

LASER APPLICATIONS

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Thermographic system with a laser scanning device

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***Abstract*. It is shown that laser photothermal radiometry (LPTR) in combination with laser beam scanning within the instantaneous field of view of a single-element photodetector can be used to develop a scanning thermal emission microscope. An expression is derived for estimating its temperature resolution. The results of calculations are presented and the factors influencing the spatial lateral resolution of the technique and the time of image formation with the help of an acousto-optical deflector are analysed.**

Keywords: *infrared thermography, laser photothermal radiometry, scanning thermal emission microscopy.*

1. Introduction

Classical thermography is a passive method based on the detection of intrinsic IR radiation from an object. A classical infrared imager with a single-element detector is essentially a radiometer with a narrow instantaneous field of view, which surveys an object with the help of mechanical scanning. Infrared imaging systems with a charge coupled device (CCD) without optomechanical scanning systems are being used extensively at present [1].

Unfortunately, electron scanning involves problems caused by the nonuniformity of parameters of photosensitive array elements and the existence of gaps between them. As a result, it is difficult to detect small temperature contrasts between images of individual pixels [1]. Because the spatial resolution of passive infrared imagers cannot be smaller than the instantaneous field of view of individual CCD elements, it becomes impossible to measure the temperature of small objects when their angular dimensions are smaller than the angular size of instantaneous field of view of the IR radiation detection system. This circumstance is of fundamental importance in the investigations of small objects in medicine, biology, microelectronics, criminalistics, and other fields of science and technology. Finally, infrared imagers with CCD cameras are quite expensive devices.

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In view of all this, it is certainly quite interesting to create an infrared imager with a single-element photodetector for investigating temperature fields of low-dimensional objects without using an optomechanical scanning system.

It can be expected that laser photothermal radiometry (LPTR) [2 – 6] can be used in combination with a scanning system to solve this problem. In this case, various points of the object can be analysed without using optomechanical devices, for example, by two-dimensional acousto-optical laser-beam scanning within the instantaneous field of view of an IR radiometer. It is important, the field of view of the system is also the instantaneous field of view of the single-element photodetector.

2. Main parameters of the scanning system

Scanning of an object, i.e., the spatial displacement of a laser beam according to a preset law, can be performed with the help of deflectors which can be optomechanical or electronic (acousto-optical and electro-optical deflectors). A discrete acousto-optical deflector (AOD) is found to be most suitable for our purposes [7]. Discrete deflection technique can be used for addressing (positioning) of laser radiation in any of the resolvable positions and is quite convenient for digital processing of the obtained information. Moreover, repeated irradiation of the same spot is possible to accumulate the useful signal.

The main parameters of the deflector are its resolving power and speed of response. The resolving power is defined as the number N of spatially resolved light spots (positions) that can be fitted on the object along the scan line. The resolving power of the deflector in one of the mutually orthogonal directions, for example, along the x (N_x) axis is described by the known expression [7]

$$N_x = \frac{\Delta\theta}{\delta\theta} = \frac{\Delta\nu_{\mathrm{a}}\tau}{\gamma}, \tag{1}$$

where $\Delta\theta$ is the maximum angle of deflection of the light beam upon a variation of the acoustic frequency (scanning angle); $\delta\theta$ is the angular width of the diffracted light beam in the far zone; $\Delta\nu_{\mathrm{a}}$ is the acoustic frequency band in which the laser beam can be deflected; τ is the time for which the deflector can be switched from one position to another; and γ is a parameter depending on the criterion chosen for resolving two adjacent directions taking into account the light intensity distribution in the beam cross section.

The angular dimension $\delta\theta$ of the deflected light field in the far zone is determined by the diffraction of incident light at the aperture of the deflector. It depends on the distribution of the incident wave over the aperture and on the criterion chosen for resolving two adjacent light spots. The resolution is usually estimated with the help of the Rayleigh criterion [8]. According to this criterion, the parameter $\gamma_R = 1$ for a homogeneous rectangular beam, while $\gamma_R = 1.22$ for a homogeneous beam of a circular cross section. The case when a wave with a Gaussian field distribution is incident on the deflector is of considerable practical importance. In this case, the angular dimension of the spot in the far zone will depend on the degree of confinement of the incident light by the aperture of deflector D and its shape [7, 9, 10]. For a Gaussian beam restricted by the circular aperture of the deflector at the $1/e^2$ level of its maximum intensity ($D = 2r_0'$, where r_0' is the characteristic radius of the laser beam measured at the $1/e^2$ level), and $\gamma_R = 1.34$. If the Gaussian beam is not restricted by the aperture of the deflector, we find that $\gamma_R = 4/\pi \approx 1.27$. This approximation is valid for $D \geqslant 3r_0'$ because in this case the diffraction losses at the edge of the aperture are negligible. In the specifications of the detectors, the number of positions resolved in space is usually indicated for a homogeneous beam of a rectangular cross section under the assumption that $\gamma_R = 1$ [9, 10]. The resolution (N_y) of the deflector along the y axis can be defined in an identical manner. Thus, an xy-deflector is capable of addressing a laser beam at one of the $N = N_x N_y$ positions in the xy plane.

In the classical thermography, the time T_f of formation of a frame is the time between the instants when the scanning system detects the first point in the field of vision and the instant when the system returns to its initial position after scanning all the remaining points in the field of vision [1]. Let τ_p be the time in which a laser beam acts on a single position (i.e., the duration of the laser pulse). For $\tau_p \gg \tau$, the time of formation of a frame in this problem can be estimated from the relation $T_f = nN\tau_p$, where n is the number of passes along each row.

3. Lateral resolution of the LPTR technique with a scanning device

The method of laser photothermal radiometry is based on the modulation of the sample surface temperature by laser radiation. The intensity of thermal radiation emitted by the part of the object exposed to laser radiation is modulated in this case [2–6]. In view of this circumstance, it is expedient to clarify the definition of a number of important parameters characterising the thermographic system whose operation is based on the LPTR technique with a scanning device.

Consider the case when a rectangular image is obtained by line-by-line scanning of the object by a laser beam moving discretely in the plane of the object with a constant step. We have mentioned above the values of parameter γ_R corresponding to the Rayleigh criterion. While determining the resolution of the deflector intended for use as a part of the active thermographic system in the above mode, we must use a different criterion according to which the lateral resolution of adjacent light beams must depend on temperature resolution requirements. This is due to the fact that the variable component of the heat flux being registered in this case is $\Delta\Phi_\lambda \sim \Delta T_\tau$ (ΔT_τ is the maximum temperature of the surface heated by the laser beam) [2–6].

Due to thermal diffusion, lateral heat propagation over the sample surface takes place. As the laser beam is deflected to the adjacent position, the effect of this process on the temperature at the new position of the laser beam should be restricted by the resolution required for this parameter. Hence, a knowledge of the surface temperature profile of the sample heated by a laser pulse becomes essential. It is not possible to derive an explicit general expression for the excess temperature $\Delta T(r, t)$ of the surface as a function of coordinates and time. Hence we shall present the results of numerical calculation of this dependence for a number of cases which appear to be most interesting.

Consider the heating of the surface of a semi-infinite medium by a rectangular laser pulse, which reflects fairly accurately the real situation when an acousto-optical deflector is used under the condition $\tau_p \gg \tau$. In this case, the intensity $J(t) = J_0\theta(\tau_p - t)$, where J_0 is the intensity of laser radiation incident on the surface; τ_p is the laser pulse duration, which is nearly equal to the time for which the acoustic frequency has a certain value from a set of discrete values; and

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

is the Heaviside function.

We will consider a Gaussian beam because it is of most interest. The temperature at the sample surface as a function of distance r from the centre of the laser spot at the instant t can be obtained by integration [11]:

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

where r_0 is the characteristic radius of the Gaussian beam at the 1/e level; k is the thermal conductivity; and a is the thermal diffusivity of the sample.

From the point of view of applications of this technique, it should be quite interesting to study the heating of a substance by a focused laser beam. In this case, the laser beam diameter determined by the diffraction divergence of radiation may lie in the range $d = 2r_0 \simeq 1 - 10$ μm, which is much smaller than the size of the sensitive element of the existing CCDs for the IR spectral range [12].

By way of an example, let us compare two samples made of materials with quite different values of thermal diffusivity (biological tissue and iron). Figures 1 and 2 show the theoretical time dependences of the temperature increment at the sample surface at various distances from the laser spot centre. A comparison of these dependences shows that they have different shapes. Note that the value of maximum temperature at the centre of the laser spot is nearly the same in both cases. For the dependences presented in Fig. 1, the temperature achieves its peak value over a period of time equal to the pulse duration, after which it starts decreasing. This means that heat does not propagate over the distances considered by us in the directions parallel to the surface. However, the dependences shown in Fig. 2 point towards a considerable influence of transverse propagation of heat since the temperature peaks are attained after termination of the laser pulse.

Assuming that a temperature resolution $\Delta T_{th} = 0.1$ K is sufficient, it follows from the curves in Fig. 1 that the minimum separation between two resolvable positions can

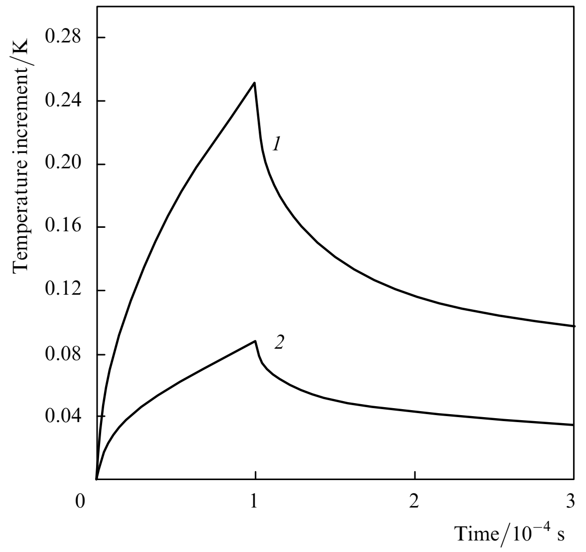

Figure 1. Theoretical dependences of the increment in surface temperature at distances $r = 0.0040$ [curve (*1*)] and 0.0045 cm [curve (*2*)] from the centre of the laser spot for a material with a low thermal diffusivity. The parameters of the problem are: $a = 1.5 \times 10^{-3}$ cm^2 s^{-1}, $k = 4 \times 10^{-3}$ W cm^{-1} K^{-1}, $r_0 = 0.002$ cm, $\tau_p = 10^{-4}$ s, temperature increment at the centre of the laser spot is $\Delta T_\tau = \Delta T_{max}(0) = 13.24$ K.

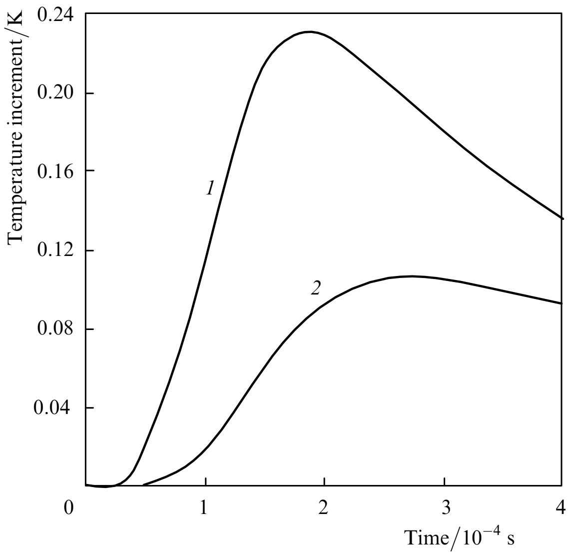

Figure 2. Theoretical dependences of the increment in surface temperature of the sample at distances $r = 0.010$ [curve (*1*)] and 0.013 cm [curve (*2*)] from the centre of the laser spot for a material with a high thermal diffusivity. The parameters of the problem are: $a = 0.125$ cm^2 s^{-1}, $k = 0.5$ W cm^{-1} K^{-1}, $r_0 = 0.002$ cm, $\tau_p = 10^{-4}$ s, temperature increment at the centre of the laser spot is $\Delta T_\tau = \Delta T_{max}(0) = 13.38$ K.

be taken as $r = 2r_0$, where $r_0 = r_0'/\sqrt{2}$ is the laser spot radius at the 1/e level of the highest intensity. This means that the parameter γ in expression (1) is equal to $\gamma_R/\sqrt{2}$, where $\gamma_R = 1.34$ is the value of the parameter for a Gaussian beam restricted by the circular aperture of the deflector at the 1/e^2 level of its highest intensity. Thus, the lateral resolution of the deflector in one of the directions is about $\sqrt{2}$ times higher than the Rayleigh resolution. At the same time, the minimum separation r between two resolvable positions is $6.5r_0$ and $\gamma = 2.3\gamma_R$ in the second case, i.e., for the material with a higher thermal diffusivity. Hence the lateral resolution of the deflector is 2.3 times lower than that obtained from the Rayleigh criterion.

4. Scheme of measurements

In the most general form, a laser thermographic system consists of a scanning device, IR optics, a detector of thermal radiation and a visualisation unit. For xy-scanning of a light beam, two successively arranged one-dimensional acousto-optical deflectors oriented along two orthogonal directions are used [7]. Consider, for example, deflectors with a circular aperture between which no additional optical elements are required. Because the lateral resolution of a deflector is proportional to its aperture, the laser beam diameter at the input of the deflecting system must be close to the deflector aperture. Laser radiation deviated by a deflector towards the object under investigation forms a beam which is focused by a lens at a certain position of the plane of the object with a given address within the framework of the instant field of view of the IR radiation detector. With the help of an IR objective, the same position is mapped onto the sensitive area of the radiation detector. Figure 3 shows the simplified view of the measuring scheme conforming to the technique described above with the optical system forming the laser radiation beam.

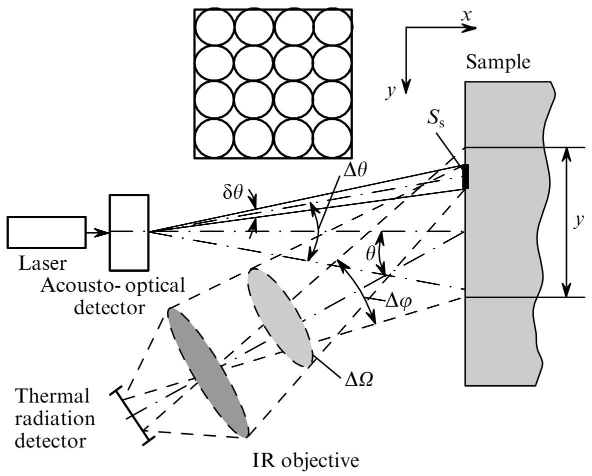

Figure 3. Scheme of a laser scanning radiometer with a single-element IR radiation detector: $\Delta\theta$ – scanning angle; $\delta\theta$ – angular width of a diffracted optical beam; $\Delta\Omega$ – solid angle of thermal flow directed towards the optical system; θ – angle between the directions of the optical flux being registered and the normal to the surface; $\Delta\varphi$ – angular size of the photodetector (line angle confining its instantaneous field of vision).

5. Estimate of the parameters of a laser thermographic system

Noise-equivalent temperature difference (NETD), which will be denoted below as ΔT_{th}, is an important parameter of any thermographic system [1]. The expression for calculating this parameter can be derived from the expression for the spectral flux $\Delta\Phi_\lambda$ perceived by the IR detector for laser irradiation of the surface [3, 6]:

$$\Delta\Phi_\lambda = \Delta B_\lambda G t_\lambda = \Delta T_\tau \Delta\Omega S_s \cos\theta \frac{1}{\pi} \varepsilon_\lambda t_\lambda \frac{\partial W_\lambda(T)}{\partial T} \mathrm{d}\lambda, \quad (3)$$

where ΔB_λ is the variation in the spectral intensity of a black body; W_λ is the spectral density of the thermal radiation flux emitted by it; ε_λ is the spectral emissivity; $G = \Delta\Omega S_s \cos\theta$ is a geometrical factor of the optical system; T is the temperature of the body being measured; ΔT_τ is the maximum value of the temperature increment at the surface of the sample heated by laser radiation; $\Delta\Omega$ is the solid angle of the thermal flux being directed into the optical system; θ is the angle between the direction of the optical flux being measured and the normal to the surface exposed to laser radiation; S_s is the area of the laser spot at the sample surface; and t_λ is the spectral transmission coefficient of the optical system.

We are interested in the time dependence of the differential variation of flux for a constant value of ΔT_τ. Differentiating both sides of Eqn (3), we put the differential equal to the threshold spectral sensitivity $\Phi_{th}(\lambda)$ of the detector:

$$d(\Delta\Phi_\lambda) = \frac{\Delta\Omega}{\pi}\Delta T_\tau S_s \cos\theta \varepsilon_\lambda t_\lambda \frac{\partial^2 W_\lambda(T)}{\partial T^2} d\lambda dT$$

$$= \frac{\sqrt{S_d \Delta f}}{D^*(\lambda)} = \Phi_{th}(\lambda), \quad (4)$$

where $D^*(\lambda)$ is the specific spectral detecting power of the IR detector; Δf is the width of the electric transmission bandwidth; and S_d is the area of the detecting element of the detector.

By integrating expression (4) in the wavelength range $\Delta\lambda = \lambda_2 - \lambda_1$, we obtain the following relation for the temperature resolution of the LPTR technique:

$$\Delta T_{th} = \sqrt{S_d \Delta f}\left[\frac{\Delta\Omega}{\pi}\sqrt{n}\Delta T_\tau S_s \cos\theta \times \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda \frac{\partial^2 W_\lambda}{\partial T^2} t_\lambda D^*(\lambda) d\lambda\right]^{-1}. \quad (5)$$

To improve the temperature resolution, we can use the signal accumulation after multiple passes of the laser beam along each line. In this case, the useful electric transmission band decreases by a factor of $\sqrt{n}$, which is reflected in the obtained expression (n is the number of passes). In the case considered by us, the width of the electric transmission band of the measuring system is $\Delta f \approx 1/\tau_p$. Setting $\tau_p = 10^{-4}$ s, we obtain a rough estimate $\Delta f = 10^4$ Hz. Note that $\tau_p \gg \tau, \tau_d$ (τ_d is the time constant of the detector).

Let us set the temperature resolution at $\Delta T_{th} = 0.1$ K and estimate the parameters of the method using the existing elemental base. For the photodetector, we take the standard MCT-13-0.50 HgCdTe detector, optimised for the wavelength range 2–13 μm [12]. The time constant τ_d of the detector is 0.4×10^{-6} s, the sensitive element has a size of 0.5×0.5 mm ($S_d = 2.5 \times 10^{-3}$ cm^2), the specific detection power is $D^*(12, 10000, 1) > 4 \times 10^{10}$ cm Hz$^{1/2}$ W^{-1}, and its mean value is $\bar{D}^* = 2.5 \times 10^{10}$ cm Hz$^{1/2}$ W^{-1}. In the wavelength range considered by us, the integral $\int_{\lambda_1}^{\lambda_2} (\partial^2 W_\lambda / \partial T^2) \times d\lambda = 5.34 \times 10^{-6}$ W cm^{-2} K^{-2} at $T = 300$ K

For the IR optical system, we consider a germanium lens with a numerical aperture NA = 0.7. Estimates are made for the case when the object and its image are at a distance of double the focal length from the objective. We shall assume that the diameter of the laser spot (at the 1/e^2 level of its highest intensity) on the sample surface is $2r_0' = d_s = 30$ μm ($S_s = 7 \times 10^{-6}$ cm^2). In this case, the geometrical factor of the optical system $G = 2.4 \times 10^{-6}$ cm^2 sr. For the wavelength range considered by us, we set $\varepsilon_\lambda = \varepsilon = 0.9$ and $t_\lambda = t = 0.8$. Moreover, we assume that $\Delta T_\tau = 10$ K ($\Delta T_\tau \ll T$) [5, 6]. Taking into account the above values of the parameters appearing in formula (5), the minimum number of passes n required for image formation will be equal to ~ 50.

While choosing the acousto-optical deflector, we proceed from the requirements imposed on two of its main parameters: the speed of the response and spatial resolution. Considering the results presented in Section 3, the number of allowed positions of the xy-deflector for a material with a low thermal diffusivity is twice the value corresponding to the Rayleigh criterion, i.e., $N_1 \geqslant 2S_d/d_s^2$ for the optical scheme chosen by us. While estimating the number of positions, we disregarded the effect of defocusing of laser radiation during scanning in view of a narrow field of view of the system. Thus, the deflector must resolve at least $\sqrt{N_1} \geqslant 30$ positions in each direction. In this case, the time of formation of a frame must not exceed $T_f = nN_1\tau_p = 4$ s for a deflector of response time $\tau \ll \tau_p$. Analogous estimates carried out for a material with high thermal diffusivity show that the number of resolved positions in each direction does not exceed $\sqrt{N_1} \leqslant 10$. Accordingly, the time of frame formation is $T_f \leqslant 1.3$ s. These conditions are met, for example, by the DTXY-100 acousto-optical xy-deflector [10] having the following main parameters: switching time $\tau = 2.6 \times 10^{-6}$ s, the number of resolved positions (according to Rayleigh criterion) for the Gaussian beam (radiation wavelength $\lambda = 532$ nm) is $N = N_x N_y = 100 \times 100$, the aperture is $D = 1.7$ mm, the scanning angle is $\Delta\theta = (41 \times 41) \times 10^{-3}$ rad, and the working frequency band is $\Delta\nu_a = 50$ MHz.

6. Conclusions

We have shown that the method of LTPR with acousto-optical scanning of laser radiation can be used for thermal imaging during an analysis of the temperature fields. Since the scanning of focused laser beam takes place within the instantaneous field of view of a one-element photodetector, the method considered by us is especially efficient for studying small objects. According to the results of our investigations, the method can be used for studying the temperature profile at the surface of an object with a micrometer-scale lateral resolution, which makes it a strong contender for use in thermal imaging microscopy. It should be emphasised that spatial (lateral) resolution of the method does not follow from the Rayleigh criterion, but is rather associated with the specific requirements imposed on temperature resolution. An increase in lateral resolution for a constant temperature resolution leads to an increase in the time spent in obtaining one thermal image, and hence a compromise has to be sought in the choice of these parameters. The examples considered in this work indicate that temperature fields can be investigated in several cases in the dynamics with high temperature and spatial lateral resolutions. In this case, the time of formation of the thermogram can be reduced by increasing the geometrical factor of the optical system using, for example, a more refined infrared optical system [4, 13].

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