

Infrared pyrometer for temperature measurement of objects of both wavelength- and time-dependent emissivity

ZBIGNIEW BIELECKI, KRZYSZTOF CHRZANOWSKI

Military University of Technology, Institute of Optoelectronics, 01-489 Warszawa, Poland.

ROBERT MATYSZKIEL

Military Institute of Communication, 05-130 Zegrze Płd., Poland.

TADEUSZ PIĄTKOWSKI

Military University of Technology, Institute of Optoelectronics, 01-489 Warszawa, Poland.

MAREK SZULIM

Military University of Technology, Institute of Fundamentals of Electronics, 01-489 Warszawa, Poland.

The multiband MBP 98A pyrometer developed for non-contact temperature measurement of objects with unknown and wavelength-dependent emissivity has been presented. The pyrometer has been designed using single thermoelectrically cooled PbS detector of spectral band of 1–2.5 μm and eight narrow-band optical filters. It enables temperature measurement of objects at temperature within a range of 773–1473 K and a speed of 75 Hz. It can be used for controlling various industrial-technological processes as well as in research works for the testing of classic single-band pyrometers in temperature measurement of objects whose emissivity depends on the wavelength and time.

1. Introduction

A division of systems for non-contact temperature measurements employing radiation emitted by an object is based on a number of spectral bands used by the measuring system. There are three groups of systems currently in use: single-band, dualband, and multiband ones. The single-band systems determine the temperature of an object on the basis of the signal measured in one spectral band; for dual systems – in its two spectral bands, and for multiband systems – in at least three bands.

Nowadays, some 90% of systems in the market are single-band ones; dualband systems are rather uncommon and multiband systems are still at laboratory stage of development. However, an increasing interest in multiband systems can be noted [1]–[6] as they can potentially bring significant improvement in accuracy in

non-contact temperature measurements, particularly in the case of so-called “difficult objects”. These objects are considered to be the ones whose emissivity depends on the wavelength and time. Such cases can be found in many industrial applications, and particularly often in the steel and semiconductor industry. This paper presents the results of development of the multiband pyrometer for a non-contact temperature measurement of objects with unknown and wavelength-dependent emissivity. The errors of temperature measurements of such objects using classic single-band systems are often relatively high. Moreover, it is very difficult to estimate such errors.

A review of infrared systems for non-contact temperature measurement, using radiation emitted by the object being tested, is presented in Sec. 2. The basic concept of the pyrometer developed is shown in Sec. 3. The design details of an experimental MBP 98 A multiband pyrometer developed at the Institute of Optoelectronics of the Military University of Technology are presented in Sec. 4. Results of its testing are given in Sec. 5, and conclusions are drawn in Sec. 6.

2. Division of IR systems for non-contact temperature measurement

Single-band systems enable direct measurement of power of radiation emitted by an object in a single spectral band. Radiation emitted by the object that reaches detector produces a signal at detector output. The value of this signal carries information about object temperature, and the latter parameter is usually determined using the system calibration chart. The measurement method requires knowledge about object emissivity. Inaccurate estimation of this parameter is the most common source of significant errors in temperature measurement for single-band systems.

Dualband systems measure radiation in two separate spectral bands. Object temperature is usually determined by using the system calibration chart that presents the interrelationships between the signals measured in these two bands and the object temperature. However, their indications still depend on the object emissivity in applications where the non-grey-body objects are tested.

The multiband systems apparently differ from the single- or dualband systems only because of the higher number of system spectral bands. However, the differences are much more significant. Single- or dualband systems usually use their calibration chart or a single analytical formula for temperature determination. Multiband systems determine object temperature by solving a set of n equations with m unknowns, as presented below:

$$\begin{aligned} S_1 &= f(T_{\text{ob}}, \varepsilon(\lambda_1)), \\ S_2 &= f(T_{\text{ob}}, \varepsilon(\lambda_2)), \\ S_n &= f(T_{\text{ob}}, \varepsilon(\lambda_n)) \end{aligned} \quad (1)$$

where n is the number of detection bands, S_n is the signal measured at the band n , T_{ob} is the real object temperature, $\varepsilon(\lambda)$ is the object emissivity at the wavelength λ . If the number of system spectral bands n is higher than the number of the unknowns

of m the theoretical model, then it is possible to solve the set of equations (1) and to determine the object temperature T_{ob} . The different values of the object emissivity for different spectral bands are the main obstacle to obtain the number of system spectral bands equal to the number of the unknowns. The system closure can be achieved by setting equal emissivities in certain pairs of spectral bands [1]. Other methods include the so-called balancing of intermediation observation [2] and curve fitting of spectral emissivity [3].

3. Basic concept of the developed MBP 98A pyrometer

It has already been mentioned that the system closure of the set of equations (1) can be achieved using different methods. Any of these methods enables solving the set of Eqs. (1) and determination of the object temperature. However, on the basis of the reports on practical multiband systems [4] and patent analysis it seems that the recent method presented in this report can be commonly accepted as the standard one for the multiband systems. Therefore, it has been decided to design a system by applying the method of curve fitting of spectral emissivity and to assume that the object emissivity can always be presented in the following form:

$$\varepsilon_{ob}(\lambda) = a_0 + a_1\lambda + a_2\lambda^2 + \dots + a_{m-2}\lambda^{m-2} \quad (2)$$

where m must never be higher than the number of spectral bands.

With this assumption for the object emissivity there are at least m unknowns ($m-1$ polynomial coefficients plus an object temperature) in the set of Eqs. (1). On the basis of the analysis of emissivity curves of objects in industrial applications the assumption was made that emissivity curves of such objects can be well interpolated using polynomials of the degree not higher than 2 [7]. As it can be seen from Fig. 1, the possible emissivity curves interpolated by polynomials of 2nd degree are close to emissivity curves of many materials used in industry. If we analyse the emissivity tables from [7], we can find that spectral emissivity of almost all materials and alloys can be well approximated by the assumed polynomials.

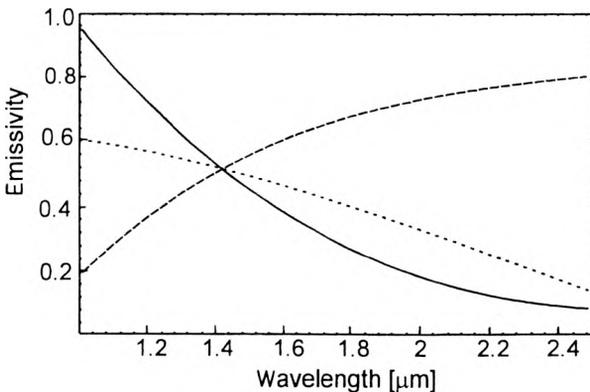


Fig. 1. Examples of emissivity curves interpolated by 2nd degree of polynomials.

The errors of temperature measurement with multiband systems caused by a detector noise and other internal disturbances decrease when the difference between the number of system spectral bands n and the number of the unknowns m increases [8]. Therefore, the system of eight spectral bands has been designed, *i.e.*, with the number of bands n being twice as that of unknowns m . For the system of $n = 8$ and the object of emissivity interpolated with polynomials of degree not higher than 2 we have to solve the following set of equations:

$$\begin{aligned} S_1(T_{\text{ob}}) &= (a_0 + a_1\lambda_1 + a_2\lambda_1^2)S_{\text{bb}}(T_{\text{ob}}, \lambda_1, \Delta\lambda_1), \\ S_8(T_{\text{ob}}) &= (a_0 + a_1\lambda_8 + a_2\lambda_8^2)S_{\text{bb}}(T_{\text{ob}}, \lambda_8, \Delta\lambda_8) \end{aligned} \quad (3)$$

where S_n is the signal at the output of the detector from the real object at n spectral band, λ_n is the effective center of the n spectral band, $\Delta\lambda_n$ is the effective width of the n band, T_{ob} is the object or black body temperature and S_{bb} is the signal caused by the radiation emitted by a black body for the calibration condition equal to

$$S_{\text{bb}}(T_{\text{ob}}, \lambda_n, \Delta\lambda_n) = kM(T_{\text{ob}}, \lambda_n)\tau_0(\lambda_n)\tau_F(\lambda_n)s(\lambda_n)\Delta\lambda_n d\lambda \quad (4)$$

where: $M(T_{\text{ob}}, \lambda_n)$ is the spectral excitance at the temperature T_n and the wavelength λ_n , and k is the constant influenced by the optics F number, the detector sensitivity and electronics gain that can be determined experimentally during the calibration process.

Finally, we have a new set of equations:

$$\begin{aligned} S_1 &= k_1(a_0 + a_1\lambda_1 + a_2\lambda_1^2)s(\lambda_1)\tau_{F_1}\tau_0(\lambda_1)\Delta\lambda_1 \left\{ \lambda_1^5 \left[\exp\left(\frac{c_2}{\lambda_1 T_{\text{ob}}}\right) - 1 \right] \right\}^{-1}, \\ S_8 &= k_8(a_0 + a_1\lambda_8 + a_2\lambda_8^2)s(\lambda_8)\tau_{F_2}\tau_0(\lambda_8)\Delta\lambda_8 \left\{ \lambda_8^5 \left[\exp\left(\frac{c_2}{\lambda_8 T_{\text{ob}}}\right) - 1 \right] \right\}^{-1} \end{aligned} \quad (5)$$

where: τ_0 is the optics transmittance, τ_F is the filter transmittance, $s(\lambda)$ is the detector relative responsivity.

The set of Eqs. (5) cannot be solved analytically. It can be solved only by means of various numerical methods. The least square method was chosen for the MBP 98A pyrometer.

Using the above mentioned method, the unknown parameters T_{ob} , a_0 , a_1 , a_2 can be determined by finding the global minimum of the function $\text{lsm}(T_{\text{ob}}, a_0, a_1, a_2)$ presented below

$$\text{lsm}(a_0, a_1, \dots, a_2, T_{\text{ob}}) = \sum_{i=1}^8 \left\{ S_i - \frac{k_i(a_0 + a_1\lambda_i + a_2\lambda_i^2)s(\lambda_i)\tau_0(\lambda_i)\tau_{Fi}\Delta\lambda_i}{\lambda_i^5 \left[\exp\left(\frac{c_2}{\lambda_i T_{\text{ob}}}\right) - 1 \right]} \right\}^2. \quad (6)$$

The fast algorithm enabling us to solve Eq. (6) was developed. Next, it was implemented in a software package that made it possible to determine an object temperature during real time measurements.

4. Design of the MBP 98A pyrometer

A block diagram of the MBP 98A pyrometer is presented in Figure 2. A principle of operation of the pyrometer is as follows.

An infrared radiation from the object tested is focused on a photoconductive infrared detector of the PbS type using BK 7 glass–silica achromat type optical system on photo-conductive type PbS infrared detector. The optical system was optimised to have the aberration blurring smaller than the diameter of the detector. Moreover, the optical system is characterised by a small *F*-number that enables us to obtain a high signal-to-noise ratio.

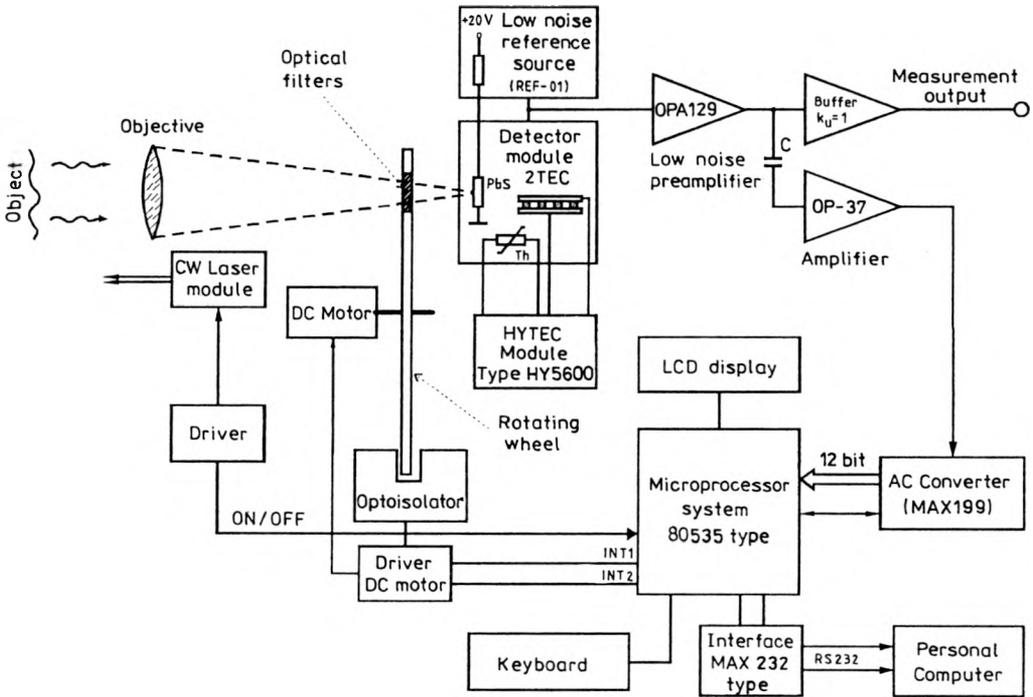


Fig. 2. Diagram of the designated pyrometer.

A signal from the object is modulated by a rotary plate on which eight optical filters are fitted. Spectral bands of most of the filters were chosen to minimise an influence of atmospheric absorption on a signal from the object to the detector. The detector absorbs infrared radiation with the wavelengths shorter than its cut-off wavelength. Absorption of such radiation causes an increase in electrical conductivity of materials and corresponding decrease in the detector resistance. This effect enables us to measure radiation reaching the detector. However, the resistance is changed only by a small fraction, typically by less than 1%. A photoconductive type PbS infrared detector of a spectral band 1–2.5 μm was chosen for application in the pyrometer due to several factors. First, it was noticed from the simulations

that 1–2.5 μm is an optimum spectral band for the required temperature measurement range. Second, low-cost materials can be used to design an optical system for 1–2.5 μm spectral band. Third, this type of IR detectors is characterised by a relatively low price in comparison with HgCdTe detectors.

A two-stage thermoelectric cooler that ensures a detector temperature about 248 K, when the ambient temperature is about 298 K, is used in order to increase detector sensitivity. The thermoelectric cooler is biased by subminiature proportional temperature controller of the HY-5600 type, the HYTEC firm. This device is intended for “cool only” fixed temperature applications where the front panel controls and digital read-outs are not required. The HY-5600 operates in conjunction with a thermistor bridge to precisely measure and regulate the temperature of a device affixed to the TEC with resolution below 0.1 K. The Th thermistor is located as close to the TEC as possible in order to avoid a thermal lag.

A preamplifier is used to amplify a very small signal at the output of the PbS detector. The preamplifier is characterised by a low noise and ultra-low input current. Total gain of this preamplifier can be set as high as 1000 V/V. The preamplifier has typical gain-bandwidth products from DC to 20 kHz. The signal from the output of the preamplifier is sent both to the amplifier in the main measurement channel and to an additional analogue output. The amplified analogue signal from the amplifier is next converted to a digital 12-bit word by IC MAX 199 type converter. The signal after digitisation is registered in a computer memory. All functions of the pyrometer are controlled by a microprocessor system, single chip computer 80535 of the Siemens company. This microprocessor system groups and processes data from each filter. Next, the information is sent to a microcomputer system. An interface between a microprocessor system and a slot RS 232 of a personal computer is performed by MAX 232. Additionally, the μP system controls the driver of DC motor. The LCD display allows us to present the data from measurements. Rotation of a plate is assured by a DC motor, which is controlled by a driver and microprocessor system of 80 535 type. A speed of rotation was optimised to have a signal from the object modulated with frequency of 600 Hz. A CW laser module is used as an indicator, which allows an operator to specify the place of temperature measurement. The module is controlled by a microprocessor system.

The information about the signals measured in the system spectral bands is sent from the microprocessor system through the RS 232 to personal computer. A software application was developed to control the communication process between the microprocessor system and the PC, to carry out the necessary calculations, and visualise the measurement results. The application was written in Visual Basic v. 5.0 language and consisted of 6 modules. The configuration module is responsible for the control of the serial port of the PC. The calibration module is responsible for calibration of the pyrometer. The command module is responsible for speed of the communication between the PC and the pyrometer. The interpretation module sorts the information coming through the serial port and writes it into a special file. The calculation module determines temperature using the algorithm

presented earlier. Finally, the visualisation module presents the measurement results in the form of graphs or tables.

5. Results of tests

Since the authors of this paper did not have a selective body of precisely controlled temperature and known emissivity, a black-body was used as the reference object of temperature measurement. However, the black-body was tested as an object of unknown emissivity to simulate real measurement mode and the task of the system

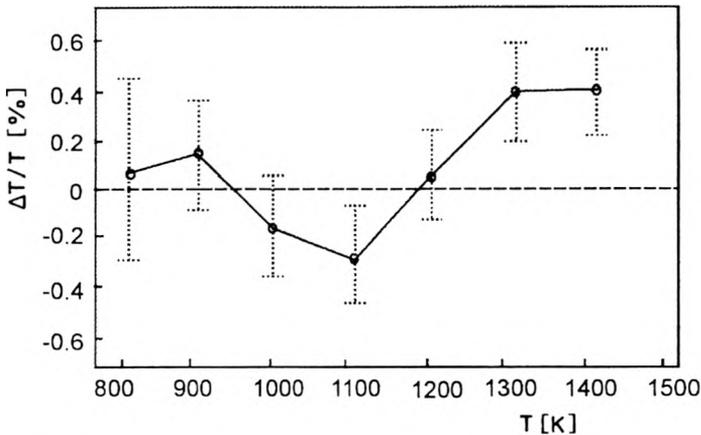


Fig. 3. Relative errors of temperature measurement of the reference object.

was to determine not only the object temperature T_{ob} but also the emissivity coefficients a_0 , a_1 , a_2 . Results of temperature measurement of this black-body with the developed multiband pyrometer are shown in Fig. 3. As we can see in this figure, the pyrometer enabled temperature measurement of the reference object with relative errors below the level of $\pm 0.5\%$.

6. Conclusions

An experimental 8-band pyrometer for non-contact temperature measurements of objects with unknown and wavelength-dependent emissivity was developed. It enables temperature measurement of objects at a temperature of 773–1473 K and with a speed of 75 Hz. It was experimentally verified that errors of temperature measurement of the reference object with the developed pyrometer are below the level of $\pm 0.5\%$. We can estimate that accuracy of temperature measurement of other objects, whose emissivity can be exactly interpolated by a polynomial of 2nd degree, will be of similar level. The pyrometer can be used for control of various industrial-technological processes, in research works, for control of thermal imager indications as well as for control of classic single-band pyrometers.

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