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Thermostabilized photodiode for monitoring radiation of medical lasers

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Abstract. The construction of cooled photodiode for medical lasers with non-linearity of output performance in the range from 10^{-8} to 10^{-1} W not more than 1.05 % is suggested. Regulation of cooling the crystal of photodiode is performed by means of specific software controlling the temperature of the photodiode crystal depending on the value of its photocurrent.

Keywords: photodiode, non-linearity, medical laser, thermoelectric module, output performance.

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1. Introduction

Linearization of output performance of sensors transforming energy fluxes into an analogue signal is one of topical tasks in modern optoelectronics. The degree of linearization of a sensor in a certain range of energy or power of optical radiation determines the range of measurements by using a corresponding device. The energy range of the sources of optical radiation, laser sources in particular, changes from a few microwatts to hundreds and thousands of watts. These conditions require nonlinearity of output performance in such ranges of received power from sensors and, in particular, photodiodes intended for measuring the fluxes of laser radiation. Actually, the necessity of providing the dynamic range of a photodiode from 9 to 10 orders is meant; and this is a rather difficult task. This problem is urgent when dealing with monitoring the flux of laser radiation produced by medical lasers, since their radiation affects human body. In this case, measurements of laser radiation power should be performed with a minimal error. Nonlinearity of output performance is one of the constituent parts of the measurement error of laser radiation output power as a flow of optical radiation. Generally, for serial sensors this error is less than ± 1 % in the dynamic range of 7…8 orders [1].

Thus, the problem of enlarging the dynamic range of a photodiode or minimization of nonlinearity of output performance in the wide dynamic range – up to 10 orders – appears to be important for modern measuring equipments intended for measuring output performance of laser radiation sources for medical purposes.

Therefore, the aim of this research is to study the factors affecting the nonlinearity of output performance of a photodiode in the wide range of energy or power measurement for optimization of the construction of meters of output performance of laser radiation sources for medical purposes.

2. Results

Nonlinearity of output performance determining the dynamic range of a photodiode as a quality parameter is widely used in world practice [2]. Nowadays, the output performance or photocurrent of photodiodes is limited by two factors: the value of photocurrent achieved due to the increase of space charge in the volume of photodiode [3] and heat released in the photodiode crystal, because it is heated by the motion of charges caused by the first factor. These two factors are the reasons of disastrous intensification of charge carriers' motion through *p-n* junction. It is shown in [4] that the decrease of the effect related with space charge can be achieved by changing the construction and technique of photodiodes contacts, with maintaining high performance and good linearity. The advantage of the suggested structure consists in the fact that only electrons possessing higher velocity than a certain boundary value are used as active carriers. A new construction has an additional layer controlling the relative voltage of electric field in the absorption layer of collector region [5]. Such an approach enabled to achieve the maximal photocurrent of 152 mA at 6 V of reverse bias at 18 GHz. The diameter of the area of photosensitive element was 40 μm. Illumination of the photodiode was performed from the back side of the photodiode crystal. In this device, the heat generated in the gain region of mesostructure is generally diffused on the substrate and partially – to the ambient air. The light passes through the substrate that has an antireflective coating on its surface receiving optical radiation. The maximal output photocurrent reached in this structure of a photodiode is not limited by saturation and thermal injury.

Among other different techniques of improving the heat diffusion, it appeared to be possible to reach the best result on the suggested structures. Go with coauthors F.-M. Kuo, M.-Z. Chou, and J.-W. Shi [6] reported about two cascaded photodiodes with similar structure and output performance 63 MW at 95 GHz [6]. Itakura *et al*. demonstrated maximal output performance from 790 MW at 5 GHz with the use of a flip-chip of 4-diode matrices with monolithic integrated Wilkinson power combiner [7].

The present-day state-of-the-art in the problem under study – minimization of nonlinearity of output performance of photodiodes in the wide dynamic range – is presented in [8]. Here, the problems concerning production of high-power photodiodes with a modified construction providing high level of linearity of the output signal from the incident optical power named by the authors as “flip-chips” are considered.

The dependence of nonlinearity of output power at more intensive illumination (photocurrent reaches the value 100 mA) as the dependence on the area of a photosensitive element [9] was also investigated. It has been shown that sensitivity of photodetectors with greater area of gain region reached saturation at higher photocurrent if compared with the devices based on photodiodes with smaller gain region.

A short review of the known solutions of this problem shows that two main factors determining nonlinearity of output performance of a photodiode – photocurrent saturation obtained due to increase of space charge in the volume of photodiode and heat generated on the crystal of photodiode as a result of its heating by charges motion caused by the first factor – are interrelated. It is evident that, having solved the problem of photodiode heating that grows in proportional to the growth of optical radiation received by the photosensitive plate of the photodiode, it would be possible to decrease nonlinearity of output performance of the photodiode and thus, to enlarge its dynamic range.

Non-stability of photodiode sensitivity (δ_t) in time assessed by five measurements registered in equal time intervals (1–15 min) also leads to increase of nonlinearity of output power of a photodiode.

Another reason of deviation in the output performance of a photodiode from linearity, in our opinion, consists in temperature error of photodiode operation, though it comes from the main problem – heating of a photodiode under the impact of incident optical radiation.

It comes from all the mentioned above that minimization of nonlinearity of output performance can be obtained by means of reducing heat emission of the sensitive element and adjacent to it parts of a photodiode [10-12], *i.e.* by cooling the photodiode.

Thermoelectric modules are rather efficient in this sense [13]. However, in our case, when using thermoselectric cooling, besides the problem of minimizing the nonlinearity of output performance at simultaneous enlarging the dynamic range of a photodiode, we face the task of producing the thermoelectric modules (TEM) with the time of reaching the operation mode 1…4 s. We should also achieve homogeneity of temperature distribution on the cold edge of TEM within 0.1…0.3 °C for uniform cooling the photodiodes with large areas of a photosensitive element.

It is suggested in [14, 15] to obtain simplified constructions and decrease the time of reaching the working temperature of cooling by a semiconductor thermostatic photodetector through uniting the TEM and a photodiode crystal in one device, in which on the back side of a photodiode crystal the insulating layer with electric commutation paths connected to branches of thermoelectric module is formed. Such a device enables to operate the time of thermoelectric module reaching the cooling mode due to the fact that this time, besides other reasons, depends on the thickness of commutation layer, which in this case is used in the form of insulating layer on the back side of a photodetector. The thickness of insulating layer can be regulated by the time of its deposition and, thus, within certain limits, it is possible to create the devices with the given time of reaching the operation mode of cooling.

The crystal of a photodiode produced on the basis of high-resistance silicon of *n*-type conductivity (resistivity of original silicon is about 600 Ohm/cm) intended for registration of optical radiation with the wavelengths 635, 665, 810, 915 nm, is widely used in medical devices. The suggested wavelengths correspond to absorption spectrum of optical radiation in silicon, which enables to use it for registering radiation of above mentioned wavelength.

Fig. 1 presents the scheme of the suggested temperature-controlled *p-i-n* photodiode.

The photo of a temperature-controlled photodiode based on PD-288 with TEM is adduced in Fig. 2.

The back side of the photodiode crystal (*1*) contains the insulating layer (*2*), on which the electric commutation paths (*3*) are formed with branches of thermoelectric module (*4*) connected with them. The branches of thermoelectric module are connected with electric commutation paths (*5*) of heat-absorbing ceramic plate of the module (*6*), united with the header of the device (*7*) functioning as a heatsink. By means of copper-tinned (*8*) and golden (*9*) conductors, the thermoelectric module and photodetector are connected to the outputs of the device (*10*). The device assembled on the header is encapsulated with the cover (*11*) possessing the glass input window (*12*).

The suggested semiconductor temperature-controlled photodetector operates in the following way. Being in the operation regime, when receiving optical radiation, it is heated. The error of readout of e.g. illumination measured by the photodiode PD-288 increases by 0.2%. It occurs due to the increase of photodiode noise with the growth of its temperature. This leads to the increase of nonlinearity of output performance and deterioration of its dynamic range.

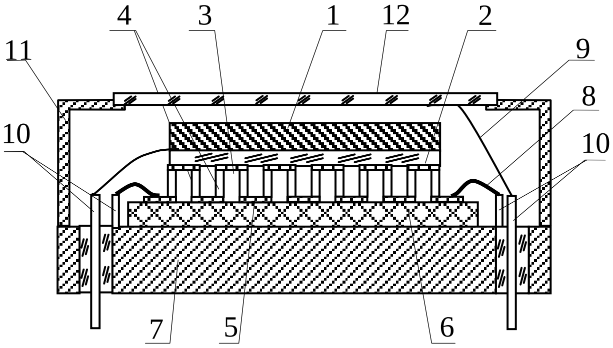

Fig. 1. Scheme of the suggested temperature-controlled *p-i-n* photodiode. *1* – crystal photodiode; *2* – dielectric layer; *3* – electrical switching paths; *4* – branches of the thermo-electric module; *5* – electrical switching tracks heat-ceramic plate module; *6* – heat absorbing ceramic plate; *7* – base; *8*, *9* – tinned copper conductors and gold; *10* – terminals of the device; *11* – cover; *12* – glass entrance window.

Fig. 2. Photo of a temperature-controlled photodiode based on PD-288 with TEM.

When the thermoelectric module is switched on, electric current flows in its branches; which causes temperature reduction of the cold edge of the module and temperature reduction of the photodiode crystal located on this side of the module. Owing to small thickness of insulating layer on the back side of the photodetector, the temperature on it changes fast, practically simultaneously with cooling the cold seals of the module. In this case, the speed of cooling the cold edges of branches is determined by their geometric parameters, in particular by height that depends on how the photodiode should by cooled. Therefore, simplifying the construction of the device and reducing the time of its reaching the operation temperature is achieved due to the fact that, on the one hand, heat transmission from the photodetector to thermoelectric module is performed directly without loss on additional elements, and, on the other hand, due to the small height of the branches.

The silicon *p-n* photodiode of PD-288 type, the thickness of which is 300 μm and area – 100 mm^2, was used as a crystal in the experiment. The operation regime of the photodiode is photovoltaic. On the back side of the photodiode, the insulating layer – silicon oxide 1…3 μm thick is applied, on which electric commutation copper paths with antidiffusion nickel substrate are formed by the method of vacuum deposition. The branches of the thermoelectric module made from solid solution of Bi-Te-Se-Sb [12] with the height 1 mm are assembled on the electric commutation paths of commutation plate and by means of ПОС 61 solder are connected with electric commutation paths of the cold edge of the module. The commutation plate made from ceramics 22XC is connected with metallic header of the device, which acts as a heatsink. The whole construction is encapsulated by the cover with glass input window.

The construction of the thermoelectric module is calculated according to the classical technique [16] and consists of six rows by six branches of *p*- and *n*-type of conductivity. Geometrical sizes of a branch are 1.1×1.1×1.8 mm. The maximal current consumption of the module is 0.3 A. The maximal refrigeration capacity is 1 W.

However, further research showed that such a construction has certain lag. At the thickness of insulating layer 2 μm, the photodiode is cooled to 5 °C within the time of about 10 s. Further, this temperature of the photodiode crystal does not remain stable; it rather “fluctuates” within 4…7 °C depending on the illumination change. Knowing that the temperature error in the measurements is 0.2%/°C, one can assess that at illumination of 1000 lux at 20 °C and at 1000 lux at 40 °C the range of fluctuations of the real value of illumination will amount to 40 lux. In this case, the nonlinearity of output performance of the photodiode will fluctuate, too.

To reduce the influence of this factor, we suggested the scheme of monitoring the temperature of a photodiode. According to this scheme, the crystal of the photodiode is a cold side of TEM, while the supply current of TEM is determined by the value of photocurrent generated by the photodiode $I_{TEM} \approx f(I_F)$.

To be more exact, the supply current of TEM is controlled by photocurrent. The greater the photocurrent is, the smaller the TEM supply current is. The control of the process of maintaining the temperature of a photodiode crystal through controlling its photocurrent is performed by means of analogue-digital scheme, created according to the technical solution described in [17]. The suggested schematic constructive solution enables to monitor the microprocess beginning with the photocurrent 10^{-12} to $4 \cdot 10^{-10}$ A and finishing 10^{-3} A, which corresponds to the power from 10^{-8} to 10^{-1} W. Thus, it is obvious that the photodiode with the suggested cooling scheme in the form of TEM operated by microcontroller is capable of providing the dynamic range not less than 9 orders. In this range, the nonlinearity of output performance of a photodiode does not exceed 1…2% according to provisional assessment.

To verify our suggestion, five crystals of the photodiode PD-288 were selected. On their base, the temperature-controlled photodetectors were assembled according to the above described construction (Fig. 1) and their dynamic range, nonlinearity of output performance and temperature dependence were investigated.

The authors of [18] suggested a new way of assessment of output performance nonlinearity of a photodiode consisting in the fact that this parameter is estimated by means of three measuring systems to compare the measurement accuracy of various parameters. It is shown that this method can be used for specification of measurement errors in nonlinearity of output performance and establishes the criteria of mutual changeability of these settings.

To investigate the dynamic range and nonlinearity of output performances, we used in general a similar but simpler method of additional illumination [19]. To realize this method, a special light source was used [20].

The temperature characteristics was investigated according to the standard technique [21].

The results of above mentioned parameters of temperature-controlled photodiodes are presented in Fig. 3 (Dependence of nonlinearity of output performance of thermostabilized photodiode on optical power), Fig. 4 (Output performance), Fig. 5 (Thermal dependence of photocurrent).

It can be seen in the figures that experimental samples of photodiodes show nonlinearity of output performance not less than 0.75…1.8% in the power range from 10–8 to 10–1 W. That is, the change of nonlinearity does not exceed 1.05%. The temperature dependence of the photodiodes shows that fluctuations in photocurrent within the range from 10–12 to 10–2 A heat the photodiodes to no more than 5 K (from 276 to 281 K). Thus, TEM keeps the temperature of a crystal under the condition of measuring the optical radiation flow within 278 K.

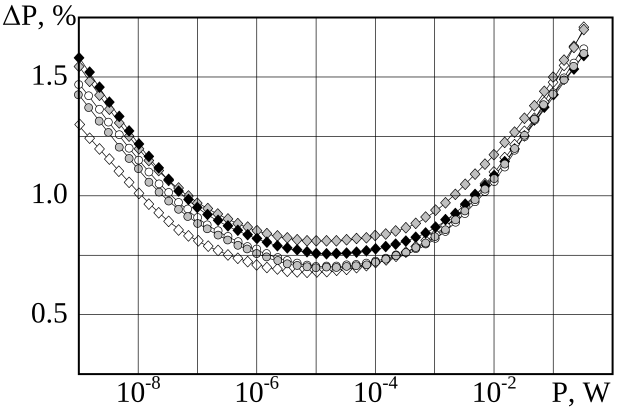

Fig. 3. Dependence of nonlinearity of output performance of thermostabilized photodiode on optical power. Here are five of crystals according to the photodiodes PD-288.

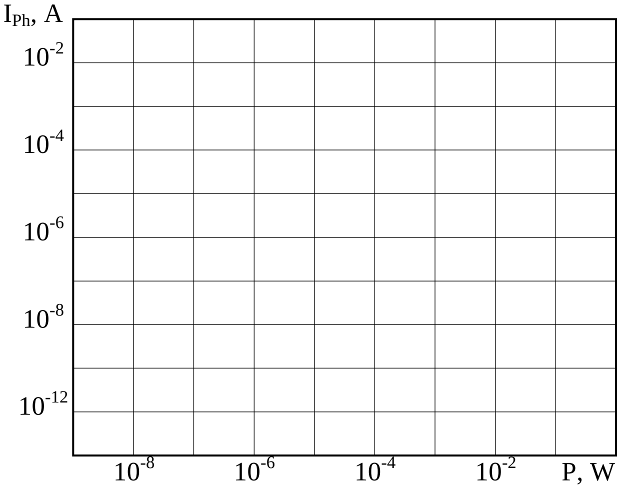

Fig. 4. Energy characteristic of thermally stabilized photodiode. Here are five of crystals according to the photodiodes PD-288.

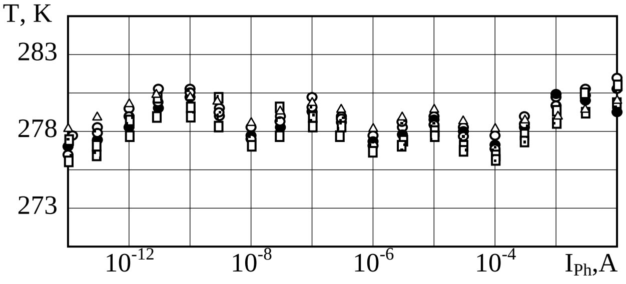

Fig. 5. Thermal dependence of photocurrent. Here are five of crystals according to the photodiodes PD-288.

It should be taken into account that the measurements were performed on experimental samples of photodiodes assembled in the laboratory. At more thorough selection of couples “photodiode – TEM”, it is possible to obtain more precise characteristics. Dispersion of parameters between the samples are explained by non-identity of both the crystals of photodiodes and TEM characteristics. Measurement errors of photocurrent did not exceed 5%.

The suggested approach to solving the problem of enlarging the dynamic range of a photodiode and, consequently, to reducing its nonlinearity enables to make preconditions for virtual enlarging the dynamic range of a photodiode in the region of evident nonlinearity of a photosignal. At more detailed work-out of the technique of producing the suggested cooling photodiode structures, it is possible to reach minimization of nonlinearity of output performance in the investigated power range to the value of less than 1%. This enables to reduce the measurement error of output performance of laser radiation and to increase accuracy of doses of laser impact on man, which is one of the most topical tasks of modern medical equipment.

3. Conclusions

1. The factors affecting nonlinearity of output performance of photodiodes have been analyzed. It has been shown that these can be reduced due to decrease of temperature characteristics of a photodiode.
2. To optimize the temperature characteristics of a photodiode, the construction of cooling photodiode for medical lasers has been suggested, in which the photodiode crystal is the upper edge of a thermoelectric module. This provides its cooling to 5 °C within 10 s.
3. The scheme of controlling the temperature of cooled diode has been suggested, in which the value of TEM supply current is determined by that of photocurrent generated by the photodiode. In this case, the nonlinearity of output performance in the range from 10^{-8} to 10^{-1} does not exceed 1.05%.

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