Absolute calibration of analog photodetectors with a biphoton field

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(Submitted December 9, 1986)

Pis'ma Zh. Tekh. Fiz. 12, 795–798 (July 26, 1986)

A field with unique statistical properties is produced in a medium without a center of symmetry during spontaneous parametric scattering of light. Some of the effects of greatest interest from the practical standpoint are the superclassical spatial and temporal grouping of photons into pairs, resulting in the formation of biphotons. The biphoton nature of a field presents the possibility of a fundamentally new method for absolute calibration of analog photodetectors, without the use of standards.

Spontaneous three-wave parametric light scattering in media without a center of symmetry is one of the nonlinear-optics processes in which the quantum properties of the field are exhibited most obviously. The elementary event in this scattering process is the decay of a photon of monochromatic light (the pump) with a frequency ω_0 and a wave vector k_0 into a pair of photons, with frequencies ω_1, ω_2 and wave vectors k_1, k_2. Spatial and temporal matching conditions must be satisfied[1]:

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_0 ; \quad \omega_1 + \omega_2 = \omega_0 . \tag{1}$$

An emission spectrum with a complex spatial-frequency distribution of the scattering intensity is formed at the exit from the scattering medium. The light which arises covers a broad range. The particular frequency-spatial distribution is determined by the dispersive characteristics of the medium. The width of the range spanned by the emission is determined on the one hand by the pump frequency and on the other by the lattice absorption edge of the medium in accordance with the condition $\alpha l \ll 1$, where l is the thickness of the scattering layer along the pump propagation direction, and α is the Bouguer absorption coefficient.

A theoretical analysis[2] has shown, and experiments have varified,[3] that the photons produced in the elementary event in two parametrically coupled modes with parameter values satisfying conditions (1) are strictly correlated in time and space both at the time of production and in the course of the propagation inside and outside the scattering medium. Consequently, a flux of photons which are tightly bound in pairs – biphotons – is formed at the exit from the medium. A fact of practical importance is that the temporal mismatch of the photons of one pair (the difference in the times at which they pass fixed spatial points), which is determined by the difference in the group velocities for the different photons in the medium, due to its dispersion, can be reduced to $\Delta t \sim 10^{-12} \ldots 10^{-14}$ s. Consequently, the temporal mismatch of the photons in a pair can be ignored for all existing detectors.

So far, the method of calibrating photodetectors by means of a biphoton field has been used only to determine the absolute parameter values of photon counters. It was shown in Ref. 4, however, that a biphoton field can also be used for calibration of a much broader range of analog photodetectors.

The method for calibrating analog photodetectors is based on the circumstance that the light flux in the exit circuit of the detector can be expressed as the sum of a random train of pulses: $i(t) = \Sigma q_k f_k(t-t_k)$, where q_k is the height of a pulse, and t_k is the time at which it appears. In the case of a detector with an amplification of the electron flux, and under the assumption that only a single electron is produced in the absorption of a single photon, we can write $q = eM$, where e is the electron charge and M is the current gain of the detector. The function $f_k(t)$ describes the shape of the photocurrent pulse in the load of the detector. By simultaneously measuring the autocorrelation functions of the currents of each of the detectors, $G_1(\tau) = \langle i_1(t) i_1(t+\tau)\rangle$, and $G_2(\tau) = \langle i_2(t) i_2(t+\tau)\rangle$ and the mutual correlation function of the currents, $G_{12}(\tau) = \langle i_1(t) i_2(t+\tau)\rangle$, by means of analog correlation circuits, we can determine the values of the absolute quantum efficiency in natural units of coulombs per photon:

$$\eta_{1,2}\langle q_{1,2}\rangle = \xi_{2,1}\langle q_{2,1}\rangle \langle i_1, i_2\rangle / \langle i^2_{2,1}\rangle . \tag{2}$$

Here $\xi_m = \langle q_m^2\rangle / \langle q_m\rangle^2$ is a statistical factor which incorporates the fluctuations of the gain and other noise characteristics of the photodetectors. The values of ξ_m can easily be determined from the pulse height distribution of the noisy current with the help of a pulse height analyzer.

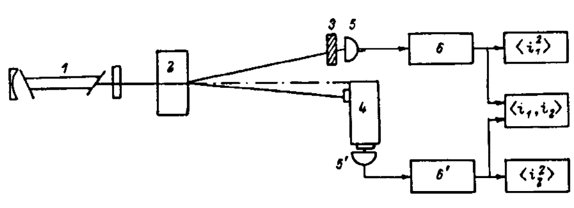

FIG. 1. Experimental arrangement for absolute calibration of analog photodetectors. 1) Pump light source; 2) nonlinear crystal; 3) interference filter; 4) spectral instrument; 5, 5') photoelectron detectors; 6, 6') electronic amplification circuits.

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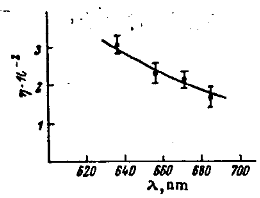

FIG. 2. Measured spectrum of a photomultiplier operating in the charge-integration mode. The integral cathode sensitivity according to the technical specifications is 238 μA/lm.

The values of η_m found from (2) also incorporate, as a product, the transmission coefficients of the optical elements of the detector channels and the crystal. They can be determined easily by independent relative measurements with any required accuracy. The accuracy of the η_m measurements is affected to the greatest extent by the reflection at the exit face of the scattering layer, which influences the degree of photon grouping. The effect of a deviation from a strictly biphoton nature of the scattered field on the results of the measurements can be taken into account by introducing a correction factor in the final result.[5]

The method of absolute calibration of analog photodetectors with the use of a biphoton field has been implemented in the two-channel apparatus whose block diagram is shown in Fig. 1. The light detectors are FÉU-79 photomultipliers, operated in a charge-integration mode. The light source is a cw cadmium-vapor laser with an output power of 3 mW at the wavelength $\lambda_0 = 325$ nm. The biphoton field is produced in a lithium iodate crystal. The orientation of the sample is chosen in such a way that the scattered light at the exit from the crystal, over the wavelength interval 550-750 nm, propagates in a cone with a vertex angle $\theta \sim 3...5°$ along the pump propagation direction. The biphoton flux density reaches 10^8 per second in a 0.25-nm band. At a fixed frequency, the scattered light forms a conical layer with an angular width no greater than 30'. The frequency-selective element is an ISP-51 spectrograph, operated in a monochromator mode.

The electrical systems for processing the signals are identical, so that the difference in the parameters, of the elements of the two channels does not exceed 1%. A bandpass amplifier amplifies the photocurrent in the detector load over the frequency band 10^3-10^6 Hz. The lower limit on this band provides a defense against zero drift, slow fluctuations of the parameters of the apparatus, and 1/f noise. The upper limit is chosen to eliminate any effect of an instability of the photomultiplier gain on the pulse shape. The length of the pulses at the photomultiplier load is $\tau_p \sim 200$ ns. The analog-correlator arrangement which we used made it possible to achieve a conversion linearity within 1% over the dynamic range 10^{-2}-10 V of the input signal. The integration time can be varied over the range 10^{-2}-1 s. The signal accumulation time in the accumulation systems after the analog-to-digital converter is varied over the range 1-10^3 s.

The statistical factor ξ_m varies over the range 1.2-1.6, depending on the particular photomultiplier used.

Figure 2 shows the spectrum of the quantum efficiency of a photomultiplier found with this apparatus. According to the technical specifications of this photomultiplier, the quantum sensitivity integrated over the spectrum is 240 μA/lm. The relative error of the measurements is no greater than 8-10%. Most of this error comes from the instability of the parameters of the electric circuits. The results found from the measurements of the magnitude and the variance σ_m^2 agree well with the results of measurements carried out in the counting mode of the photomultiplier, also by the biphoton-field method.

On the basis of these results, we can say that there is a good outlook for the development of this new method for standard-free absolute calibration of analog photodetectors such as avalanche photodiodes, multichannel amplifiers, and photodetectors using metal–insulator–semiconductor and metal–oxide–metal structures.

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Translated by Dave Parsons