

## ACTIVE MULTIBAND PYROMETER

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*Abstract: An active multiband pyrometer for non-contact temperature measurement of objects of unknown and spectrally-dependent emissivity was developed. It enables temperature measurement of the objects of temperature within 500°C-1200°C range with a speed up to 1500 Hz. The pyrometer consists of a source of infrared radiation that emits radiation on the object under measurement and a receiver that measures radiation reflected and emitted by the object into four narrow spectral bands. Tests show that the developed pyrometer enables temperature measurement of real selective objects with the standard uncertainty equal to 1 % of the output temperature in its temperature measurement range.*

*Keywords: Temperature, Infrared, Radiometry*

### 1 INTRODUCTION

According to the number of spectral bands of the detection system the radiation thermometers can be divided into single-, dual- and multiband systems. The same systems according to criterion of presence of an additional radiation source can be divided into active systems that represent a radiation source co-operating with a receiver and passive systems that consist of only a receiver. Practically only passive single- and dualband systems are available commercially so far. Incomplete knowledge about emissivity of selective objects is often a source of significant errors of temperature measurement with these systems. Indications of passive multiband systems do not depend theoretically on object emissivity even when the latter depends significantly on wavelength and changes during technological process. There can be noticed a significant interest in passive multiband systems and have been published reports about designs of a few passive multiband pyrometers or thermal cameras [1-6]. However, there are also studies that suggest distinct disadvantages of passive multiband systems and the conclusion that these systems should not be capable of producing accurate results in most practical applications [7,8].

Active single-, dualband or multiband thermometers represent another possible solution to ensure better temperature measurement accuracy. Active singleband pyrometers (a classical passive singleband pyrometer integrated with a radiation source, for example- a laser) are available nowadays commercially [9]. However, in many cases their accuracy degrades significantly when the angle between the object surface and line the measurement point – the pyrometer is not normal. There was published a report about achieving a very good accuracy of temperature measurement of selective objects with a system that can be called an active multiband pyrometer and consists of a commercially available source of infrared radiation and a spectroradiometer [10]. However, due to high costs of its components, low measurement speed, laboratory character and complicated measurement procedure this active multiband pyrometer cannot be used in most industrial applications. A low cost mobile active four-band AMP 2000A pyrometer developed for high-speed non-contact temperature measurement in industrial applications of objects with unknown and wavelength-dependent emissivity has been developed and is presented in this paper. It is especially targeted for temperature measurement of rapidly heated metals during technological processes with high power lasers.

### 2 BASIC CONCEPT

It is well-known that due to problems with estimation of emissivity of the tested objects, the errors of temperature measurement with classical passive singleband (mono-color) systems are often significant. In spite of this fact, the systems of this type clearly dominate on the market because of their relative low cost and that, so far, there are no alternative systems of significantly better accuracy in industrial conditions.

Manufactures of passive dualband (dual-color) systems sometimes advertise that indications of these systems do not depend on object emissivity and atmospheric conditions. However, it can be shown that it is true only in case of grey body type objects and when atmospheric transmittance is the same in the two system spectral bands [11].

The passive 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. Passive single- or dualband systems usually use their calibration chart or a single analytical formula for temperature determination. Passive multiband systems determine object temperature by solving a set of  $n$  equations with  $m$  unknowns, as presented below:

$$\begin{aligned} S_1 &= f(T_{ob}, e(I_1)), \\ S_2 &= f(T_{ob}, e(I_2)), \\ &\vdots \\ S_n &= f(T_{ob}, e(I_n)), \end{aligned} \tag{1}$$

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,  $e(I)$  is the object emissivity at wavelength  $\lambda$ .

If the number of system's spectral bands  $n$  is higher than the number of the unknowns  $m$  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 unknowns. The system closure can be achieved by setting equal emissivities in certain pairs of spectral bands, by the so called balancing of intermediation observation or curve fitting of spectral emissivity. In order to approximate well a curve of object emissivity that depends lightly wavelength using any of these methods it is necessary to input to the set of equations (1) at least three unknown parameters representing object emissivity; in case of the strong variations of object emissivity on wavelength the minimal number of these parameters must be significantly higher. It was shown in Ref. [12] that high number of unknown parameters representing object emissivity in the set of equations (1) makes the indications of passive multiband systems very sensitive to any disturbances in the measurement channel. Therefore, in spite of theoretical potential to measure accurately temperature of objects of unknown and wavelength-dependent emissivity, accuracy of practical such systems can be comparable to accuracy of typical passive singleband systems [12].

Active singleband systems consists of a classical passive singleband system working as a receiver integrated with an emitter of optical radiation. These systems use generally two-phase measurement procedure. Object emissivity is determined during the first phase on the basis of the measured power of radiation emitted by the emitter and reflected by the tested object. Object temperature is determined during the second phase on the basis of the measured power of the radiation emitted by the object and the calculated earlier value of the object emissivity. However, reflectance of typical objects of reflective-diffusive surfaces significantly depends on the angle of incident radiation. Therefore, accuracy of determination of object emissivity significantly degrades when the angle between the object surface and line the measurement point – the pyrometer is not normal.

To summarise the presented above discussion we can say that accuracy of passive singleband systems can be low in so called difficult cases like objects of unknown and wavelength-dependent emissivity. However, alternative solutions to these classical systems such as passive dualband systems, passive multiband systems and active singleband systems so far failed to show high accuracy of measurement of temperature of such objects, too.

High accuracy of temperature measurement of objects of unknown and wavelength-dependent emissivity was achieved using a system that can be called an active multiband system [10]. The system consists of a commercially available source of infrared radiation and a IR spectroradiometer [10]. Object temperature is determined on the basic of measured three spectrums:  $S_0(I)$  – the spectrum of radiation emitted by the co-operating source,  $S_1(I)$  – the spectrum of radiation emitted by the tested object, and  $S_{11}(I)$  – the spectrum of sum of radiation emitted by the co-operating source and reflected by the object and the spectrum of radiation emitted by the tested object by solving a set of equations of two unknowns: object temperature and an additional constant that depends on geometry of the set: the co-operating source, the system and the tested object.

Due to high costs of its components, low measurement speed, laboratory character and measurement procedure requiring direct measurement of spectrum of radiation emitted by the co-operating source, this active multiband pyrometer cannot be used in most industrial applications.

The system presented in this paper can be also classified as an active multiband pyrometer like the system presented above. However, its design and measurement procedure was significantly simplified. First, instead of using a sophisticated and expensive spectroradiometer, a much simple four-band receiver is used. Second, the measurement procedure was modified to enable determination of object temperature when the mentioned above spectrums are measured at only a few spectral bands. What is also important in many applications the speed of measurements was significantly increased enabling temperature measurement of objects of rapidly changing temperature.

### 3 MEASUREMENT METHOD

A following algorithm is used to determine temperature of the tested object.

First step, the output electrical signals caused by modulated radiation emitted by the source and reflected by the object in all system spectral bands  $S_{1r}, S_{2r}, S_{3r}, S_{4r}$  are measured.

Second step, the output electrical signals caused by radiation emitted by the tested object  $S_1, S_2, S_3, S_4$  are measured.

Third step, calculation of the relative reflectance of the tested object  $r_n$  in all spectral bands

$$r_n = S_{nr} / S_{n0r} \quad (2)$$

where  $r_n$  is relative object reflectance in  $n$  spectral band,  $S_{nr}$  is the signal due to reflected radiation by the tested object in  $n$  spectral band, and  $S_{n0r}$  is the signal caused by reflected radiation by the standard object of very high reflectance close to 1 in  $n$  spectral band.

Step fourth, solving numerically the following set of equations

$$\begin{aligned} S_1 &= [1 - k \times r_1] \times S_{bb1}(T_{out}) \\ S_2 &= [1 - k \times r_2] \times S_{bb2}(T_{out}) \\ &\dots\dots\dots \\ S_4 &= [1 - k \times r_4] \times S_{bb4}(T_{out}) \end{aligned} \quad (3)$$

where  $S_1, S_2, S_3, S_4$  are the output electrical signals caused by radiation emitted by the tested object in  $n$  pyrometer spectral bands,  $k$  is an unknown constant, and  $S_{bbn}(T_{out})$  are output signals caused by radiation emitted by a blackbody of temperature  $T_{out}$ .

The latter signals is calculated using this formula

$$S_{bb(n)} = \frac{a_n}{I_{ef(n)}^5 \left[ e^{\frac{c_2}{I_{ef(n)} T}} - 1 \right]}, \quad (4)$$

where  $a_n$  is a design constant for  $n$  spectral channel, and  $I_{ef(n)}$  is effective wavelength of  $n$  spectral band. Both parameters are determined experimentally during calibration of the pyrometer.

The set of equations (2) is solved and the unknowns  $T_{out}$  and  $k$  are determined using the least squares method by finding the global minimum of the function  $min(T_{out}, k)$

$$\min(T_{out}, k) = \sum_{i=1}^4 \{ S_i - k [1 - r_i] S_{bbi}(T_{out}) \}. \quad (5)$$

However, any other numerical method can be used to find the unknowns parameters  $T_{out}$  and  $k$ .

### 4 PYROMETER DESIGN

The AMP 2000A pyrometer consists of three basic blocks: the IR emitter that irradiates the tested object, the receiver that registers the radiation emitted and reflected by the tested objects in four separate spectral bands, and a PC computer that is used to calculating the object temperature and for storage of the measurement results. The basic diagrams of the first two blocks are presented in Fig.1.

A high temperature small body is used as a source of infrared radiation in the emitter block. The image of the source is projected onto the surface of the tested object using a multi-lens optical system shown in Fig.1a. The optical system is characterised by a low F-number in order to increase power of radiation emitted by the source that comes to the tested object. Special care was also taken to assure uniformity of irradiation of the tested object.

The radiation emitted by the source on its way from the source to the tested object is modulated using a mechanical chopper. Rotation of the chopper plate is assured by a high speed DC motor of optimised and stabilised speed of rotation.

An optical objective of the receiver with a beam splitter generates four separated images of the tested object into the focal plane of the objective.

Four NIR detectors (2 Ge detectors and 2 Si detectors) integrated with optical filters of narrow spectral bands within 0.8-2  $\mu m$  range are located at points of the focal plane where the images of the tested object are generated. The electrical signals generated at outputs of these detectors by radiation emitted and reflected by the objects are amplified using four separate preamplifiers, digitised and sent to PC.

The system optical objective – beam splitter was optimised to have the aberration blur smaller than the diameter of the detectors. Moreover, the this optical system is characterised by a small F-number that enables to obtain a high signal-to-noise ratio at outputs of the detectors.

The temperature of the detectors is decreased and stabilised in order to increase detectivity of the detectors and eliminate variations of the dark current of the detectors.

Ge and Si photodiodes were chosen for application in the pyrometer in spite of some problems with high dark current of the Ge detectors due to several factors. First, it was noticed from the simulations that the 0.8-2  $\mu\text{m}$  is an optimum spectral range for the required temperature measurement range. Second, low-cost materials can be used to design an optical system for this spectral band. Third, this type of IR detectors is characterised by a relative low price in comparison to InGaSb and HgCdTe detectors.

For separate preamplifiers are used to amplify very small signals at the output of the four detectors. The preamplifiers are characterised by a low noise and ultra low input current. Total gain of these preamplifiers can be set as high as  $10^5$  V/A. The preamplifier has typical gain–bandwidth products from DC to 10 kHz.

The signals from the outputs of the preamplifiers are sent both to the amplifiers in the main measurement channel and to an additional analogue output. The amplified analogue signals from the amplifier is next converted to a digital by a 16-bit word A/D converter. The signals after digitisation are registered in a computer memory.

The most important functional parameters of the developed pyrometer are shown in Tab.1.

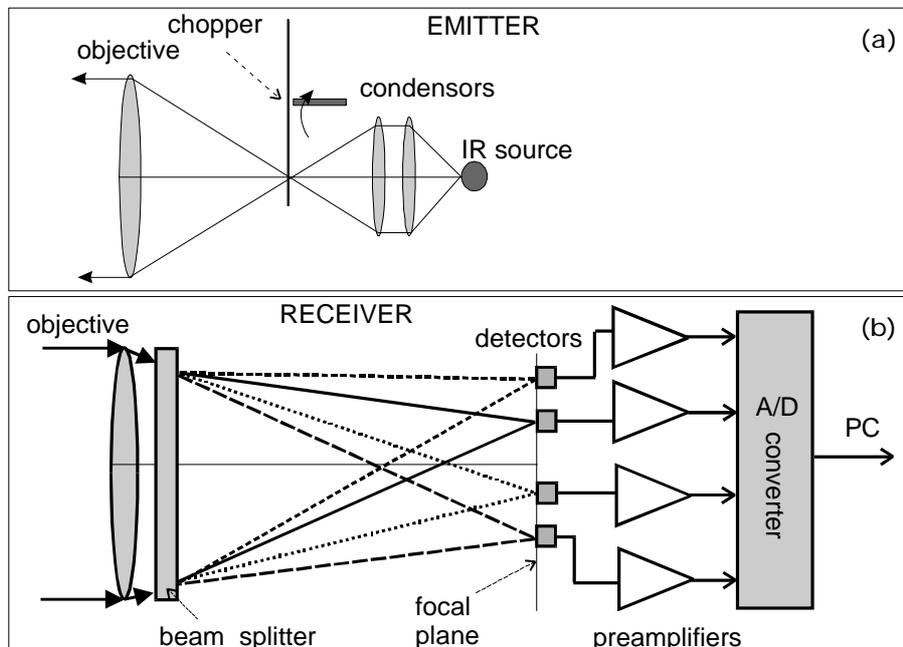


Figure 1. Basic diagram of the emitter (a) and the receiver (b) of the pyrometer AMP2000A

Tab.1 Functional features of the developed pyrometer

measurement temperature range	500-1200 C
measurement frequency	up to 1500 Hz
measurement distance range	1-30 m
spatial resolution	5 mrad (standard optics)
field of view for distance 1 m	5x5 mm
range of operation temperatures	5°C-30°C (can be extended)
dimensions	200/110/200mm – receiver 200/150/300mm - emitter
mass	2 kg – receiver 3 kg - emitter
additional features	laser pointer, infrared reference source, portable tripod, case

## 5 TEST RESULTS

The AMP 2000A pyrometer was developed with aim of to use it in applications requiring temperature measurements of objects using high power lasers. Such applications require high speed measurements of frequency over 1000 Hz. This pyrometer was used in such applications and its users were satisfied with it. They estimated that accuracy of temperature measurement with the AMP 2000A is much better than with typical singleband pyrometers. However, it was not possible to determine accurately true errors of temperature measurement of laser heated objects with this pyrometer as no method of better accuracy was available for comparisons. Typical contact methods that enable very accurate temperature measurement are too slow and additionally the sensors cannot be used as they change mechanical properties of the heated material.

In order to estimate the intrinsic uncertainty of the pyrometer there were made comparisons of its readings with readings of a contact thermometer during low speed measurements. The intrinsic uncertainty of the contact thermometer was estimated by the manufactures as equal to 0.2% of the output temperature and can be treated as negligible in comparison to uncertainties of the pyrometer. The tests were carried out during temperature measurements of slowly heated blocks made from different type of steel. The results indicate that the standard uncertainty of the pyrometer during such measurements is equal to 1% of the output temperature. We can estimate that the uncertainty of the pyrometer should be the same during high speed measurement, too.

## 6 CONCLUSIONS

A mobile active four-band AMP 2000A pyrometer that enables high speed non-contact temperature measurement of rapidly heated objects of unknown and wavelength-dependent emissivity was developed. The tests show that it enables temperature measurement of such objects with the standard uncertainty equal to 1% of the output temperature. It can be considered as a significant improvement as typical passive singleband pyrometers can offer similar accuracy only in case of blackbodies or objects of exactly known emissivity.

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## REFERENCES

- [1] N.A. Khan, C. Allemand, T.W. Eagar, Non-contact temperature measurement: least squares based techniques, *Rev. Sci. Instrum.* **62** (1991) 403-409.
- [2] V. Tank, H. Dietl, Multispectral Infrared Pyrometer For Temperature Measurement With Automatic Correction Of The Influence Of Emissivity, *Infrared Phys.* **30** (1990) 331-342.
- [3] Y.A. Levendis, K.R. Estrada, H.C. Hottel, Development of multicolor pyrometers to monitor transient response of burning carbonaceous particles, *Rev. Sci. Instrum.* **63** (7) (1992) 3608-3621.
- [4] S. Hejazi, D.C. Wobschall, R.A. Spangler, M. Anbar, Scope and limitation of thermal imaging using multiwavelength infrared detection, *Opt. Eng.* **31** (1992) 2383-2392.
- [5] C.D. Hunter, Prototype device for multiwavelength pyrometry, *Opt. Eng.* **25** (11) (1986) 1222-1231
- [6] H. Jiang, Y. Qian, High-speed multispectral infrared imaging, *Opt. Eng.* **32** (6) (1993) 1281-1289.
- [7] P.B. Coates, Multi-Wavelength Pyrometry, *Metrologia* **17** (1981) 103-109.
- [8] K. Chrzanowski, M. Szulim, A measure of the influence of detector noise on temperature-measurement accuracy for multiband IR systems, *App. Opt.* **37** (22) (1998) 5051-5057.
- [9] Pyrometer Inc. Catalog of products 1994
- [10] N. Daniel, D. Williams, Full spectrum multiwavelength pyrometry for non-grey surfaces, *Proceedings of the SPIE* Vol. 1682 (1992) 260-270.
- [11] Chrzanowski K., Influence of measurement conditions and system parameters on accuracy of remote temperature measurement with dualspectral IR systems, *Infrared Phys. and Technology*, **37**, (1996)295-306.
- [12] Chrzanowski K., Szulim M., Errors of temperature measurement with multiband IR systems, *App. Opt.*, **38** (10), (1999)1998-2006.

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