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Application of two-colour pyrometry for measuring the surface temperature of a body activated by laser pulses

V.M. Kirillov, L.A. Skvortsov

***Abstract*.** **The features of contactless measurements of the surface temperature of bodies by the method of two-colour pyrometry of samples activated by periodic laser pulses are considered. The requirements imposed on the parameters of laser radiation and a measuring circuit are formulated. It is shown experimentally that surface temperatures close to room temperature can be measured with an error not exceeding 3 % after elimination of the superfluous static component of the excess temperature. The sensitivity of the method is estimated. Advantages of laser photothermal radiometry with repetitively pulsed excitation of surfaces over the case when samples are subjected to harmonic amplitude-modulated laser radiation are discussed.**

Keywords: *contactless temperature measurement technique, photothermal radiometry, infrared pyrometry.*

1. Introduction

In most of the cases, the emissivity ε of objects is not known. It has been established that a difference by 1% in the emissivities of different parts of an object is equivalent to a temperature difference by 1 K [1]. The use of the so-called two-colour pyrometry is one of the methods of eliminating the effect of emissivity on the results of measurements [2]. This technique involves the measurement of a radiometric signal in two rather narrow spectral intervals $\Delta\lambda_1$ and $\Delta\lambda_2$ for which the spectral emissivities ε_λ are assumed to be equal. This technique is used both in active and passive photothermal radiometry [3, 4]. In the latter case, investigations were performed by exposing the sample to harmonic amplitude-modulated laser radiation. At the same time, active photothermal radiometry in the repetitively pulsed regime has its own peculiarities [5]. The temperature of an object can be measured in the pulsed regime for a shorter time, which is especially important for moving objects. In addition, laser radiation parameters can be varied over a wide range in the pulse regime and hence the effect of the static component of the excess temperature on the results of measurements can be eliminated. It was shown in [3] that the effect of the static component results in a nonlinear dependence of the photothermal signal on the sample temperature.

The aim of this paper is to develop the two-colour pyrometric technique for measuring the temperature of an object upon repetitively pulsed activation of its surface by laser radiation.

2. Theoretical analysis of the technique for photothermal radiometry of a pulse-activated surface

Let us apply the two-colour pyrometric technique for active laser radiometry upon repetitively pulsed activation of a surface by laser radiation. In this case, the thermal signal is detected with an IR detector at the laser pulse repetition rate and comes from a part of the sample surface modulated periodically by laser radiation pulses. This allows us to neglect in calcualtions the background radiation from other sources which is reflected by the sample surface or is transmitted through it [5].

The excess surface temperature ΔT is the sum of two components: $\Delta T = \Delta T_0 + \Delta T_\tau$, where ΔT_τ is the quasi-periodic component of the excess temperature at the laser pulse repetition rate and ΔT_0 is the so-called static correction to the sample surface temperature, which increases slowly during the irradiation time. Note that this component can be almost completely eliminated, for example, by increasing the delay time between pulses (Fig. 1) [5]. We assume below that

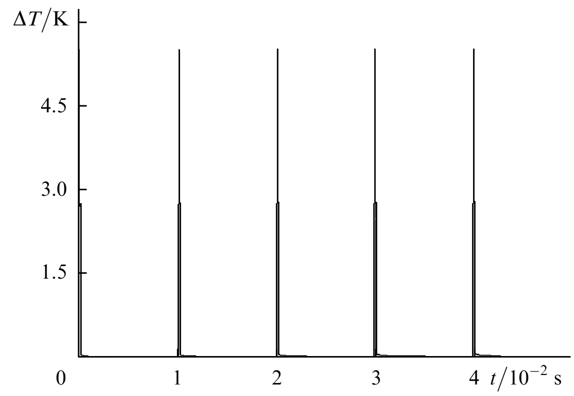

Figure 1. Theoretical time dependence of the excess temperature ΔT of iron surface for the first five laser pulses of duration $\tau_p = 10^{-8}$ s, the delay time $\tau_d = 10^{-2}$ s, and intensity $J_s = 10^5$ W cm^{-2}.

V.M. Kirillov, L.A. Skvortsov Institute of Cryptography, Communications and Informatics, Academy of Federal Security Service of Russian Federation, Michurinskii prosp. 70, 117602 Moscow, Russia; web-site: http://academy.fsb.ru; e-mail: hitmanpnd@mail.ru

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$\Delta T_0 \ll \Delta T_\tau \ll T$, where T is the sample temperature being measured.

Following the analysis performed in [5], we represent the variable component of the thermal flux incident on the receiving area of the IR detector in a narrow wavelength range $\Delta\lambda$ in the approximation of a grey body emitting radiation according to Lambert's law in the form:

$$\Delta\Phi_\lambda = \Delta B_\lambda G\tau_\lambda = \frac{1}{\pi}\varepsilon_\lambda \frac{\partial W_\lambda(T)}{\partial T}\Delta\lambda\Delta T_\tau \tau_\lambda \Delta\Omega S_s \cos\theta, \quad (1)$$

where ΔB_λ is the variable component of the spectral brightness; W_λ is the spectral flux density of thermal blackbody radiation; $G = \Delta\Omega S_s \cos\theta$ is the geometrical factor for the optical IR system; $\Delta\Omega$ is the solid angle in which the heat flow directed to the optical system propagates; θ is the angle between the direction of propagation of the light flux being detected and the normal to the object surface exposed to laser radiation; S_s is the irradiated sample surface; and τ_λ is the transmission coefficient of the optical IR system.

It can be easily verified that

$$\frac{\partial W_\lambda}{\partial T} = \frac{c_1 c_2 \exp[c_2/(\lambda T)]}{\lambda^6 T^2\{\exp[c_2/(\lambda T)]-1\}^2}$$

$$= W_\lambda \frac{c_2 \exp[c_2/(\lambda T)]}{\lambda T^2\{\exp[c_2/(\lambda T)]-1\}^2}, \quad (2)$$

where $c_1 = 2\pi hc^2 = 3.74 \times 10^4$ W μm^4 cm^{-2}; $c_2 = ch/k_B = 1.44 \times 10^4$ μm K; c is the velocity of light; k_B is the Boltzmann constant; and h is Planck's constant. If the condition $\exp[c_2/(\lambda T)] \gg 1$ (Wien's approximation) is satisfied, we obtain

$$\frac{\partial W_\lambda}{\partial T} \approx W_\lambda \frac{c_2}{\lambda T^2}. \quad (3)$$

At room temperatures ($T \sim 300$ K), this condition holds if $\lambda \ll c_2/T \sim 40$ μm, and hence Wien's approximation can be used in many practical cases, for example, for evaluating sample temperatures at the environment temperature $T \simeq 300$ K.

The differential signal S_λ from the photodetector (in volts) caused by quasi-periodic fluctuations ΔT_τ of the surface temperature, can be obtained by multiplying expression (1) by the detector sensitivity D_λ (in V W^{-1}):

$$S_\lambda = D_\lambda \Delta B_\lambda G\tau_\lambda = D_\lambda \frac{1}{\pi}\varepsilon_\lambda \frac{\partial W_\lambda(T)}{\partial T}\Delta\lambda\Delta T_\tau \Delta\Omega S_s \cos\theta. \quad (4)$$

It can be shown easily from (3) and (4) that, when the IR detector signals are detected by using interference filters with the transmission bandwidths $\Delta\lambda_1$ and $\Delta\lambda_2$ centred at wavelengths λ_1 and λ_2, the surface temperature of the object under study can be determined from the expression

$$T = c_2\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\left\{\ln\left[\frac{S_{\lambda_1}}{S_{\lambda_2}}\frac{\tau_{\lambda_2}}{\tau_{\lambda_1}}\frac{D_{\lambda_2}}{D_{\lambda_1}}\frac{\varepsilon_{\lambda_2}}{\varepsilon_{\lambda_1}}\frac{\Delta\lambda_2}{\Delta\lambda_1}\left(\frac{\lambda_1}{\lambda_2}\right)^6\right]\right\}^{-1}. \quad (5)$$

One can see that this expression does not contain the amplitudes of the quasi-periodic temperature fluctuations or the geometrical factor of the optical IR system.

Because the wavelengths λ_1 and λ_2 are close to each other and the bandwidths of the interference filters are small ($\Delta\lambda_1 \ll \lambda_1$ and $\Delta\lambda_2 \ll \lambda_2$), we assume that $D_{\lambda_1} = D_{\lambda_2}$. This condition is well satisfied for IR photodetectors based on solid solutions of mercury cadmium telluride HgCdTe [6]. For germanium optical components with antireflection coatings, we can also assume that the transmission coefficients τ_λ of the optical system in close spectral ranges are equal. In addition, the IR radiation wavelengths in the two-colour technique are chosen so close to each other and the corresponding spectral ranges are so narrow that the spectral emissivities ε_{λ_1} and ε_{λ_2} can be assumed to be equal.

Therefore, the surface temperature of a sample can be calculated from a simple expression:

$$T = c_2\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\left\{\ln\left[\frac{S_{\lambda_1}}{S_{\lambda_2}}\frac{\Delta\lambda_2}{\Delta\lambda_1}\left(\frac{\lambda_1}{\lambda_2}\right)^6\right]\right\}^{-1}. \quad (6)$$

3. Substantiation of the choice of parameters for a pulsed laser two-colour IR radiometer

Before using the results obtained above, let us estimate the thermal radiation flux incident on the sensitive area element of the detector in a narrow spectral wavelength range $\Delta\lambda$. Obviously, the transmission band of the interference filter should be located in one of the atmospheric transparency windows. The transparency window between 8 and 13 μm is quite significant because it corresponds to the maximum of thermal radiation emitted by objects at $T \approx 300$ K.

An HgCdTe photoresistor cooled to liquid nitrogen temperature has the highest sensitivity in this spectral range. The time constant of this detector is $\tau \leqslant 10^{-6}$ s [6]. The photosensitive element has a size of 350×350 μm (the detector area element has an area $S_d = 1.2 \times 10^{-3}$ cm^2). For such an emission wavelength range at a signal frequency of $\sim 10^2$ Hz, the mean specific detection ability is $D^* = 2 \times 10^9$ cm Hz$^{1/2}$ W^{-1}, which corresponds to the noise equivalent power (NEP) $\Phi_{th} = 2 \times 10^{-11}$ W in the unit frequency range [6].

To estimate the detected thermal flux, we consider a laser radiometer with the following optical and geometric parameters. A single-lens germanium objective with the aperture ratio of 2 : 1 has the optical diameter $D = 50$ mm. The antireflection coating provides the transmission coefficient ~90 % in this wavelength range. The interference filters used in the experiments and centred at wavelengths $\lambda_1 = 8.7$ μm and $\lambda_2 = 9.1$ μm have bandwidths $\Delta\lambda_1 = 0.2$ μm and $\Delta\lambda_2 = 0.15$ μm, respectively, and the transmission ~80 %. The transmission coefficient τ_λ of the entire optical system in this wavelength range is 0.7. In turn, the derivative $\partial W_\lambda/\partial T \approx W_\lambda c_2/(\lambda T^2)$ at a temperature $T = 300$ K and a radiation wavelength $\lambda = 8 - 10$ μm is ~ 0.5 W m^{-2} μm^{-1} K^{-1}. In this spectral range, the emissivity is $\varepsilon_\lambda \sim 0.2$ (for iron) [6].

Let $L \sim 1$ m be the distance between the sample and the objective plane. Assuming that the radiation is emitted by a point source whose size is determined by the diameter $d_s \sim 1$ mm of the laser spot at the sample, we obtain the value $\sim 2 \times 10^{-3}$ sr (it is assumed that $\cos\theta \approx 1$) of the solid angle $\Delta\Omega = \pi D^2/(4L^2)$ within which the thermal flux falls on the optical system. The instant field of view of the detector corresponds to the region of size $d' \sim \sqrt{S_d}L/F \sim 1$ cm in the object plane (where F is the focal length of the objective), which is much larger than the laser beam diameter on the sample ($d_s \sim 1$ mm). Recall that the instantaneous field of view of the IR detector determines the spatial resolution of the radiometer in the passive operation regime.

We will estimate the variable component of the surface temperature in the case of a rectangular pulse for a uniform intensity distribution in the beam plane from the expression [7]

$$\Delta T_\tau = \frac{2J_s(\tau_p)^{1/2}}{(\pi k c_{sp}\rho)^{1/2}}(1-R), \tag{7}$$

where J_s is the intensity of laser radiation acting on the sample; τ_p is the laser pulse duration; k, c_{sp}, and ρ are the thermal conductivity, specific heat and the density of the material of the sample, respectively; and R is the reflectivity of the laser radiation. For the iron sample under study, $k = 0.5$ W cm^{-1} deg^{-1}, $c_{sp} = 0.5$ J g^{-1} deg^{-1}, $\rho = 8$ g cm^{-3}, and $R \approx 0.3$. The sample was a cylinder of diameter 8 mm and length 4 mm.

We will estimate ΔT_τ upon irradiation by pulses of duration 10^{-8} s separated by 10^{-2} s (the pulse repetition rate is $f = 1/\tau_d$). To achieve a periodic temperature fluctuation $\Delta T_\tau \sim 5$ K at the sample surface, the laser radiation intensity should be $J_s = 10^5$ W cm^{-2} (taking into account the reflectivity), which corresponds to a pulse power $P_s = 10^3$ W and energy $W_s = 10^{-5}$ J. The average radiation power is $\bar{P}_s = P_s f \tau_p = 1$ mW.

Taking these parameters into account, we obtain the following estimate for the thermal flux:

$$\Delta\Phi_\lambda = \frac{1}{\pi}\varepsilon_\lambda \frac{\partial W_\lambda(T)}{\partial T}\Delta\lambda \Delta T_\tau \tau_\lambda \Delta\Omega S_s \cos\theta \geqslant 3\times 10^{-10}\ \text{W}.$$

This value is more than an order of magnitude higher than the NEP of a HgCdTe IR detector used in our experiments, thus indicating the possibility of using a pulsed laser IR radiometer for measuring the surface temperature of solids close to room temperature. It should be noted in particular that the spatial resolution (~ 1 mm) achieved in this example is considerably (about an order of magnitude) higher than the resolution (no less than 1 cm) realised in passive IR radiometers.

4. Experimental part

Figure 2 shows the scheme of the experimental setup. Samples were activated by radiation of a single-mode (TEM_{00}) Nd : YAG laser with an active element of diameter 3 mm and length 50 mm. The diameter of the laser spot at the output was $d_0 = 2r_0 = 0.8$ mm (at the 1/e level of the maximum intensity J_0). The uniform intensity distribution of laser radiation over the sample was achieved by a $6^\times$ broadening of the laser beam using a telescopic objec-tive and separating its central part by a diaphragm. The inhomogeneity of the sample surface illumination in this case did not exceed ~ 3 % in a spot of diameter ~ 1 mm.

The output pulse power P_0 was estimated from the expression

$$P(r) = P_0\left[1 - \exp\left(-\frac{r^2}{r_0'^2}\right)\right],$$

where

$$P_0 = 2\pi J_0 \int_0^\infty \exp\left(-\frac{r^2}{r_0^2}\right) r\,\mathrm{d}r = J_0 \pi r_0^2$$

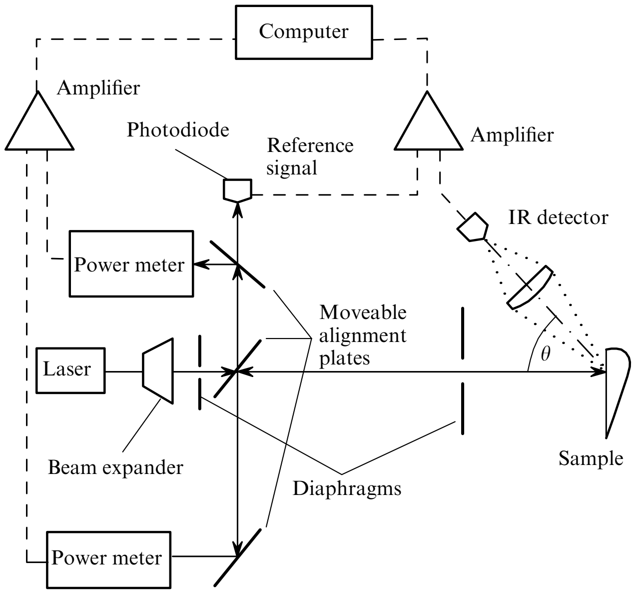

Figure 2. Experimental scheme of the pulsed laser radiometer.

is the total pulse power; $P(r)$ is the radiation power transmitted through a diaphragm of diameter $d = 2r = 1$ mm; and r_0' is the characteristic radius of a Gaussian beam behind the objective ($r_0' = 6r_0 = 2.4$ mm). To provide the required parameters of the laser beam at the sample surface, the output pulse power P_0 should be $\sim 2.5\times 10^4$ W. In turn, the pulse energy should be $W_0 \approx 0.25$ mJ and the average output power – $\bar{P}_0 = 25$ mW. Taking into account the diffraction losses at the diaphragm, the parameters of the laser used in our experiments exceed the above values by 15 %. The instability of the average output power during a short-time action on the sample did not exceed 1 %. These values of the laser parameters can be easily obtained in Q-switched Nd : YAG lasers operating in the fundamen-tal transverse mode, including compact diode-pumped lasers [8, 9].

The sample temperature was monitored with a chro-mel – alumel thermocouple. The sample was placed in a furnace in which its temperature could be varied in the range 290 – 400 K. A temperature stability of ± 1 K was attained in this temperature interval.

Figure 3 shows the temperature dependence of the ratio $S_{\lambda_1}/S_{\lambda_2}$ of the amplitudes of variable signal components calculated by (6). In the temperature range 290 – 400 K, this dependence can be presented in the form of a linear approximation:

$$\frac{S_{\lambda_1}}{S_{\lambda_2}} = 1.063 + 0.001T, \tag{8}$$

which does not differ by more than 0.1 % from the dependence shown in Fig. 3.

Measurements were made in the accumulation regime using an UPI-2M pulse amplifier – converter. To avoid the influence of the static temperature component, the time of a measurement did not exceed ~ 1 s. Figure 4 shows the results of measurements. One can see that the sample surface temperature T measured by pulsed laser photothermal radiometry did not differ by more than 2 % – 3 % from the actual temperature T_{ref}. If, however, the surface is

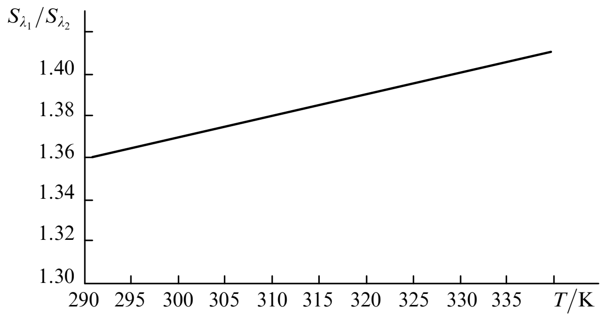

Figure 3. Theoretical dependence of the ratio $S_{\lambda_1}/S_{\lambda_2}$ of amplitudes of signals detected at the IR detector output on the iron surface temperature in the range 290 – 340 K.

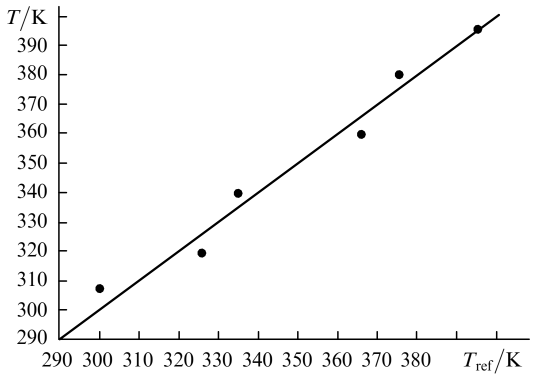

Figure 4. Dependence of the temperature T measured at the sample surface (circles) on its actual value T_{ref} measured with a thermocouple (solid line).

activated by harmonically amplitude-modulated laser radiation, a considerable deviation (by more than 10 %) of the measured temperature T from its value measured by a thermocouple is observed at temperatures $T \sim 300$ K. It seems that this is explained by the effect of the static excess temperature component ΔT_0 which cannot be eliminated in this radiation regime [3]

5. Conclusions

We have shown that two-colour radiometry can be used for remote measurements of the temperature of solid surfaces activated by laser pulses in the interval 290 – 400 K with an error not exceeding 2 % – 3 %. However, this is possible only for an appropriate choice of the laser parameters, the IR detector and the measuring time. Estimates of the spatial resolution of this technique show that for distances ~ 1 m from the object, the spatial resolution is an order of magnitude higher than that for the traditional passive methods. In addition, the advantages of the active laser photothermal radiometry concerning the elimination of the background effects are preserved. Finally, pulsed laser photothermal radiometry allows a much faster measurement of the surface temperature than in the case of harmonic amplitude modulation of laser radiation. This circumstance is especially important for investigations of moving objects.

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