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Measurement of the body surface temperature by the method of laser photothermal radiometry

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***Abstract*. The specific features of contactless measurements of the body surface temperature by the method of repetitively pulsed laser photothermal radiometry are considered and the requirements to the parameters of the laser and measurement scheme are formulated. The sensitivity of the method is estimated. The advantages of laser photothermal radiometry over the conventional passive radiometric method are discussed.**

Keywords: *temperature measurement, infrared thermometry, laser photothermal radiometry.*

1. Introduction

Recently many contactless methods were proposed for measuring the surface temperature of solids using various physical phenomena [1]. However, the so-called passive radiometry based on the detection of thermal radiation of an object still remains the most popular and universal method [1, 2]. Thus, compact IR thermometers with a pyroelectric photodetector, which are reliable, convenient, and comparatively low-cost, have found wide applications for contactless measurements of the body temperature during monitoring and control of parameters in a variety of industrial fields [2, 3].

However, the method of passive radiometry has a number of drawbacks, which restrict its applications. For example, the measurement of the temperature of solids in the presence of intense radiation background produced by external sources can lead to substantial errors. In this case, it is very difficult to separate the intrinsic thermal radiation of a sample from the background signal, i.e., from reflected (scattered) or transmitted through a sample radiation emitted by the surrounding heated bodies. The application of passive radiometry is also inefficient at low temperatures due to a decrease in the intensity of thermal radiation.

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2. Formulation of the problem

In view of the above said, the method based on laser photothermal radiometry [4 – 7] seems to be promising for the development of radiometric measurements of the surface temperature of solids. A special feature of this method is that it is active because a sample is irradiated during measurements by periodic laser pulses. Due to the sample heating caused by absorbed laser radiation, the sample surface temperature and the detected thermal signal are modulated at the frequency equal to the laser pulse repetition rate. The detected thermal signal depends in this case both on the sample temperature and its quasi-periodic fluctuation caused by laser radiation.

The periodic laser action enhances the sensitivity of the method because allows the separation of a weak signal at the noise level or even at a lower level using the signal accumulation. Laser photothermal radiometry is conventionally used for remote spectral analysis and measurements of optical absorption in various media. This method can be efficiently employed for measuring the surface temperature of solids [8 – 11]. The aim of this paper is the development of laser photothermal radiometry for measuring the surface temperature of solids, the estimate of its thermal resolution, and a comparison of this method with the conventional passive radiometric method for measurements at room temperature.

3. Theoretical description

Consider the problem of heating of a semi-infinite medium by laser beams with a Gaussian distribution of the intensity over the beam cross section. We assume that the medium is irradiated by periodic rectangular laser pulses, and a sample under study is a thermally thick medium, i.e.,

$$L \gg (naT_{\rm p})^{1/2}, \qquad (1)$$

where L is the sample thickness; a is the temperature conductivity of the sample; $T_{\rm p}$ is the laser pulse repetition rate; and n is the number of laser pulses irradiating the sample.

In this case, the time dependence of the laser radiation intensity is described by the expression

$$J(t) = J_0[\Theta(t) - \Theta(t - \tau_{\rm p}) + \Theta(t - \tau_{\rm p} - \tau_{\rm d}) - \ldots], \qquad (2)$$

where J_0 is the incident laser radiation intensity; τ_p is the laser pulse duration; τ_d is the delay time between the pulses (interpulse time); and

$$\Theta(t) = \begin{cases} 1, & t \geqslant 0, \\ 0, & t < 0 \end{cases}$$

is the Heaviside function. We assume that the spatial distribution of the laser radiation intensity in the sample plane has the Gaussian profile

$$J(r, t) = J(t) \exp\left(-\frac{r^2}{r_0^2}\right), \tag{3}$$

where r_0 is the Gaussian beam radius.

Consider the process of heating of optically opaque media satisfying the relation

$$\alpha L \gg 1, \tag{4}$$

where α is the absorption coefficient of a sample at the laser wavelength λ. We assume that laser radiation is absorbed in a thin layer of thickness $\sim 10^{-4} - 10^{-5}$ cm.

A change in the surface temperature of a semi-infinite body produced by source (3) as a function of the distance r from the centre of a heated spot at the instant t is described by the expression [12]

$$\Delta T(r, t) = \frac{r_0^2}{k}\left(\frac{a}{\pi}\right)^{1/2} \int_0^t \frac{J(t - t')\mathrm{d}t'}{\sqrt{t'}(4at' + r_0^2)} \times \exp\left(-\frac{r^2}{4at' + r_0^2}\right), \tag{5}$$

where k is the thermal conductivity. Hereafter, we are interested in the temperature in the vicinity of the laser spot centre, i.e., at distances $r \ll r_0$. In this case, the temperature can be calculated by neglecting the exponential in the integrand in (5). It is convenient to introduce the notation

$$t_0 = \frac{c\rho r_0^2}{4k}, \quad T_0 = \frac{J_0 r_0}{2k\sqrt{\pi}},$$

where ρ is the substance density; c is the specific heat of the substance; t_0 is measured in seconds; and T_0 is in kelvins. Then, expression (5) takes the form

$$\Delta T(0, t) = T_0 t_0^{1/2} \int_0^t \frac{\mathrm{d}t'}{\sqrt{t'}(t_0 + t')} \frac{J(t - t')}{J_0}. \tag{6}$$

Let us divide the process of interaction of periodic laser pulses with the sample into n cycles. In this case, in the course of each of the cycles, whose duration is equal to the pulse repetition rate T_p, the sample is heated and cooled. For n full cycles, i.e., for $n\tau_p + (n-1)\tau_d < t < n(\tau_p + \tau_d)$, expression (6) can be represented as a series with alternating signs

$$\Delta T(0, t) = 2T_0 \Bigg\{ \arctan\left[\frac{t - (n-1)(\tau_p + \tau_d)}{t_0}\right]^{1/2} - \arctan\left[\frac{t - (n-1)(\tau_p + \tau_d) - \tau_p}{t_0}\right]^{1/2} + \arctan\left[\frac{t - (n-2)(\tau_p + \tau_d)}{t_0}\right]^{1/2} - \arctan\left[\frac{t - (n-2)(\tau_p + \tau_d) - \tau_p}{t_0}\right]^{1/2} + \ldots + \arctan\left(\frac{t}{t_0}\right)^{1/2} - \arctan\left(\frac{t - \tau_p}{t_0}\right)^{1/2} \Bigg\}. \tag{7}$$

This sum should be cut off from the left, when $n - 1$ vanishes. For example, during the first pulse, i.e., for $n = 1$ and $t < \tau_p$, we have

$$\Delta T(0, t) = 2T_0 \arctan\left(\frac{t}{t_0}\right)^{1/2}. \tag{8}$$

At the same time, during the first delay (during the first cycle), i.e., for $n = 1$ and $\tau_p < t < \tau_p + \tau_d$, we obtain

$$\Delta T(0, t) = 2T_0 \left[\arctan\left(\frac{t}{t_0}\right)^{1/2} - \arctan\left(\frac{t - \tau_p}{t_0}\right)^{1/2}\right]. \tag{9}$$

Consider, for example, the heating of the iron surface ($k = 0.5$ W cm^{-1} K^{-1}, $c = 0.5$ J g^{-1} K^{-1} and $\rho = 8$ g cm^{-3}) by a train of laser pulses. Let us assume that the characteristic size of the laser beam on the iron surface is $r_0 = 0.5$ cm. We perform calculations for two irradiation regimes: (i) $\tau_p = 10^{-8}$ s and $\tau_d = 10^{-5}$ s and (ii) $\tau_p = 10^{-8}$ s and $\tau_d = 5 \times 10^{-2}$ s. In both cases, the laser radiation intensity is 2.5×10^5 W cm^{-2}, which corresponds to the pulse energy $W = 0.002$ J. The calculated changes in the surface temperature are presented in Table 1 and in Fig. 1 for the first five pulses. Note that the parameters of modern 1.06-μm Nd : YAG lasers, in particular, pumped by diode

Table 1. Change ΔT in the iron surface temperature calculated for different regimes of repetitively pulsed laser irradiation.

n	Regime 1: $\tau_p = 10^{-8}$ s, $\tau_d = 10^{-5}$ s, $J_0 = 2.5 \times 10^5$ W $\times$ cm^{-2}, $r_0 = 0.5$ cm		Regime 2: $\tau_p = 10^{-8}$ s, $\tau_d = 5 \times 10^{-2}$ s, $J_0 = 2.5 \times 10^5$ W $\times$ cm^{-2}, $r_0 = 0.5$ cm	
	$\Delta T/°C$		$\Delta T/°C$	
	Maximum	Minimum	Maximum	Minimum
1	19.947	0.315	19.947	0.004
2	20.262	0.538	19.951	0.007
3	20.485	0.720	19.954	0.009
4	20.667	0.878	19.956	0.010
5	20.825	1.019	19.957	0.011
6	20.966	1.148	19.958	0.012
7	21.094	1.266	19.959	0.013
8	21.213	1.378	19.960	0.014
9	21.325	1.483	19.961	0.015
10	21.430	1.582	19.962	0.016
...	...	...	...	...
91	25.481	5.567	19.977	0.03
92	25.514	5.600	19.977	0.03
93	25.546	5.632	19.977	0.03
94	25.579	5.665	19.977	0.03
95	25.612	5.697	19.977	0.03
96	25.644	5.730	19.977	0.03
97	25.676	5.761	19.977	0.03
98	25.708	5.793	19.977	0.03
99	25.740	5.825	19.977	0.03
100	25.771	5.856	19.977	0.03

lasers, correspond quite well to the second irradiation regime taking into account the reflection coefficient of the oxidised iron $R \leqslant 30\,\%$ [13]. One can see from Fig. 1 that the sample surface temperature changes under the action of periodic laser pulses. In this case, simultaneously with the quasi-periodic fluctuation of the temperature ΔT_τ, the static increase ΔT_0 in the temperature is observed, which is the greater, the higher the average power of laser radiation.

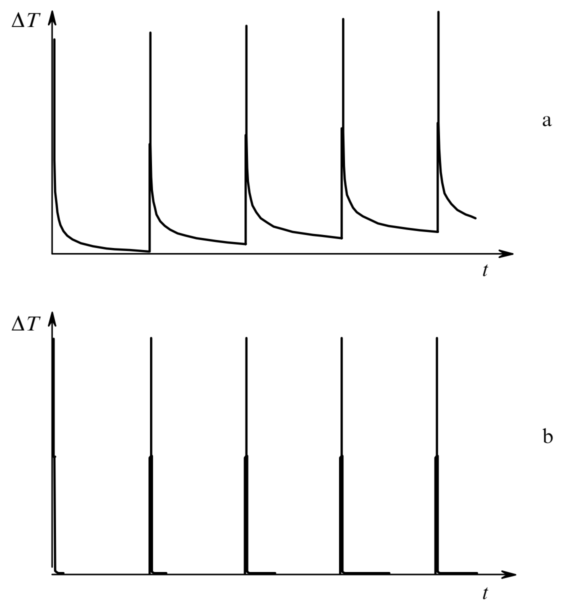

Figure 1. Change in the iron surface temperature calculated for the first five laser pulses for $\tau_\text{p} = 10^{-8}$ s, $\tau_\text{d} = 10^{-5}$ s (a) and $\tau_\text{p} = 10^{-8}$ s, $\tau_\text{d} = 5 \times 10^{-2}$ s (b). The laser radiation intensity is $J_0 = 2.5 \times 10^5$ W cm^{-2}.

It is obvious that the static addition is nothing but the temperature by the instant of termination of the total nth cycle: $\Delta T_0 = \Delta T_{0n} = \Delta T[0, n(\tau_\text{p} + \tau_\text{d})]$. The rate of an increase in the static component decreases with increasing interaction time (Table 1). In turn, an increase in the off-duty ratio of laser pulses makes it possible to reduce ΔT_0 to the required minimum. The quasi-periodic component $\Delta T_\tau = \Delta T_{\tau n}$ of the excess temperature also depends on the interaction time. In the case of sufficiently large values of n, it can be represented as the difference of the temperature increments after the nth pulse and after the nth delay, i.e., $\Delta T_{\tau n} = \Delta T(0, n(\tau_\text{d} + \tau_\text{p}) + \tau_\text{p}) - \Delta T(0, n(\tau_\text{d} + \tau_\text{p}))$. One can see from Table 1 that already at $n \geqslant 10$ the value of $\Delta T_{\tau n}$ is almost independent (within an accuracy of $\sim 0.03\,^\circ$C) of the interaction time and can be considered constant:

$$\Delta T_{\tau n} = \Delta T_{\tau 1} = \Delta T(0, t) = 2T_0 \arctan\left(\frac{\tau_\text{p}}{t_0}\right)^{1/2} = \text{const.}$$

4. Specific features of the radiometric method of measuring the temperature of bodies upon laser activation of surface

According to the Stefan – Boltzmann law, the change in the integrated density $\Delta W_{T\tau}$ of a thermal flux emitted by a grey body at all wavelengths is described by the expression

$$\Delta W_{T\tau} = 4\varepsilon\sigma(T + \Delta T_0)^3 \Delta T_\tau, \tag{10}$$

where $\sigma = 5.67 \times 10^{-12}$ W cm^{-2} K^{-4} is the Stefan – Boltzmann constant and ε is the sample emissivity. It is assumed that $\Delta T_\tau / T \ll 1$.

If the non-informative static component ΔT_0 of the sample temperature can be neglected ($\Delta T_0 \ll T$), then, as follows from (10), the same fluctuations ΔT_τ at different surface temperatures T produce different variable components of the thermal flux $\Delta W_{T\tau}$ emitted by the sample surface. In this case, the sample surface temperature T can be unambiguously determined from the measured signal. Therefore, the key problems of the laser-activation radiometric method are the elimination of the effect of the static component ΔT_0 of the sample temperature and the provision of the stable and constant quasi-periodic fluctuation ΔT_τ of the surface temperature during measurements. We will assume that the value of ΔT_0 does not affect the results of measurements if the relation $\Delta T_0 \leqslant \Delta T_\text{ac} \ll T$ is fulfilled, where ΔT_ac is the required temperature resolution.

In the general case, the temperature fluctuation is $\Delta T_\tau = \Delta T_\tau(\alpha)$, i.e., it depends on the absorption coefficient for laser radiation. Therefore, the value of $\Delta W_{T\tau}$ also depends both on the optical and thermal properties of a sample. However, this takes place only in the absence of saturation, whereas in the case of saturation, the detected signal $\Delta W_{T\tau}$ is independent of the optical properties of the medium, in particular, of the absorption coefficient $\alpha(\lambda)$ [4, 7]. It is this case that is of special interest for laser radiometric IR thermometry. There are two mechanisms providing the detection of a photothermal signal in the case of saturation. The first one is related to the fact that the detected signal $\Delta W_{T\tau}$ is determined by the total heat released in the surface layer of a body, whose thickness is comparable to the thermal diffusion depth l_T. Therefore, as in acoustics [14], the relation

$$l_\alpha \ll l_T \tag{11}$$

should be fulfilled, where $l_\alpha = \alpha^{-1}$ is the depth of optical absorption and

$$l_T \sim (a T_\text{p})^{1/2} = \left(\frac{k T_\text{p}}{\rho c}\right)^{1/2}.$$

The second mechanism is caused by a finite depth l_β of the substance layer that is transparent for thermal radiation emitted by the substance, which also leads to saturation [4, 7, 11]. Therefore, the condition

$$l_\beta = \beta^{-1} \gg l_\alpha \tag{12}$$

should be fulfilled simultaneously, where β is the averaged absorption coefficient of a sample at the wavelengths of detected thermal radiation.

Taking into account the assumption that a sample is heated on its surface, i.e., upon the appropriate choice of the laser wavelength, the conditions for the detection of a thermal signal in the saturation regime formulated above are fulfilled almost for any regime of laser action.

Nevertheless, there are conditions that restrict indirectly the possible ranges of variations in the laser pulse duration and repetition rate and have the form $\Delta T_\tau / T \ll 1$ and $\Delta T_0 \leqslant \Delta T_\text{ac} \ll T$. The first condition restricts the laser radiation intensity, while the second one restricts the average power of the laser.

The reflection coefficient of materials, especially metals, depends substantially on the state of their surface (structure, processing quality, oxidation degree). Therefore, the reflectivity $R(\lambda)$ of a material should be controlled during thermometry. The surface roughness can severely prevent any optical diagnostics. In this case, a quantitative model of the interaction of laser radiation with samples should take scattering into account or substantiate its insignificant role. The surface roughness can introduce a noticeable systematic error in the measurements of the reflection coefficient of samples. Therefore, it is necessary to study preliminary the effect of scattering on the detected signal.

If scattering of light can be neglected, such a control can be readily performed. One of the possible schemes for measuring the surface temperature of solids by the method of laser radiometry is shown in Fig. 2. The optical system in the measuring scheme is used to increase the field of view of a photodetector. Both lens and mirror optics can be employed, depending on the requirements formulated for specific problems [15].

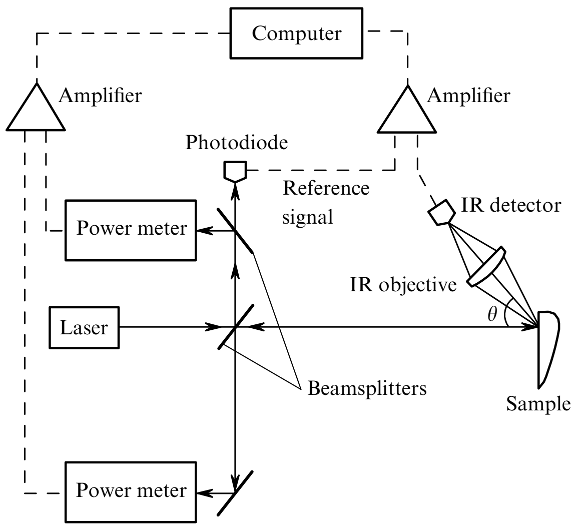

Figure 2. Principal scheme of a laser radiometric thermometer.

5. Estimate of the temperature resolution of a radiometric laser thermometer

To determine the possible fields of application of laser radiometric thermometers and for comparison of these thermometers with other devices based on other principles, it is interesting to estimate the limiting parameters of laser radiometric thermometry. The most important parameters are the temperature resolution ΔT_{ac} and the spatial resolution of a device [2, 15]. The value of ΔT_{ac} is defined as the difference ΔT of temperatures of the object at which the signal-to-noise ratio is unity [15]. In turn, the spatial resolution of a radiometric thermometer is determined by the area S_{ob} of the region of temperature measurement on the object surface. Because the total radiation flux emitted by this region should be collected on a photosensitive element of a photodetector of area S_{ph}, the area of the region of the temperature measurement can be determined from a simple relation

$$S_{\mathrm{ob}}\cos\theta = S_{\mathrm{ph}}(L_0 x^{-1})^2, \tag{13}$$

where L_0 is the distance from the objective plane to a radiation source; θ is the angle between the direction of the detected light flux and the normal to the illuminated surface (the principal plane of the objective); and x is the distance from the optical system to the photodetector. It is assumed that the area of a circle of minimum scattering for the optical system used is $S_{\mathrm{sc}} \ll S_{\mathrm{ob}}$. To provide the fulfilment of the approximation $r_{\mathrm{ob}} \approx S_{\mathrm{ob}}^{1/2} \ll r_0$ used in the problem, it is possible to employ a beam expander in the scheme in Fig. 2.

Another important parameter of radiometric thermometers is the sight factor K_{ob} equal to the ratio of the distance to the object to the diameter of the region of temperature measurement on the object surface and characterising the possibility of measuring the temperature of small objects at large distances [2].

Let us make a simple estimate of the temperature resolution using the expression for the variable component of the integrated thermal flux incident on an IR detector in the approximation of a grey body emitting radiation according to the Lambert law:

$$\Delta\Phi_{T\tau} = \Delta B_{T\tau} G K_{\lambda T}\tau_{\mathrm{opt}}$$
$$= 4\varepsilon K_{\lambda T}\sigma T^3\pi^{-1}\tau_{\mathrm{opt}}\Delta T_\tau S_{\mathrm{ob}}\Delta\Omega\cos\theta, \tag{14}$$

where $\Delta B_{T\tau} = 4\varepsilon(\sigma T^3/\pi)\Delta T_\tau$ is the change in the source brightness; $G = S_{\mathrm{ob}}\Delta\Omega\cos\theta$ is the geometrical view factor; $S_{\mathrm{ob}} = \pi r_{\mathrm{ob}}^2$ the area of the region emitting the variable component of IR radiation incident on a radiometer; $\Delta\Omega$ is the solid angle of the flux directed to the optical system; the coefficient τ_{opt} characterises the transmission of the optical system (absorption in the atmosphere is neglected) and is assumed constant over the spectral region $\Delta\lambda$; the coefficient

$$K_{\lambda T} = \int_{\Delta\lambda} \frac{\partial W_\lambda(T)}{\partial T}\,\mathrm{d}\lambda\,\frac{1}{4\varepsilon T^3}$$

takes into account the fraction of thermal radiation in the interval $\Delta\lambda$ of the detected wavelengths for small ΔT; and $W_\lambda(T)$ is the spectral density of the radiation flux of a black body. Assuming that $\Delta T/T \ll 1$, we can neglect the temperature dependence $\varepsilon(T)$.

In the point source approximation, the solid angle $\Delta\Omega$ is described by the expression

$$\Delta\Omega = 2\pi\left\{1 - \left[1 + \left(\frac{D}{2L_0}\right)^2\right]^{-1/2}\right\},$$

where D is the light diameter of the objective and L_0 is the distance to the object. In most practical cases, as a rule, the relation $[D/(2L_0)]^2 \ll 1$ is fulfilled, i.e., $\Delta\Omega = \pi D^2/(4L_0^2)$.

We are interested in the differential change in the variable component of the detected flux as a function of the object temperature at $\Delta T_\tau = \mathrm{const}$. Therefore, by differentiating both parts of expression (14) and assuming that the value of $\delta(\Delta\Phi_{T\tau})$ is equal to the noise-equivalent power (NEP) Φ_{th} of the photodetector, we obtain the estimate for the temperature resolution of a radiometric laser thermometer:

$$\Delta T_{\rm ac} = \frac{\pi \Phi_{\rm th}}{12\sigma\varepsilon\tau_{\rm opt}K_{\lambda T}S_{\rm ob}\Delta\Omega\cos\theta}\,\frac{1}{T^2\Delta T_\tau}\,. \quad (15)$$

In the IR region, lens optical systems are often used. This is explained by the fact that a variety of available materials and the possibilities for processing their surfaces make it possible to realise compact optical systems with good parameters. Because the sensitivity of an optical system for detecting IR radiation is related to its aperture, wide-aperture optical systems are used, as a rule. Lenses are often made of germanium because this material has low absorption losses and weak dispersion in the spectral range from 2 to 16 μm. Taking into account the transparency region of germanium and the possibility of using an achromatic anti-reflection coating in the spectral range between 8 and 12 μm, we obtain the estimate $K_{\lambda T} \leqslant 0.3$ at 300 K [15].

One of the possible optical schemes for measuring the temperature of samples located at a finite distance from the objective can be designed so that a photodetector and the illuminated region of a sample will be located at the double focal distance from the lens plane. In this case, a lens of the measuring system completely images the source on the photosensitive region of the photodetector, i.e., $S_{\rm ob} = S_{\rm ph}$. If the lens can provide approximately equal area of scattering circles in the sample plane and on the photodetector surface (in this case, $S_{\rm sc} \ll S_{\rm ob} = S_{\rm ph}$), then the total thermal flux from a point source ($S_{\rm ob}$) within the solid angle $\Delta\Omega$ will be detected by the photodetector.

As an example we consider a simplest single-lens objective with the relative aperture 2 : 1. In this case, $\Delta\Omega = \pi/4 \approx 0.8$ and $\cos\theta \approx 1$ for $D = 40 - 50$ mm. Assuming that an anti-reflection coating can provide in the wavelength range 8 – 12 μm the transmission coefficient for one lens surface equal to 95 %, we obtain the transmission coefficient for the optical lens $\tau_{\rm opt} = (0.95)^2 \approx 0.9$. Assuming that $\varepsilon \approx 0.7$ (oxidised iron) [15], we can transform (15) to

$$S_{\rm ph}\Delta T_{\rm ac} \approx \Phi_{\rm th}\,\frac{3\times10^{11}}{T^2\Delta T_\tau}\,. \quad (16)$$

One can see that this system allows one to find the compromise between the temperature and spatial resolutions. As the size of the sensitive element of the photodetector decreases (spatial resolution increases), the value of $\Delta T_{\rm ac}$ increases, resulting in the decrease in the temperature resolution. Depending on the requirements imposed on the measuring system, the temperature or spatial resolution is preferred.

The NEP $\Phi_{\rm th}$ of a pyroelectric detector with a sensitive element of area $S_{\rm ph} \sim 1$ mm^2 within the unit frequency bandwidth $\Delta\nu = 1$ Hz for the 20-Hz modulation frequency of the detected signal does not exceed 1.4×10^{-9} W [3, 15]. Assuming, in accordance with an example presented in Table 1, that the periodic fluctuation of the surface temperature is $\Delta T_\tau \approx 20\,^\circ$C at $T = 300$ K, we obtain from (16) for our measuring system the inequality

$$S_{\rm ph}\Delta T_{\rm ac} \geqslant 2\times10^{-4}\ {\rm cm^2\,K}, \quad (17)$$

from which it follows that $\Delta T_{\rm ac} \sim 0.02\,^\circ$C. This values is comparable to the static temperature component $\Delta T_0 \sim 0.03\,^\circ$C for the second irradiation regime (see Table 1). In this case, the sight factor is $K_{\rm ob} = L_0/S_{\rm ob}^{1/2} = 2f/S_{\rm ph}^{1/2} \geqslant 50$ (for $f = 25 - 30$ mm).

6. Conclusions

We have shown that the temperature resolution $\Delta T_{\rm ac}$ of a laser radiometric thermometer with a pyroelectric photodetector in our measurement scheme can be no more that $\sim 0.05\,^\circ$C for a comparatively high sight factor $K_{\rm ob} \geqslant 50$. For comparison, note that the temperature resolution of passive IR thermometers with pyroelectric detectors in the best case is $\Delta T_{\rm ac} \geqslant 0.1\,^\circ$C for the same minimal size of the field of view (~ 1 mm) and the sight factor $K_{\rm ob} \leqslant 5$ [2]. We have shown that this advantage of laser photothermal radiometry is achieved due to the enhancement of the variable component of the detected thermal flux without a substantial perturbation of the surface temperature. This suppresses almost completely the influence of background radiation from external sources on the results of measurements.

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