International Journal of Thermophysics, Vol. 13, No. 1, 1992

A New Multiwavelength Pyrometer: Design and Feasibility Study[1]

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A multiwavelength pyrometer is described in which the wavelength bands are selected with a direct vision prism and a diode array. The main optical and electronic parameters of the instrument are specified.

KEY WORDS: high-temperature measurements; multiwavelength pyrometry; pyrometer; radiation thermometer.

1. INTRODUCTION: STATE OF THE ART

Several multiwavelength pyrometers have been proposed in the last decade [1–4]. Figure 1 shows the common configuration of this type of instruments. All of them use multibranch fiber optics to split the radiation beam into a number of channels. Each branch carries radiation to a detector through interference filters to sort out different wavelength bands in which the temperature measurement must be performed.

The detectors are silicon photodiodes, each connected to a transconductance amplifier. Generally, the amplifier outputs are connected to an analog multiplexer which branches the analog signals to an ADC, so that the temperature signals related to each wavelength band are sent to a computer to be processed through a variety of algorithms.

The speed of this type of instruments is conditioned by the diode response speed (of the order of picoseconds), by the conversion time (ultimately related to the number of bits of the digital signal), and by the multiplexer switching time. Modern technology presents components that allow a switching and 12-bit conversion time of about 5 μs, so that a temperature measurement with six wavelength bands would require some

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[1] Paper presented at the Second Workshop on Subsecond Thermophysics, September 20–21, 1990, Torino, Italy.

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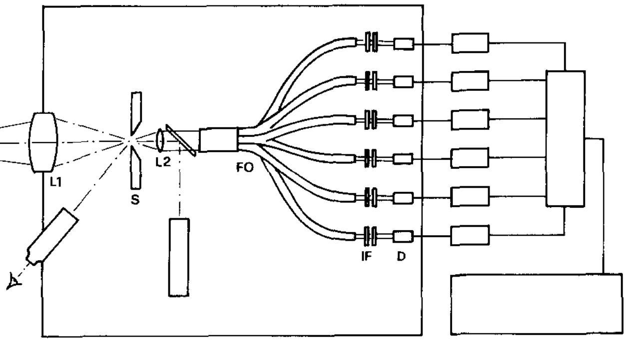

Fig. 1. Multiwavelength pyrometer with fiber optics channels. L_1: Objective lens. S: Field stop. L_2: Field lens, projecting the aperture stop on the end face of the fiber optics. FO: Fiber optics. IF: Interference filters. D: Photodiodes.

30 μs. This time could be reduced if we attach one ADC to each amplifier and use a digital multiplexer.

An interesting feature has been introduced by Minolta Co. in an instrument of this type, described in the paper by Makino et al. [4]; see Fig. 2. In this case, the modulated radiation of an incandescent lamp is injected by means of fiber optics into the target in order to measure the reflectivity in the pertinent bands by synchronous demodulation of the signal generated by the reflected radiation. This device certainly increases the information collected by the instrument but reduces its response speed.

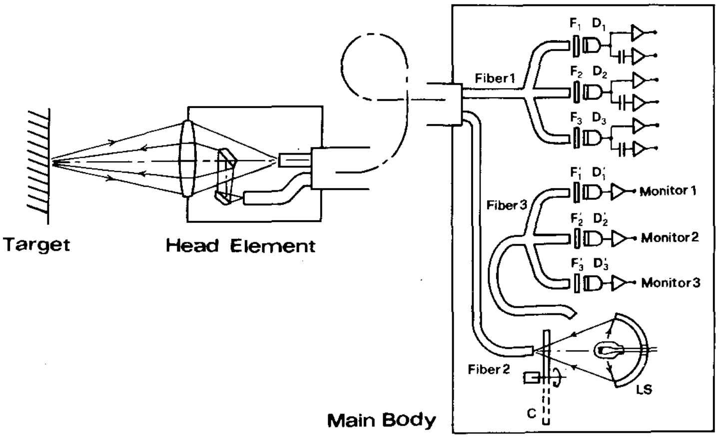

Fig. 2. Minolta multiwavelength pyrometer [4]. F and F′: Interference filters. D: Diodes. LS: Light source. C: Chopper.

A condition which must be fulfilled by a multiwavelength fiber optics pyrometer is that the common end face of the fiber bundle must be located on the aperture stop of the instrument instead of the field stop. In this case, unless the fibers are absolutely randomly mixed, each optical channel would select a different portion of the target, which is not necessarily isothermal. Each channel accepts only one fraction of the radiation flux available for the measurement. A severe reduction to this flux is added by the transmittance of the bandpass filters. Good filters have peak transmittances of about 80%, so that each channel of this kind of radiation thermometers utilizes at most 13% of the total radiation flux available to the instrument.

2. BASIC CONCEPT OF A NOVEL DESIGN OF A MULTIWAVELENGTH PYROMETER

Wasting of available radiation flux is avoided if we disperse the radiation with a prism and place a detector to intercept a band of the dispersed radiation. A prism is preferable to a grating because the latter does not suppress completely the radation diffracted into orders different from the one pertinent to the blazing angle.

Use of a direct vision prism (Amici prism), by avoiding any bend of the optical axis, could aid the mechanical design, expedite the adjusting operation, and improve the handling of the instrument.

The fact that the detectors are now located on the radiation spectrum suggests the use of linear diode arrays instead of discrete detectors which are actually used with fiber optics.

The basic optical design of the new multiwavelength pyrometer is shown in Fig. 3. Radiation emitted by the target is focused by lens L_1 on the field stop S. The latter and lens L_2 collimate the radiation to the prism P. Finally, lens L_3 projects the spectrum on detector array, D.

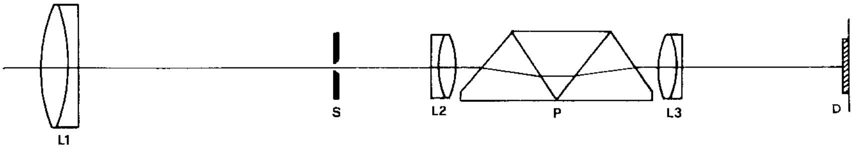

Fig. 3. Multiwavelength pyrometer with dispersing prism and diode array. L_1: Objective lens. S: Field stop. L_2: Collimating lens. P: Direct vision prism. L_3: Spectrum focusing lens. D: Diode array.

3. HIGHLIGHTS OF THE OPTICAL DESIGN

The input parameters of the optical design are the target shape and dimensions, the prism dispersion angle, and the length of the array.

3.1. Target

Since the spectral band of each channel is extracted from the total flux emitted by the source, it is allowed to disperse the flux exiting the field stop and, therefore, to locate the latter on the focal plane of the collimating lens. Then, optimum throughout is achieved if the field stop has the same shape as the detector, consisting of a group of array elements. This shape is rectangular. Giving this shape to diaphragms and cavity openings may cause some problems: a round form is acceptable if the detector conjugates are inscribed in the circles of the openings.

3.2. Prism

Manufacturers offer direct-vision prisms working in the visible with a dispersion angle of about 4.5° (0.08 rad) for F and C lines. Using these commercially available prisms between 500 and 1000 nm would yield a nonsymmetrical spectrum with the optical axis and a slightly different dispersion. We would prefer to redesign a prism for part of the visible and near-infrared, aiming at the same dispersion angle. A computer program has been developed for designing Amici prisms by introducing the two refracting indexes of the glasses to get the combinations of the two prism angles. This program will be used to select the best match of flint and crown glasses for our particular application.

3.3. Diode Array

For our application arrays with a small number of elements (order of tens, instead of hundreds or thousands) are preferable. We chose the Hamamatsu S4111 series, consisting of 35 elements, with dimensions of 4.4 × 0.9 mm each, spaced by 0.1 mm. By discarding the first five elements and dividing the rest into five-element groups, we get six detectors of 4.4 × 5 mm (19.8 mm^2 of useful area and a total length of 30 mm).

3.4. Dimensions of the Optics

To cover the length of the array, given a prism dispersion of 0.08 rad, lens L_3 must have focal length of 375 mm. Laboratory pyrometers usually have the following object specifications: target size, 1 mm; and distance from front lens L_1, 500 mm. This is achieved with unit magnification of the objective lens (focal length, 250 mm) and magnification of -5 of the system L_2–L_3. Therefore, lens L_2 must have a focal length of 75 mm.

4. ELECTRONIC CIRCUIT

Diode arrays can work in the photovoltaic, photoconducting, or charge storage mode. In the latter mode, the charge stored in the junction of each element, which is proportional to the product of radiation intensity per exposure time, can be read out in sequence by a multiplexer. The array (or matrix) of diodes (or charge-coupled devices; CCD) and multiplexer are generally integrated in the same chip. The sequential output is connected, via a charge amplifier, to an ADC.

We chose the photovoltaic mode. In this way transconductance amplifiers are connected between each diode and the multiplexer, whose common output feeds the signal to a computer via the ADC (Fig. 4). Thus we have the option, unavailable in the charge storage mode, of grouping elements, either in hardware (with parallel wiring) or in software, if the multiplexer switches are sufficient for each array channel.

Sampling the sensing elements, amplifying the signals, and converting them into digital form are under the control of a personal computer. Thus, the latter selects in software the bands and their central wavelength within a spectrum from 500 to 1000 nm.

5. CALIBRATION

The calibration of the instrument is achieved through the following steps. (a) The wavelength calibration is performed by aiming the pyrometer

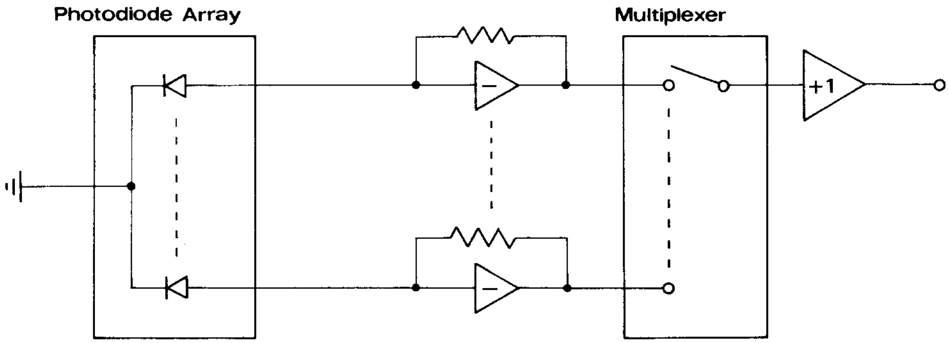

Fig. 4. Electronic circuit for the signal treatment of the diode array.

at the exit slit of a monochromator and proceeding for each band as for a monochromatic pyrometer. With this type of instruments, the transmission bands will be strictly square-shaped, thus yielding effective wavelengths with a higher precision. An alternative method uses spectral lamps (Hg and Ne) and counts the pixels where every line is focused: the wavelength calibration curve is determined through a polynomial fitting. (b) The reference signals for each band are taken by focusing the radiation thermometer on a blackbody at a fixed temperature (the freezing point of copper). The responsivity of each detector element is determined by weighing its output signal with Planck's function at the reference temperature. This quantity and the number of pixels contained in a partial band define the pyrometer wavelength function.

6. OPERATION

To measure the spectral temperature at each band the ratio of the signals at the unknown and at the reference temperature is processed by a computer program, which contains the pyrometer wavelength function for each band. Thus the present instrument behaves like a battery of monochromatic pyrometers. Any one of the proposed algorithms for monochromatic or multiwavelength pyrometry can be implemented by a simple software choice.

7. CONCLUSIONS

The advantages of this instrument are the following: (i) great versatility achieved by software operation; (ii) high throughput, which is limited only by the ratio of the array width to the diameter of the field stop image (as opposed to the conventional type of instruments, where the throughput is governed by the filling factor and the splitting ratio into a number of branches of the fiber bundle, plus the filter transmittance); (iii) stability of the system transmittance as compared to one of the fibers and the filters; and (iv) great simplicity in construction.

This system shares the common difficulty of all multiwavelength pyrometers, namely, the achromatization of all lenses over a wide band. Therefore lenses must be specially designed, a step which is not commonly taken into consideration by pyrometer designers.

The present pyrometer may have several applications. (i) It can measure temperature in a multiwavelength procedure with any of the proposed algorithms, so that they can be compared and critically evaluated. Its speed in this application depends on the scanning and conversion times: according to common array and associated circuit specifications, a frequency of 100 readings per second can be anticipated. (ii) It can be used as a single-band pyrometer at any effective wavelength. (iii) It can transfer the calibration of a strip lamp, currently given at 650 nm, to any other wavelength, within its overall bandwidth, and therefore it can act as a transfer standard between two wavelengths. (iv) By measuring the temperature in a small hole, acting as a blackbody, drilled in a sample, and the radiance temperature on the surface around the hole, this instrument can give the spectral normal emissivity of the sample at a number of wavelengths within its total bandwidth. This instrument is under construction.

REFERENCES

1. J.-F. Babelot, J. Magill, and R. W. Ohse, in *Temp. Its Measure. Contr. Sci. Ind., Vol. 5, Part 1*, J. F. Schooley, ed. (Am. Inst. Phys., New York, 1982), pp. 439–446.
2. A. Cezairliyan, in *Proc. 2nd Asian Thermophys. Prop. Conf.*, N. Seki and B. X. Wang, eds. (1989), pp. 1–7.
3. J.-P. Hiernaut, R. Beukers, W. Heinz, R. Selfslag, M. Hoch, and R. W. Ohse, *High Temp. High Press* **18**:617 (1986).
4. T. Makino, T. Kosaka, J. Arima, S. Aoyama, and H. Tsujimura, *Soc. Contr. Inform. Eng. (Japan)* **4**:331 (1988).