MEASUREMENT OF THE NONLINEAR ERROR IN SIGNAL RESPONSE OF A PHOTODETECTOR

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A modification of the light flux summation method is proposed capable of routine control over nonlinearity of signal response of a photodetector.

To measure relative variations of the light flux Φ with a photodetector, its signal response (SR) should be known (Fig. 1*a*). "Nonlinearity of the SR characterizes the identity of minimum output signal increment in the entire working range and is defined as the maximum deviation of the output signal from the straight line drawn through the zero point and the point of the maximum output signal.[1,2]" The signal response of a photodetector can be represented as a sum of two functions, the first is described by the straight line crossing the zero point and the point of the maximum output signal and the second represents the nonlinear error Δ in SR:

$$u = a_1\, \Phi + \Delta, \qquad (1)$$

where u is the output signal of the photodetector,

$$a_1 = m \tan\alpha,$$

and m is the scale factor.

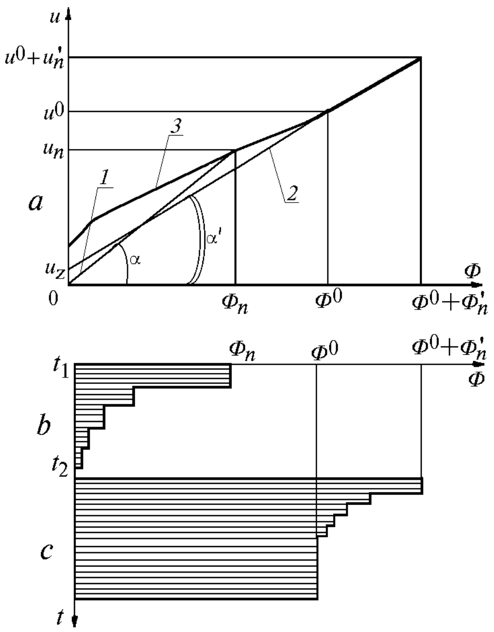

FIG. 1. Signal response of the photodetector (curve 3, case a) and diagrams of the source signal Φ (b) and of the sum of signals Φ and Φ^0 (c).

When the SR is linear in the measurement range $\tau = \Phi/\Phi_{max}$, a procedure for determining τ substantially simplifies. In this case, the linearity of the SR up to the point Φ_{max} is important irrespective of Φ_{max}, because the error due to the SR nonlinearity is introduced only into the signal corresponding to Φ. In this case, the relative error in measuring τ is

$$\delta\tau = \Delta/u, \qquad (2)$$

where u is the output signal of the photodetector corresponding to the light flux Φ and Δ is the nonlinear error in SR for measurable flux Φ.

The nonlinear error in SR of the photodetector depends on the magnitude of the background light flux which is always present in the measurable light flux whose modulation frequency differs from the background, because nonlinear distortions in a modulating signal at the output from a sensitive element of the photodetector may be intensified or partially suppressed in the next cascades as a function of their frequency characteristics due to the nonlinearity of the light response of the photodetector. For this reason, it is desirable to measure the SR for realistic background accompanying optical measurements.

Devices harnessing the light flux summation method are most widely used to measure the SR nonlinearity. "They harness the principle of linear scales that implies the summation of the known or identical quantities. To measure the nonlinearity of radiation detectors, this principle can be realized using many light sources or a single light source and a diaphragm with many openings, inserted between a source and a detector. " ecause of apparent advantages, various modifications of the latter method have gained wide acceptance in practice of measuring the radiation detector nonlinearity. A desirable gradation of the detector illuminance corresponding to the gradation of cross sectional areas of the openings in the diaphragm can be obtained by successive shutting or opening of these openings. In so doing, a conclusion about the linearity of the detector can be drawn based on the correspondence between relative variations of the output signal and the known law of variations of the illuminance or the magnitude of the

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detector nonlinearity can be determined.[3]" In this case, the measurement error is due to the nonuniform distribution of light over the diaphragm with the openings and deviations of their sizes from preset ones.

Now advances in microelectronics allow precision controllable sources to be developed on the basis of digital-to-analog converters (DACs). On the basis of multiplying DACs, gain-controlled amplifiers (GCAs) are developed. In its turn, the light flux summation method capable of fast determination of the nonlinear error in SR can be realized on the basis of DACs and GCAs. In this method, the source of optical radiation should produce stepwise varying light flux. In so doing, stability of ratios of flux increments is of importance rather than stability of step levels. Photodiodes possessing linear regions of the candela-ampere characteristics meet these requirements. However, the candela-ampere characteristic of photodiodes is nonlinear at small currents due to recombination in the space charge zone. The injection coefficient of photodiode is also small at large currents due to saturation of luminescence centers and temperature quenching of luminescence in the process of heating of semiconductors.[5]

In a static regime, superlinearity of photodiodes is preserved only up to comparatively small currents that exceed the nominal current from 1.5 to 2 times, whereas in a pulsed regime, it is still preserved when currents are several factors of ten larger than the nominal current[6] (the range of currents with superlinear dependence of the candela-ampere characteristic is extended as the pulse duty factor increases). This can be explained by the fact that in the static regime of operation of the photodiode the light-emitting junction zone is significantly heated at currents smaller than in the pulsed regime. This leads to the decrease of the quantum yield of the photodiode. From the above reasoning it is clear that the stepwise change of the photodiode current should be within the linear region of its candela-ampere characteristic and should take a short time so that the temperature of light-emitting junction had no time to change significantly. The photodiode construction should provide low thermal resistance of the zone light-emitting junction – surrounding medium. The photodiode crystal should be massive.

To measure Δ_i of SR in the range $0 \ldots \Phi_n$, the light flux of the source Φ is used modulated with a frequency of a measurable signal (Fig. 1*b*). During measurements, the light flux Φ is varied stepwise according to the law

$$\Phi = \Phi_i > \Phi_{i-1},\quad i = 0, 1, \ldots, n. \tag{3}$$

This light flux is produced by the photodiode of the source Φ (Fig. 2) and is recorded by the photodetector against the background. An output signal of the photodetector is applied at the input *1* of the GCA whose gain K_i is changed so that

$$\Phi_i\, K_i = B = \text{const.} \tag{4}$$

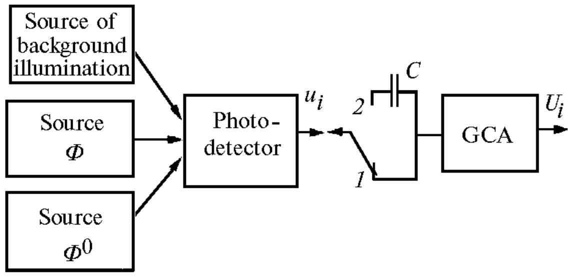

FIG. 2. Scheme of measuring the nonlinear error in SR of the photodetector.

Then an output signal of the GCA is

$$U_i = K_i\,(a_1\,\Phi_i + \Delta_i) = a_1\,B + \Delta_i\,K_i. \tag{5}$$

From Eq. (1) it follows that $\Delta_n = 0$ when $U_n = a_1 B$ and

$$\Delta_i = (U_i - U_n)/K_i. \tag{6}$$

Hence, the output signal of the GCA remains unchanged when the SR is linear and is changed stepwise when it is nonlinear (Fig. 3). To determine the SR for light flux Φ^0 (see Fig. 1) in excess of the maximum light flux of the photodiode, it can be extrapolated given that the slope of a tangent to SR is known for Φ^0. It should be mentioned that Pakhomov[7] also suggested to reconstruct the SR of a photomultiplier from measurement of SR derivative. To determine the slope of the tangent, the photodetector is illuminated simultaneously with the light flux Φ^0 of constant amplitude and the variable light flux from the source Φ (see Fig. 1*c*). Thus, the light flux incident on the photodetector is

$$\Phi = \Phi^0 + \Phi'_i > \Phi^0 + \Phi'_{i-1}, \qquad i = 0, 1, \ldots, n. \tag{7}$$

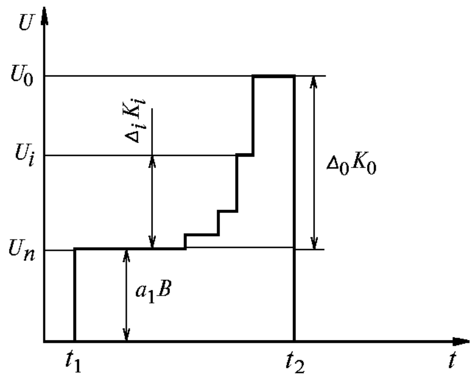

FIG. 3. Diagram of the output signal of the GCA for nonlinear SR of the photodetector.

If we represent the straight line intersecting the points of the SR curve corresponding to Φ^0 and $\Phi^0 + \Phi'_i$ in the form

$$u = a'_1\,\Phi + u_z, \tag{8}$$

where u_z specifies the position of the point of intersection of straight line (8) and the axis u (see Fig. 1*a*), the output signal of the photodetector for the incident light flux $\Phi^0 + \Phi_i'$ can be written as

$$u_i = a_1' (\Phi^0 + \Phi_i') + u_z + \Delta_i', \quad (9)$$

where Δ_i' denotes the deviation of SR from this straight line. Then we select the signal against the level $u^0 = a_1' \Phi^0 + u_z$ and apply it at the GCA. This procedure is fairly simple because the process u_i comprises pulses with constant background component u^0. Then we select the pulse duty factor u_i in excess of 10. This will not introduce large error if we apply u_i at the input *2* of the GCA through a blocking capacitor whose value is high enough and the voltage on the capacitor changes only insignificantly within the time over which the pulsed component acts. The output signal of the GCA is

$$U_i = (a_1' \Phi_i' + \Delta_i') K_i. \quad (10)$$

If K_i is varied so that $\Phi_i' K_i = b' = \text{const}$, we derive

$$U_i = a_1' B' + \Delta_i' K_i. \quad (11)$$

The range of variations of the photodiode current can be adjusted to set Φ_n' so that $\Delta_i' K_i$ will be insignificant, that is, the points of the SR curve corresponding to Φ^0 and $\Phi^0 + \Phi_n'$ will lie practically on the tangent to the SR curve at the point corresponding to Φ^0. In this case,

$$U_i = a_1' B' = U_n' = \text{const}. \quad (12)$$

From Eq. (8) it follows that $\tan\alpha' = m\, a_1'$; therefore, $\tan\alpha' = (a_1'/a_1) \tan\alpha$. The parameter $\Phi_n/\Phi_n' = B/B' = s$ is then determined by the ratio of the ranges of variations of photodiode currents and is set when Φ_n and Φ_n' are adjusted. Measurements of $a_1' b$ allow us to find

$$a_1'/a_1 = a_1' B' s / a_1 B = U_n' s / U_n. \quad (13)$$

A current generator of the photodiode of source Φ was built around a 12-bit K1108PA1 DAC and the GCA was built around a 12-bit multiplying DAC 572PA2. The DAC was controlled so that log1, presented only in one bit, ran through all bits from the highest-order bits to the lowest-order ones.

Considering that the proposed method is new, we now analyze in detail the factors that affect the relative error in determining Δ_i. From Eq. (6) we obtain

$$\delta\Delta_i = \delta(U_i - U_n) + \delta K_i,$$

where $\delta(U_i - U_n)$ is the relative error in determining $U_i - U_n$ and δK_i is the relative error in determining K_i.

Substitution of $a_1 \Phi_i K_i = a_1 \eta I_i K_i$ by $U_n = a_1 \eta I_n K_n$ introduces an error due to the spread of η caused by the nonlinearity of the candela-ampere characteristic of the photodiode in its working range, because the laws of variations of I_i and K_i differ from linear. Here, I_i is the photodiode current corresponding to Φ_i and $\eta = \Phi_i / I_i$. The absolute error of this substitution is

$$\Delta (a_1 \Phi_i K_i) = \Delta (a_1 \eta \Pi_i) = U_i (\Delta\eta/\eta + \Delta\Pi_i/\Pi_i), \quad (14)$$

where $\Pi_i = I_i K_i$ and $\Delta\eta$ is the increment of η in the working range of the photodiode. The ratio $\Delta\Pi_i/\Pi_i$ can be estimated when the signal I_i produced by the source is applied through the capacitor at the GCA input from the instability of the GCA output signal for different i. This error is systematic. Considering the random error ΔU in measuring the GCA output signal, it can be written as

$$\delta\Delta_i = [\Delta U \sqrt{2} + U_i (\Delta\eta/\eta + \Delta\Pi_i/\Pi_i)] \times$$
$$\times (U_i - U_n) + \delta K_i. \quad (15)$$

Here, δK_i can be set equal to the DAC nonlinearity parameter δ_{nl}. For 572PA2 DAC, it is equal[8] to $0.02 \cdot 10^{-2}$. For our assembled device, we have for the first ten high-order bits

$$\delta\Pi_i \le 0.04 \cdot 10^{-2}.$$

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