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Application of laser diodes and photodetectors on multiple-quantum wells at the hot-metal pyrometry

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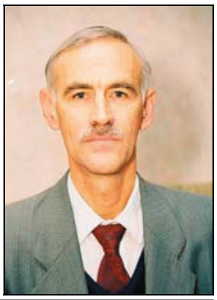

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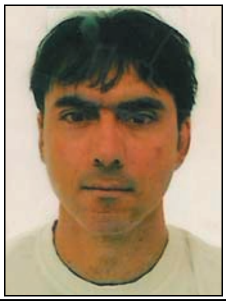

Streszczenie

W pracy zaproponowano metodę spektrofotometrii porównawczej z wykorzystaniem fotodetektorów podczerwieni o szerokim zakresie czułości spektralnej. Określono błędy systematyczne związane z wykładniczą i kątową zależnością od długości fali i współczynnika emisyjności obiektów. Przedstawiono jedną z możliwych konstrukcji pirometru do pomiaru rozgrzanych metali. Dyskutuje się również możliwość zastosowania diod laserowych o rozmiarach kwantowych oraz fotodetektorów zbudowanych w oparciu o złącza GaSb.

Słowa kluczowe: pirometria, spektroreflektometria, zakres bliskiej podczerwieni, fotodetektor, dioda laserowa, pomyłka metodyczna

Abstract

In the paper,the method of relative spectroreflectometry at using the infra-red photodetectors with a wide diapason of the spectral photosensitivity is suggested.Methodical errors at exponential and power dependencies of the emissivity of an object on the wavelength are analysed. Possible design of a pyrometer for measurements of temperature of hot metals is described and attractiveness of quantum-well laser diodes and superlattice photodetectors based on the GaSb compounds is discussed.

Keywords: pyrometry, spectroreflectometry, near-infrared range, photodetector, laser diode, methodical error

1. Introduction

Methods of optical pyrometry are widely applied at scientific researches and in industry [1]. For control of the thermodynamic (actual) temperature of hot metals under forging, tempering, etc., at unknown emissivity, methods of relative spectroreflectometry based on measurements of intensities of intrinsic and reflected radiation at two wavelengths λ_1 and λ_2 are generally used [1–4].

In the paper a method of pyrometry measurements is suggested at using two photodetectors with a wide spectral diapason of the photosensitivity and three laser diodes emitting at the wavelengths in the near-infrared range. Accuracy of the temperature estimations by the given method is examined in details.

2. Relative spectroreflectometry with monochromatic channels

At using two monochromatic channels for the relative coefficient of reflection in first and second channels we have $\rho_{1,2} = \rho_1/\rho_2 = (1-\varepsilon_1)/(1-\varepsilon_2)$, where ρ_1 and ρ_2 are the reflectances, ε_1 and ε_2 are the emissivities of an object at the wavelengths λ_1 and λ_2. In the Wien approach one obtains the equation [1]

$$\frac{1-\rho_{1,2}}{I_1}\exp\left(-\frac{c_2}{\lambda_1 T}\right)+\rho_{1,2}\frac{I_2}{I_1}\exp\left(\frac{c_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\right)=1\,, \qquad (1)$$

where I_1 and I_2 are the luminous brightnesses (relative to $c_{1L}/\lambda^5 = c_1/\pi\lambda^5 = 2hc^2/\lambda^5$) at the wavelengths $\lambda_1 < \lambda_2$, $c_2 = hc/k$. Taking the wavelengths as $\lambda_2 = 2\lambda_1$ and marking $a = (1-\rho_{1,2})/I_1$, $b = \rho_{1,2}I_2/I_1$, we receive the quadratic equation $x^2-bx-a = 0$, where $x = \exp(c_2/2\lambda_1 T)$ is the unknown quantity. Measuring the parameters a and b and finding the solution of Eq. (1), it is easy to evaluate the object temperature.

Shortcoming of this method is dependence of obtained results on characteristics of the optical system and conditions of measurements. Indeed, in the second term of Eq. (1) there is the ratio of pyrometry signals I_2/I_1 and the first term includes only the value of the pyrometry signal I_1.

If to carry out measurements at three wavelengths $\lambda_1 < \lambda_2 < \lambda_3$, we get a system of two equations similar to Eq. (1). As a result of simple transformations this equation system can be reduced to the form

$$\left(\frac{1-\rho_{1,2}}{1-\rho_{2,3}}+\rho_{1,2}\right)\frac{I_2}{I_1}\exp\left(\frac{c_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\right)- \\ -\frac{1-\rho_{1,2}}{1-\rho_{2,3}}\rho_{2,3}\frac{I_3}{I_1}\exp\left(\frac{c_2}{T}\left(\frac{1}{\lambda_3}-\frac{1}{\lambda_1}\right)\right)=1. \qquad (2)$$

In Eq. (2), in contrast to Eq. (1), there are only ratios of pyrometry signals. However in the general case it needs to solve Eq. (2) numerically.

Express Eq. (2) in a quadratic form by determining the relation between the wavelengths. At $\lambda_1 < \lambda_2 < \lambda_3$ we give the condition

$$2\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)=\frac{1}{\lambda_3}-\frac{1}{\lambda_1}, \qquad (3)$$

which is fulfilled at $\lambda_2 = 2n\lambda_1/(n+1)$, $\lambda_3 = n\lambda_1$, where number $n > 1$. In particular, at $n = 2$ one has $\lambda_2 = 4\lambda_1/3$, $\lambda_3 = 2\lambda_1$. As a result, we get the equation $x^2 - Bx + A = 0$, where $x = \exp\left(c_2(n-1)/2n\lambda_1 T\right)$ is the unknown quantity, the values $A = (1-\rho_{1,2})\rho_{2,3}/(1-\rho_{2,3})(I_3/I_1)$ and $B = ((1-\rho_{1,2})/(1-\rho_{2,3})+\rho_{1,2})(I_2/I_1)$ are the measured parameters. Then, solution of Eq. (2) allows determining the heated body temperature.

This method excludes the methodical error connected with ignorance of the material emissivity at the following situations. It is considered that the ratio of direct-directional reflectances is equal to the ratio of direct-hemispherical reflectances for a given material and laser wavelengths, i. e., $\rho_{1,2} = \rho_1(\vartheta_0,\varphi_0:\vartheta,\varphi,\omega)/\rho_2(\vartheta_0,\varphi_0:\vartheta,\varphi,\omega) \approx \rho_1(\vartheta_0,\varphi_0:2\pi)/\rho_2(\vartheta_0,\varphi_0:2\pi)$, $\rho_{2,3} = \rho_2(\vartheta_0,\varphi_0:\vartheta,\varphi,\omega)/\rho_3(\vartheta_0,\varphi_0:\vartheta,\varphi,\omega) \approx \rho_2(\vartheta_0,\varphi_0:2\pi)/\rho_3(\vartheta_0,\varphi_0:2\pi)$, where ϑ_0,φ_0 are the radiation incidence angles, ϑ,φ are the angles of reflection of the radiation descended on the object, ω is the solid angle at which the radiation reflected from the object is detected. The photodetection device has to posses enough narrow spectral diapasons of the sensitivity in the range of applied lasers that complicates its construction.

In practice, for raising the relation “signal–noise”, photodetectors with a rather wide diapason of the spectral sensitivity are generally applied. In this case, formulae (1) and (2) do not provide accurate estimations of the temperature. Therefore it needs in more details to carry out numerical modeling of characteristics of a pyrometer with wide-spectrum photodetectors.

3. Pyrometry at using wide-spectrum photodetectors

The value of the pyrometry signal Q_k arising at the output of a photodetector element k is determined as

$$Q_k(T)=\frac{e}{hc}K_0\int_0^{\infty}\varepsilon(\lambda,T)M_T(\lambda,T)\tau(\lambda)s_k(\lambda)\lambda d\lambda, \qquad (4)$$

where $K_0 = S_{el}\left((l-f)^2/f^2\right)\left(D^2/4l^2\right)\cos\theta$ is the factor connecting the emissive power of the radiation source and irradiance of its image, l is the distance from the object, f is the focal length of the objective, D is the diameter of the objective lens, S_{el} is the area of the photodetector element, θ is the angle between the optical axis of the objective and direction to the object, $\tau(\lambda)$ is the transmission of radiation by the pyrometer objective, $s_k(\lambda)$ is the relative spectral sensitivity of the photodetector, $M_T(\lambda, T)$ is the spectral emissive power of the blackbody at the wavelength λ and temperature T determined by the Planck formula, $\varepsilon(\lambda, T)$ is the emissivity of the object. Examples of marked change in the spectral emissivity $\varepsilon(\lambda, T)$ in the range of 1–5 μm are given in Fig. 1. Therefore temperature calculations with no accounting the spectral sensitivity of photodetectors lead to appearing the methodical error of the order of tens of percent [1].

For solving this problem reference wavelengths and correcting factors are generally introduced [1]. By means of them the real pyrometry signal can be determined through the monochromatic intensity, i. e.,

$$Q_k(T)=c_1 K_0\varepsilon(\lambda_k)R_k\lambda_k^{-5}\exp\left(-\frac{c_2}{\lambda_k T}\right). \qquad (5)$$

Obviously the correcting factor R_k will be a function of temperature and it also depends on spectral characteristics of applied photodetectors and spectral emissivity of the object, i. e., $R_k = R_k(T, s_k(\lambda), \varepsilon(\lambda))$. Therefore at arbitrary spectral dependence of $\varepsilon(\lambda)$ it is not possible to determine simple temperature of a heated body. Then one has to suppose that the emissivity of the material $\varepsilon(\lambda)$ is approximated by some function of the wavelength λ in the range of the photodetector sensitivity.

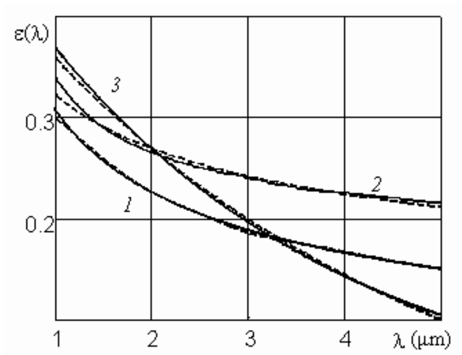

Fig. 1. Emissivity ε(λ) of iron at temperature (*1*) 1120 and (*2*) 1518 K and (*3*) of steel at room temperature and (dashed curves) approximation of ε(λ) by (iron) power and (steel) exponential functions

Emissivity of metals (especially of ferrous ones) is often approximated by an exponential law $\varepsilon(\lambda)=\varepsilon_0\exp(a\lambda)$ or by a power function $\varepsilon(\lambda)=\varepsilon_0\lambda^{\alpha}$, where a and α are constants, $\varepsilon_0(T)$ is the function of temperature [1, 5]. As seen from Fig. 1, the emissivity of iron is approximated more precisely by the power function and of steel by the exponential one. Examine in more detail the case of using the exponential approximation of the dependence $\varepsilon(\lambda)$.

3.1. Correcting factors and approximating coefficients

Let to have two photodetectors ($k = 1, 2$) and three laser diodes emitting at three wavelengths $\lambda_1 < \lambda_2 < \lambda_3$. Emissivity of an object will be approximated by the exponential function. Using the correcting factors in expression (5) for real pyrometry signals through monochromatic intensities and introducing the arbitrary intensity $I_k = Q_k\lambda_k^5/c_1$, we get the system of three equations, i. e.,

$$\frac{1-\varepsilon_0\exp(a\lambda_1)}{1-\varepsilon_0\exp(a\lambda_2)}=\rho_{1,2},\quad \frac{1-\varepsilon_0\exp(a\lambda_2)}{1-\varepsilon_0\exp(a\lambda_3)}=\rho_{2,3}, \\ \frac{I_1}{I_2}=\exp\left(a(\lambda_1-\lambda_2)\right)\frac{R_1}{R_2}\exp\left(\frac{c_2}{T}\frac{(\lambda_1-\lambda_2)}{\lambda_1\lambda_2}\right). \qquad (6)$$

The combined numerical solving of the first and second equations allows to find the coefficient a at the exponential approximation of the emissivity.

Now let to examine the dependence of the ratio of the correcting factors on the temperature and on value of the coefficient a. As the numerical modeling showed, for specific photodetectors based on GaSb [6] with the sensitivities $s_1(\lambda)$ and $s_2(\lambda)$ (Fig. 2) the logarithm of the ratio of correcting factors can be approximately expressed by the formula

$$\ln\left(\frac{R_1}{R_2}\right) \approx b_1 a + b_2 a T + b_3 \frac{a}{T} + m + nT + \frac{p}{T}. \qquad (7)$$

For such photodetectors the approximating coefficients are equal to $m \approx -1.0006$, $n \approx -1.77\times10^{-5}$ K^{-1}, $p \approx 635.4$ K, $b_1 \approx 2.06\times10^{-8}$ m, $b_2 \approx -7.91\times10^{-5}$ m/K, $b_3 \approx 1.3\times10^{-10}$ K m.

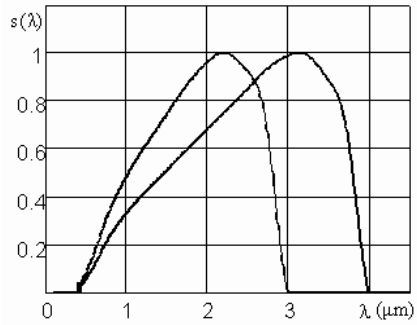

Fig. 2. Sensitivity of model photodetectors based on the InAs–GaSb superlattices. The cut-off wavelength corresponds to 3 or 4 μm

Error of the approximation $\ln(R_1/R_2)$ according to expression (7) at $T = 700\div1600$ K does not exceed by 0.15 % (Fig. 3). It is necessary to mention that the coefficient a depends on the character of change in the emissivity of the object versus the wavelength (and thus it serves as a specific kind of the object characteristics) and the coefficients m, n, p, b_1, b_2, and b_3 are determined by the spectral sensitivity of applied photodetectors.

So, the third equation from system (6) is transformed to the form

$$\ln\left(\frac{I_1}{I_2}\right) = a(\lambda_1 - \lambda_2) + b_1 a + b_2 a T + b_3 \frac{a}{T} + m + nT + \frac{p}{T} + \frac{c_2}{T}\frac{(\lambda_1 - \lambda_2)}{\lambda_1 \lambda_2}. \qquad (8)$$

In this equation the coefficient a is determined by means of numerical solving the first two equations of system (6) and thus Eq. (8) represents the quadratic equation versus temperature, i. e.,

$$UT^2 + WT + V = 0, \qquad (9)$$

$U = b_2 a + n$, $\quad W = a(b_1 + \lambda_1 - \lambda_2) + m - \ln\left(Q_1\lambda_1^5 / Q_2\lambda_2^5\right)$, and $V = b_3 a + p + c_2(\lambda_1 - \lambda_2)/\lambda_1\lambda_2$.

To determine the approximating coefficients b_1, b_2, b_3, m, n, and p it is necessary to know the spectral sensitivities $s_1(\lambda)$ and $s_2(\lambda)$ of applied photodetectors. The coefficients m, n, and p approximate the temperature dependence of $\ln(R_1/R_2)$ in the case of blackbody or grey one. Therewith for the case, where $a = 0$, formula (8) is simplified as

$$\ln\left(\frac{I_{1T}}{I_{2T}}\right) + \frac{c_2}{T}\frac{(\lambda_2 - \lambda_1)}{\lambda_1\lambda_2} \approx m + nT + \frac{p}{T}. \qquad (10)$$

Applying the method of root-mean-square quantities and calculating according to formula (4) values of pyrometry signals at several values of temperature one can to get a set of equations for determining the coefficients m, n, and p [7]. The rest of the coefficients b_1, b_2, and b_3 can be similarly found by means of calculating according to Eq. (5) quantities of pyrometry signals for a set from N_a values of the coefficient a_j and from N_T values of temperature T_i.

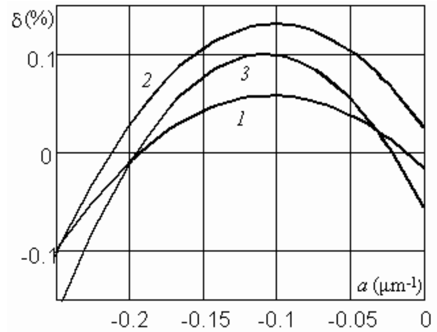

Fig. 3. Accuracy of the approximation of $\ln(R_1/R_2)$ by expression (7) at temperatures (*1*) T = 720 K, (*2*) T = 1270 K, and (*3*) T = 1670 K

In the case of power dependence of the emissivity versus the wavelength the logarithm of the ratio of the correcting factors can be approximately described by a formula similar to Eq. (7), i. e.,

$$\ln\left(\frac{R_1}{R_2}\right) \approx b_1\alpha + b_2\alpha T + b_3\frac{\alpha}{T} + m + nT + \frac{p}{T}. \qquad (11)$$

Therewith, formulae for finding the approximating coefficients n, m, and p remain the same and for estimating the coefficients b_1, b_2, and b_3 values a_j in the corresponding set of equations are substituted for values α_j.

3.2. Determining of the reflectance ratios and methodical errors

For determining the ratios $\rho_{1,2}$ and $\rho_{2,3}$ it is proposed to measure pyrometry signals in turn. At first, a pyrometry signal from an object Q_k (where $k = 1, 2$ is the number of the spectral channel) is measured with no the probing laser radiation (the signal value is described by Eq. (4)). Then in turn signals Q_{ki} are measured which appear at switching by turn the laser diodes at the wavelengths λ_i ($i = 1, 2, 3$) and of the radiation power P_i

$$Q_{ki}(T) = \frac{e}{hc}K_0\int_0^\infty \varepsilon(\lambda,T)M_T(\lambda,T)\tau(\lambda)s_k(\lambda)\lambda d\lambda + \frac{e}{hc}P_i\rho_i(\vartheta_0,\varphi_0:\vartheta,\varphi,\omega)\omega\tau(\lambda_i)s_k(\lambda_i)\lambda_i. \qquad (12)$$

It gives possibility to calculate the unknown quantities for ratios $\rho_{1,2}$ and $\rho_{2,3}$ by the formulae

$$\rho_{1,2} = \frac{Q_{k\lambda_1} - Q_{k0}}{Q_{k\lambda_2} - Q_{k0}}\frac{P_2}{P_1}\frac{\tau(\lambda_2)}{\tau(\lambda_1)}\frac{s_k(\lambda_2)}{s_k(\lambda_1)}\frac{\lambda_2}{\lambda_1},$$
$$\rho_{2,3} = \frac{Q_{k\lambda_2} - Q_{k0}}{Q_{k\lambda_3} - Q_{k0}}\frac{P_3}{P_2}\frac{\tau(\lambda_3)}{\tau(\lambda_2)}\frac{s_k(\lambda_3)}{s_k(\lambda_2)}\frac{\lambda_3}{\lambda_2}. \qquad (13)$$

Cause of the methodical error at determining the temperature by the described method is, firstly, deviation of the real emissivity of the object from exponential or power approximations and, secondly, deviation of true value of the ratio of correcting factors $\ln(R_1(T, s_1(\lambda), \varepsilon(\lambda))/R_2(T, s_2(\lambda), \varepsilon(\lambda)))$ from approximations (7) or

(11). In spite of this, careful corrections involving the object spectral emissivity and the photodetector sensitivity provide enough high accuracy of measurements (Fig. 4).

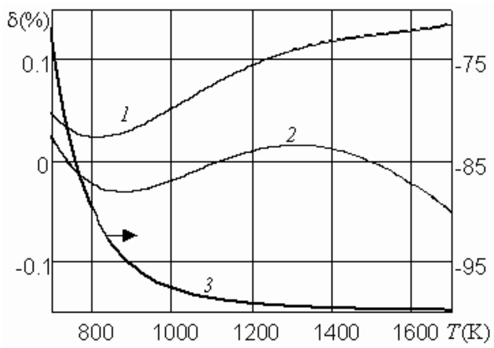

Fig. 4. Methodical error of determining the temperature at (*1*) exponential and (*2*) power dependencies of ε(λ) with taking into account the spectral sensitivity of the photodetectors and (curve 3) also at calculations according Eq. (1)

The suggested method of the estimation of temperature allows practically excluding the methodical error component, which is related to the width of the spectral diapason of photodetectors. As seen from Fig. 4, if do not take into account the width of the spectral band of photodetectors and as usually to use Eq. (1) for evaluating the temperature, the methodical error can be up to 100 %.

4. Scheme of a pyrometer for relative spectroreflectometry with wide-spectrum photodetectors

Functional scheme of a model pyrometer is presented in Fig. 5. Thermal radiation of an object by means of an objective is focused to photodetectors. As the photodetectors, a system of photodetectors, displaced one close by another, based on the InAs–GaSb superlattices [6], model spectral sensitivities of which are shown in Fig. 2. Signal from the photodetectors goes into an electronic processing block. Radiation of laser sources passes by means of optical fibers through connector C to the objective. The control block provides switching in turn laser diodes LD1, LD2, and LD3, amplification of signals from the photodetectors, their processing and indication of obtained values of temperature.

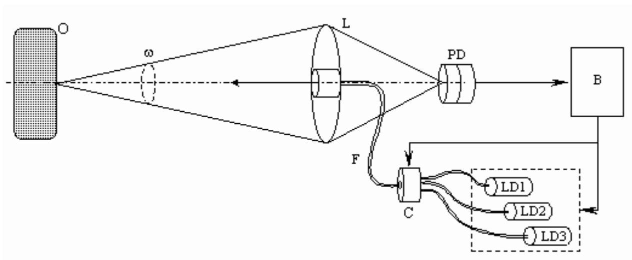

Fig. 5. General working scheme of the pyrometer, (O) object, (L) objective lens, (F) optical fiber, (PD) photodetector, (B) electronic control and processing block, (LD1, LD2, LD3) laser sources at the wavelengths λ_1, λ_2, λ_3, respectively, (C) connector for passing in turn radiation of LD1, LD2, and LD3 into the optical fiber

For convenience of the directing of the pyrometer at the object one can to apply illumination of a control point of the object from a red laser through the pyrometer objective. Therewith, so that the optical radiation of the illuminating red laser did not exert influence on results of temperature measurements it is possible to use in front the photodetectors the Si optical filter not transmitting visible radiation.

As sources, quantum-well laser diodes based on the GaSb compounds can be applied [8–10]. Such lasers emit in the range of 2–3 μm and therefore can be used, e. g., as radiation source LD3 at the wavelength $\lambda_3 \approx 2.2$ μm. These laser diodes are applied for purposes of the absorption spectroscopy and trace gas detection [11, 12].

At the selection of sources according to relation (3) one can to take the set of the wavelengths of $\lambda_1 \approx 1.1$ μm (LD1), $\lambda_2 \approx 1.47$ μm (LD2), and $\lambda_3 \approx 2.2$ μm (LD3). Laser diodes of the near-infrared diapason (LD1 and LD2) posses enough high quality characteristics [13] and their application simplifies technique of the spectroreflectometry. As infrared sensors, traditional photodetectors and as well as optimized infrared detectors of new type are applicable [14].

5. Conclusion

Suggested method of relative spectroreflectometry with using the photodetectors with a wide spectral band of the sensitivity allows quite exactly to estimate temperature of heated metals with exponential or power dependencies of the emissivity ε(λ). As sources of radiation, quantum-well laser diodes based on the GaSb compounds and traditional injection lasers of the near-infrared diapason are applicable and a photodetector can to include neither more than two sensor elements with known relative spectral sensitivities. The components of the described pyrometer system were built and investigated experimentally.

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