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Quantum efficiency improvement of optical radiation trap-detectors

D.N. Tatyanko[1], **P.I. Neyezhmakov**[2,3], **Ye.P. Timofeev**[2], **A.S. Litvinenko**[3], **K.I. Suvorova**[3], **O.M. Didenko**[3]

[1]*O.Ya. Usikov Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine,*
12, Academica Proskury str., 61085 Kharkiv, Ukraine
E-mail: tatyanko@ukr.net
[2]*National Scientific Centre "Institute of Metrology",*
42, Myronositska Str., 61002 Kharkiv, Ukraine
E-mail: timofeev@metrology.kharkov.ua; pavel.neyezhmakov@metrology.kharkov.ua
[3]*O.M. Beketov National University of Urban Economy,*
17, Marshala Bazhanova str., 61002 Kharkiv, Ukraine
E-mail:kisuvorova17@gmail.com

Abstract. The ways to increase the quantum efficiency of trap detectors of optical radiation have been discussed. Presented here has been a brief review of trap detectors, in which high quantum efficiency is ensured by their design. The obtained results of performed studies confirm the practical meaning of the new developed schemes for the construction of trap detectors. Results of investigations of optical receivers based on trap detectors that were applied at the state primary measurement standards of the optical radiation units have been presented, too.

Keywords: trap detectors, optical radiation, quantum efficiency.

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1. Introduction

Trap detectors of optical radiation have been recognized as detectors for highly accurate measurements and are used in national metrological institutions as a part of the measurement standards of energy and spectral characteristics of optical radiation [1]. The quantum efficiency of modern trap detectors exceeds 99.9%, and the uncertainty of reproducing the power of optical radiation of measurement standards based on trap detectors is less than 0.1% [2].

Continuous intense development of metrological equipment for telecommunications, medicine, *etc.*, requires increasing the accuracy of optical detectors. The paper provides an overview of optical trap detectors, the original design of which increases their external quantum efficiency, which allows increasing the accuracy of absolute measurements of the energy characteristics of optical radiation.

2. Main part

In modern measuring devices, photodiodes are widely used as detectors of optical radiation. But one of the drawbacks of photodiodes is their nonlinear spectral sensitivity. The use of modern semiconductor materials can significantly reduce the spectral dependence of photodiodes. In particular, some silicon photodiodes, such as photodiodes of the series Hamamatsu S1337, possess 100% internal quantum efficiency, that is, each photon absorbed by a semiconductor, is involved in generation of one electron. The advantage of the new photodiode is well illustrated in Fig. 1, where the dependence of quantum efficiency on the radiation wavelength for different types of optical detectors is shown [3].

At the same time, a significant part of photodiode radiation (more than 35%) is not absorbed by the photosensitive material and is reflected from their surface. The value of the reflected optical power depends on the spectral sensitivity of material.

Photodiode spectral sensitivity S is characterized by the photocurrent I generated per optical power unity P, incident on the photodiode surface [4]:

$$S = \frac{I}{P} = \frac{\eta n e \lambda}{hc}, \qquad (1)$$

where h is the Planck constant; c – speed of light in vacuum; e – elementary charge; n – air refraction index; λ – wavelength of the radiation incident on the photodiode; η – external quantum efficiency, that is, the

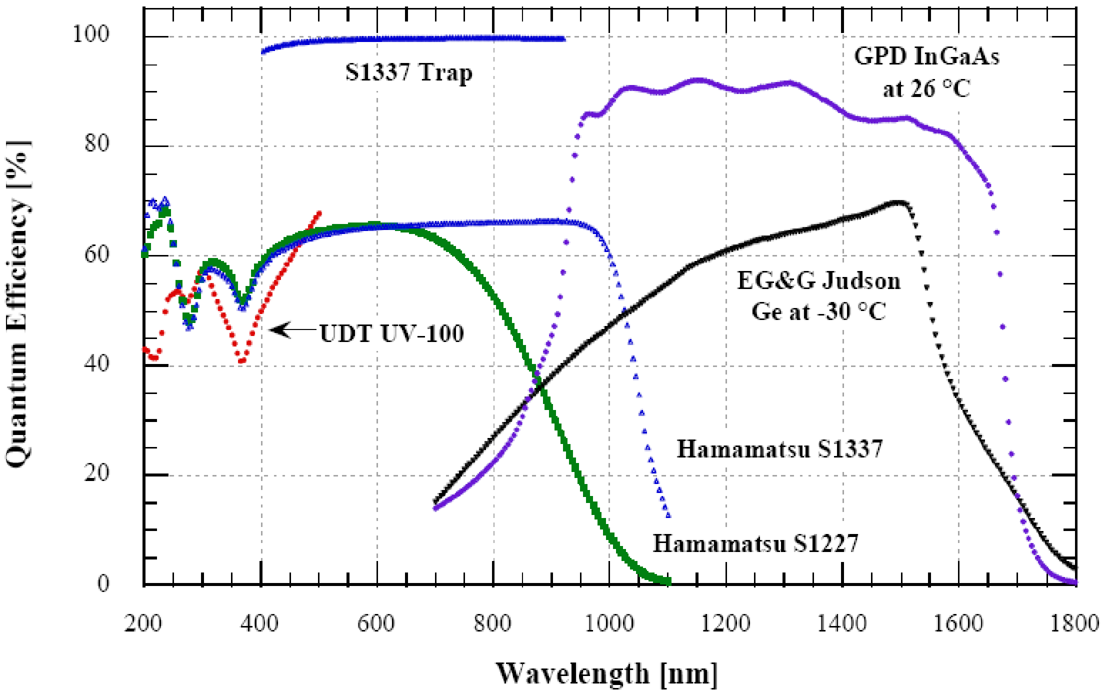

Fig. 1. Quantum efficiencies of typical Si, InGaAs, and Ge photodiodes.

ratio of the number of generated electron-hole pairs to the number of photons falling on the surface of photodiode:

$$\eta = \eta_i (1 - \rho(\lambda)) = (1 - \rho(\lambda)) \varsigma \left(1 - e^{-\alpha(\lambda)\omega}\right), \qquad (2)$$

where η_i is the internal quantum efficiency of the photodiode; ζ – part of the electron-hole pairs that take part in the photocurrent (in relative units); $\alpha(\lambda)$ – wavelength-dependent absorption coefficient; ω – thickness of the photodiode layer on which optical power is absorbed; $\rho(\lambda)$ – the coefficient dependent on the wavelength of reflection from the surface of the photodiode.

Thus, in the expression (2) for quantum efficiency, there are two components depending on the wavelength of optical radiation – the reflection coefficient from the photodiode surface $\rho(\lambda)$ and the absorption coefficient of the photosensitive layer of photodiode $\alpha(\lambda)$. The maximum linearity of the spectral sensitivity can be obtained by minimizing the nonlinearity of these two components. The spectral sensitivity, in this case, will only linearly depend on the wavelength of radiation.

The photodiode absorption coefficient $\alpha(\lambda)$ depends on the material of the photosensitive layer. Thus, for more accurate detection of optical radiation, it is necessary to have a photodiode with the best linearity of the absorption coefficient of photosensitive layer in the given spectral range. Another possibility to minimize the influence of the nonlinear component of the spectral sensitivity inherent to photodiodes [5] is to reduce the coefficient of reflection $\rho(\lambda)$ and, therefore, to increase the external quantum efficiency of the photosensor, since, as it was mentioned earlier, more than 35% of the power of optical radiation falling on it can be reflected from the surface of the photodiode [6].

It is possible to reduce the optical power loss associated with the reflection of radiation from photodiodes by using the so-called “trap detector” as an optical radiation detector.

The trap detector model, for example, proposed in [7, 8], consists of four photodiodes located at an angle to one another along the propagation of optical radiation. The beam of the optical source, falling on the surface of photodiodes, is partially absorbed, and the remaining energy of the beam is reflected. Reflecting from each photodiode in the trap detector, the beam hits the next photodiode along the beam propagation and, reflected from the last one in the photodiode chain, is directed to the previous photodiode, thus returning to the photodiode system [9]. Photodiodes are electrically connected to each other in parallel, *i.e.*, currents from all photodiodes are summed up.

Due to the repeated hit of the beam on the photosensitive surfaces of photodiodes inside the trap detector, almost all optical radiation is absorbed, therefore, losses due to reflection of radiation from the surface of photodiodes in the detector structure decrease and the external quantum efficiency of the detector increases. The reduction of the losses caused by the reflection of radiation increases the external quantum efficiency and improves the linearity of the spectral sensitivity of the trap detector as compared to that of individual photodiodes [10]. To reduce the losses associated with the reflection of radiation in the above-mentioned photodetectors, an improved design of a

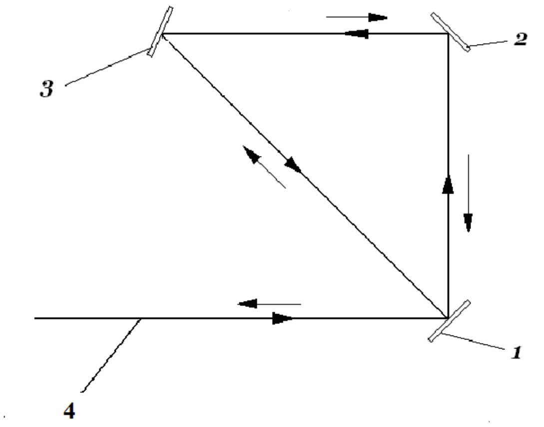

Fig. 2. New model of a trap detector based on three photodiodes. *1–3* – photodiodes, *4* – direction of the incident and reflected optical radiation. Total number of reflections (2*N*+1).

three-diode trap detector [11–13] was proposed (Fig. 2), which provides a greater number of beam reflections in the detector structure without increasing the number of photodiodes.

In presented in Fig. 2 a three-diode trap detector model, optical radiation from the last photodiode *3* in the chain is not reflected back to the previous photodiode, as it is in the classical trap detector models, but due to the photodiode positioning at a certain angle to the incident beam, is reflected to the first photodiode *1*. From the first photodiode *1* in the chain, radiation is reflected back into the system of photodiodes, *i.e.*, on the photodiode *3* and further in series on the photodiodes *2* and *1*. Thus, the number of reflections in the proposed trap detector model (Fig. 2) is 2*N*+1, where *N* is the number of photodiodes in the trap detector, in contrast to the classical models [9], in which the number of reflections is 2*N*–1.

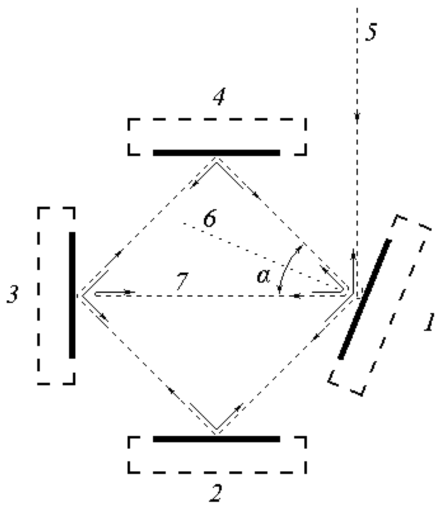

Fig. 4. Scheme of the trap detector with 4 photodiodes. Total number of reflections (2*N*+3).

A comparative analysis carried out in the paper [14] showed that the output of the proposed model of a trap detector in Fig. 2 generates the maximum current level from all the considered types of trap detectors, namely: the new design has the highest quantum efficiency.

The quantum efficiency of this new model, in comparison with the already known, previously developed models is 0.25…0.26% higher than of the detector TRAP-100 and 0.15…0.2% higher than the QED-200 detector (for the radiation wavelength 633 nm). Regarding the QED-100 detector in a three-diode configuration, the quantum efficiency of the new design is higher by more than 1%. This is a pretty good result that the accuracy of reproduction of a unity of optical radiation power in measurement standards based on trap detectors is less than 0.1%.

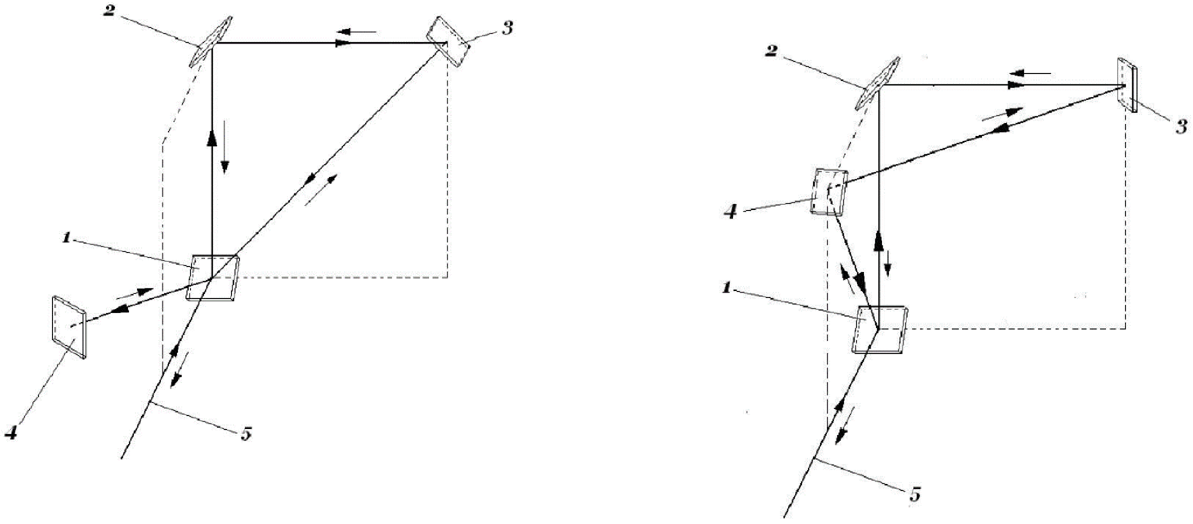

Fig. 3. New polarization-independent models of trap detectors based on four photodiodes. *1–4* – photodiodes, *5* – direction of the incident and reflected optical radiation. Total number of reflections (2*N*+1).

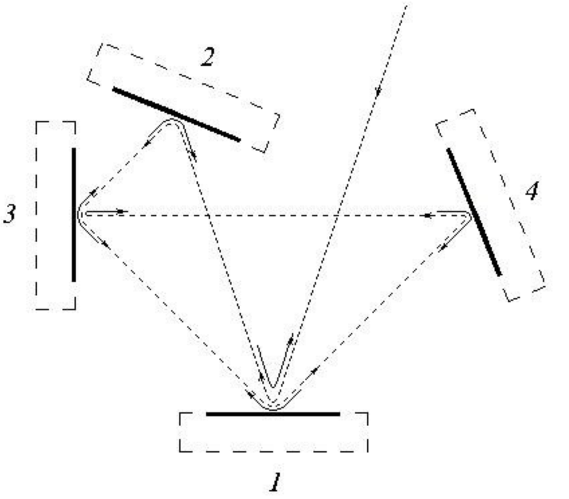

Fig. 5. Scheme of the trap detector with 4 photodiodes. Total number of reflections (4*N*–5).

Fig. 3 shows the spatial versions of the model of the trap detector in Fig. 2, in which the photosensitive surfaces of the photodiodes are inclined to each other in such a manner that the radiation polarization vector, *i.e.*, the vertical and horizontal polarization components of radiation are maximally absorbed [11].

In the development of the model shown in Fig. 2, the models in Figs. 4–7 are proposed. In Fig. 4, a trap detector model is proposed, in which the number of radiation reflections inside the detector is 2*N*+3 [15].

In Fig. 5, a trap detector model is proposed, in which the number of radiation reflections inside the detector is 4*N*–5 [16].

Figs. 6, 7 shows the variants of the trap detector model shown in Fig. 5.

An alternative to the above-described approach to detecting optical radiation can be developed designs based on the property of a mirror ellipse surface to reflect any beam that passes through one of the ellipsoid foci in the direction in which it necessarily passes through the second focus and, having reflected, a second time from the ellipse surface, the beam will again pass through the first focus, *etc*., each time clinging to the major axis of the ellipsoid of rotation until it completely merges with it [17-20].

Fig. 8 shows the configuration of the proposed trap detector with an ellipse mirror [20].

Fig. 9 shows the design of the trap detector using photodiodes in the form of parts of an ellipsoid of rotation. Radiation is introduced into the detector using discrete optics (lens) or optical fiber (light guide). The beam is focused to a point that coincides with the focus of the ellipsoid of rotation.

Photodiode *1* is located at a distance equal to half the major axis of the ellipsoid from the elliptical mirror.

The constructions of the trap detectors without mirrors are shown in Figs. 9a, 9b. Fig. 9a shows a configuration with two photodiodes made in the form of parts of an ellipsoid of rotation. Fig. 9b shows a configuration with flat and ellipse photodiodes. These trap detectors are used in the modes similar to those shown in Fig. 8. The advantages of these configurations are the absence of unaccounted losses on the mirrors, which increases the accuracy of the absolute power measurements.

Ellipsoidal configurations allow excluding reflected radiation in the direction of the radiation source. They are convenient for measuring incoherent radiation sources, since each subsequent reflection causes a narrowing of the radiation pattern. In addition, all the proposed

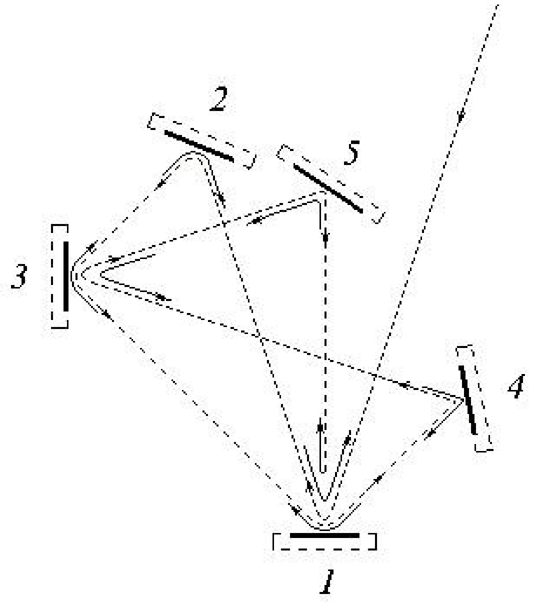

Fig. 6. Scheme of the trap detector with 5 photodiodes.

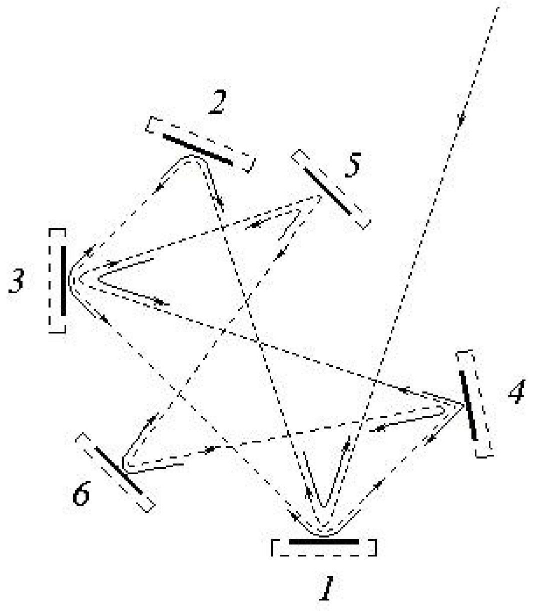

Fig. 7. Scheme of the trap detector with 6 photodiodes.

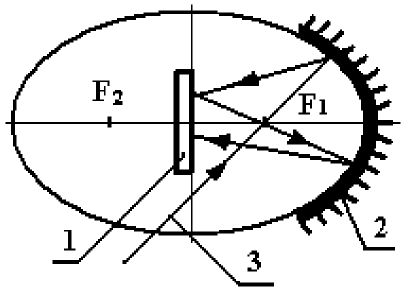

Fig. 8. Diagram of the trap detector with a mirror in the form of a part of an ellipsoid of rotation.

Fig. 10.

Fig. 11.

Fig. 10. The physical configuration of the reference primary measuring transducer with the 3-diode circuit.

Fig. 11. The physical configuration of the reference primary measuring transducer with the 4-diode circuit.

configurations allow taking into account the diffuse component, which positively affects the accuracy of measurements.

Part of the above-mentioned constructions schemes for receivers on the basis of trap detectors were implemented when creating the state primary measurement standard of the unities of mean power in the radiation pulse, power of continuous radiation in the light guide and radiation propagation time in the light guide (DETU 11-03-09) as well as the state of primary measurement standard of the unities of mean power and energy inherent to laser radiation (DETU 11-04-12).

The reference primary measuring transducer included in DETU 11-03-09 is made using the traditional 3-diode circuit (Fig. 2) and the reference primary measuring transducer included in DETU 11-04-12 is made of the 4-diode circuit (Fig. 5).

The physical configuration of the reference primary transducer DETU 11-03-09 is shown in Fig. 10 and the physical configuration of the reference primary transducer DETU 11-04-12 is shown in Fig. 11.

The authors have performed studies of the specified reference primary measuring transducers by using various construction schemes for trap detectors. A signal from a He-Ne-stabilized laser with the emission wavelength 633 nm was gradually applied to both trap detectors. The plots (Figs 12 and 13) show the time dependences of the output signal when measuring the laser power by the reference primary measuring transducer DETU 11-03-09 and DETU 11-04-12, respectively.

The mean value of the output signal of the reference primary measuring transducer DETU 11-04-12 is equal to 821.5925 μA and the mean value of the output signal of the reference primary measuring transducer DETU 11-03-09 is 821.4274 μA.

The relative difference in the measurement indications with reference primary measuring transducers is 0.02%. Since the mean value of the output signal of the reference primary measurement transducer DETU 11-04-12 is higher than that of the output signal of the reference primary measurement transducer DETU 11-03-09, this shows the advantage of constructing a trap detector with the 4-diode circuit, since under all the other equal conditions of measurements, the trap detector with the

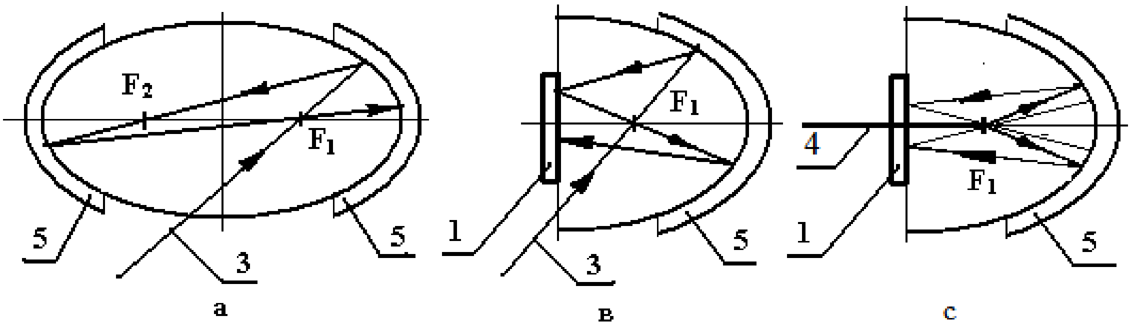

Fig. 9. Drain detector scheme (a – using photodiodes in the form of parts of an ellipsoid of rotation; b – using a flat photodiode and a photodiode in the form of a part of an ellipsoid of rotation; c – with radiation input through a light guide). *1* – flat photodiode, *2* – elliptical mirror made as part of ellipsoid of rotation, *3* – beam of radiation source which power is measured, *4* – light guide, *5* – ellipse photodiode made as a part of ellipsoid of rotation; F1, F2 – foci of ellipsoid of rotation.

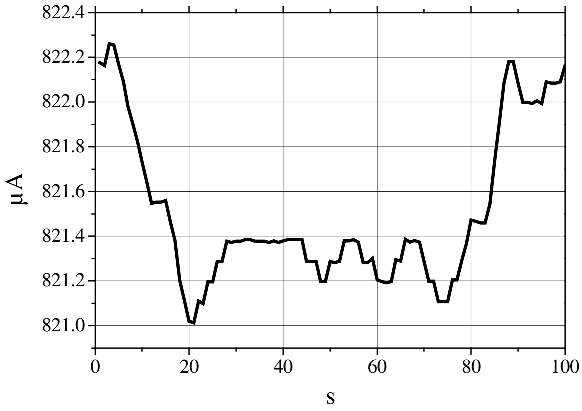

Fig. 12. The output signal from the reference primary measuring transducer DETU 11-03-09.

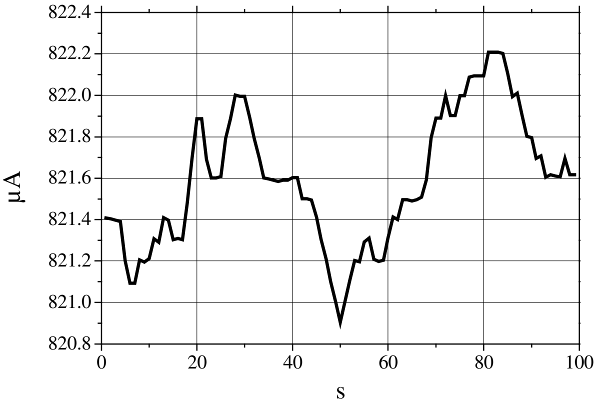

Fig. 13. The output signal from the reference primary measuring transducer DETU 11-04-12.

new 4-diode circuit shows a higher quantum efficiency and a better approximation to the ideal trap detector. Considering that the type B standard uncertainty of DETU 11-04-12 is 0.03%, the reference primary measuring transducer with the 4-diode circuit provides the measurement of the laser power with less uncertainty.

The performed studies also confirm the practical value of the developed new schemes for the construction of trap detectors.

3. Conclusions

The use of trap detectors provides a higher quantum efficiency and better linearity of the spectral sensitivity of these detectors, as compared to detectors based on single photodiodes. New models of trap detectors have been proposed, with the improved spectral sensitivity linearity and increased quantum efficiency. The use of trap detectors makes it possible to increase the accuracy of optical radiation power measurements in the operation wavelength range as compared to individual photodiodes and well-known trap detectors, which allows applying them in the State Primary Measurement Standards of Ukraine and calibration laboratories as high-accurate measuring instruments of optical radiation power.

Due to its characteristics, such as high sensitivity and good linearity in a wide frequency range, trap detectors can be effectively used in the following research areas: twilight photometry [21], studies of circadian rhythms [22], multi-functional multi-channel laser systems [23] and so on.

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Authors and CV

Dmytro N. Tatyanko, PhD, Senior Researcher, O. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine, Department of nonlinear dynamics of electronic systems. Authored over 75 scientific publications, 4 patents. The area of scientific interests is low-coherence spectral interferometry; energy and spectral characteristics of optical radiation; optical radiation detectors, optical reflectometry; ultra-bright LEDs; software defined radars; processing random signals for noise radars based on FPGA systems; microelectronics; microcontrollers.

Pavel I. Neyezhmakov, General Director of National Scientific Centre “Institute of Metrology” (Kharkov, Ukraine). Doctor of Sciences, professor; CIPM member. Professor of Department “Lighting Engineering and Sources of Light”, O.M. Beketov National University of Urban Economy in Kharkiv, Ukraine; Chief Editor of Ukrainian Metrological Journal; Chief Editor of Information Bulletin on International Metrology; Associate Editor of NCSLI Measure for candela; Editor of International scientific journal “Lighting Engineering & Power Engineering”. Authored over 230 publications, 3 patents. The area of scientific interests is metrology and measurement standards, photometry and radiometry, photodetectors and light sources.

Yevgen P. Tymofeev, Doctor of Sciences, senior researcher, leading researcher at the National Scientific Centre “Institute of Metrology”, specializes in the field of metrological support of measurements of energy characteristics of lasers and LEDs.

Anatoliy S. Litvinenko, PhD, Assistant professor, senior lecturer at the Department of Lighting Engineering and Sources of Light, O.M. Beketov National University of Urban Economy in Kharkiv, Ukraine. Authored over 28 works, 39 patents. The area of scientific interests is holography, metrology, lighting engineering.

Krystyna I. Suvorova, PhD, senior lecturer at the Department of Lighting Engineering and Sources of Light, O.M. Beketov National University of Urban Economy in Kharkiv, Ukraine. Authored over 20 works. The area of scientific interests is energy and spectral characteristics of optical radiation; optical radiation detectors, light for circadian rhythms, lighting engineering, LEDs metrology.

Olena M. Didenko, PhD, senior lecturer at the Department of Lighting Engineering and Sources of Light, O.M. Beketov National University of Urban Economy in Kharkiv, Ukraine. Authored over 30 works. The area of scientific interests is unconventional renewable energy sources, lighting.