histogram with the amplitude of input pulses. The time-correlated photons produced a peak corresponding to the delay of setting; on the other hand, the uncorrelated photons produced a flat background. The data were directed to computer for storage and analysis. SCA generated a standardized amplitude output pulse for each input pulse which had amplitude included in a pre-selected voltage window. By setting the upper and lower thresholds of the voltage window in SCA, we can obtain countable signal pulses for the correlated photons. Following the preamplifiers, a counter with double channels was placed to record the number of output pulses of signal and idler photons. According to Eqs. (2)—(4), we can calculate quantum efficiencies of detectors.

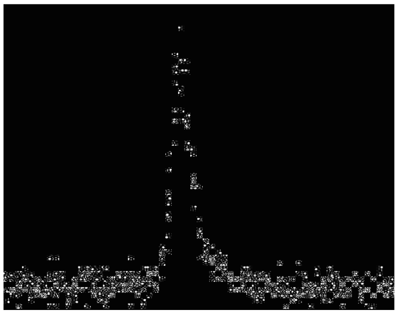

Fig. 3. Time-correlation profiles of PMT1 and PMT2 with 25-ns channel delay. The full scale is 50 ns, and the peak width is about 5 ns.

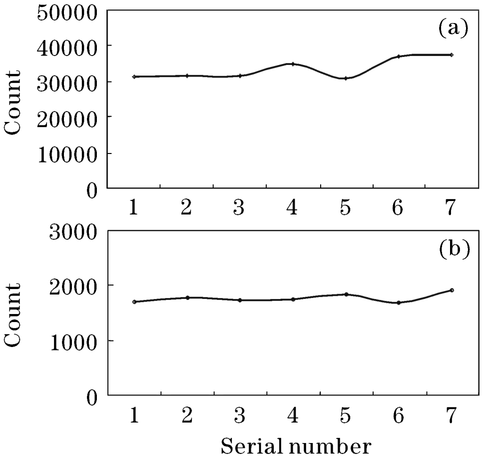

Fig. 4. Counts of trigger channel (a) and coincidence channel (b) in 10 s when the pump power is 12 mW.

Using the experimental setup described above, we calibrated the quantum efficiency of PMT1 at 702.2 nm. Figure 3 shows the time-correlation profiles of two PMTs; the peak refers to the true coincidence counts of correlated photons. In the figure, the full scale of TAC is 50 ns, the channel delay is 25 ns, the coincidence peak width is about 5 ns. When the pump power of laser was 12 mW, we measured the mean count rates of coincidence events and trigger channel. Figure 4 shows the details. According to Eq. (4), we calculate the quantum efficiency of PMT1 to be about 5.05% at 702.2 nm. According to the guidelines for evaluating and expressing the uncertainty of measurement results[4], we deduce the formula of relative combined standard uncertainty of quantum efficiency by means of correlated photons

$$u_{r\eta}=\frac{u_\eta}{\bar{\eta}}=\sqrt{(\frac{1}{N_{\mathrm{t}}})^2u_{N_{\mathrm{t}}}^2+(\frac{1}{N_{\mathrm{c}}})^2u_{N_{\mathrm{c}}}^2}=\sqrt{u_{rN_{\mathrm{t}}}^2+u_{rN_{\mathrm{c}}}^2}, \tag{5}$$

where N_{t} is counts of trigger channel and N_{c} is counts of coincidence channel. The uncertainty of this measurement is calculated to be 5.87%.

In order to understand the results of measurement, we should emphasize that this value is not the pure quantum efficiency of detector. It includes factor of transmittance of the glass filter which is about 74% at 702.2 nm. For calculating the pure quantum efficiency of PMT1, we introduce the transmittance of the glass filter in Eq. (4), then the quantum efficiency of PMT1 at 702.2 nm is 6.82%, and the corresponding uncertainty is 7.93%.

According to the parameters of PMT1, its typical quantum efficiency is about 5.9% at 702.2 nm. The experimental results agree with the reference value fairly. The reasons making the error are analyzed as follows. Firstly, the output power of Ti:sapphire laser has a definite excursion along its working time. It would directly lead to the difference in the counts of trigger and coincidence channels. Secondly, we did not use interference filter at DUT channel during measurement, and the diameter of iris1 is larger than that of iris2. So, some noise photons may be detected as coincidence signal by PMT1. Finally, PMT2 was not placed at the optimum position, thus the correlated photons may not be detected entirely. All these factors can increase the value of quantum efficiency measured by correlated photon method.

In order to check PMT1 and correlated photon technique, we are designing a conventional measurement of quantum efficiency of PMT1 based on trap detector.

Although the result is not very accurate, it has largish comparability with typical value of quantum efficiency of PMT. And it is enough to be the proof of principle experiment of absolute calibration in detectors based on correlated photons. Furthermore, an uncertainty comparable with conventional method could be allowed by improving this system. To our knowledge, as a consequence of significant improvements in the overall uncertainty, a final level of 10^{-3} seems to be reasonably feasible[5].

In comparison with traditional methods based on radiometric sources or detectors, correlated photons method has following advantages. Firstly, it is an absolute process which can be accurately reproduced; secondly, it does not need a transfer chain and the uncertainty from transfer of standard is reduced; thirdly, the quantum efficiency of trigger path does not influence the results of calibration; finally, since correlated visible-infrared photons are available, infrared (IR) detectors can be calibrated by a high precision detector for visible light based on this method.

We implemented an experimental system of radiometric calibration based on correlated photons, and measured the quantum efficiency of PMT at 702.2 nm, the experimental result is close to the typical value. It would allow accuracy comparable with conventional methods of radiometric calibration by improving setup. Further investigation will reduce uncertainty of measurement. This intrinsically absolute calibration technique is independent of any other standards or transfer train. It would become the development direction of radiometric calibration technique in the future.

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