J. Light & Vis. Env. Vol.19, No.2, 1995

Development of a Photometer Having Variable Spectral Responsivity

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Received June 21, 1995.

ABSTRACT

A photometer having variable spectral responsivity has been developed. The equipment is composed of a linear variable interference filter (LVIF), a MOS linear image sensor (CCD), driver/amplifier circuits, a 12-bits A/D converter and a note-type personal computer. The intrinsic relative spectral responsivity has been calibrated throughout the wavelength range from 400 to 700 nm by using the distribution temperature standard lamps. Then, it is possible to change its effective spectral responsivity as desired by weighting the output of each CCD element. In this study, the performance of the equipment as an illuminance meter, a simple spectroradiometer and a colorimeter has been evaluated by setting the relative spectral responsivity of the equipment to the spectral luminous efficiency, to a constant and to the matching functions, respectively. As a result, it is shown that the equipment has similar performance to a precise class of illuminance meter on the market. It is confirmed that the performance of the equipment almost meets the requirement for its use as a simple spectroradiometer and a colorimeter. Consequently, it is expected that this equipment can function as a mesopic photometer whose spectral responsivity varies with brightness.

1. Introduction

It is known that the spectral responsivity of a human visual system varies with brightness level. It is quantified that the spectral responsivity of human vision in bright surroundings is a function of spectral luminous efficiency for photopic vision and in dark surroundings is a function of spectral luminous efficiency for scotopic vision.

Vision between photopic and scotopic visions is called mesopic vision. In mesopic vision, the spectral responsivity of human vision varies with brightness. With the increase of human nighttime activity, the desirability of estimation of the visual environment in mesopic vision and the importance of photometric technique were recognized. Therefore, studies on evaluating brightness in mesopic vision were carried out extensively, various measuring systems were proposed[1-3], and trial measuring equipment based on the preceding system was manufactured[4], but such equipment was very expensive and cumbersome.

A photometer with variable spectral responsivity which was composed of an LVIF and a Si photodiode array (SPDA) with 38 elements was previously reported[5]. The photometer can be applied to equipment which estimates the visual environment in mesopic vision. However, such equipment had the following drawbacks. The length of the LVIF is longer than that of the SPDA, so moving the SPDA is time-consuming and it is difficult to achieve irradiance distribution uniformity at the surface of the LVIF. The resolving power of wave number is poor because the SPDA has only 38 elements. In this paper, the outline of the trial photometer and the operating principle are described, and the equipment is evaluated as follows.

1. (1) Measure the intrinsic relative spectral responsivity of the equipment by using the distribution temperature standard lamps.
2. (2) Evaluate the performance of the equipment as an illuminance meter (including the measurement of the detectivity).
3. (3) Evaluate the performance of the equipment as a simple spectroradiometer.
4. (4) Evaluate the performance of the equipment as a colorimeter.

This equipment has the features of compactness, high chromatic light intensity and superior angular response, compared with the conventional polychrometor. The resolving power of wave number is higher than that of the polychrometor with the SPDA.

2. Outline of the equipment

The schematic diagram of the photometer is shown in Fig.1. The equipment consists of a detector head, a control & power supply block and a data processing & display block.

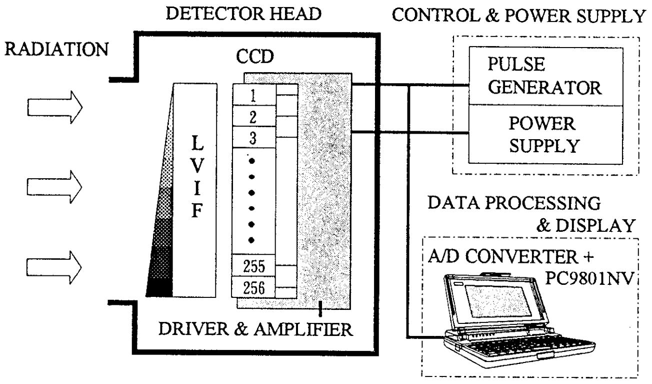
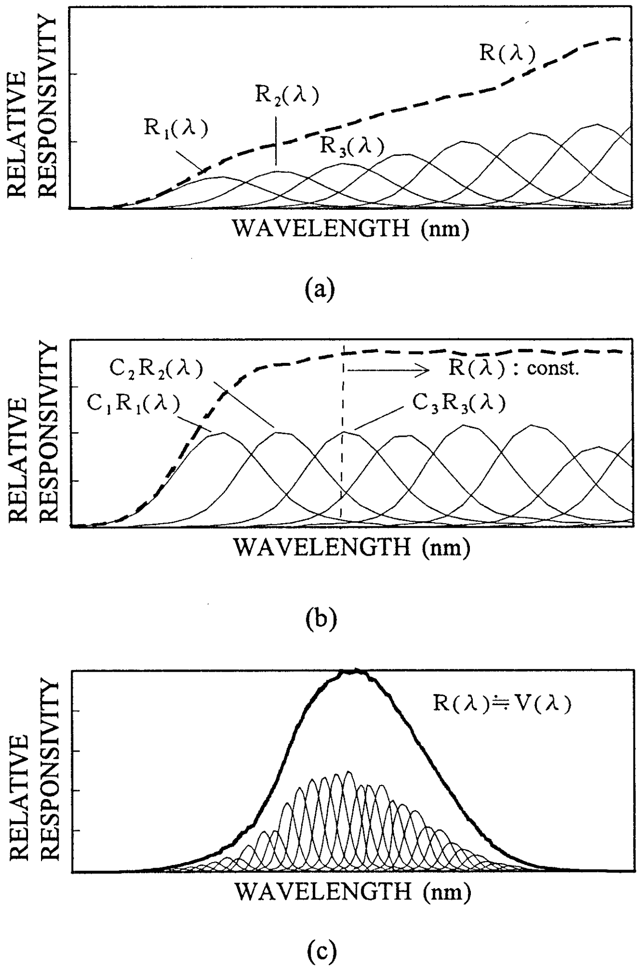


Fig.1 Schematic diagram of the photometer.

The detector head is composed of an LVIF (OCLI Inc., 10×5×2 mm, transmission wavelength 400 to 700 nm, with IR cut filter), a CCD (Hamamatsu Photonics, S3901-256Q, 256 elements, 2.5×0.05 mm/element, response wavelength 200 to 1000 nm), and driver/amplifier circuits for the CCD (Hamamatsu Photonics, C4070). The detector is of a small size of about 12.5×7.5 mm. The control & power supply block consists of a control pulse generator (+5 V, 5 to 200 μsec single pulse) and a clock pulse generator (+5 V, 10 to 375 kHz) to start the driver & amplifier circuits, and power supplies for each part. The data processing & display block consists of a note-type personal computer (NEC, 9801NV) and an A/D converter board (ADC, CANOPUS, ADXM-98S, 12 bits, conversion time 3.6 μsec). The temperature dependences of the spectral transmittance and the spectral dispersion of the LVIF were extremely small, so the change of the spectral responsivity of the equipment owing to the temperature dependence was ignored here.

The equipment operates on the following principle. As shown in Fig.1, the incident radiation passes through the IR cut filter, is then dispersed with the LVIF and is incident on the CCD. An electric charge corresponding to the incident radiant flux is integrated in each element of the CCD. The integrated charges are sequentially converted into voltages in the driver & amplifier circuits. The voltage is proportional to the product of (incident radiant flux) and (duration of open gate). Output from the CCD is input to the personal computer via the ADC. The personal computer stores the input data. When the spectral responsivity of the optical detector has been measured in advance, the personal computer outputs the spectral distribution and the irradiance of incident radiation on the display. For initial positioning of the CCD, a He-Ne laser beam of 632.8 nm is used. The beam is made uniform over a wide range by the diffuser and the lenses, and irradiates the detector head. The arrangement of the LVIF and the CCD is determined by evaluating the output profile from the CCD.



(a)

(b)

(c)

Fig.2 Relative spectral responsivity of the photometer. (a) intrinsic, (b) flat, (c) $V(\lambda)$

The procedure for setting the relative spectral responsivity of the equipment is explained below. Each detector element comprising the LVIF and the CCD shows relative spectral responsivity $R_n(\lambda)$. When all the elements are summed, a total relative spectral responsivity $R(\lambda)$ ($=\Sigma R_n(\lambda)$) can be obtained (Fig.2(a)). The total relative spectral responsivity, which is the intrinsic relative spectral responsivity of the detector head, can be measured using the distribution temperature standard lamps$^{5)}$. Calculating the inverse of $R(\lambda)$, which is $C(\lambda)$, the coefficient Cn corresponding to the center wavelength of each detector element is determined. On multiplying $R_n(\lambda)$ by C_n, the effective relative spectral responsivity becomes almost constant (Fig.2(b)). For example, when the equipment is used as an illuminance meter, on multiplying the value of $C_nR_n(\lambda)$ by the spectral luminous efficiency $V(\lambda)$, the final effective relative spectral responsivity of the equipment becomes $V(\lambda)$ (Fig.2(c)). As a result, the relative responsivity of this equipment can be set as desired. Finally for calibrating the absolute value, the coefficient C is determined using the standard lamp. Practically weighting is managed by the personal computer.

3. Results

3.1 Calibration of the relative spectral responsivity of the equipment

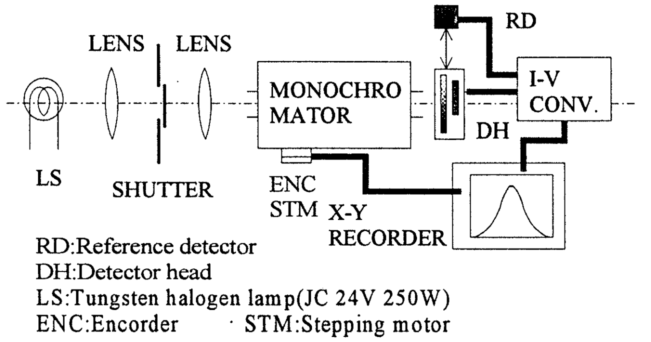


Fig.3 Experimental setup for measuring the spectral dispersion of the LVIF and the half-bandwidth of the detector element.

Fig.3 shows the experimental setup for measuring the spectral dispersion of the LVIF and the half-bandwidth of the detector element. A standard detector is a Si photodiode (SPD, Hamamatsu Photonics, S1337-1010BQ), whose relative spectral responsivity is calibrated in advance. Fig.4 shows the results of the spectral dispersion of the LVIF and the spectral characteristics of the half-bandwidth of the detector element. The spectral dispersion of the LVIF was almost constant and its average value was about 28.3 nm/mm. The half-bandwidth, which increases with wavelength, was 7.3 nm at 400 nm and 13.7 nm at 700 nm, and about 2 % of the wavelength.

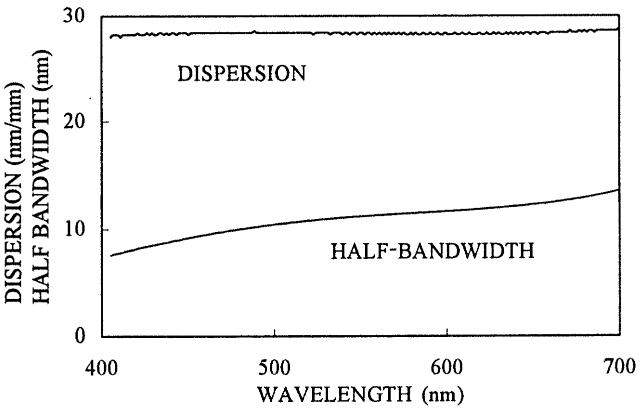


Fig.4 Spectral dipersion of the LVIF and spectral characteristics of the half-bandwidth of the detector element.

The relative spectral responsivity of the detector head was measured by assuming the standard lamp to be a black body. It has already been reported that the relative spectral responsivity can be measured using a standard lamp whose distribution temperature is known[5]. When the relative spectral irradiance on the detector element n is $P_r(\lambda_n)$ and the detector response is $I(\lambda_n)$, the relative responsivity $R'(\lambda_n)$ of the detector head is given by

$$R'(\lambda_n) = I(\lambda_n) / P_r(\lambda_n)\,, \qquad (1)$$

where λ_n is the center wavelength of the detector element n.

The intrinsic relative spectral responsivity was calculated using three lamps which were calibrated at distribution temperatures of 2450, 2856 and 3265 K. The result is shown in Fig.5. The relative spectral responsivities at three distribution temperatures were nearly equal within 1 %.

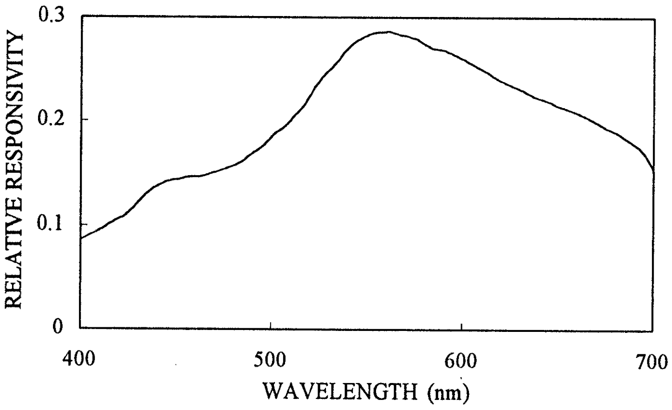


Fig.5 Intrinsic relative spectral responsivity property of the detector head measured by three distribution temperature standard lamps.

3.2 Evaluation of the performance as an illuminance meter

The equipment can be used as an illuminance meter by approximating the relative spectral responsivity to the spectral efficiency $V(\lambda)$. Output from the CCD is proportional to the product of the incident radiant flux and the duration of open gate. The frequencies of a master clock pulse generator were 5, 10, 100, 200 and 375 kHz, which corresponded to the duration of open gate 200, 100, 10, 5 and 2.7 µsec, respectively. Changing of the frequency widened the dynamic range of the equipment. Illuminance was calibrated at each frequency using a precise class of illuminance meter available on the market (Minolta, T1-M). The differences between the values of illuminance measured at each frequency were within 1%. The equipment was evaluated as an illuminance meter using a luminous intensity standard lamp (2856 K, 672 cd), based on JIS (JIS C1609-1993). The accuracy was better than 2 %, which shows that the equipment belongs to the precise class. The detectivity at an S/N ratio of 10 was about 0.03 lx. It took about 0.2 seconds for one measurement of illuminance.

The responses of the equipment in UV and IR regions were measured using a mercury and an incandescent lamp. The response in each region was found to be less than 1 % in both cases.

The angular response was measured. As a result, the deviation from the cosine law was determined to be less than 1 % within 15 degrees and larger than 18 % for over 20 degrees. The result shows that the angle of incidence should be restricted to within 15 degrees. The equipment did not exhibit satisfactory performance as an illuminance meter in terms of the angular response. The shape of the detector head makes the angular response poor, so the detector head will be reshaped.

3.3 Evaluation of the performance as a simple spectroradiometer

On multiplying the relative spectral responsivity of each element by its inverse, the relative spectral responsivity becomes almost constant, as shown in Fig.2(b). The output of the equipment matches the spectral power distribution of incident radiation. Hence the equipment can be used as a simple spectroradiometer. Then, the equipment was used to measure three kinds of lamps for comparison with a monochromator (NIKON, G250, slit bandwidth 5 nm). The light sources were a three band radiation type of fluorescent lamp FL10EX-N (10 W, 0.23 A), a metal halide lamp MF100L (100 W, 1.35 A) and a high pressure sodium lamp HICA150FG (150 W, 2.0 A). Fig.6 shows the result for the three band radiation type fluorescent lamp. The error for the center wavelength of the line spectrum was less than 8 nm. Since the half-bandwidth of the equipment is wider than that of the monochromator, the profile of the line spectrum is broad.

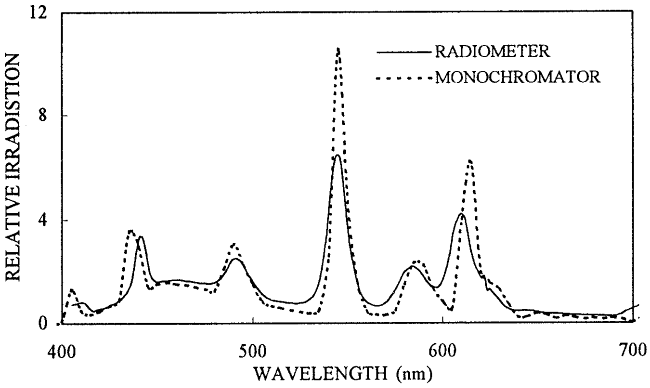


Fig. 6 Relative spectral distribution of a three band radiation type lamp.

3.4 Evaluation of the performance as a colorimeter

The equipment can be used as a colorimeter by approximating the relative spectral responsivity to the color matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$. The equipment was used to measure the three lamps used in 3.3 for comparison with a monochromator. UCS (uniform chromaticity scale) chromaticity coordinates, correlated color temperatures and deviation from the Planckian locus were used as indices to evaluate color. The comparison of the measurements using the equipment and a monochromator for the three lamps is shown in Table 1. The error of the correlated color temperature was 242 K and the error of the reciprocal correlated color temperature was 9 MK^{-1} for the metal halide lamp. The correlated color temperatures measured using the equipment were higher than that measured using the monochromator. Thus when the correction factor is applied, the error may be reduced.

Table 1 Performance of the equipment used as a colorimeter on three kinds of lamps, comparing with the monochromator.

	TBR fluorescent lamp*		Metal halide lamp		High pressure sodium lamp	
	Colorimeter	Monochromator	Colorimeter	Monochromator	Colorimeter	Monochromator
Chromaticity coordinate u	0.201	0.207	0.191	0.202	0.263	0.266
Chromaticity coordinate v	0.324	0.322	0.333	0.327	0.354	0.353
Correlated color temperature (K)	5471	5313	5514	5272	2672	2613
Reciprocal correlated color temperature (MK^{-1})	183	188	181	190	374	383
Deviation from Planckian locus	-0.008	-0.003	-0.009	-0.005	-0.002	-0.004
Error of correlated color temperature (K)	158		242		59	
Error of reciprocal correlated color temperature (MK^{-1})	5		9		9	

*TBR fluorescent lamp: Three band radiation type fluorescent lamp

4. Discussion

To operate the equipment as a mesopic vision photometer, its spectral responsivity must be variable according to brightness and the detectivity must be higher than 0.01 lx. The detectivity of the equipment is 0.03 lx. Fig.7 shows the relationship between the detectivity and the master clock frequency. Detectivity higher than 0.01 lx is attained when the master clock frequency is 2 kHz. Therefore, the master clock frequency must be made lower than 2 kHz. It is confirmed that the equipment exhibits satisfactory performance as a colorimeter. The mesopic photometric system evaluated from tristimulus values and a scotopic luminance has been proposed⁶⁾. In this study, it is assumed that the equipment can function as a mesopic vision photometer because it is possible to use the equipment as an illuminance meter and a colorimeter at the same time.

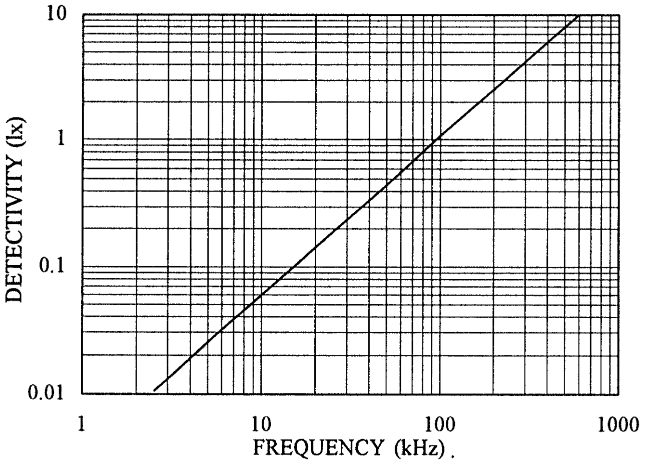


Fig.7 Dependence of the detectivity of the equipment on the master clock frequency.

The length of both the LVIF and the CCD were about 10 μm, so the irradiance distribution uniformity at the surface of the LVIF was sufficient to evaluate the performance of the equipment. The width of the detector element was 50 μm and so we expected a half-bandwidth as small as the spectral dispersion. However the half-bandwidths were about 2 % of the wavelength and they did not match the spectral dispersion. The resolving power of wave number was improved by changing the detectors from the SPDA with 38 elements to the CCD with 256 elements.

Since the equipment can retain several relative spectral responsivity values in its memory, it can be applied to the estimation of the action effects on living organisms and plants. When the action effects curves on several species of plants are known in advance, the action effects on each plant can be evaluated at the same time by a single measurement. The equipment has a compact design, which makes it easy to handle and portable. In the future, the equipment will be used to obtain the data of the action effects curves.

5. Conclusion

A photometer having variable spectral responsivity has been developed. The equipment has a detector head consisting of an LVIF and a CCD, whose relative spectral responsivity can be controlled by a personal computer. In this study, improvements to the previously reported equipment⁵⁾ and evaluations of the performances have been described. A compact LVIF and a CCD were used at the detector head. Duration of open gate of a CCD could be variable. An A/D converter board, whose conversion time was faster than the previously reported one, was adopted. Software for measurement was also revised.

The intrinsic relative spectral responsivity of this equipment was measured throughout the wavelength range from 400 to 700 nm using the distribution temperature standard lamps. The performances of the equipment as a spectroradiometer were evaluated. The relative spectral responsivity was set to the spectral luminous efficiency $V(\lambda)$ and the equipment was evaluated as an illuminance meter. The relative spectral responsivity was set to the color matching functions and the equipment was also evaluated as a colorimeter.

In conclusion, it is assumed that the equipment can function as a mesopic vision photometer whose spectral responsivity varies with brightness, because it is possible to use the equipment as an illuminance meter in the scotopic vision and a colorimeter at the same time.

6. Acknowledgment

The authors would like to thank Daisuke HIKI (ex-, Saitama University) for his technical contribution and encouragement. This work was supported by The Research & Education Grant-in-Aid of IEI-J.

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