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MULTIBAND INFRARED PYROMETER

The multiband MBP 98A pyrometer developed for non-contact temperature measurement of objects with unknown and wavelength-dependent emissivity has been presented in this paper. The pyrometer was designed using single PbS detector of spectral band of 1 – 2.5 μm and 8 narrow-band opical filters. It enables temperature measurement of objects at temperature within a range of 500°C – 1200°C and a speed of 75 Hz. A high measurement frequency allows the user to test fast thermal phenomena. A small field of view, as compared with the one of typical pyrometers, gives opportunity to measure the temperature of small details. Generally, the obtained parameters enable a precise temperature measurement of objects with small angular dimensions in real time conditions. It can be used for controlling various industrial-technological processes as well as in research works for testing of classic singleband pyrometers.

1. INTRODUCTION

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

Nowadays, not less than 90%of systems in the market are singleband systems; dualband systems are rather infrequent; the multiband systems are still at laboratory stage of development. However, an increasing interest in multiband systems can be noted [1, 2, 3, 4, 6] as they can potentially bring significant accuracy improvement 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 measured in hot background conditions. The cases can be found in many industrial applications; and particularly often in the semiconductor industry.

This paper presents the development results in the multiband pyrometer for a non-contact temperature measurement of the objects with unknown and wavelength-dependent emissivity. The errors of temperature measurements of such objects using classic singleband systems are often relatively high. Moreover, it is very difficult to estimate such errors.

A review of infrared systems for the non-contact temperature measurement, using radiation emitted by the tested object, is presented in Section 2. The basic concept of the developed pyrometer is shown in Section 3. The design details of an experimental MBP 98 A multiband pyrometer developed in the Institute of Optoelectronics of the Military University of Technology are presented in Section 4.

2. DIVISION OF IR SYSTEMS FOR NON-CONTACT TEMPERATURE MEASUREMENT

Singleband systems enable direct measurement of power of radiation emitted by the tested 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 calibration chart presents the dependence of the system's output signal on the object temperature and is determined in laboratory conditions using blackbodies as temperature reference sources. The calibration chart can be corrected for real objects if only their effective emissivity is known. Inaccurate estimation of this parameter is the most common source of significant errors in temperature measurement for singleband systems.

The power emitted by the grey-body at two different wavelengths does not depend on the object's emissivity bu tonly on its temperature. It is employed in dualband systems. These measure radiation in two separate spectral bands. Object temperature is usually determined by using the system calibration chart that presents the inter-relationships of the signals measured in these two bands on the object's temperature. However, these systems are more complicated than the signleband ones and their indications still depend on the object's emissivity in applications where the non-gray-body objects are tested.

The multiband systems apparently differ from the single- or dualband systems only because of the higher number of system's 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:

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

where n is the number of detection bands, S_n is the signal measured at n band, T_{ob} is the real object's temperature, $\varepsilon(\lambda)$ is the object emissivity at wavelength.

If the number of system's spectral bands n is higher than the number of the unknown m of 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 is the main obstacle to obtain the number of system spectral bands equal to the number of the unknown. 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. THE BASIC CONCEPT OF THE DEVELOPED MBP 98A POYROMETER

As it was mentioned earlier the system closure of the set of equations (1) can be achieved using different methods. Any of these methods enable solving the set of the equations (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 work can be commonly accepted as the standard one for the multiband systems. Therefore, it has been decided to design a system with application of the method of curve fitting of spectral emissivity and to assume that the object emissivity can be always presented in the following form

$$\varepsilon_{ob}(\lambda) = a_0 + a_1\lambda + a_2\lambda^2 + \ldots + a_m\lambda^m, \tag{2}$$

where m must be always not higher than the number of spectral bands.

With this assumption for the object emissivity there are at least $m+1$ unknowns (m polynomial coefficients plus an object temperature) in the set of equation (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

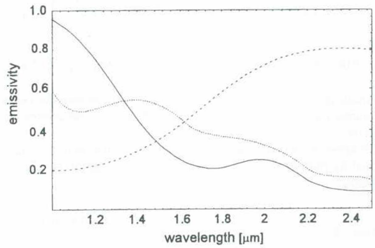

Fig. 1. Examples of emissivity curves interpolated by polynomials of a degree not higher than 4

using polynomials of the degree not higher than 4 [7]. As it can be seen in Fig. 1 the possible emissivity curves can be interpolated by polynomials of 4-th degree the emissivity curves of most materials used in industry can be well interpolated by such the 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 measured unknowns m rise [8]. Therefore, the system of eight spectral bands has been used; i.e., two times higher number of bands than maximal degree of the polynomial (2).

For the system of $n=8$ and the object of emissivity interpolated with polynomials of degree not higher than $m=4$ we have to solve the following set of equations

$$\begin{aligned} S_1(T_{ob}) &= (a_0+.+a_5\lambda_1^m)\, S_{bb}(T_{ob}, \lambda_1, \Delta\lambda_1), \\ S_n(T_{ob}) &= (a_0+.+a_5\lambda_n^m)\, S_{bb}(T_{ob}, \lambda_n, \Delta\lambda_n), \end{aligned} \tag{3}$$

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 system with n spectral band, $\Delta\lambda_n$ is the effective width of the band, T_{ob} is the object or blackbody temperature and S_{bb} is the signal caused by the radiation emitted by a blackbody for the calibration condition equal to

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

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

Finally, we have a new set of equations

$$\begin{aligned} S_1 &= k(a_0+a_1\lambda_1+\ldots+a_n\lambda_1^m)s(\lambda_1)\tau_0(\lambda_1)\Delta\lambda_1 \left\{\lambda_1^5\left[\exp\left(\frac{c_2}{\lambda_1 T_{ob}}\right)-1\right]\right\}^{-1}, \\ &\vdots \\ S_n &= k(a_0+a_1\lambda_n+\ldots+a_n\lambda_n^m)s(\lambda_n)\tau_0(\lambda_n)\Delta\lambda_n \left\{\lambda_n^5\left[\exp\left(\frac{c_2}{\lambda_n T_{ob}}\right)-1\right]\right\}^{-1}. \end{aligned} \tag{5}$$

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

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

$$\mathrm{lsm}(a_0, a_1,\ldots,a_m, T_{ob}) = \sum_{i=1}^{n}\left\{S_i - \frac{k(a_0+a_1\lambda_i+..+a_m\lambda_i^m)s(\lambda_i)\tau_0(\lambda_i)\Delta\lambda_i}{\lambda_i^5\left[\exp\left(\frac{c_2}{\lambda_i T_{ob}}\right)-1\right]}\right\}^2. \tag{6}$$

The fast algorithm enabling to solve the equation (6) was developed. Next, it was implemented in a package written in C^{++} language that made it possible to determine an object's temperature during real time measurements.

4. DESIGN OF THE MBP 98A PYROMETER

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

An infrared radiation from the tested object is focused on a photo-conductive 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 blur smaller than the diameter of the detector. Moreover, the optical system is characterised by a small *F*-number that enables to obtain a high signal-to-noise ratio.

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 wavelength shorter than its cut-off wavelengths. 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 photo-conductive 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 $1-2.5$ 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 relative low price in comparison to HgCdTe detectors.

Two-stage thermoelectric cooler that ensures a detector temperature about -25°C when the ambient temperature is about $+25$°C, is used in order to increase detector sensitivity. The thermoelectric cooler is biasing by subminiature proportional temperature controller of the HY-5600 type, of the HYTEC firm. This device is intended for "cool only" fixed temperature applications where the front panel controls and digital readouts are not required. The HY-5600 operates in conjunctions 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. According to manufacturer recommendations, this detector should be connected to a constant voltage power supply. Among other solutions supply from such a source by means of polarizing resistor R_L (Fig. 3a) has been used. A voltage signal is read off from a voltage divider formed as the detector of dark resistance R_D and resistor R_L.

The bias voltage required for optimum performance depends on size, shape, and composition of the used detector. We use alow noise reference source of the REF-01

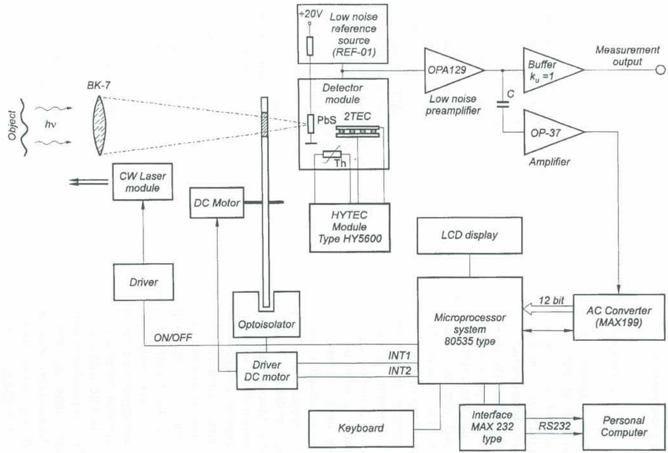

Fig. 2. Diagram of the designed pyrometer

type of supply the PbS photoresistor. When the load resistance R_L and the dark resistance R_d of PbS detector are the same the signal of the highest value can be obtained. The relationship between the R_L/R_d and the signal value is shown in Fig. 3b.

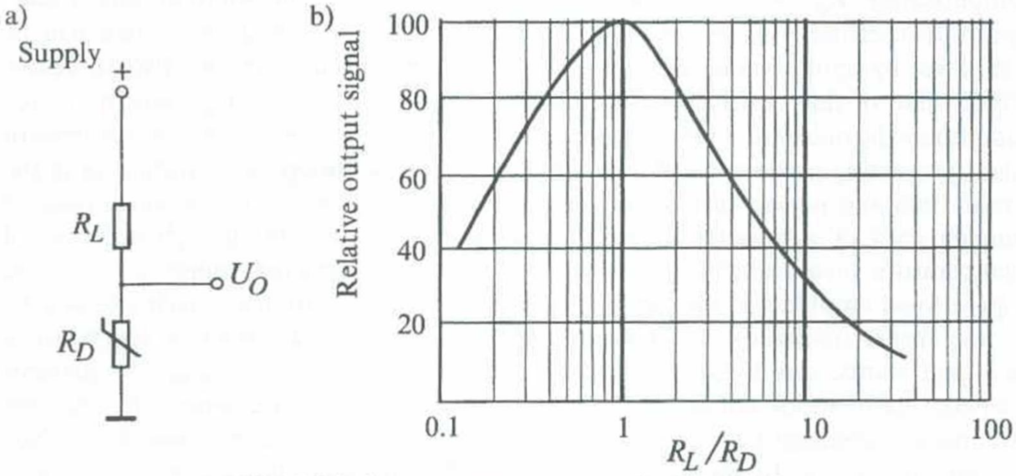

Fig. 3. Relationships between R_L/R_d and output signal

In the analysed pyrometer a detector is supplied from the voltage source U_B of value of +20 V. This source should be characterised by high stability of a voltage value and low noises level. Stability of the output voltage U_B ensures stability of supply voltage of a detector, so a polarization system does not influence essentially on the changes of the emitted power and the same does not introduce an additional active source in a temperature stabilization system. Simultaneously, this solution enables application of a constant component, e.g., for verification of temperature of detector operation by means of a microprocessor system. Especially imortant factor is a level os noises which, due to R_L/R_D divider, influences on a noises level of the input stage. Having in view the above mentioned requirements a supply source system was proposed the scheme of which is presented in Fig. 4.

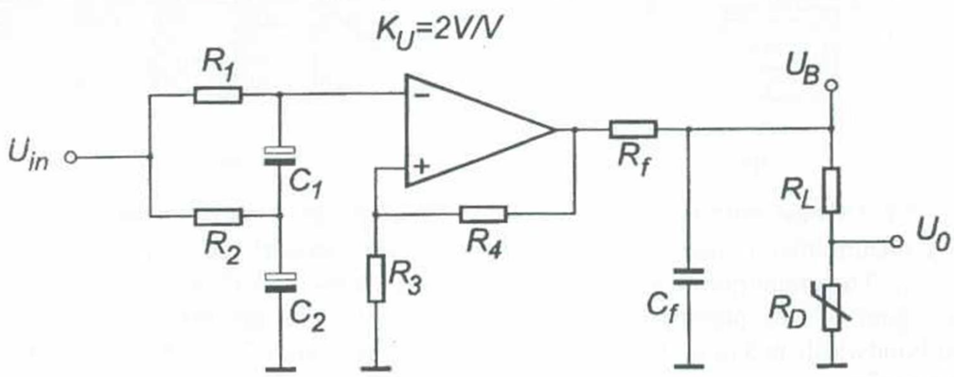

Fig. 4. Scheme of a supply systems of PbS detector

As a reference source an integrated circuit of the REF-01 type was used. This circuit ensures an output voltage $U_Z=10$ V. In order to obtain the final value of a supply voltage of $U_B=+20$ V an additional amplification stage of a voltage amplification $K_u=2$ V/V is required. Unfortunately, in this solution also a temperature coefficient of the output voltage changes of the REF-01 system will be amplified by similar value. Temperature drift of operational amplifier also influences final value of this coefficient. Moreover, an additional amplifying stage noit only amplifiers the noises of a voltage source but also it adds its own noises. Algorithms of data processing used in the pyrometer ar especially sensitive for disturbances in the input data and noises. In real conditions a low level of noises of the input stage of analog path of pyrometer is one of basic conditions to obtain high accuracy of temperature measurement [8]. In a system of PbS detector supply a low-noise operational amplifier of the Op-07 type was used. This amplifier is characterised by a low corner frequency of a noise of the $1/f$ type. For low values of resistance of a signal source this frequency is lower than 10 Hz (Fig. 5a). Figure 5b presents dependence of a total voltage of input noise of this system on frequency [10]. The level of noises introduced by a reference source can be estimated on the basis of the chart shown in Fig. 5a. In the supply system of PbS detector the possibility of noises reduction by means of high-pass filter — $R_1R_2C_1C_2$ eleements have been used. Due to the above mentioned system solutions a noises level of the order of 100 μV was obtained.

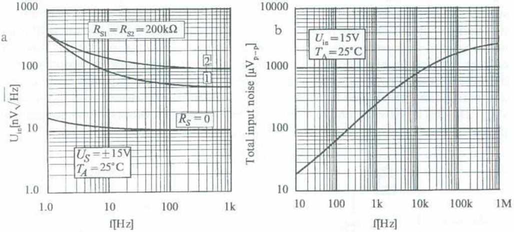

Fig. 5. Output wideband nosise vs bandwidth — a), Total input noise vs frequnecy — b)

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 is set 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 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. LCD display allows us to present the measurements data.

Rotation of a plate is assured by DC motor, which is controlled by a driver and microprocessor system of 80 535 type. A speed of rotation was optimized to have a signal from the object modulated with frequency of 600 Hz. An analysis that was carried out with the data supplied by the detector's manufacturer shown that it is optimum frequency for this application, Fig. 6.

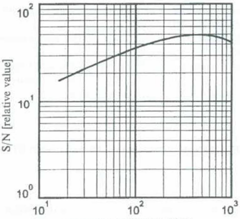

Fig. 6. Signal to noise ratio at a preamplifier output vs chopping frequency

CW laser module is used as an indicator which allows an operator to specify a place of temperature measurement. The module is controlled by a microprocessor system.

5. CONCLUSIONS

An experimental 8-band pyrometer for non-contact temperature measurements of the objects with unknown and wavelength-dependent emissivity was developed. It enables temperature measurement of the objects with a temperature of 500°C – 1200°C with a speed of 75 Hz. High measurement frequency allows the users to test the fast thermal phenomena. A small field of view, comparing with typical pyrometers, gives the opportunity to measure temperature of small details. Generally, the obtained parameters enable us to precisely measure a temperature of the objects with small angular dimensions in real time. It can be used for control of various industrial-technological processes, in research works, for control of thermal imagers indications as well as for control of classic singleband pyrometers.

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WIELOPASMOWY PIROMETR PODCZERWIENI

Streszczenie

W pracy zaprezentowany jest wielopasmowy pirometr podczerwieni MBP 98A. Pirometr jest przeznaczony do bezkontaktowych pomiarów temperatury obiektów o nie znanej i zależnej od długości fali emisyjności. Jest on zbudowany z wykorzystaniem pojedynczego detektora PbS o zakresie widmowym 1 – 2.5 μm i 8 wąskopasmowych filtrów optycznych o pasmach transmisji znajdujących się w przedziale czułości widmowej detektora. Pirometr umożliwia bezkontaktowy pomiar temperatury obiektów w przedziale temperatur od 500°C do 1200°C, z częstotliwością 75 Hz.