Measurement of the cutoff frequency of the electroluminescence of LEDs at low currents

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The purpose of the investigation. This report presents the result of an analysis of errors that occur when measuring the LEDs 3dB frequencies(cutoff frequency) at currents in the microcurrent region.

Description of the measurement technique and setup.

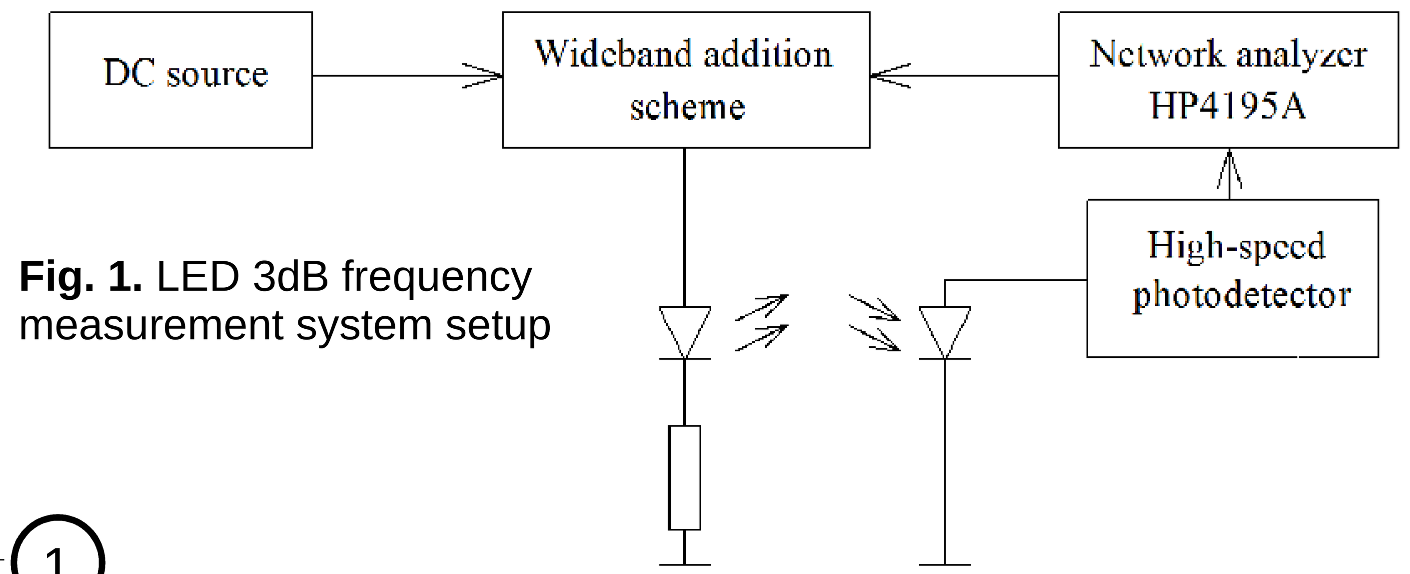

Fig. 1. LED 3dB frequency measurement system setup

The study of the dependence of the LED 3dB frequency on the current was carried out using the installation, the block diagram of which is shown in fig. 1. The LED is powered by DC, which is modulated by low amplitude AC from the output of the HP4195A network analyzer in the frequency range 0.1 - 10 MHz in frequency sweep mode. The registration of the LED optical signal is carried out by a high-speed photodectector. The electrical signal from the output of the photodetector is fed to the input of the HP4195A network analyzer, which reads the 3dB frequency value at a given LED DC current level.

Analysis of measuremen errors.

Let us consider the errors due to the nonlinearity of the *P-I* characteristic when measuring 3dB frequency by detecting harmonic radiation and converting the alternating voltage of the photodiode by the root-mean-square (RMS) detector.

1

The watt-ampere characteristic *P(I)* of the LED in the vicinity of the operating point I_0 can be expanded in a Taylor series:

$$P(I)=P_0+a\Delta I+b\Delta I^2+\dots$$

where P_0 is the power value at the operating point I_0: $P(I_0)=P_0$; and the coefficients *a* and *b* are respectively equal:

$$a=\left.\frac{dP(I)}{dI}\right|_{I_0},\quad b=\left.\frac{1}{2}\frac{d^2P(I)}{dI^2}\right|_{I_0}$$

2

Limiting to the quadratic term in *P(I)*, an expression is obtained for estimating the relative measurement error f_{3dB} of the LED without taking into account the noise in the measuring circuit:

$$\varepsilon \approx \frac{b^2}{10a^2} I_m^2 100\%$$

where I_m is the amplitude of the variable component of the LED electric current.

3

Based on the ABC-model of charge carrier recombination, the watt-ampere characteristic of LEDs at low currents can be approximated by the function:

$$P(I)=m\left(1-\sqrt{1+2qI}+qI\right)=\frac{m}{2}\left(\sqrt{1+2qI}-1\right)^2$$

$$m=\eta_{extr}V\frac{hc}{\lambda}\frac{A^2}{2B},\qquad q=\frac{\eta_{inj}}{eV}\frac{2B}{A^2},$$

A – nonradiative recombination coefficient,
B – radiative recombination coefficient.

Parameter *q* has dimension [A^{-1}]. The value of this parameter depends on the degree non-linearity of the LED *P-I* characteristic. The *q* parameter values for LEDs of different types are about 10^5 … 10^7 A^{-1}. The larger *q*, the less the degree of nonlinearity of the *P-I* characteristic (fig. 2).

4

The coefficients *a* and *b* for the dependence in expansion (1) of the radiation power will be equal to:

$$a=\left.\frac{dP(I)}{dI}\right|_{I_0}=mq\left(1-(2qI_0+1)^{-1/2}\right)$$

$$b=\left.\frac{1}{2}\frac{d^2P(I)}{dI^2}\right|_{I_0}=\frac{mq^2}{2(2qI_0+1)^{3/2}}$$

5

Substituting the expressions for the coefficients in (2), we obtain the expression for the error:

$$\varepsilon \approx \frac{0,7q^2}{(2qI_0+1)^2\left(\sqrt{2qI_0+1}-1\right)^2} I_m^2$$

Using expression, the dependence of the measurement error of the LED 3dB frequency on the current amplitude at currents 1 μA (a) and 10 μA (b) was constructed, due to the nonlinearity of the *P-I* of the LED (fig. 3).

6

By adding additive noise U_n to the photodiode signal and carrying out mathematical transformations, an expression was obtained for estimating the relative error, taking into account the noise of the measuring circuit:

$$\varepsilon=\left(\frac{x}{3}-1\right)100\%$$

$$x=-\frac{\left[5\left(\frac{1}{2}-\frac{U_n}{SaI_m}\right)^2-\frac{b^2I_m^2}{4a^2}-4\right]+\sqrt{\left[5\left(\frac{1}{2}-\frac{U_n}{SaI_m}\right)^2-\frac{b^2I_m^2}{4a^2}-4\right]^2-16\left(\frac{1}{2}-\frac{U_n}{SaI_m}\right)^2*\left(\left(\frac{1}{2}-\frac{U_n}{SaI_m}\right)^2-\frac{b^2I_m^2}{4a^2}-1\right)}}{8\left(\frac{1}{2}-\frac{U_n}{SaI_m}\right)^2}$$

where *S* is the power conversion coefficient of the LED into the output voltage of the photodetector, which is determined by the sensitivity of the photodiode, the gain, the radiation patterns of the LED and the photodiode and has the dimension [V/W].

7

The SFH203 photodiode was used to register optical radiation. The current from the photodiode output is converted to voltage by a trans-impedance amplifier(high-sped phoodeecor) based on the OPA656 operational amplifier.

To calculate the noise voltage U_n from the output of the amplifier, its noise equivalent circuit was compiled. Based on this scheme, an expression was obtained for calculating the RMS noise level of the output voltage for a trans-impedance amplifier in the frequency band Δf :

$$U_n=\sqrt{e^2+4kTR_f\Delta f+(iR_f)^2+2qIR_f{}^2\Delta f}$$

where *I* is the average value of the current flowing through the photodiode; *q* - electron charge, *e* – RMS noise voltage at the op-amp input, *i* - noise of the op-amp input current, the second and third terms of the expression are the thermal noise of the feedback resistor of the amplifier and the shot noise of the photodiode, respectively.

For the selected elements for the transimpedance amplifier, using expression (7), the RMS value of the noise voltage at the output U_n = 43 μV was calculated.
Using (6), dependences of the LED 3dB frequency measurement error on the current amplitude at 1 μA (a) and 10 μA (b) were plotted, due to the nonlinearity of the watt-ampere characteristic of the LED and the noise of the photodetector U_n = 43 μV, at *S* = 20 V/W (fig. 4).

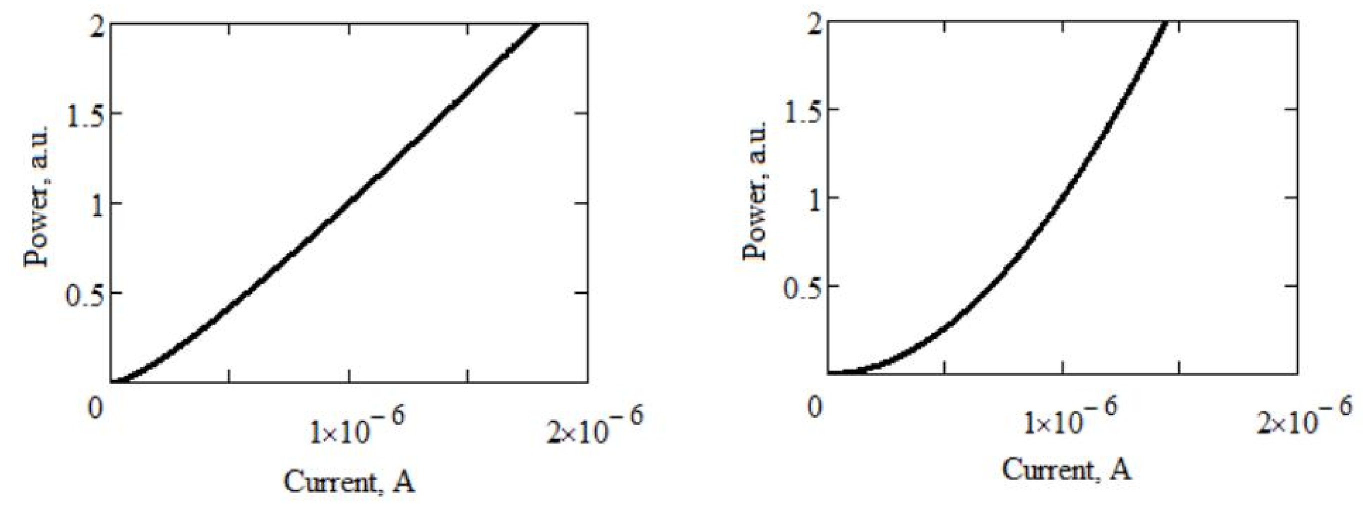

Fig. 2. *P-I* characteristics of LEDs at different values of parameter *q*: a) *q* =10^7 A^{-1}; b) *q* =10^5 A^{-1}.

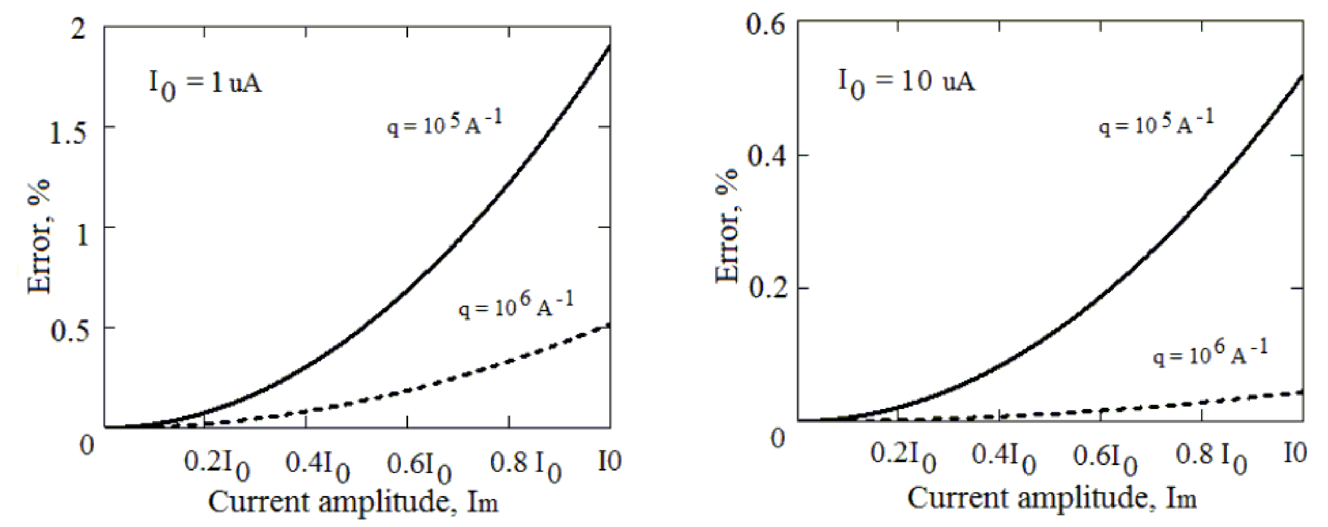

Fig. 3. Measurement error of the LED 3dB frequency on the current amplitude at currents 1 μA (a) and 10 μA (b), due to the non-linearity of the LED *P-I* characteristic.

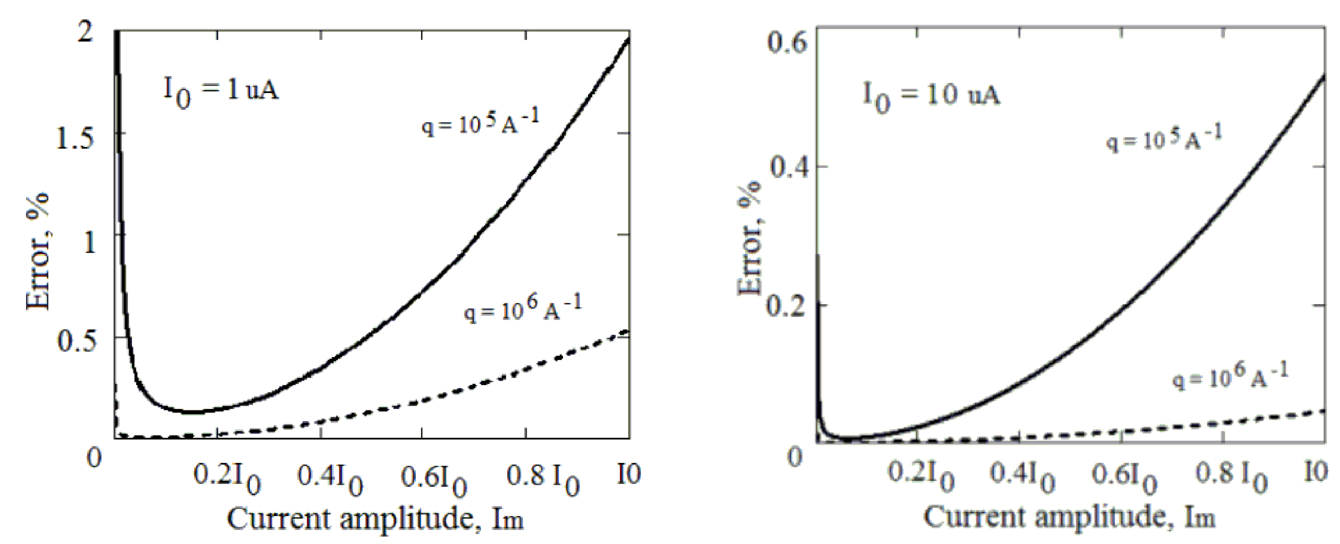

Fig. 4. 3dB frequency measurement error of the LED as a function of the current amplitude at a currents 1 μA (a) and 10 μA (b) due to the non-linearity of the LED *P-I* characteristic and photodetector noise.

Conclusions.

The dependences of the relative errors of measuring the LED 3dB frequency on the amplitude of the test harmonic current are obtained when the alternating radiation is detected by a photodiode and the alternating voltage of the photodiode is converted by the RMS detector. It has been established that due to the nonlinearity of the *P-I* of the LED and in the presence of additive noise in the measuring circuit, there is an optimal value of the test current amplitude, at which the total relative measurement error takes the minimum value.

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