Portable infrared spectral radiance measurement apparatus based on PbSe detectors

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A portable infrared spectral radiance measurement apparatus without the cooling based on PbSe detectors is designed to measure the spectral radiance of the object in the wavelength range from 2.1 to 4.1 μm. Cores Luxell 256 module is applied which integrates 256 pixel line array PbSe detectors, amplifiers, analog-to-digital convertors, and Universal Serial Bus output interface. Electric aperture is applied to eliminate the effect of temperature drift. Wavelength and response function of the apparatus is calibrated with the blackbody. Results show that the wavelength resolution is 10 nm. The relative error of measured spectral radiance is below 2.3%.

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The spectral radiance is an important parameter in the thermal radiative property of a material. It plays an important role in the emissivity and temperature measurements made by a pyrometer, in the analysis of the radiative heat transfer between several objects, in an infrared missile, and so on[1–3].

The first spectrometers with complete structure have been developed by Kirchhoff and Bunsen in 1859. Spectral radiance measurement apparatus is very important to measure the spectral radiance of materials and analyze material composition in the fields of aerospace, remote sensing, materials, and the military[4,5]. The Fourier-transform infrared (FTIR) spectrometer is a powerful instrument for measuring spectral radiance with a high wavelength resolution[6–8]. Many research works on measuring spectral emissivity of materials were based on FTIR in recent years[9,10]. But traditional FTIR is importable and used mainly in laboratory. Attenuated total reflectance (ATR) FTIR spectroscopy is a rapid, portable, and dynamic spectroscopic technique using deuterated tri glycine sulfate detectors with the wavelength range 2–20 μm. ATR–FTIR must be accessorized with ATR crystal which is produced with ZnSe or germanium. When measuring the liquid, the ATR accessory with the liquid pool is needed. When measuring the solid, the solid must be smooth in order to have a direct contact with the ATR crystal. So ATR–FTIR is not suitable for a rough solid or a gas[11]. There are several microspectrometers based on different principles, such as fiber spectrometers[12,13] and grating spectrometers[14–17]. Fiber spectrometers have a narrow waveband and energy loss for the long fiber. Grating spectrometers with mercury cadmium telluride (MCT) detectors must be cooled in liquid nitrogen and are nonportable. Grating spectrometers with CCD detectors is used in the wavelength no longer than 1.6 μm. With the development of microoptical electro-mechanical system (MOEMS), the micromation and integration is the main direction for spectrometers. And spectrometers are needed with fast response speed, small size, and small weight.

In this work, a portable spectral measurement apparatus is designed to measure the spectral radiance of object in the wavelength range 2.1–4.1 μm.

Figure 1 presents the diagram of spectral radiance measurement apparatus, which includes several components: a slit used to block the light, a long-pass optical filter to ensure the light with the wavelength longer than 2.1 μm, an electric aperture to control whether the light passes or not, a parabolic collimation mirror to collimate the light to parallel light on the grating, a grating to separate the light into monochromatic light, a parabolic focus mirror to focus the light on the detectors, PbSe detectors arrays to receive the infrared light and convert it to electrical signal, amplifiers to amplify electrical signal and process the signal and convert analog signal into digital signal, power supply to provide the supply the whole system, and microcomputer PC104 with a 10 inch LED display to run the software and control the whole system. Controlling software in PC104 is designed by Labview to control the state of the system, process, and display, and save the measured data.

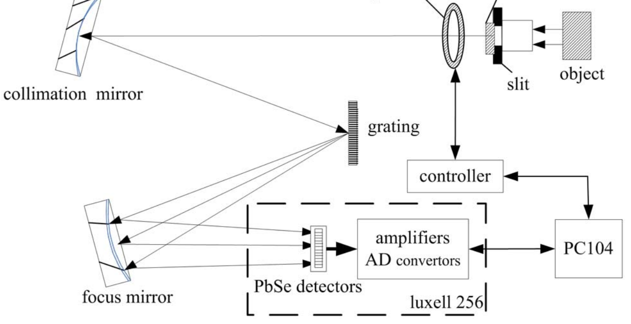


Fig. 1. Diagram of spectral radiance measurement apparatus.

Spectral measurement apparatus proposed is improved as described next. MCT detectors with the wavelength range 2–20 μm must work in the condition of cooling by liquid nitrogen which cannot be provided in most occasions. PbSe detectors have a high response in the wavelength 1–5 μm and work at room temperature. So in the wavelength range from 2.1 to 4.1 μm, PbSe detectors but not MCT detectors are chosen. In order to minimize the size and weight of the apparatus and improve the application condition, Cores Luxell 256 module made by New Infrared Technologies Company in Spain is introduced to detect light signal and process the signal, which integrates 256 pixel line array PbSe detectors, amplifiers, analog-to-digital (AD) convertors, and Universal Serial Bus (USB) output interface.

PbSe detectors working under room temperature have a temperature drift, which affect its output. Electric aperture is applied to eliminate the effect of temperature drift and is normally closed. In every measurement period, the zero point is corrected first. Then electric aperture is opened. The light from the object is detected and converted by Luxell 256. The output of Luxell 256 is acquired with USB interface, displayed in the screen, and stored in the personal computer (PC) disk. Then electric aperture is closed. This measurement period ends.

Measurement principle is described next. According to Planck's law, spectral radiance of a blackbody was calculated by the blackbody temperature[18–20]

$$L_{\lambda,b}(\lambda, T) = \frac{M_{\lambda,b}(\lambda, T)}{\pi} = \frac{\mathrm{c}_1}{\lambda^5[\exp(\mathrm{c}_2/\lambda T) - 1]}, \tag{1}$$

where $L_{\lambda,b}(\lambda, T)$ is the spectral radiance of the blackbody depending on the wavelength λ and the surface temperature T. Terms c_1 and c_2 are the first radiation constant and the second radiation constant, respectively.

The detector output proportional to the radiation of the sample or blackbody is given by

$$\begin{aligned} V_{\lambda,b}(\lambda, T) &= \tau R_d(\lambda) \cdot (L_{\lambda,b}(\lambda, T) + L_0(\lambda)) \\ &= \tau R_d(\lambda) \cdot L_{\lambda,b}(\lambda, T) + V_0(\lambda), \end{aligned} \tag{2}$$

where $V_{\lambda,b}(\lambda, T)$ is the voltage measured by Luxell 256, $R_d(\lambda)$ is the response function of the Luxell 256, and τ is the product of the filter transmittance and the mirror reflection losses. $L_0(\lambda)$ and $V_0(\lambda)$ are the spectral radiance and the voltage of the background, respectively.

The output of the apparatus $V_t(\lambda, T)$ is

$$V_t(\lambda, T) = R_t(\lambda) \cdot L_\lambda(\lambda, T) + b_t(\lambda), \tag{3}$$

where $R_t(\lambda)$ is the response function of the spectral radiance measurement apparatus, which is related to the detector response, the filter transmittance, and the mirror reflection losses. Term $b_t(\lambda)$ is the system compensation depending on the temperature of environment and the noise of the circuit without the out radiation. With different spectral response under different wavelength, $R_t(\lambda)$ and $b_t(\lambda)$ need to be calibrated using the blackbody.

In our work, the wavelength and the response function of the apparatus are calibrated.

The monochromator and the halogen lamp are used to calibrate the wavelength of the apparatus. The monochromator separates the light from halogen lamp into a desired monochromatic light, which enters the apparatus. By changing the monochromator wavelength from 2.1 to 4.1 μm, the peak output of the apparatus is detected. Meanwhile, the peak wavelength and corresponding pixels are recorded in Table 1. After calibration, the first valid pixel is 31, and the last one is 230. The pixels from 1 to 30 and from 231 to 256 are useless.

The wavelength resolution is 10 nm

$$\Delta\lambda = (4.102 - 2.101)/200 = 10. \tag{4}$$

Quadratic polynomial is used to calibration the relationship between the wavelength λ and the pixel x as

$$\lambda = \mathrm{a} + \mathrm{b}x + \mathrm{c}x^2. \tag{5}$$

After fitting, the relationship is obtained as Fig. 2, and described as

$$\lambda = 1.756 + 0.011x - 4.06 \times 10^{-6}x^2. \tag{6}$$

We use the standard blackbody to calibrate the response function of the apparatus. The blackbody furnace with the diameter 80 mm is separately heated to the temperatures of 473 and 1073 K and set about 100 mm in front

Table 1. Peak Wavelengths and Corresponding Pixels

Peak wavelength (μm)	Pixel
2.101	31
2.625	81
3.149	131
3.644	181
4.102	230

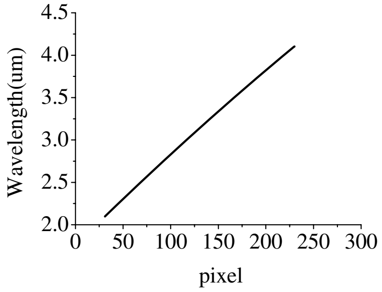
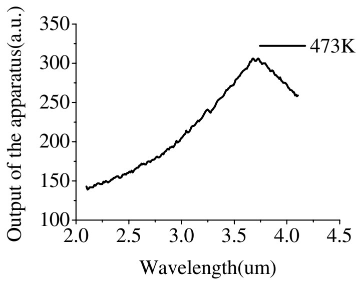
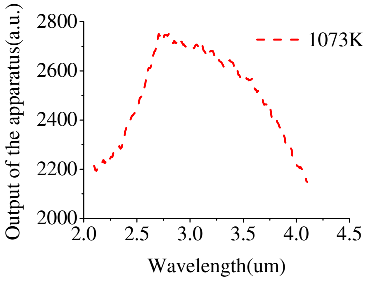


Fig. 2. Relationship between the wavelength and the pixel.



(a) At 473K



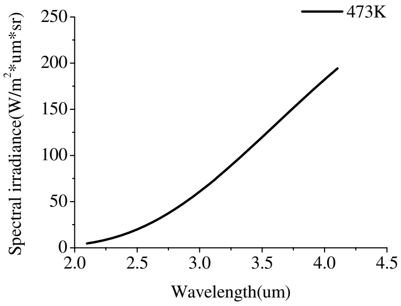
(b) At 1073K

Fig. 3. Output of the apparatus at 473 and 1073 K.

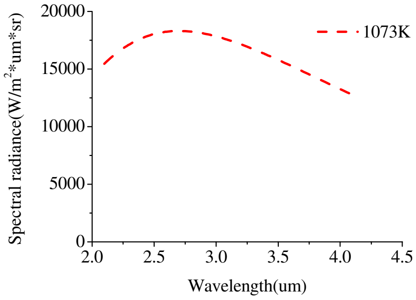
of the apparatus. The output of the apparatus $V_t(\lambda, T)$ is measured as Fig. 3. The calculated theoretic spectral radiance by Planck's law at the temperature of 473 and 1073 K are shown as Fig. 4.

$$R_t(\lambda) = \frac{V_t(\lambda, 1073) - V_t(\lambda, 473)}{L_{\lambda,b}(\lambda, 1073) - L_{\lambda,b}(\lambda, 473)}. \tag{7}$$

Calibrated response function of the apparatus is shown in Fig. 5.



(a) At 473K



(b) At 1073K

Fig. 4. Spectral radiance of the blackbody at 473 and 1073 K.

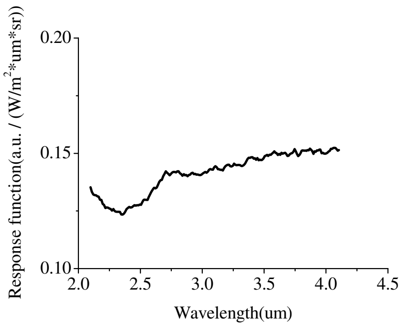


Fig. 5. Response function of the apparatus.

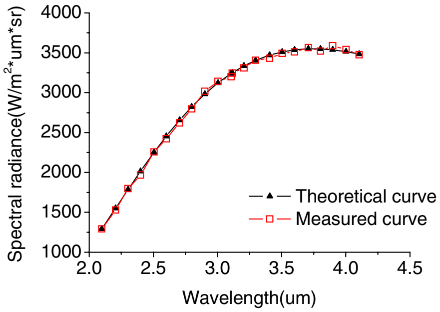


Fig. 6. Measured spectral radiance and theoretical spectral radiance for the blackbody at 773 K.

In order to verify the apparatus, we detect the blackbody at the temperature 973 K. Measured spectral radiance and theoretical spectral radiance are shown in Fig. 6. The maximum relative error between the measured and theoretical spectral radiance is calculated as 2.3%.

In conclusion, a portable spectral radiance measurement apparatus based on Cores Luxell 256 is designed to measure the spectral radiance of the object in the wavelength range from 2.1 to 4.1 μm. This apparatus operates without cooling. Electric aperture is applied to eliminate the effect of temperature drift. The wavelength resolution is 10 nm. Response function of the apparatus is calibrated with the blackbody at 473 and 1073 K. The relative error between the measured and theoretical spectral radiance for the blackbody at 773 K is 2.3%. For its integration, the total weight of the apparatus is less than 6 kg, and the size is 450 mm × 350 mm × 350 mm. This apparatus with the advantages of fast response speed, small size, and less weight could be convenient and helpful to measure spectral radiance of object.

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