Technical Notes

RGB Laser Meter TM6102, RGB Laser Luminance Meter TM6103, Optical Power Meter TM6104

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Abstract—The TM6102, TM6103, and TM6104 accurately measure the optical characteristics of laser displays (characteristics such as centroid wavelength, radiometric quantities, chromaticity, and photometric quantities). In addition, they provide functionality for reducing production hours by aiding in the adjustment of white balance. This paper describes these products' features, architecture, and characteristics.

I. Introduction

In recent years, light sources for displays have been transitioning to lasers, which offer a variety of advantages as next-generation light sources. Novel applications are also emerging to take advantage of the features of this new technology, for example high luminance and compact size. Accurate evaluation methods will play an important role in facilitating the smooth growth of the market for laser displays, which offer numerous advantages for users.

Broadly speaking, there are two approaches to measuring light source color: spectrophotometric colorimetry and photoelectric tristimulus colorimetry (under JIS standards [1]). The former technique, which is characterized by high instrument costs, tends to be utilized when accuracy is the top priority, for example in research and design applications. By contrast, the latter has entered into widespread use for reasons that include its simplicity and the low cost of the instruments needed to perform it. However, photoelectric tristimulus colorimetry provides inadequate measurement accuracy due to the difficulty of using photometric colorimetry with lasers, a challenge that stems from their uniquely narrow-band spectrum.

Hioki sought to address these challenges by developing the Discrete Centroid Wavelength Method, a new photometric colorimetry technique that is well suited for measuring laser displays, and introducing the TM6102, TM6103, and TM6104 as instruments that utilize the new method.

II. Overview

A number of concerns have emerged with regard to the mass production of laser displays:

Appearance of the TM6102, TM6103, and TM6104.

- High-accuracy spectrophotometric instruments are used to design laser displays during the product development stage. However, less expensive photoelectric tristimulus colorimetry instruments are used on production lines, with the result that measurement results obtained using the photoelectric tristimulus colorimetry method do not agree with design values due to the technique's insufficient accuracy.
- Experienced technicians have been required to expend an enormous amount of time on adjusting the white balance of displays in a process that relies excessively on experience and instinct.

In light of these challenges, Hioki chose "High Accuracy and One-touch Adjustment" as the design concept for these instruments. In addition, the company has brought to market three products with different input optics to accommodate the requirements of a variety of production processes and made communications commands available so that users can control the products with a high degree of freedom.

III. Features

A. High Accuracy

The photoelectric tristimulus colorimetry method uses three sensors that correspond to the human eye to directly measure the tristimulus values X, Y, and Z, on the basis of which it then calculates chromaticity and photometric quantities. Although the sensors' spectral sensitivity characteristics approximate the color-matching function, it is not possible to match the function completely due to factors including an insufficient selection of optical filters and variability among production lots. Fig. 1 provides a schematic illustration of a light source spectrum and associated color-matching function approximation error. Past display designs have been characterized by a broad spectrum, balancing out the effects of approximation error and decreasing measurement error. However, approximation error results in a large measurement error when the spectrum is narrow, as with lasers, and reports indicate that instrument performance is failing to satisfy user requirements [2][3][4]. Consequently, numerous users have encountered difficulty due to the failure of measurement results obtained from the photoelectric tristimulus instruments used on production lines to align with data from the high-accuracy spectrophotometric instruments used to design displays during the product development stage.

Hioki addressed this issue by developing the Discrete Centroid Wavelength Method, which separates RGB lasers into red, green and blue colors; measures the centroid wavelength and radiometric quantities of each; and then calculates chromaticity and photometric quantities based on the color-matching function. Since this method does not in principle suffer from color-matching function approximation error, it is capable of high-accuracy measurement [2][3][4].

B. Centroid Wavelength: Essential for High-accuracy Chromaticity Measurement

The emission spectrum of semiconductor lasers is distorted, as is illustrated in Fig. 2. The wavelength with the highest optical power (the peak wavelength) is typically used as the representative wavelength value.

Color and brightness indicators play an important role in determining the performance of laser displays. To measure these quantities precisely requires the sum of products of an emission spectrum that has been measured using an optical spectrum analyzer with high wavelength resolution and a color-matching function. However, due to the narrow spectrum of semiconductor lasers, the quantities can also be calculated from a color-matching function, which is determined by the representative wavelength, and optical power.

When the peak wavelength is used as the representative wavelength, unintended chromaticity values and photometric quantities may result. Unanticipated chromaticity values and photometric quantities are likely to be obtained when calculating them by applying the color-matching functions near the peak wavelength of 518 nm despite optical power values that are distributed near 516 nm, as shown in Fig. 2.

By contrast, the centroid wavelength as defined in Fig. 2 is the average wavelength taking into account the emission spectrum's optical power density distribution. Here $P(\lambda)$ indicates the laser's optical power distribution, while λ indicates the wavelength. Consequently, it is apparent that use of the centroid wavelength makes it possible to accurately calculate chromaticity and photometric quantities. By using this centroid wavelength, the TM6102, TM6103, and TM6104 are able to accurately measure chromaticity and photometric quantities.

Fig. 3 illustrates the results of a chromaticity accuracy simulation. This simulation supports the conclusion that peak wavelength results in large variability in measurement

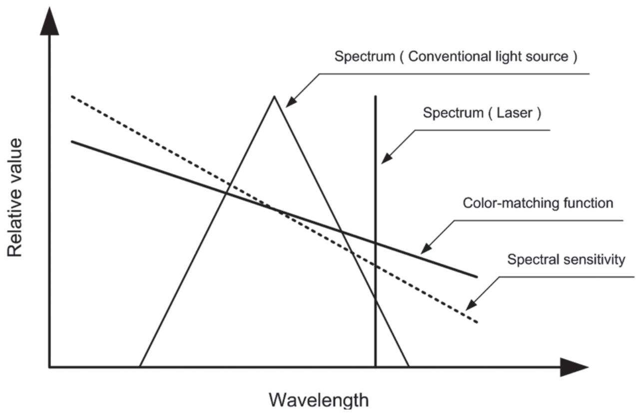

Fig. 1. Color-matching function approximation error and light source spectrum.

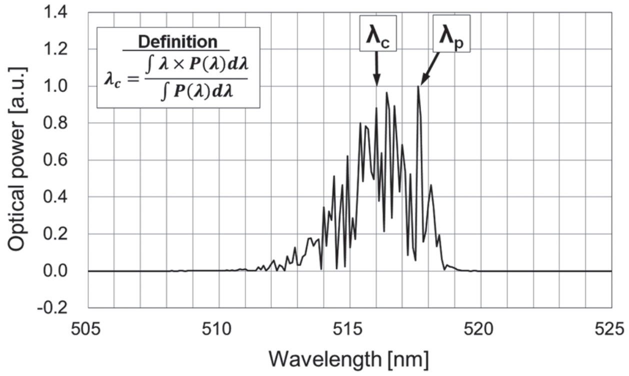

Fig. 2. Example of a semiconductor laser's emission spectrum.

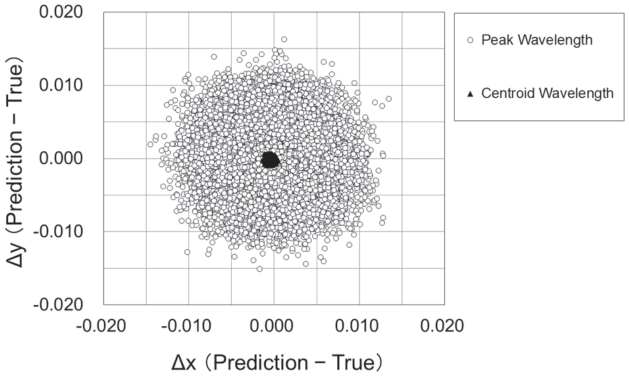

Fig. 3. Simulation forecasting chromaticity accuracy.

error, while use of centroid wavelength results in less measurement error.

1) Verification-use light source: The following range of wavelength values were used as the wavelengths for the verification-use RGB lasers based on their anticipated use in laser displays:

Red: 615 nm to 666 nm

Green: 505 nm to 550 nm

Blue: 435 nm to 477 nm

Spectrum widths ranged from 1 nm to 5 nm, and the spectrums exhibited random shape profiles that lacked horizontal symmetry. The characteristics of the red, green, and blue lasers noted above were selected randomly, and the mixed light that resulted when they were combined was subjected to radiometric quantity balancing to yield the chromaticity of the CIE standard light source D65.

2) Verification method: Peak wavelength, centroid wavelength, and radiometric quantities were calculated from the verification-use light source's emission spectrum, and chromaticity was predicted based on calculations from the color-matching function.

Theoretical chromaticity values were calculated based on the verification-use light source's emissions spectrum and the color-matching function. Based on those values, the error between the predicted chromaticity calculated based on the peak wavelength and the predicted chromaticity calculated based on the centroid wavelength was calculated.

C. Traceability

Conventional photometry and colorimetry instruments (illuminometers, color-illuminometers, luminance meters, chromameters, spectral radiance meters, etc.) are calibrated using standard lamps. However, various error factors are introduced because the lasers that are used as the actual measured light sources generate a spectral shape that differs significantly from that of the standard lamp (Fig. 4). In addition, caution is necessary because although the accuracy of conventional photometry and colorimetry instruments is defined using a standard lamp, they exhibit a large degree of error relative to lasers [2][3][4].

Hioki addressed these challenges by building an on-site single-color irradiance calibration facility using lasers with technical support from the National Institute of Advanced Industrial Science and Technology [5]. In this way, the company is able to provide highly reliable measurement that can be traced to national standards for lasers.

D. White Balance Navigation Function

This section describes assistive functionality provided by the TM6102, TM6103, and TM6104 to simplify the white balance adjustment process for laser displays. Fig. 5 illustrates the process by which the function is used.

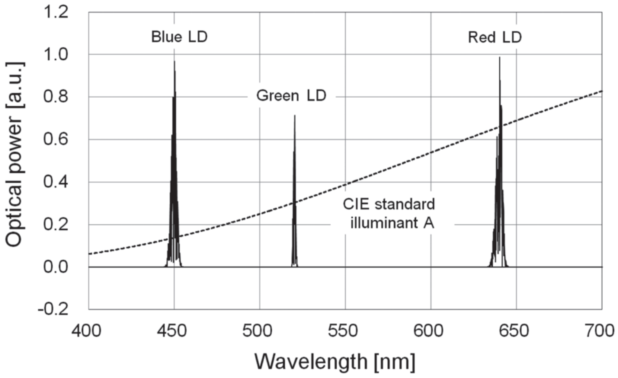

Fig. 4. Calibration light source and measurement target emission spectrums.

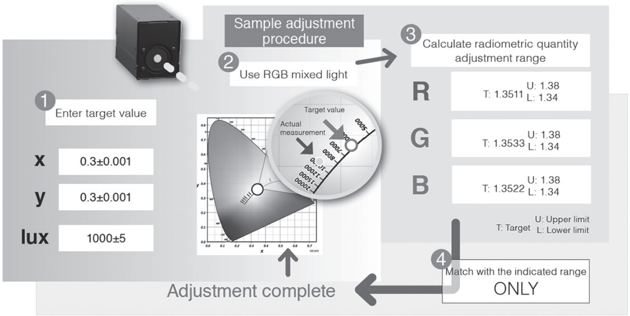

Fig. 5. Use of the white adjustment navigation function.

1) Target value of radiometric quantity: In conventional white balance adjustment, radiometric quantities for red, green, and blue lasers are varied while repeating the process to check chromaticity and photometric quantities. Even if the chromaticity matches the target value, the lasers are adjusted so as to yield the target photometric quantity while maintaining the irradiance ratios for all three lasers if the photometric quantity fails to match its target value. This process requires intuition and an enormous number of labor hours.

With the TM6102, TM6103, and TM6104, the user sets the target values for chromaticity and photometric quantities as desired in the adjustment process (Step 1 in Fig. 5). By measuring the centroid wavelength and radiometric quantities for red, green, and blue lasers (Step 2 in Fig. 5), the instruments calculate and indicate the target value of radiometric quantity for each laser needed in order to yield the target chromaticity and photometric quantity values (Step 3 in Fig. 5). The measurement target is adjusted to yield the target chromaticity and photometric quantity values by adjusting the radiometric quantity of each of the three lasers so that the target values are achieved (Step 4 in Fig. 5).

2) Tolerance of radiometric quantity: When there is no tolerance for the target value of radiometric quantity, as in the conventional adjustment process, the red irradiance would be adjusted until it reaches 1.3511 as in the example shown in Fig. 5. The green and blue lasers would also be adjusted until they yield irradiance values of 1.3533 and 1.3522. Since it is not clear how accurately irradiance values need to be adjusted to satisfy the test standard of chromaticity and photometric quantity, a series of fine-grained adjustments is needed.

By contrast, when configured with a tolerance (test standard) as well as target values for chromaticity and photometric quantities, the TM6102, TM6103, and TM6104 use a proprietary algorithm to indicate the tolerance of radiometric quantity. In the example shown in Fig. 5, adjustment process starts with a red radiometric quantity of 1.5 and ends once the value is less than the indicated tolerance upper limit of 1.38, which results in saving man hours. The number of man-hours required to adjust the green and blue lasers is similarly reduced.

E. Simultaneous RGB Measurement

Conventional optical power meters must be separately exposed to the red, green, and blue lasers, and the wavelength of each must be set. Consequently, it is typical to use the white balance adjustment process shown in Fig. 6. Specifically, that process consists of measuring the red, green, and blue lasers in sequence; calculating the target value of radiometric quantity; adjusting each laser in turn; and then performing a final check. Conventional optical power meters experience the issues listed below. By contrast, the TM6104 can measure red, green, and blue incident light simultaneously, eliminating those issues. The TM6102 and TM6103 also provide functionality for simultaneously measuring RGB light.

- When an expensive wavelength-measuring instrument (for example, an optical spectrum analyzer) is not available, target values are calculated based on the wavelengths defined in the semiconductor lasers' specifications. Since actual emission wavelengths differ from the values defined in specifications, the final check may not indicate the anticipated chromaticity and photometric quantities. In addition, since the wavelength with which the optical power meter is configured may differ from the actual wavelength, it may be impossible to correct the instrument's sensitivity in an accurate manner, contributing a source of error in optical power measurement.
- Since the red, green, and blue lasers are illuminated, measured, and adjusted separately, factors such as the conditions under which the lasers heat up vary. Consequently, values diverge from the emission wavelengths and radiometric quantities that would be envisioned if the lasers were activated simultaneously, preventing the process from yielding the anticipated chromaticity and photometric quantities. In this case, significant time may be required to repeat the adjustment process.

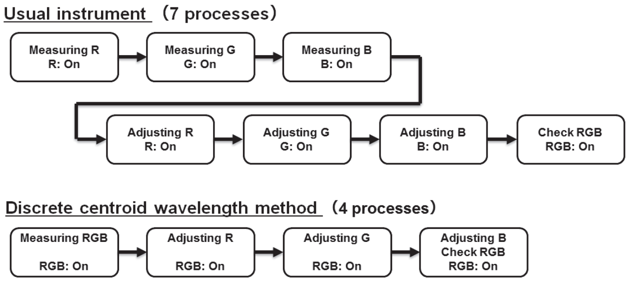

Fig. 6. Comparison of white balance adjustment processes.

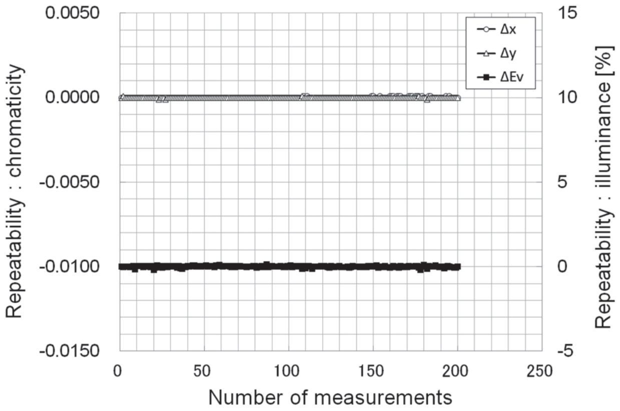

Fig. 7. Stable measurement using the modulated light function.

- Since it is not possible to activate and measure the red, green, and blue lasers simultaneously in the first place, it is not possible to test chromaticity and photometric quantities while all three lasers are active. Results are only predictions based on measurement results obtained while activating the lasers individually. Consequently, it is necessary to provide a separate photometric and colorimetric instrument to verify values while all three lasers are illuminated.

F. Modulated Light Function

1) Support for a variety of refresh rates: When measuring raster-scanning laser projectors that use RGB lasers and MEMS mirrors, the light incident upon the instrument flashes on and off in synchronization with the refresh rate. Consequently, use of an inappropriate measurement frequency setting for the instrument introduces variability in measured values.

The TM6102's modulated light frequency setting allows the optimal measurement frequency to be set so that the instrument can perform stable measurement (Fig. 7). The TM6103 and TM6104 also provide this functionality.

2) Refresh rate period measurement: The period can be measured by inputting an electric signal that is

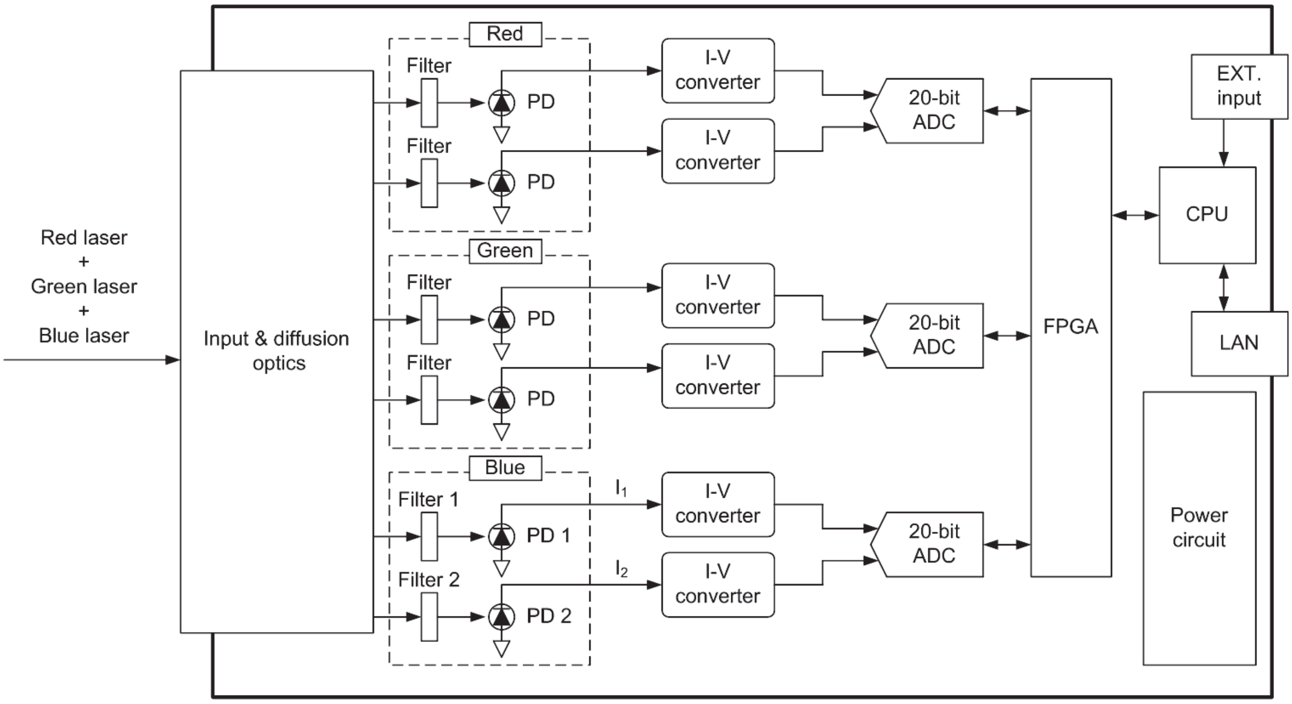

Fig. 8. Block diagram.

synchronized with the measurement target's refresh rate to the external input terminal (SYNC) provided on the rear panel of each instrument. Although the refresh rate period of measurement targets is defined by their specifications, there are miniscule variations among individual pieces of hardware. To eliminate the effects of these variations, it is useful to measure the refresh rate period.

G. Correction Functions (Reducing Instrumental Error)

It is typical to measure a large number of points on the screen during optical measurement of laser displays, for example at 9 or 13 separate locations. Therefore, it is common to manage photometric and colorimetric instruments by providing a reference instrument and correcting the instruments so that they yield the same measured values for the same light source as the reference instrument.

In the past, a single light source was measured, and offset values (x, y) used as correction values so that the instrument being corrected would yield the same chromaticity values (x, y) as the reference instrument. In addition, the gain coefficient was used as a correction value so that the instrument being corrected would yield the same photometric quantity as the reference instrument. However, as illustrated in Fig. 1, the difference between instruments' spectral sensitivity characteristics and color-matching functions vary significantly with wavelength, which affects the sign of the error. Consequently, offset correction may result in even larger errors relative to the reference instrument's value. The TM6102, TM6103, and TM6104 address this issue by providing functionality to set a correction coefficient based on centroid wavelength and radiometric quantities.

As with conventional instruments, the same light source is measured and correction values determined so that the instrument being corrected yields the same measured value as the reference instrument. A method can also be used in which correction values are generated using a light source with known centroid wavelength and radiometric quantity values. Since corrections are made at the radiometric quantity stage, the results are not subject to the effects of factors such as the wavelength dependence of color-matching function approximation error, allowing accurate correction.

IV. Measurement Principles and Architecture

A. Measurement Principles (Discrete Centroid Wavelength Method)

Fig. 8 provides a block diagram. Light given off by devices such as laser displays consists of mixed light from red, green, and blue lasers. That light enters the TM6102, TM6103, and TM6104, where it is routed via the input optics and diffusion optics to sensor pairs that measure the light's red, green, and blue components.

Optical filters separate the mixed laser light into its constituent red, green, and blue components and provide functionality for attenuating the light according to its centroid wavelength.

Consider as an example the principle by which centroid wavelength is measured by the blue sensor pair (Fig. 9). The spectrum sensitivity of the sensors, each of which consists of an optical filter and photodiode, comprises the centroid wavelength linear function. The sensors have no sensitivity outside the blue domain.

The sensor pair's output current (I_1, I_2) can be calculated using (1) and (2).

$$\begin{aligned} I_1 &= \int \{P(\lambda)\times(k\lambda + l)\} d\lambda \\ &= k\int \lambda P(\lambda)d\lambda + l\int P(\lambda)d\lambda \end{aligned} \tag{1}$$

$$\begin{aligned} I_2 &= \int \{P(\lambda)\times(m\lambda + n)\} d\lambda \\ &= m\int \lambda P(\lambda)d\lambda + n\int P(\lambda)d\lambda \end{aligned} \tag{2}$$

Here $P(\lambda)$ represents the laser's optical power distribution, while λ represents the wavelength. The variables k and m represent slope, while l and n represent intercepts. λ_c corresponds to the weighted mean of wavelength, which is defined as the centroid wavelength in IEC 61280 [6] and is calculated as follows based on (3). Based on the definition of output current ratio and centroid wavelength shown in (4), centroid wavelength can be calculated using (5). However, it is necessary to calculate k, m, l, and n in advance by measuring a light source whose centroid wavelength and radiometric quantities are known.

$$\lambda_c \equiv \frac{\int \lambda P(\lambda)d\lambda}{\int P(\lambda)d\lambda} \tag{3}$$

$$\begin{aligned} \frac{I_1}{I_2} &= \frac{k\int \lambda P(\lambda)d\lambda + l\int P(\lambda)d\lambda}{m\int \lambda P(\lambda)d\lambda + n\int P(\lambda)d\lambda} \\ &= \frac{k\lambda_c + l}{m\lambda_c + n} \end{aligned} \tag{4}$$

$$\lambda_c = \frac{lI_2 - nI_1}{mI_1 - kI_2} \tag{5}$$

Since lasers have a narrow spectrum, (1) and (2) can be approximated by (6) and (7). Once the centroid wavelength has been calculated, the radiometric quantitiesy can be calculated using (8). Values such as the chromaticity and photometric quantities can be calculated using the color-matching function based on the centroid wavelength and radiometric quantity measurement results for each of the red, green, and blue lasers.

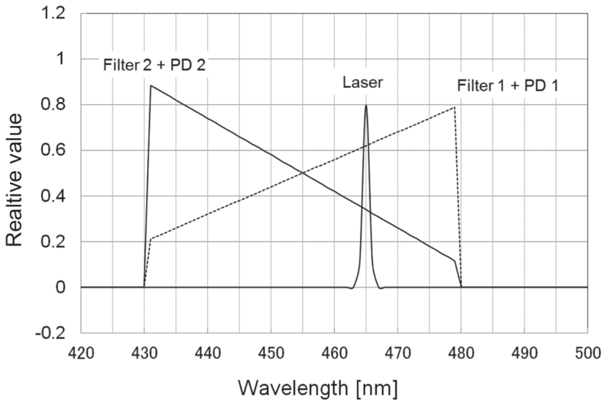

Fig. 9. Spectrum sensitivity characteristics and emission spectrums of sensor pairs.

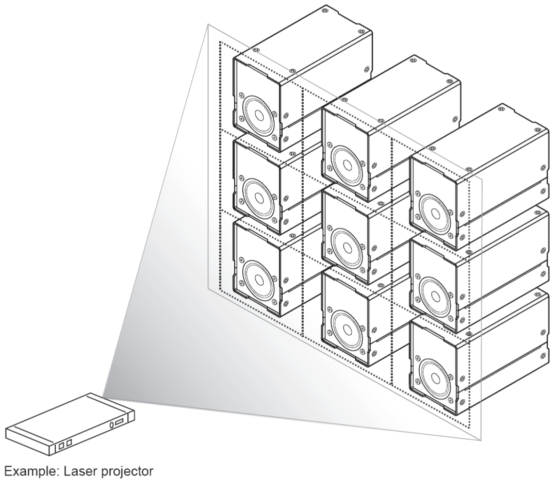

Fig. 10. Example multipoint measurement setup.

$$I_1 = P\times(k\lambda_c + l) \tag{6}$$

$$I_2 = P\times(m\lambda_c + n) \tag{7}$$

$$P = \frac{I_1}{k\lambda_c + l} = \frac{I_2}{m\lambda_c + n} \tag{8}$$

B. LAN Interface

Each instrument provides a LAN interface to simplify multipoint measurement. Fig. 10 illustrates a setup in which nine TM6102 instruments have been arrayed to evaluate a pico-projector. LAN connectivity makes it easy to expand the number of units in an installation.

C. External Input

The instruments provide external input to facilitate frequency measurement and external trigger functionality. The functionality described in section III-F, "Modulated Light Function," is used to provide this capability.

D. Power Supply Circuit

Power is supplied from the AC Adapter Z1008, a dedicated accessory that ships with each instrument, and used to generate and supply the power required by each instrument's constituent circuits.

V. Example Optical Characteristics

A. Repeatability

Fig. 11 illustrates the TM6102's repeatability. RGB lasers were subjected to continuous wave activation to provide a test light source that was evaluated at a test illuminance of 200 lx. Chromaticity variations exhibited a standard deviation of 0.00003, while illuminance variations exhibited a standard deviation of 0.03%, indicating stable performance.

B. Oblique Incidence Characteristics

Illuminance meters are required to provide performance in the form of oblique incidence characteristics that approximate the cosine law. Fig. 12 provides an example of the TM6102's oblique incidence characteristics.

Illuminance measured values approximate the cosine law. In addition, systematic divergence from the oblique optical characteristics f_2 as defined by JIS standards for illuminance meters is 1.3, indicating that the instrument provides oblique incidence characteristics that are equivalent to those of a standard Class AA illuminance meter. Moreover, chromaticity measured values are affected only slightly when the angle of incidence changes.

VI. Comparison with High-Accuracy Spectrometers

This section describes a comparison of the TM6103 (which uses the Discrete Centroid Wavelength Method) with a high-accuracy spectral radiance meter that is used in design and development (the SR-3AR, from TOPCON TECHNOHOUSE CORPORATION).

A. Test Method

Fig. 13 provides a diagram of the optical setup. A uniform luminance area (white) with stable chromaticity and luminance was generated, and measurement results obtained from the two types of instrument described above were compared. The TM6103 was not present when measuring the target with the spectral radiance meter.

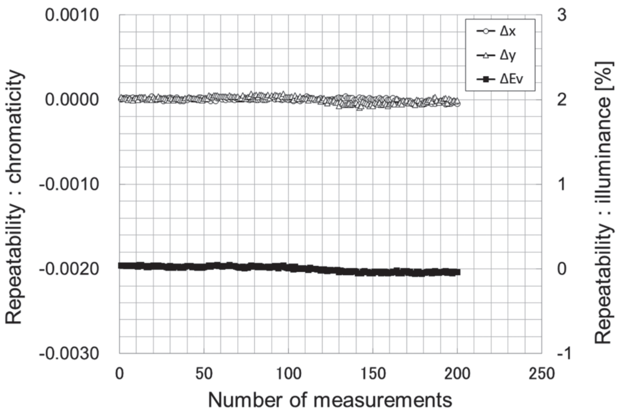

Fig. 11. Example repeatability.

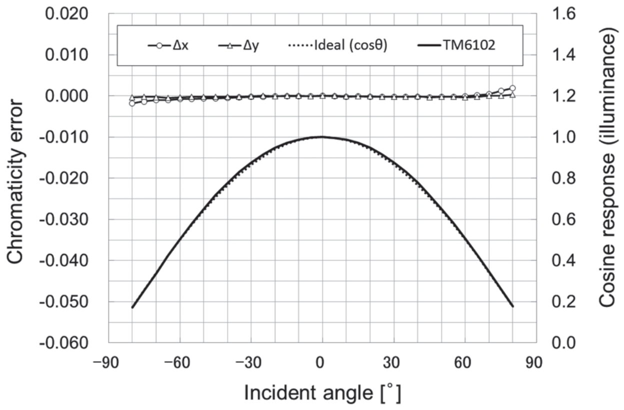

Fig. 12. Example oblique incidence characteristics.

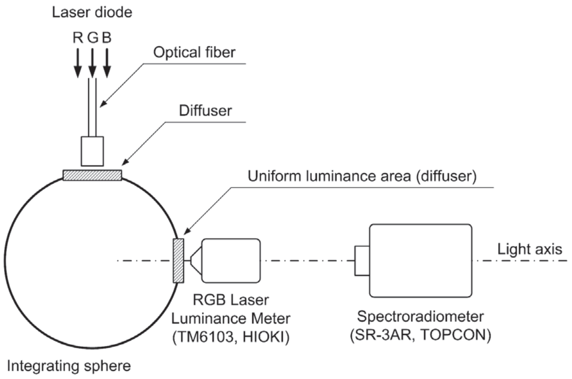

Fig. 13. Optical setup.

The uniform luminance area consisted of red, green, and blue semiconductor lasers, an integrating sphere, and a diffuser. To stabilize the optical output, the setup was driven by a constant current, and temperature was kept constant using a Peltier device.

B. *Test Results*

TABLE I lists the results of comparing chromaticity and luminance results, while TABLE II lists the results of comparing centroid wavelength results. These figures exhibit an excellent level of agreement for results obtained from instruments that use different measurement principles and calibration methods. In addition, there was little difference in centroid wavelength results, other than for the calibration wavelength.

TABLE I. MEASURED VALUES (LUMINANCE AND CHROMATICITY) AND DIFFERENCES

	Luminance [cd/m²]	***x***	***y***
SR-3AR	64.5	0.3261	0.3515
TM6103	63.1	0.3294	0.3521
Difference	−2.2%	+0.0033	+0.0006

TABLE II. MEASURED VALUES (CENTROID WAVELENGTH) AND DIFFERENCES

	Red [nm]	***Green [nm]***	***Blue [nm]***
SR-3AR	635.59	517.71	450.07
TM6103	635.50	517.57	450.08
Difference	−0.09	−0.14	+0.01

VII. CONCLUSION

The TM6102, TM6103, and TM6104 can measure displays using RGB lasers with a high degree of accuracy, and they provide navigation functionality that shortens the adjustment processes. Furthermore, the instruments provide a number of useful features, including simultaneous measurement of red, green, and blue light, modulated light functionality, and correction functionality.

These instruments can be expected to see wide use in the development, design, and manufacture (adjustment and testing) of laser displays. Furthermore, by making possible accurate evaluation, they promise to facilitate the steady growth of the laser display market.

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