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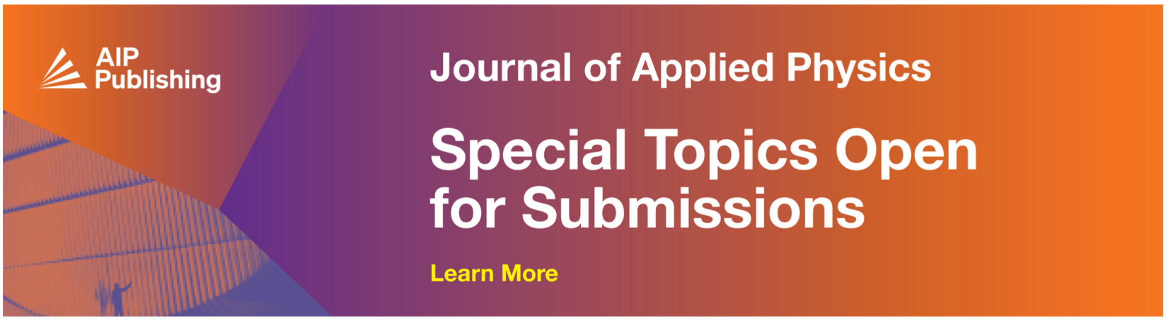

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D. A. Safronenkov,[a)] P. A. Prudkovskii, A. V. Osipenkov, and G. Kh. Kitaeva

AFFILIATIONS

Physics Department, Lomonosov Moscow State University, 119991 Moscow, Russia

[a)]**Author to whom correspondence should be addressed:** safronenkovda@my.msu.ru

ABSTRACT

A modified Klyshko method for standardless calibration of analog photodetector efficiencies is suggested and experimentally implemented. The method is based on the measurement of the number of incident photons using correlation properties of biphotons generated under spontaneous parametric downconversion, and on the determination of the mean number of discrete elementary responses of a photodetector by deconvoluting the statistical distribution of the output photocurrents. As an example, the generalized efficiency of an analog photomultiplier is measured as the ratio of the average number of elementary current responses to the average number of incident photons. The statistical properties of the elementary responses of an analog photodetector depend not only on the detector itself, but also on the parameters of the subsequent electronic circuit. Nevertheless, it has been shown that the generalized efficiency determined by this way allows one to calibrate the photon fluxes by the analog photodetector without involvement of any reference sources or detectors.

INTRODUCTION

Since the time of Einstein, it has been known that the absorption of light is usually a discrete process. In particular, any photodetector that operates on the principle of light absorption transforms continuous intensity of light into a photocurrent consisting of separate photopulses. In the single-photon detectors, a separate photopulse is registered as a single photocount that responds to the absorption of one photon. The probability of such events is determined by the detection efficiency, while the statistics of the number of photocounts accumulated over some detection time and the statistics of the light intensity are in most cases related by the semi-classical Mandel formula.[1] Single-photon detectors are actively used in the quantum optics and quantum information techniques. Suggested by D. N. Klyshko, the method of absolute calibration of such detectors is based on correlation properties of the biphoton radiation and allows one to calculate the detection efficiency of a single-photon detector without the use of any reference photometric devices.[2,3]

The possibility of using the Klyshko method for absolute detector calibration is based on the fact that, under spontaneous parametric downconversion (SPDC), the magnitude of quantum correlation between the radiation intensities in the conjugated signal and idler modes is inversely proportional to the number of photons in these modes.[4] In fact, the same property of parametric downconversion is used in any modifications of the Klyshko method, both for photon-number-resolving detectors,[5] and for the calibration of CCD matrices[6,7] and transition edge sensors[8] by measuring the noise reduction factor (NRF) in the field of bright squeezed vacuum.

However, many detectors cannot be used in the photon counting mode. First of all, the parameters of single photopulses may fluctuate intensively rendering them not distinguishable against the background of the detector's dark current. Second, if individual photopulses overlap or fall within a certain dead time interval of an electric circuit, they merge into a continuous photocurrent, in which no more than one photocount can be detected in the photon counting mode. Even in the optical range, there are plenty of such "imperfect" analog detectors, while in the terahertz, mid- and far-IR ranges for low-frequency photons there are almost no single-photon detectors. In such cases, in the analog detection mode, it is possible to measure only the value of the photocurrent, on average proportional to the incident light intensity, and applications of all the above mentioned variations of the Klyshko method are impossible. But, even the continuous photocurrent of an analog detector has a discrete structure, although at first glance, it does not seem to be detectable.

The discreteness of photodetection can show itself under sufficiently low light intensity. In this case, the photocurrent at the output of an analog detector usually represents the sequence of separate pulses. They can overlap or be barely distinguishable against the background of the detector's dark current, and their value can noticeably fluctuate. However, these pulses can be considered elementary: they represent the minimum possible detector response to incident radiation. For example, the elementary response of a photomultiplier tube (PMT) or an avalanche photodiode (APD) is a pulse resulting from multiplication of a photoelectron in the dynode system of a PMT, or from the avalanche breakdown in an APD. In the case of a superconductor-based hot-electron bolometer, the elementary pulse is formed as a result of an increase in the resistance of a small area of the superconducting element near the "hot spot" that arises due to photon absorption. In most cases, the appearance of an elementary response at the output of a detector corresponds to absorption of a single photon, although, as we will see later, it is not always so. Note once again that we are considering analog detectors for which it is impossible to register individual elementary photocurrent responses, since they strongly fluctuate and it is difficult to separate them from each other and from the dark current.

Summing up, if an analog detector during the detection time manages to capture a small number of photons, we can only analyze the statistical properties of the mean photocurrent, consisting of the fluctuating dark current and a small number of elementary responses of a detector. Furthermore, both the amplitudes of these elementary responses and their numbers are random variables. If light intensity is constant, and the elementary responses of a detector appear independently from one another, then, as in the Mandel's formula, their number is described by Poisson distribution. With these assumptions, and under several additional conditions, it is possible to perform deconvolution of the distributions of the mean photocurrent and thus determine both the distribution function of the amplitude of an elementary detector response and the poissonian mean number of such responses. This average number of elementary responses can be used to calibrate the detector.

The possibility of calibrating photodetectors by deconvolution of the distributions of the mean photocurrent was initially proposed in the works with scintillators that register elementary particles.[9–11] In these works, the distribution of the mean photocurrent of PMTs was approximated by the poissonian sum of the elementary photodetector responses with additional account of the dark current distribution. The distributions of both the amplitudes of elementary pulses and the fluctuations of the dark current were described by the Gaussian function or a superposition of the Gaussian and the exponential functions. Later, in Ref. 12, the attempt was made to derive a more complicated formula, which would take into account possible inhomogeneity of the PMT photocathode. However, in Ref. 13, it was shown that the approximations carried out with the simpler and the more complicated formula lead to similar results. A different approach was applied to describe an elementary photodetector response in the paper,[14] wherein the numerical procedure of restoring the distribution function of the elementary response amplitude was used without any *a priori* assumptions about the form of this function. And, the papers of Refs. 15 and 16 demonstrate that it is possible to obtain Fourier transform of the distribution of the elementary response amplitude from the distribution of the mean photocurrent. However, the use of methods that involve complex numerical procedures demands highly accurate measurements of the photocurrent distribution in an entire dynamic range of a detector which is not always possible.

In recent years, an analogous procedure of deconvolution of the photodetector response distribution was applied not only to PMTs, but also to superconducting nanowire detectors.[17,18] In these works, not only the value of the average photocurrent, but also the slope of the time dependence of the photocurrent at the initial stage of its growth were considered as characteristics dependent on the number of elementary responses.

In our papers of Refs. 19 and 20, it was shown that it is possible to generalize the Klyshko method of standardless calibration to determine the efficiency of analog photodetectors. This was achieved by using the combination of the procedures of deconvolution of the mean PMT photocurrent, thus determining the mean number of elementary responses, and calculation of the number of incident photons by taking into account the correlation properties of SPDC. However, in these works, two additional single-photon detectors were employed to measure the correlation function of biphoton radiation. In this paper for the first time, we demonstrate the possibility of absolute calibration of an analog photodetector using the modified Klyshko method, which uses only two initially uncalibrated analog detectors. In addition, the comparison with the results obtained previously enabled us to discuss the specifics of the term "elementary response" as applied to analog detectors.

EXPERIMENT AND METHOD

The scheme of experimental setup is shown in Fig. 1. The single-mode diode laser of 405 nm wavelength served as a pump source. Its radiation was focused by the lens L_p with a focal length of 40 mm on a surface of the 0.5 cm thick BiBO crystal, in which SPDC of type-I occurred. After the crystal, the pump radiation was cut off by the filter F_s, while the biphoton radiation was collected by the lens L_s of 45 mm focal length and directed toward the beam splitter (BS), which divided the incident photons into two channels. The bandpass filters F_1 (FB800-40) and F_2 (FB810-10) transmitted only the parts of the biphoton radiation with wavelengths close to 810 nm. Note that under an almost degenerate collinear SPDC of type-I, the photons in biphoton pairs do not differ in frequency, direction, or polarization. Therefore, in half of the cases, both photons from the pair entered the same channel. As a result, cross-correlation function between the intensities of radiation in the first and second channels was two times lower, than under regular noncollinear SPDC or other SPDC geometries with different polarization or frequencies of photons in the biphoton pairs.

The radiation from the first and second channels through the multi-mode fibers hit the input apertures of the PMT photodetector under calibration, H7422-20 Hamamatsu (D_1), and the additional PMT photodetector H7422-50PA Hamamatsu (D_2). The spectral band of the F_1 filter and the width of the multi-mode fiber

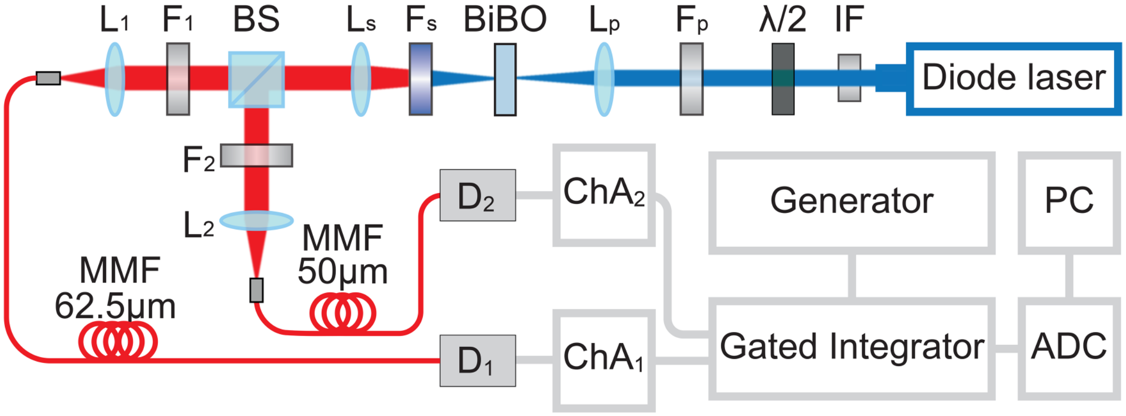

FIG. 1. Experimental setup. L_p, L_s, L_1, L_2, lenses; IF, Faraday isolator; F_p, F_s, F_1, F_2, filters; BS, beam splitter; D_1, D_2, detectors; ChA_1, ChA_2, charge amplifiers with a bypass; MMF, multi-mode fibers.

in the first channel were wider than the spectral band of the F_2 filter and the width of the multi-mode fiber in the second channel, respectively. As a result, the detector under calibration D_1 registered radiation in a larger number of spatial and frequency modes than the detector D_2. Photocurrents from both PMTs after passing through charge amplifiers ($ChA_{1,2}$) were directed to the inputs of the independent cells of Boxcar Gated Integrator SR-250 shunted by 50 Ω resistors. The integration over a strobe time interval proceeded synchronously in both cells after a trigger signal from an external generator with frequency of 10 kHz. Strobe time intervals that determined the detection time were set to $t_s = 500$ ns. The minimal strobe time intervals were limited by the duration of elementary photocurrent pulses of PMT that were stretched after passing through the charge amplifiers. The signals formed at the outputs of Boxcar Integrator cells were proportional to the detector currents $j_{1,2}$ averaged over the time period t_s. Repeatedly measured values of the mean currents were transmitted via the analog-to-digital convertor (ADC) to a computer (PC) database for subsequent mathematical processing.

Statistical distributions of the photocurrent from PMT under calibration, measured at different powers of the laser pump incident on BiBO crystal, are shown in Fig. 2. The distributions for the PMT in the second channel looked similarly. As can be seen, all distributions have virtually the same peak and an exponential tail on the right side. The peak of distributions responds to fluctuations of the dark noise. The height of the exponential tail grows with the growth of the pump power. Its value and shape allow one to assume that the average number of the elementary responses is much less than unity and that the distribution of the elementary response amplitude $S_1(j)$ can be described using an exponential function as

$$S_1(j) = b\theta(j)e^{-bj}, \tag{1}$$

where $\theta(j)$ is the Heaviside step function. Note that in almost all the previous papers (Refs. 9–13, 19, and 20), the distribution of an elementary detector response had a Gaussian form. An exponential part, if taken into account when approximating the histograms, appeared to be sufficiently small. However, in our case, only the exponential function was required to describe the elementary response. It should also be noted that with a larger average number of elementary responses in the case of a sufficiently large, as in our case, dark noise, the distribution of the average photocurrent takes the form of a single wide peak, regardless of whether the distribution of the amplitude of the elementary response is described by a Gaussian or exponential dependence.

If n elementary responses appear at the PMT output during the detection time, then the distribution of their sum is given by the convolution of n functions $S_1(j)$,

$$S_n(j) = S_{n-1}(j) \otimes S_1(j) = b^n \frac{j^{n-1}}{(n-1)!}\theta(j)e^{-bj}. \tag{2}$$

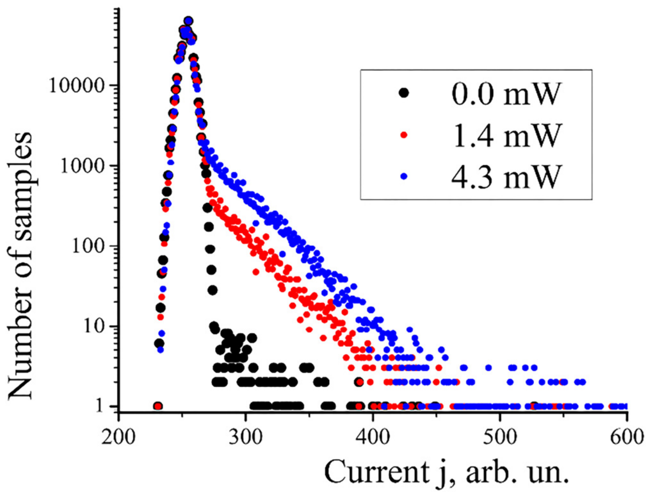

FIG. 2. Experimental distributions of the mean current of the PMT under calibration in the first channel at different laser pump powers.

Regardless of the number of elementary responses, the distribution decrease at high currents is described by the single exponential law with the decrement equal to $b = 0.038 \pm 0.001$ for the histograms in Fig. 2. Considering that the mean value of the dark current j_0 in the absence of the pump radiation in Fig. 2 is not zero, it is necessary to substitute the argument j by $(j - j_0)$ in Eq. (2).

At the same time, the distribution of the dark noise is well-described by the Gaussian function

$$B(j) = \frac{1}{\sqrt{2\pi D}} e^{-\frac{(j-j_0)^2}{2D}}, \tag{3}$$

with dispersion $D = 19.2 \pm 0.6$. In general, the distribution of the total photocurrent in the presence of n elementary responses is described by the convolution of the function $S_n(j)$ and the distribution of the dark noise. However, we can suppose with sufficiently high accuracy that $S_n(j) \otimes B(j) \approx S_n(j)$ for all n values, because in our case $b^2 D \approx 0.03 \ll 1$.

Considering that the number of elementary responses appearing at the PMT output during the detection time is described by the Poisson distribution, we get the final formula for approximating the output current distributions,

$$P(j) = C\left\{B(j) + \theta(j - j_0) e^{-b(j-j_0)} \sum_{n=1}^{\infty} \frac{A^n}{n!} \frac{b^n (j - j_0)^{n-1}}{(n-1)!}\right\}. \tag{4}$$

Here, the parameter A is the Poisson mean number of elementary responses, and C is a common normalizing constant. In previous works (Refs. 9–13, 19, and 20), in which deconvolution of the photocurrent distribution was used to determine the mean number of elementary responses, similar approximation formulas were used, but with different dependencies $S_n(j)$.

RESULTS AND DISCUSSION

In all the distributions in Fig. 2, the dark peak is significantly higher than the exponential tail. Therefore, we first found the parameters of the dark noise by approximating by the formula (3) the distribution obtained at zero pump intensity. After that with fixed parameters of the dark noise, we approximated the distributions at different pump powers by the complete Eq. (4). An example of such an approximation is demonstrated in Fig. 3. The obtained mean numbers of elementary responses at different levels of pump intensity are specified in Table I.

At the same time, the mean number of photons incident on PMT during the detection time can be obtained from quantum properties of biphoton radiation. As is well known, the SPDC photons are created in pairs. If one detector registers M spatial and spectral modes of signal radiation, and the other registers the same number or a part of the conjugated modes of idler radiation, then, according to the general theory of SPDC,[4] the normalized correlation function of the intensities $I_{s,i}$ of signal and idler radiation is described by the relation

$$g^{(2)} = \frac{\langle I_s I_i \rangle}{\langle I_s \rangle \langle I_i \rangle} = 1 + \frac{1}{M\langle N \rangle}, \tag{5}$$

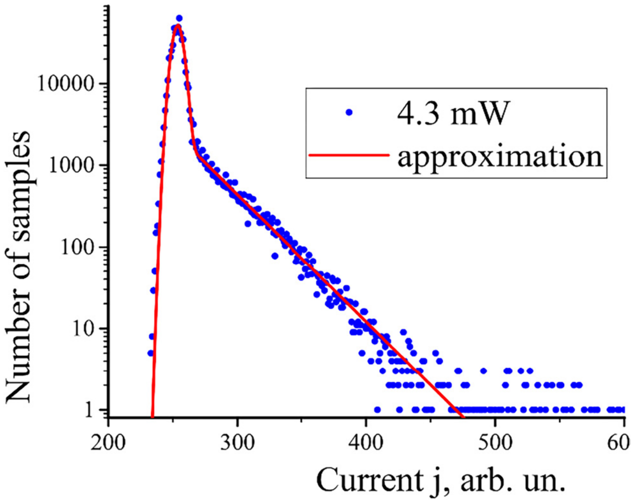

FIG. 3. Experimental distribution of the PMT mean current detected in the first channel with 4.3 mW pump power (blue dots) and the result of its approximation by Eq. (4) (red solid line).

where $\langle N \rangle$ is the mean number of photons in one mode of SPDC radiation. Due to normalization, this relation does not depend on the quantum efficiencies of detectors and the photon losses in the optical paths between the crystal and photodetectors. The reason that $g^{(2)}$ exceeds unit value is related to the biphoton character of SPDC radiation. Note that although under SPDC $\langle N \rangle \ll 1$, the total number of photons $a = M\langle N \rangle$ incident on a photodetector during the detection time depends on the number of registered modes and may not be small.

The intensity of the incident SPDC radiation in each channel we considered as proportional to the difference $J_{1,2} = j_{1,2} - (j_0)_{1,2}$ between the photocurrent of the detector averaged over the time period t_s and the mean value of the dark current. As previously noted, in our scheme of registration of almost collinear and almost degenerate SPDC of type-I using a beam splitter, the level of measured quantum correlations between the light intensities in the first and second detection channels should be two times lower than in

TABLE I. Results of measurements of the mean number of elementary detector responses A for PMT under calibration, obtained by approximating the photocurrent distributions by Eq. (4), and of the mean number of incident photons a, calculated by Eq. (7) using experimentally determined values of the correlation function $g^{(2)}$, at different pump powers.

P (mW)	A	$g^{(2)}$	a
0.4	0.0112 ± 0.0003	3.82 ± 0.96	0.06 ± 0.02
0.7	0.0165 ± 0.0003	2.56 ± 0.76	0.11 ± 0.07
1.4	0.0358 ± 0.0005	1.96 ± 0.59	0.19 ± 0.12
2.6	0.0658 ± 0.0006	1.52 ± 0.36	0.35 ± 0.25
3.6	0.095 ± 0.001	1.38 ± 0.29	0.47 ± 0.37
4.3	0.114 ± 0.001	1.30 ± 0.27	0.60 ± 0.56

SPDC geometries with possible independent registration of signal and idler photons. Consequently, the correlation function was determined by the formula

$$g^{(2)} = 1 + 2\left(\frac{\langle J_1 J_2\rangle}{\langle J_1\rangle\langle J_2\rangle} - 1\right), \tag{6}$$

where the averaging was done over a large sample of measurements. The procedure of measurement of the correlation function using analog photodetectors is described in more detail in the papers of Refs. 21 and 22. Accounting for the optical losses in the signal channel (the independently measured transmission coefficient of the elements between the crystal and the first photodetector was $K_1 = 0.180 \pm 0.005$), the mean number of photons incident on the PMT under calibration during the detection time t_s was calculated as

$$a = K_1(g^{(2)} - 1)^{-1}. \tag{7}$$

Results of the measurement of the normalized correlation function $g^{(2)}$ and the mean number of photons a incident on the PMT under calibration in the first channel at different values of pump laser power are given in Table I.

The average number of elementary responses should be proportional to the average number of photons incident on the PMT $A = \eta a$. The proportionality coefficient, determined using a linear approximation of the dependence $A(a)$, is equal to $\eta = 0.19 \pm 0.01$. This coefficient can be called "generalized efficiency of an analog PMT," since it enables us to measure the intensity of light incident on a PMT in the units of photon numbers.

In order to verify the obtained value of the generalized efficiency of PMT, we measured intensity of the attenuated radiation of an ordinary incandescent lamp, which passed through F_1 filter. The rate of photon emission from this source was measured beforehand using a photon counting APD device with known detection efficiency (precalibrated in Ref. 21 by the usual Klyshko method for single-photon detectors). The frequency of photon hits on the detector aperture turned out to be 0.575 ± 0.003 MHz. Then, instead of a reference detector, our PMT was installed in the same channel, and the statistical distribution of the mean photocurrent over the same time period as before, $t_s = 500$ ns, was measured. As a result of the approximation of the obtained distribution by the formula (4), we have determined the mean number of elementary responses: $A = 0.0502 \pm 0.0006$. Using the obtained above value of the PMT efficiency $\eta = 0.19 \pm 0.01$, we have found that during the detection time the mean number of photons incident on a detector is equal to $a = A/\eta = 0.27 \pm 0.03$. This corresponds to a photon hit frequency of 0.55 ± 0.07 MHz. The obtained value agrees well with the frequency measured using APD, though of course, the accuracy of measurements with a single-photon detector is still much higher.

Thus, the combination of the deconvolution of the mean photocurrent distributions and of the measurement the correlation function of biphoton radiation allows one to modify the Klyshko method for standardless calibration, and to measure the generalized efficiency of an analog detector in units of the mean number of elementary responses resulting from one photon hitting the detector during the detection time. Of course, the accuracy of the measurement of the generalized efficiency for analog detectors is lower than the accuracy of the measurement of detection efficiency by the Klyshko method in the case of single-photon detectors. Errors in our measurement are caused by both the inaccuracy of determining the average number of elementary responses during deconvolution of the photocurrent distribution and the lower accuracy of measuring the correlation function of light intensities by analog photodetectors (see errors in Table I). When using a single-photon detector in the photocurrent measurement mode, its generalized efficiency is equivalent to the usual detection efficiency, but the accuracy of its determination in the analog mode is still worse than that of measuring by the usual Klyshko method in the photon counting mode.[21] However, for analog detectors that cannot be used in the photon counting mode, it also opens up a unique opportunity to measure the mean number of incident photons without any reference sources or detectors.

It is crucial to note that the generalized efficiency of an analog photodetector is less universal than the detection efficiency of a single-photon detector. As noted previously, the elementary response of an analog detector does not necessarily correspond to one absorbed photon. On one hand, the multiplication of a photoelectron in a PMT dynode system, in principle, can result in the forming of several electrical pulses, if, for example, secondary electrons appearing at the first dynode have a sufficiently large energy spread. In this case, there are several elementary responses per absorbed photon. In single-photon detectors, such multiple responses are not taken into account, since they appear during the dead time interval after the moment of photocount registration, at which the value of an elementary response exceeds the discriminating threshold level.[7] However, in the case of analog detectors, elementary responses are difficult to separate from the dark current of the photodetector, and an attempt to make single-photon detectors from them using the threshold level will lead to a catastrophic drop in detection efficiency.

On the other hand, under direct measurement of the intensity of terahertz radiation by superconducting hot-electron bolometers (HEBs), the energy of one photon may not be high enough to initiate a transition into a resistive state in the region of the bolometer superconducting film, sufficient for the appearance of a noticeable current pulse.[23] This means that one elementary pulse of a HEB detector appears due to the absorption of several terahertz photons. As a result, even though it is possible to separate the bolometer photocurrent distribution into elementary responses using deconvolution,[24,25] these elementary responses cannot be considered as the single-photon ones. Thus, the generalized efficiency of an analog detector depends not only on the photon absorption probability, but also on how many elementary responses there are on average per absorbed photon.

In particular, in our previous papers (Refs. 19 and 20), the measured generalized efficiency of the same analog PMT was higher than unity, i.e., one absorbed photon corresponded to a large number of elementary responses. Contrary to the scheme in Fig. 1, in our previous schemes, the Boxcar Integrator input cells were not shunted by a 50 Om resistor, so that the single PMT elementary pulse was much longer. Figure 4 shows the temporal

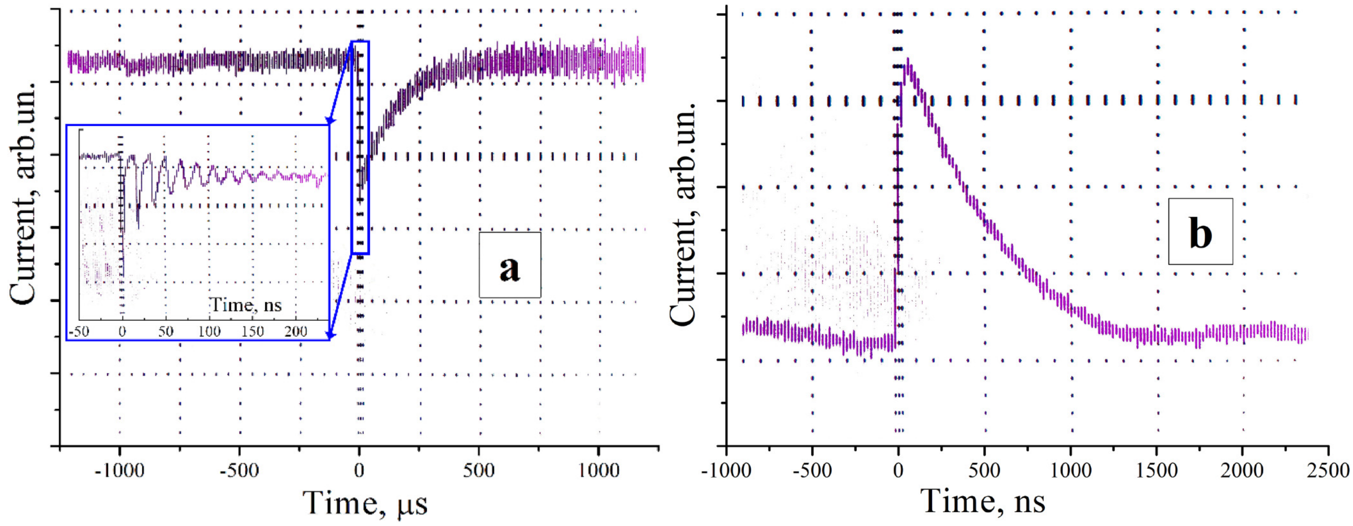

FIG. 4. The shape of a PMT elementary pulse taken from an oscilloscope: (a) in the scheme without shunting and charge amplification, the inset shows the initial part of a pulse; (b) in the scheme with the charge amplifier and 50 Ω shunt in Fig. 1.

shapes of single PMT elementary pulses which entered the gated Boxcar Integrator in the previous [Fig. 4(a)] and present [Fig. 4(b)] cases. 50 Ω shunting suppressed the long tail of elementary pulses which previously extended up to a hundred microseconds. At the same time, for reliable detection of the main short part of the PMT pulses (up to several tens of nanoseconds in duration) with also suppressed amplitudes, additional use of charge amplifiers was required. The charge amplifiers inverted and stretched the main short part of a pulse [inset in Fig. 4(a)] up to ∼500 ns [Fig. 4(b)].

It is very important that in the previous scheme (without shunting) the long tails of the elementary pulses were several orders of magnitude longer than the detection (strobe) time intervals. These tails are presumably related to the residual dynamics of the secondary electrons in the PMT dynode system. And it is precisely because of these tails that the contribution to the photocurrent was made not only by photons absorbed on the PMT photocathode during the current strobe time interval, but also by photons absorbed by the photocathode long before this time. Such contributions to the total photocurrent from the preceding photons were small in amplitude, but they noticeably increased the effective number of the recorded elementary responses. In addition, the distribution of the amplitude of the elementary response in that case had a Gaussian form, and not an exponential one as in Fig. 2. As a result, the mean number of elementary responses obtained by approximating the photocurrent distributions corresponded not to the detection time t_s, but to a significantly larger time period determined by the duration of the back front of a non-shunted pulse. Since when calculating the generalized efficiency of a detector only the photons incident during the detection time were taken into account, the value determined this way appeared to be much higher than the generalized efficiency of a PMT determined in this paper.

Despite the different values of the detector generalized efficiency obtained in different schemes, the rates of photon fluxes of an incident radiation measured using them responded to the actual true values of this quantity in this paper, and in Refs. 19 and 20. This is because the determination of the number of photons incident on a detector from correlation properties of biphoton radiation is a key element when applying the Klyshko method for standardless calibration of the detection efficiency. But the elementary response, amplitude distribution of which is determined in the process of approximation of the statistical distributions of analog readings, is a characteristic of an entire photodetector which takes into account not only the photodetector itself, but also the electronic processing circuit after it.

CONCLUSION

Summing up, in this paper, the new step was taken in the development of the Klyshko method for the standardless calibration of the efficiency of analog photodetectors. The procedure of the determination of the photodetector generalized efficiency was experimentally demonstrated for a PMT with an electronic preamplifier. This generalized efficiency relates the mean number of photons incident on a detector to the mean number of elementary detector responses appearing at its output. The number of incident photons was determined by the application of correlation properties of the biphoton SPDC radiation. As opposed to the previous papers on the same theme,[19–21] the correlation function of the biphoton radiation was measured using the two initially uncalibrated analog PMTs without the involvement of additional single-photon detectors. In turn, the number of elementary responses was obtained following the deconvolution procedure of the statistical distribution of the measured photocurrents. In the case of analog detectors that cannot operate in a photon counting mode, only a continuous photocurrent can be registered. However, the stochastic fluctuations of this photocurrent contain information about the discrete nature of the photodetection process. In our case, such necessary information was the average number of elementary detector responses. Its comparison with the number of incident photons allows calibrating the analog detector.

Successful verification of the method was carried out by measuring the photon flux in the radiation field of an independent source, by comparing the readings of the calibrated PMT with the readings of a single-photon detector with a detection efficiency independently calibrated by the usual Klyshko method.

In addition, using the example of comparing the measured generalized efficiency of PMT with the previously obtained results, it has been shown that this value depends on the properties of the elementary response of the detector, which are determined indirectly by deconvolution of the photocurrent distribution. For this reason, one absorbed photon can correspond to a different number of elementary responses, and the distribution of the amplitude of one elementary response can have both a Gaussian and an exponential form, depending on the registration conditions. As a consequence, the generalized efficiency of an analog detector can vary significantly when the electrical processing circuit is changed.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

D. A. Safronenkov: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Software (equal); Validation (equal); Writing – original draft (equal). **P. A. Prudkovskii:** Conceptualization (equal); Formal analysis (equal); Methodology (equal); Software (equal); Writing – original draft (equal). **A. V. Osipenkov:** Conceptualization (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Software (equal); Supervision (equal); Writing – review & editing (equal). **G. Kh. Kitaeva:** Conceptualization (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Software (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the finding of this study are available from the corresponding author upon reasonable request.

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