Features of measurements the IR radiation power of a laser diode used in active optoelectronic systems for studying flows

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Abstract. In active optical-electronic systems for stream research that regulate thermal-physical parameters of diagnosed stream volume, the controlled source of the heat flow can be acquired by radiation of high-power IR laser diodes into the void. In the current work the peculiarities of measurement of this radiation are considered, specified by its strong divergence. It is shown that the measurements can involve laser wattmeters IMO-4M with planar thermoelectric primary measuring transformers of the laser radiation with a flat receiving site provided.

1. Introduction
When designing active optoelectronic flow research systems that regulate the thermophysical parameters of the diagnosed flow volume, the problem of choosing a controlled source of thermal energy arises. A high-power IR laser diode (hereinafter referred to as LD) can serve as such a source in an open space. Of great practical interest is the use of the radiation beam of the end LD, the distinctive features of which are both a large divergence and the shape of the cross-section – a strongly elongated ellipse [1].

Due to these features of radiation, it is possible to simultaneously irradiate an extended section of the flow in the direction of its propagation, and therefore to provide conditions for measuring the temperature dependences of the main parameters of the diagnosed flow volume. The accuracy of determining the degree of influence of the end LD radiation on the thermophysical properties of the flow directly depends on the error in measuring the radiation power, and therefore on solving the problem of interception of a highly divergent laser beam by the receiving platform of the primary optical radiation measuring transducer.

In this paper, we propose to use the classical method of solving this problem, which is based on the inclusion in the measuring circuit of a wide-aperture radiation receiver located at the shortest possible distance from the output mirror of the laser [2].

In metrological practice, photonic and thermal radiation receivers are used to measure the power of laser beams. When choosing the type of end-face LD radiation receiver, it is necessary to take into account that the use of photon receivers for the diagnosis of intense radiation is impossible without its significant...
attenuation. The extremely small overall size of the attenuator in the direction of radiation propagation can be achieved by using calibrated neutral light filters made in the form of plane-parallel plates made of high-quality optical glasses. However, when using such light filters, there is a high probability of an external optical feedback, when part of the radiation reflected from the plate returns to the active region of the LD, causing a catastrophic degradation of its heterostructure [3]. All this makes it much more difficult to use wide-aperture photon radiation receivers for measuring the radiation power of an end-face LD.

Certain difficulties also arise when thermal radiation detectors are used to diagnose radiation from an end-face LD. This is primarily due to the presence of a parasitic heat flux emanating from the heated part of the high-power LD emitter body facing the radiation receiver. To minimize the effect of such a heat flux on the accuracy of measurements of the LD radiation power, the thermal insulation of this part of the radiator body is used, made in the form of a heat shield up to 5 mm thick with a coupling hole for radiation output. It is obvious that the use of a thermal shield limits the possibility of minimizing the distance between the output mirror of the LD and the receiving area of the thermal radiation detector and forces the use of classical calorimeters - instruments for measuring the radiation power with large, and therefore massive energy collectors [4]. However, calorimeters are characterized by high inertia, which makes it difficult to quickly control the radiation power level by blocking the laser beam at set time intervals. That is why we paid attention to the IMO-4 laser wattmeter with a wide-aperture planar thermoelectric primary optical radiation measuring transducers.

2. Design features of the IMO-4M laser wattmeter

Figure 1 shows a photographic image of the main elements of the laser wattmeter planar thermoelectric primary measuring transducers IMO-4 [5]. The IMO-4M conversion element is an integrated microcircuit, the elements of which are an energy collector and planar thermocouples connected in series into four thermopiles.

![Figure 1. Planar thermoelectric primary optical radiation measuring transducers: 1 – energy collector; 2 – one of four thermopiles; 3 – area of thermal contact of the planar conversion element with the thermostat; 4 – housing-thermostat [5].](image)

The microcircuit is made on a silicon wafer of the KEF-4.5 brand with a thickness of \( h = 0.4 \) mm. One of the thermocouple branches – silicon – is formed by local diffusion of boron into the plate, and the second, aluminum, by spraying a thin metal layer on an oxidized plate with open contact windows, followed by fusing aluminum into silicon. The packing density of thermocouples is 10 pcs/mm. The cross section of the silicon branch, taking into account the side doping, is a rectangle with sides \( a = 85 \) μm and \( w = 5 \) μm, and the cross section of the aluminum branch has the form of a rectangle with sides \( b = 80 \) μm and \( d = 0.5 \) μm. The length of the branches is \( l = 6 \) mm. Hot ends of thermocouple legs are located along the perimeter of the energy collector, and cold ends – along the inner boundary of the region of thermal contact of the converter element with the thermostat [5].
The use of planar technology for the manufacture of thermal containers provides high reproducibility of their thermophysical and thermoelectric parameters, high packing density of thermocouples, as well as simple and reliable thermal contact of the hot ends of the branches of thermocouples with the energy collector. However, the mechanism for generating the output signals of planar thermal batteries has a number of features, the analysis and consideration of which is necessary when choosing a working means for measuring the radiation power of an end-face LD.

As the metrological certification of the IMO-4 laser wattmeter showed, the main contribution to its error is made by the unevenness of the zone characteristic [6]. The unevenness is caused by the presence of distributed heat losses from the surface of the converter element and the mismatch of the heat flow lines with planar thermocouples. In the upgraded version of the IMO-4M laser wattmeter, the mirror-reflecting surface of the thermostat housing facing the converter element is used to reduce distributed heat losses, and the thickness of the air layers between the front and back surfaces of the converter element and the thermostat housing is reduced [7].

When the minimum distributed heat losses are reached, the condition for the realization of an almost uniform zone characteristic of the planar thermoelectric primary measuring transducers is fulfilled when the heat current lines are directed along the branches of the thermocouples. However, the area of total or partial absorption of laser radiation by the energy collector has finite dimensions and is removed from the thermocouples by a finite distance. Therefore, the heat flow lines are directed not along the branches of planar thermocouples, but at different $\beta$ angles (figure 2).

**Figure 2.** Shapes of heat current lines, fully matched with thermocouples (lines 2,5,8,11) and passing through the hot ends of the branches of extreme thermocouples of thermoelectric batteries (lines 1,3,4,6,7,9,10,12) at ideal thermal contact: a – the entire perimeter of the conversion element; b – only cold ends of thermocouples. I – energy collector; II – energy collector perimeter – a line along which the hot ends of the thermocouple legs are located; III – thermocouple branches; the point from which the heat current lines emanate is the energy center of the laser beam; $\beta$ is the angle between the heat current line and the branch of the extreme thermocouple. Dotted lines – lateral boundaries of the sectors of the converter element, through which heat fluxes flow into the parts of the thermostat adjacent to these sectors.
As a result, the temperature of the hot end of the silicon branch is determined not by the thermal resistance of the substrate element located under the thermocouple branch, but by the resistance of the part of the substrate through which the heat flow flows from the hot end of the thermocouple to the thermostat. The difference between these resistances increases as the $\beta$ angle increases. As a result, a component of the unevenness of the zone characteristic is formed, due to the coordinate dependence of the upper limit of the range of changes in the $\beta_{max}$ angle.

Figure 2 shows that when the energy center of the laser beam is removed from the thermal battery, $\beta_{max}$ value decreases, which means that the unevenness of the zone characteristic also decreases. The only way to reduce $\beta_{max}$ while maintaining the overall dimensions of the planar thermoelectric primary measuring transducers is to reduce the length of the branches of the thermocouples. That is why the length of the branches of the IMO-4 thermocouples is 6 mm (figure 1), and the length of the branches of the thermocouples of the modified IMO-4M laser wattmeter is 4 mm (figure 2).

At the same time, due to the increase in the size of the energy collector from $10\times10$ mm$^2$ to $14\times14$ mm$^2$, the conversion coefficients of IMO-4 and IMO-4M are practically equal, since a decrease in the output signal of each IMO-4M thermocouple is compensated by an increase in the number of thermocouples from 400 to 560.

Within the framework of this work, it was experimentally established that with an average heat transfer coefficient $\alpha_T$ equal to 20 W/(m$^2$·K), the irregularity of the IMO-4M zone characteristic does not exceed 0.5% within a circle with a diameter of 9.5 mm.

### 3. Planar substitution resistor optimization

A characteristic feature of independently calibrated primary measuring transducers is the presence of a replacement resistor, which allows periodic verification of their conversion coefficient by replacing the optical heating of the receiving element with an electric one.

To ensure a high degree of equivalence of electric heating to optical heating, the substitution resistor is located in the irradiation region of the energy collector. This area is determined by the input aperture of the primary measuring transducer, which in almost all cases of using laser wattmeters has the shape of a circle. Therefore, to ensure a high degree of substitution equivalence, the resistor has the same shape.

Of the several possible ways to create a replacement resistor, we chose the simplest and most reliable: spraying an aluminum film with a thickness of 2 $\mu$m on the back side of the energy collector, followed by forming a replacement resistor with a particular topology of its heating elements by photolithography. Electrical isolation of the current-carrying aluminum track from the energy collector is carried out by forming a layer of silicon dioxide with a thickness of 0.5 $\mu$m on the back surface of the energy collector.

Figure 3 schematically shows a replacement resistor, the current path of which has the shape of a meander inscribed in a circle. It also shows the relative position of a planar replacement resistor and thermoelectric batteries. It can be seen that planar thermoelectric batteries are located outside the irradiated part of the energy collector. Since the thermal batteries react to the temperature field in the region of their location, the degree of equivalence of substitution depends on what temperature field of the primary measuring transducer is formed in this region as a result of the absorption of optical radiation.

The degree of reproduction of the temperature field formed in the area of the location of thermal batteries when the current flows through the replacement resistor is maximum when the heat flow lines are directed along the branches of planar thermocouples. The practical implementation of this kind of heat sink in the thermostat is not possible. Therefore, the design of the replacement resistor takes into account the design features of the laser wattmeter and the IMO-4M, discussed above. Taking these features into account shows that in a planar substitution scheme, it is possible to provide a heat sink, in which the heat flow lines are directed at small angles to the branches of the thermocouples. To implement such a heat sink mode, the energy center of the laser beam must be located in the central region of the energy collector, which has the shape of a circle. In this paper, it is determined that the diameter of the central region of the wide-aperture primary measuring transducer, and hence the diameter of the replacement resistor, should not exceed 0.75 of the side of the energy collector.
Figure 3. The back surface of the converter element of the thermal receiver of laser radiation: 1 – the replacement resistor; 2 – parts of the surface of the energy collector that are not occupied by the current-carrying elements of the replacement resistor; 3 – one of the four thermoelectric batteries; 4 – the area of the thermal contact of the converter element and the thermostat (not specified in the figure); thin wavy lines – gold wires that provide electrical wiring for removing the output signals of thermal batteries; thick wavy lines – copper wire for connecting a replacement resistor to a stabilized current source.

The size of the working area of the energy collector is taken into account when designing a part of the optoelectronic flow research system, in which there is a risk of parasitic illumination of the working volume of the diagnosed flow. The illumination is caused by the reflection of the diagnostic radiation from the surface of the heat shield installed behind the radiator of the end LD. To minimize reflection, the outer surface of the heat shield outside the coupling hole is covered with a composite material that completely absorbs the radiation reflected from the flow surface. The optimal size of the surface covered by this material is consistent with the working area of the IMO-4M energy collector.

4. Conclusion

It is shown that in active optoelectronic flow research systems that regulate the thermophysical parameters of the diagnosed flow volume, a controlled source of heat flow can be the radiation of high-power end-face IR laser diodes into an open space. The features of measuring the power of such radiation due to its strong divergence and the shape of the cross-section of the radiation beam of the end-face LD are taken into account. It is shown that laser wattmeters of the IMO-4M model with planar thermoelectric converters of laser radiation with a dedicated flat receiving platform can be used to measure the radiation power of the end-face LD. A method for measuring the radiation power of laser diodes is described, which eliminates the possibility of parasitic illumination of the working volume of the diagnosed flow.

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