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Improvement of color rendering index of BGYR laser illuminants

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Abstract

Laser-driven phosphor conversion (PC)-type white light sources are receiving a great deal of attention in next-generation high-intensity lighting and display technologies. Laser lighting is attracting attention for its functions, such as energy saving and light distribution control. However, the PC-type white light source has problems with color control and thermal quenching. Thus, monochromatic light mixed- or color mixed (CM)-type white light sources are promising, but there is a problem with their color rendering properties. We investigated the CM-type white light sources that mix four colors (blue, green, yellow, and red). We have improved the color rendering index (CRI) of a four-color mixed laser. By maximizing the value through combining the wavelength of four colors and each laser output ratio, the average CRI R_a and the special CRI R_9 can be obtained when the color temperature used in general lighting is approximately 5000 K. The color rendering property was predicted by the combination of laser output ratios, and a light source with an R_a of 80 or more and R_9 of 94 was obtained experimentally. At the same time, we were able to demonstrate the high luminous efficacy of radiation.

Keywords Laser lighting · Color rendering index (CRI) · Luminous efficacy of radiation (LER)

1 Introduction

Laser lighting offers significant advantages, including high potential efficiency at high current densities [1–4]. White light sources are usually achieved using phosphor materials excited by blue or purple lasers [1]. It is generally believed that the white light produced by a set of different color lasers is not of sufficient quality for general lighting, especially with regard to the actual value of the color rendering index (CRI) of such white light. This laser illuminant technology has the potential to outperform high-intensity discharge lamps and white light-emitting diodes in terms of providing high brightness, excellent efficacy, and long life. For this laser illuminant, the very small diffused light region of the laser does not generate heat when the laser chips are placed apart. This feature is extremely useful for achieving an unprecedented, extremely lightweight, compact, low-temperature, and high-brightness white light source. There are two types of laser illuminants: a phosphor conversion (PC)-type that excites a phosphor with a blue or purple laser [1], and a color mixture (CM)-type that combines multiple monochromatic lasers [2–4]. Laser-driven phosphor conversion PC-type white lighting, which enables extremely high brightness and luminous flux, holds great promise for use in vehicle high-beam headlamps, projectors, large displays, surgery, and visible light communication applications. An alternative high-intensity white light source that uses only a blue–green–red (BGR) three-color mixed laser is not suitable for general lighting applications owing to its very low CRI. The CRI is a key indicator of lighting quality and an important criterion to consider when developing a new light source. The CRI value is based on comparing a standard set of 15 Munsell colors under illumination with a blackbody having the same correlated color temperature (CCT) as the target spectrum, with a maximum CRI value of 100. The average value of R_1 to R_8 is called the average color rendering index, R_a, and the special color rendering index that represents deep red is called R_9. For example, a BGR three-color mixed laser system gives an R_a value of -33 and an R_9 value of -364[4].

An important indicator of energy saving is the luminous efficacy of radiation (LER) of the light source. The energy efficiency of lighting is measured by the luminous efficiency

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(LE), which is measured in lumens per watt, which is the product of LER (lm/W) and energy efficiency: η_e, LE = LER · η_e. The LE of the light source is the highest in the monochromatic spectrum, at 555 nm, with an LER value of 683 lm/W, but the corresponding CRI values are the lowest of all the optical spectra [5–7]. On the other hand, the maximum CRI values are achieved by the spectrum on the blackbody radiation trajectory, but the corresponding LER is low, reaching only 96 lm/W at a relative color temperature of 6600 K. In general, there is a trade-off between the largest possible LER and CRI.

To deploy this benefit to actual laser lighting applications, the BGR three-color illuminants must evolve into a blue–green–yellow–red (BGYR) four-color mixed system. Neumann et al. [2] and Kinoshita et al. [3] reported earlier distinguished research on four-color mixed laser illuminants. They demonstrated experimentally that the CRI values of a BGYR four-color laser illuminant were high ($R_a = 83$ at a CCT of 5665 K [2]; $R_a = 90$ at 5500 K [3]). For example, there is an improvement in the CRI value and wavelength of the BGYR four-color laser. However, there are still many uncertainties regarding the BGYR laser light source.

In this study, to determine the improved CRI value of the BGYR four-color laser light source near the color temperature of 5000 K used in general lighting, the emission spectrum of the four-color mixture was examined with many combinations of BGYR four-color mixing ratios. The CRI values and luminous efficacy of the combination of the four colors were determined. From the combination of the mixing ratios of the BGYR four-color laser light sources, a maximum value region with high color rendering properties and high efficacy was obtained. We experimentally confirmed these values with a white light source using a BGYR four-color laser with high color rendering properties and high efficacy.

2 Calculation

The CRI is currently the only internationally agreed-on metric for color rendering evaluation [5, 6]. The procedure for its calculation is, first, to calculate the color differences ΔE_i (in the 1964, W*U*V* uniform color space—now obsolete) of 14 selected Munsell samples when illuminated by a reference illuminant and the given illuminant. The first eight samples were medium-saturated colors, and the last six were highly saturated colors. The reference illuminant is the Planckian radiation for test sources having a correlated color temperature (CCT) < 5000 K, or a phase of daylight for the test sources having CCT ≥ 5000 K. The special color rendering indices R_i for each color sample are obtained by [5, 6]:

$$R_i = 100 - 4.6\Delta E_i, \quad (i = 1, \dots, 14). \tag{1}$$

This gives an evaluation of the color rendering for each particular color. The maximum value of R_i (zero color difference) is 100, and its value can be negative if the color differences are very large. The general color rendering index R_a is given as the average of the first eight color samples:

$$R_a = \sum_{i=1}^{8} \frac{R_i}{8}. \tag{2}$$

The R_a score for perfect color rendering (zero color differences) is 100.

Next, we determine the relative irradiances necessary to achieve a desired color.

The chromaticity coordinates of the target color are x_T, y_T, and the chromaticity coordinates (in the CIE 1931 diagram) of a light source with lasers of four different colors are given by [7, 8]:

$$x_T = \frac{\sum_i X_i}{\sum_i \left(X_i + Y_i + Z_i\right)}, \tag{3}$$

$$y_T = \frac{\sum_i Y_i}{\sum_i \left(X_i + Y_i + Z_i\right)}, \tag{4}$$

$$z_T = 1 - x_T - y_T, \quad (i = \mathrm{B,\ G,\ Y,\ and\ R}), \tag{5}$$

where X_i, Y_i, and Z_i are the tristimulus values of the four laser colors [8–10]:

$$X_i = \mathrm{K_m} \int_{\lambda=380\mathrm{nm}}^{\lambda=780\mathrm{nm}} \overline{x}(\lambda)\, S_i(\lambda)\mathrm{d}\lambda, \tag{6}$$

$$Y_i = \mathrm{K_m} \int_{\lambda=380\mathrm{nm}}^{\lambda=780\mathrm{nm}} \overline{y}(\lambda)\, S_i(\lambda)\mathrm{d}\lambda, \tag{7}$$

$$Z_i = \mathrm{K_m} \int_{\lambda=380\mathrm{nm}}^{\lambda=780\mathrm{nm}} \overline{z}(\lambda)\, S_i(\lambda)\mathrm{d}\lambda, \quad (i = \mathrm{B,\ G,\ Y,\ and\ R}), \tag{8}$$

where $K_m = 683$ lm/W, λ is the wavelength in nm, and is a proportionality constant that relates spectral radiance [8] or spectral radiant power [9], with the spectral function $S_i(\lambda)$ of the laser. The color-matching functions are denoted by $\overline{x}(\lambda)$, $\overline{y}(\lambda)$ and $\overline{z}(\lambda)$.

Considering the application of general lighting, we assumed a multi-mode laser with a high output. The full width at half maximum (FWHM) of the longitudinal mode envelope curve in the RGB multimode laser was approximately 2 nm. In addition, the yellow laser includes a DPSS laser, and it is assumed that it will be a high-power multimode laser in the future. Assuming that it is a BGYR multimode laser, the full width at half maximum of the longitudinal mode envelope curve is 2 nm, and the shape function is a Lorentz shape. The longitudinal mode envelope function of the four lasers is given by:

$$S_i(\lambda) = \frac{B_i\left(\sigma_i/2\right)}{\left(\lambda - \lambda_i\right)^2 + \left(\sigma_i/2\right)^2}, \quad (i = \mathrm{B},\ \mathrm{G},\ \mathrm{Y},\ \text{and R}), \tag{9}$$

where λ_i is the peak wavelength of the laser, σ_i is the full width of the half value of the lasers with a value of 2 nm, and B_i is the standardized value of $\int_0^\infty S_i(\lambda)\mathrm{d}\lambda = 1\mathrm{W}$.

The four-color mixed spectral function S_{CM} (λ) is given by:

$$S_{\mathrm{CM}}(\lambda) = a_{\mathrm{B}}S_{\mathrm{B}}(\lambda) + a_{\mathrm{G}}S_{\mathrm{G}}(\lambda) + a_{\mathrm{Y}}S_{\mathrm{Y}}(\lambda) + a_{\mathrm{R}}S_{\mathrm{R}}(\lambda). \tag{10}$$

Once the power coefficients a_{B}, a_{G}, a_{Y}, and a_{R} for each laser have been determined, the four-color mixed spectral function S_{CM} (λ) can be obtained. In contrast, when the target chromaticity coordinates of the four-color mixed laser illuminant are determined, a four-color mixed spectral function and the power coefficient of each laser are obtained. If the shape of the four-color mixed spectral function is known, we use the internationally agreed method to obtain the color rendering index [5].

In the four-color mixed laser system, there are many calculation parameters, because it is a quadratic equation. The standardized four-color mixed spectrum function, $S_{\mathrm{CM\text{-}B}}$ (λ), in which the four-color mixed spectrum function is standardized by the power coefficient of the blue laser, is derived in Eq. (11):

$$\begin{aligned} S_{\mathrm{CM\,\text{-}\,B}}(\lambda) &= \frac{S_{\mathrm{CM}}(\lambda)}{a_{\mathrm{B}}} = \frac{a_{\mathrm{B}}S_{\mathrm{B}}(\lambda) + a_{\mathrm{G}}S_{\mathrm{G}}(\lambda) + a_{\mathrm{Y}}S_{\mathrm{Y}}(\lambda) + a_{\mathrm{R}}S_{\mathrm{R}}(\lambda)}{a_{\mathrm{B}}} \\ &= S_{\mathrm{B}}(\lambda) + A_{\mathrm{G}}S_{\mathrm{G}}(\lambda) + A_{\mathrm{Y}}S_{\mathrm{Y}}(\lambda) + A_{\mathrm{R}}S_{\mathrm{R}}(\lambda), \end{aligned} \tag{11}$$

$$A_i = \frac{a_i}{a_{\mathrm{B}}}, \quad (i = \ \mathrm{G},\ \mathrm{Y},\ \text{and R}). \tag{12}$$

The chromaticity coordinates of the target color are determined, because the standardized four-color mixed spectrum function is determined.

Conversely, when the target chromaticity coordinates (for example, the chromaticity coordinates of duv = 0 at a color temperature of 5000 K) are determined, many combinations of three standardized power coefficients A_{G}, A_{Y}, and A_{R} values occur. As a result, we find the maximum values of color rendering and luminous efficacy from the many combinations. This is because of the four-color mixing of BGYR, which increases the degree of freedom of the emission spectrum of the lighting device, unlike the BGR three-color mixing system [3].

The behavior of the color rendering index is as follows. First, the standardized power coefficient A_{Y}, which is the yellow/blue laser output ratio, is set for each chromaticity coordinate in the temperature range of 5000 ± 400 K of the four-color mixed laser light source. The values of A_{G} and A_{R} are obtained as the parameters. As a result, the CRI value is calculated from the emission spectrum in which four colors are mixed, and the behavior of the color rendering index is simulated.

The CRI value is calculated using the Color Calculator (Ver.7.77) provided by OSRAM Sylvania Inc., which was developed based on the internationally agreed upon color rendering index calculation method [5]. The error in the calculation result of this software is 10^{-4} or less in the color rendering index and the value when calculated and evaluated by the numerical value of the emission spectrum of the standard lamp, which is acceptable to obtain the color rendering index and value [11].

The LER, being one of the required characteristics of laser illuminants, is determined as follows: The LER is also. The LER of a four-color mixed spectrum $S_{\mathrm{CM\text{-}B}}$ (λ) is given by [12]:

$$\mathrm{LER} = \frac{K_{\mathrm{m}}\int_{\lambda=380\mathrm{nm}}^{\lambda=780\mathrm{nm}} \overline{y}(\lambda)S_{\mathrm{CM\,\text{-}\,B}}(\lambda)\mathrm{d}\lambda}{\int_0^\infty S_{\mathrm{CM\,\text{-}\,B}}(\lambda)\mathrm{d}\lambda}, \tag{13}$$

where $K_{\mathrm{m}} = 683$ lm/W, and substituting Eqs. (7)–(11) into Eq. (13) yields Eq. (14):

$$\mathrm{LER} = \frac{\mathrm{Y}_{\mathrm{B}} + A_{\mathrm{G}}Y_{\mathrm{G}} + A_{\mathrm{Y}}Y_{\mathrm{Y}} + A_{\mathrm{R}}Y_{\mathrm{R}}}{1 + A_{\mathrm{G}} + A_{\mathrm{Y}} + A_{\mathrm{R}}}. \tag{14}$$

The method for obtaining the maximum luminous efficacy was determined using Eq. (14) in the same manner as for obtaining the maximum value for thecolor rendering indexes.

Figures 1 and 2 show the R_a and R_9 contours with a yellow/blue laser power ratio (A_{Y}) of 0.8 to 1.5 in the color temperature (T_{c}) range of 4500–5500 K, respectively. The cross marks in Figs. 1 and 2 show the conditions of $T_{\mathrm{c}} = 5000$ K

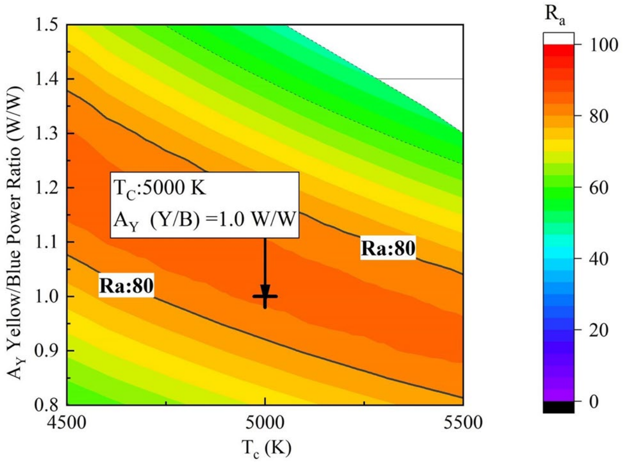


Fig. 1 Contour plots of R_a of BGYR CM-type laser illuminant at yellow/blue laser power ratio (A_Y) from 0.8 to 1.5 W/W in the color temperature range of 4500–5500 K

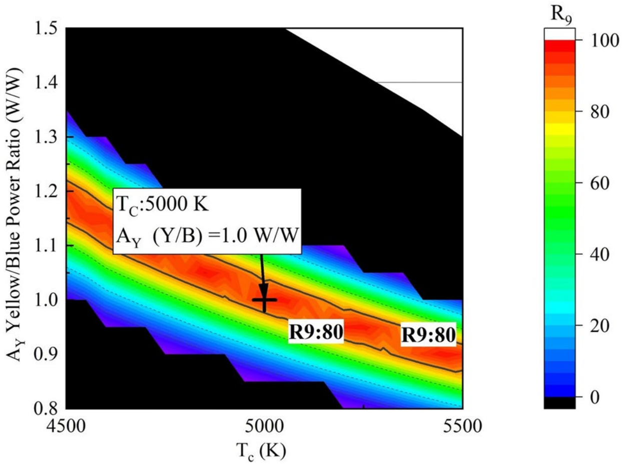


Fig. 2 Contour plots of R_9 of BGYR CM-type laser illuminant at yellow/blue laser power ratio (A_Y) from 0.8 to 1.5 W/W in the color temperature range of 4500 to 5500 K

and $A_Y = 1.0$ W/W. The surface shapes of the contour lines of R_a and R_9 show a convex shape with respect to the color temperature T_c, and the lower the color temperature T_c, the higher is the A_Y value. In other words, if an appropriate A_Y can be obtained for any color temperature T_c, high R_a and R_9 (> 80) can be obtained. The surface shape of R_a is uniformly wide. The range of A_Y with a high R_9 value of $R_9 > 80$ is a very narrow region, and a high R_9 value gives only a limited A_Y. Furthermore, it was confirmed that there is a solution of the A_Y value in which both R_a and R_9 values are high near the color temperature $T_c = 5000$ K (cross mark) used for general lighting. Figure 3 shows the relationship between

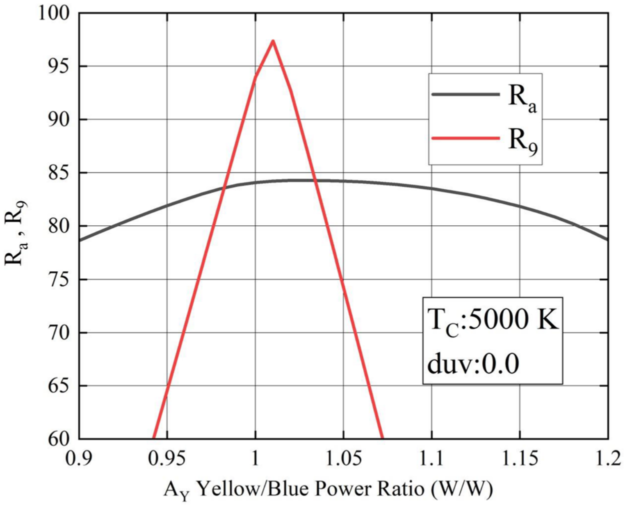


Fig. 3 Yellow/blue laser power ratio (A_Y) dependence of R_a and R_9 at $T_c = 5000$ K, duv = 0.0

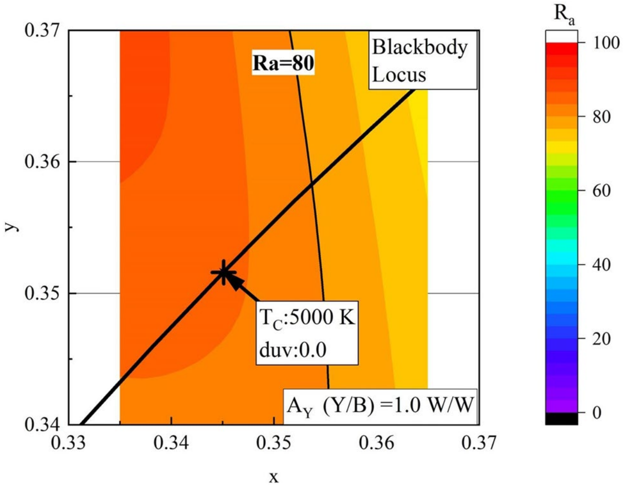


Fig. 4 2D contour plots of average color rendering index (R_a) of BGYR CM-type laser illuminant as a function of chromaticity point (CIE x and y parameters) at yellow/blue laser power ratio (A_Y) = 1 W/W

the R_a and R_9 values at the color temperature $T_c = 5000$ K, duv = 0.0, and the yellow/blue laser output ratio (A_Y). The value of R_a gradually changed with respect to the change in A_Y, and the maximum value was approximately $R_a = 85$. On the other hand, the value of R_9 increased and decreased rapidly with the change in A_Y, had a peak near $A_Y = 1$ W/W, and reached $R_9 = 97$ at the maximum value. That is, with $T_c = 5000$ K and duv = 0.0, the A_Y value above 80 for both R_a and R_9 was 1.0 W/W. Figures 4 and 5 show contour maps

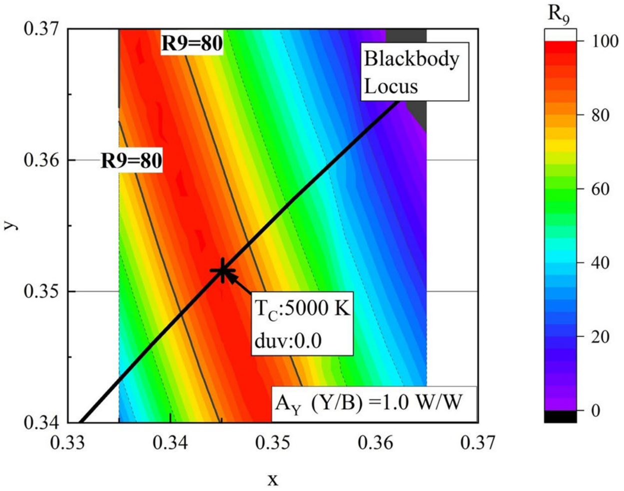


Fig. 5 2D contour plots of R_9 of BGYR CM-type laser illuminant as a function of chromaticity point (CIE *x* and *y* parameters) at yellow/blue laser power ratio (A_Y) = 1 W/W

of R_a and R_9 at $A_Y = 1.0$ W/W near $T_c = 5000$ K. The cross marks in Figs. 4 and 5 show the chromaticity coordinates under the conditions $T_c = 5000$ K and duv = 0.0. In Fig. 4, there is a region with a high value of $R_a > 80$ or more in the upper-left of the blackbody locus, and the value of R_a gradually decreases towards the lower-right. At the chromaticity coordinates of the cross mark ($T_c = 5000$ K, duv = 0.0), $R_a = 82$. In Fig. 7, R_9 increased and decreased sharply in the low color temperature direction of the blackbody radiation trajectory (from the lower-left to the upper-right in the figure). As a result, the value of R_9 became negative. In addition, the maximum value of R_9 reaches $R_9 = 97$. The region of $R_9 > 80$ is in the direction perpendicular to the blackbody radiation locus and in the direction of increase/decrease of the duv value (distance of chromaticity coordinates from the blackbody radiation locus). From the above calculation results, when $T_c = 5000$ K and duv = 0, both R_a and R_9 values may exceed 80. Figure 6 shows a 3D contour diagram of LER as a function of both the color temperature (T_c) and the average color rendering index (R_a). In the relationship between LER and color rendering, the higher the R_a value, the lower is the LER value, which tended to be the same as in previous reports [13, 14]. On the other hand, regarding the relationship between the color temperature and LER, when the color temperature was increased from 4600 to 5400 K, the LER value decreased slightly. This tendency was the same as that in a previous report [15]. By investigating the combination of output ratios of the BGYR four-color laser in detail, the light source showed a high color rendering index of $R_a > 80$ at 5000 K, and the LER showed a maximum value of 320 lm/W or higher. Figure 7 shows a 2D contour diagram of the LER of a BGYR four-color mixed laser light source for each chromaticity coordinate at a yellow/blue laser output ratio (A_Y) = 1 W/W.

As the color temperature increased (as the chromaticity coordinates *x* and *y* increased), the LER gradually decreased [15]. The luminous efficacy at the chromaticity coordinates of $T_c = 5000$ K and duv = 0.0 (cross mark in Fig. 7) is 320 lm/W, which is a high luminous efficacy value.

From these calculation results, by investigating in detail the combination of the output ratios of the BGYR four-color mixed laser light source at the chromaticity coordinates $T_c = 5000$ K and duv = 0.0, a combination that maximizes both the color rendering property and LER was obtained.

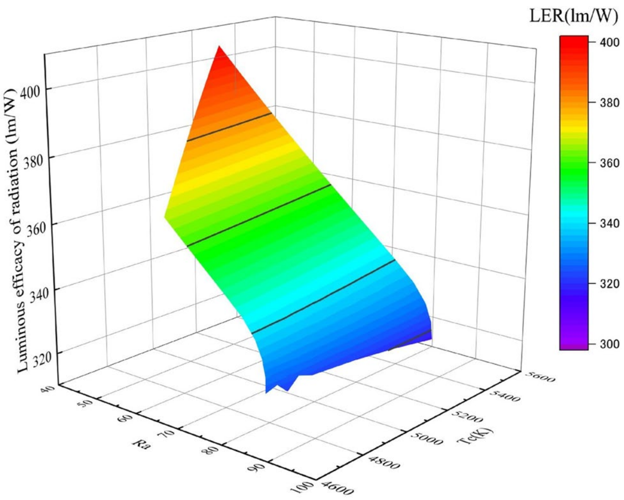


Fig. 6 3D contour plots of luminous efficacy of radiation (LER) of BGYR CM-type laser illuminant as functions of both color temperature (T_c) and average color rendering index (R_a)

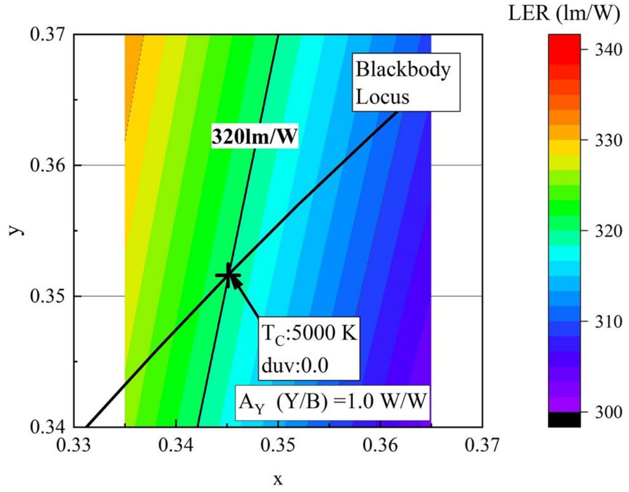


Fig. 7 2D contour plots of luminous efficacy of radiation (LER) of BGYR CM-type laser illuminant as a function of chromaticity point (CIE *x* and *y* parameters) at yellow/blue laser power ratio (A_Y) = 1 W/W

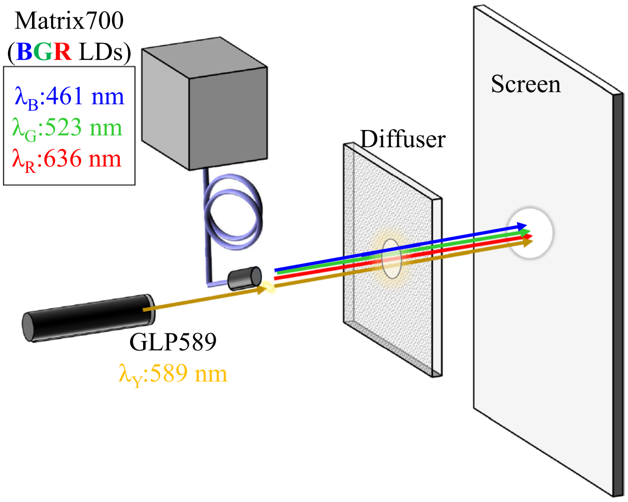


Fig. 8 Schematic diagram of BGYR CM-type laser illuminant system

Therefore, it has a high color rendering property of $R_a = 84$ and $R_9 = 92$, and can result in a high LER value of 320 lm/W.

3 Experimental procedure

To verify the results of the simulation described in Sect. 2, we carried out an experiment using four color (blue, green, yellow, and red) lasers. A schematic illustration of the experimental configuration is shown in Fig. 8. The experimental configuration of the four-color laser source was based on the BGR laser and yellow laser pointer. The light source unit of the three primary colors of the BGR laser is Matrix 700 made by USHIO Inc.. The wavelengths of the B, G, and R lasers were 462, 523, and 635 nm, respectively. The output was obtained using an optical fiber. The BGR laser was a multimode laser, and the FWHM of the longitudinal mode envelope was 2–5 nm. The yellow light source was a laser pointer GLP-589 (manufactured by Changchun Shinko Kogyo Optoelectronics Technology Co., Ltd.), which is a DPSS laser with TEM_{00} mode and a wavelength of 588 nm. The fiber output of the BGR laser and the output of the yellow laser pointer, which was independent of it, were mixed by illuminating the diffuser and screen. The mixed light of the four-color laser was measured with an SR-3AR spectrophotometer (Topcon Technohouse Corp.), and the CRI value (R_1–R_{14}) of the mixed light of the four-color laser was obtained. The wavelength resolution was set to 1 nm. The color rendering index and CRI value were calibrated using a standard lamp, and each error was 10^{-3} or less. This error is acceptable to obtain the color rendering index and value. The output of the blue, green, and red lasers was 0 to 10 mW, and the output of the yellow laser (laser pointer) was 5 mW. The BGYR output was controlled individually, a combination of four-color output ratios was created, and a combination of four-color output ratios that maximized the CRI value and LER value was obtained.

4 Results and discussion

As described in Sect. 2, by investigating the combination of output ratios of the BGYR four-color laser source, it is possible to obtain high color rendering and high LER. In the experimental configuration shown in Fig. 8, four colors were mixed, and color rendering and LER were measured at many chromaticity coordinates. In addition, the measurement and calculation results are compared. Figure 9a shows the experimental measurement points of the BGYR four-color laser light source at the chromaticity coordinates near the color temperature of 5000 K. Figure 9b shows the measured value (red circle) and the calculation result (blue square) regarding the relationship between the color rendering property and LER. Figure 9c shows the measured value (red circle) and the calculation result (blue square) regarding the relationship between the color temperature and LER. Table 1 shows the color temperature of the measurement points shown in Fig. 9a, the laser output ratio of the BGYR four-color laser, LER, and color rendering index (R_a, R_9). As shown in Fig. 9b, the LER changed significantly with the change in R_a (see No. 1–20 in Table 1). Regarding the relationship between R_9 and LER, the change in LER was smaller than the change in R_9 (see No. 10–12 in Table 1). As shown in Fig. 9c, the LER decreased as the color temperature increased, but it was 320 lm/W or more. The higher the LER value, the is lower the CRI value [13, 14]. In addition, from Fig. 9b, c, the calculated values of the color rendering property and LER characteristics obtained in the experiment were in good agreement. The validity of the calculation of this method was confirmed experimentally. When the color temperature is approximately 5000 K, there is a chromaticity coordinate region with a color rendering index of 80 or more and a LER of 320 lm/W or more. In the case of the output ratio (B/G/Y/R) of the BGYR four-color laser No. 11 in Table 1, Table 2 shows the color rendering

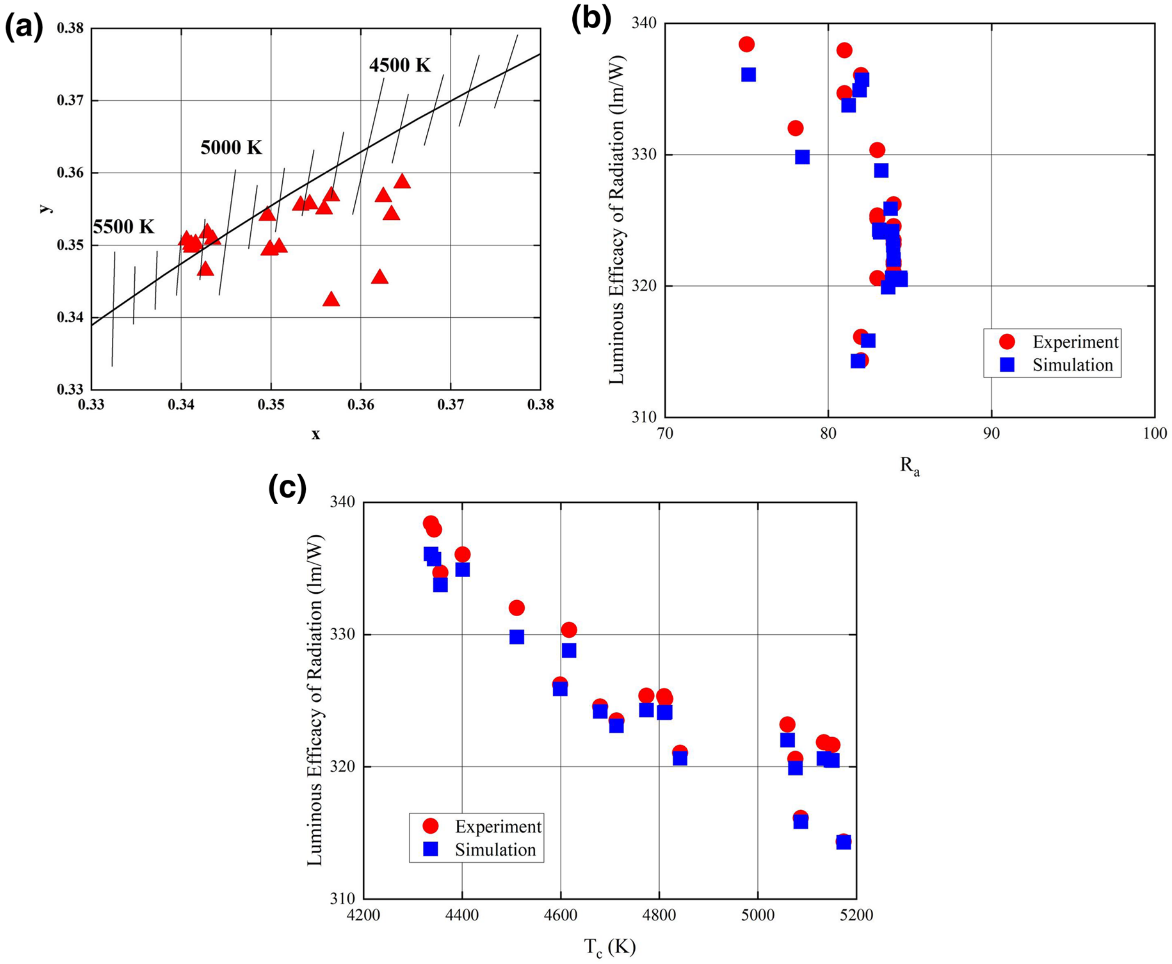


Fig. 9 **a** Experimental measurement points of the BGYR four-color laser light source at the chromaticity coordinates near the color temperature of 5000 K. **b** Relationship between average color rendering index (R_a) and the luminous efficacy of radiation, sphere (experiment, red circle), cubic (simulation, blue square). **c** Relationship between the color temperature (T_c) and the luminous efficacy of radiation, sphere (experiment, red circle), cubic (simulation, blue square)

index R_1–R_{14}. Under these conditions, the color temperature was 4713 K, duv = 0.0, and the output ratio (B/G/Y/R) was 1.0/1.20/0.96/1.09. From Table 2, the values of R_a and R_9 were 84 and 94, respectively. In addition, the other color rendering indexes were also almost high values, and the LER was also high at 324 lm/W. From these results, if the color temperature used is approximately 5000 K, a light source that maximizes high color rendering properties and high efficacy performance can be obtained by investigating the combination of output ratios of the four-color lasers. In addition, this light source is expected to be suitable for general lighting applications.

5 Conclusions

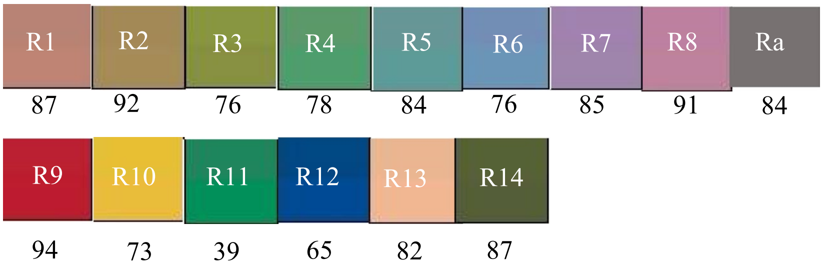
We investigated the combination of the output ratios of each of the BGYR four-color lasers in detail. It was shown that this effort can obtain high luminous efficacy of radiation as well as high color rendering properties. In the chromaticity coordinate region with a color temperature of approximately 5000 K, R_a and R_9 were high at the same time, the R_a value exceeded 90, and R_9 reached 94. Furthermore, the luminous efficacy was also high, exceeding 320 lm/W. There are many combinations of the output ratios of the four-color laser, owing to color mixing. Therefore, as a result of detailed calculation of the color rendering property and efficacy of the four-color laser white light source, the performance, such as

Table 1 Color rendering index (R_a, R_9) and luminous efficacy of radiation (LER) obtained at the measurement points of the chromaticity coordinates around the color temperature of 5000 K by changing the output ratio of the BGYR CM-type four-color laser to mix the colors

No	T_c (K)	duv	Laser power ratio			CRI		LER (lm/W)
			G/B	R/B	Y/B	R_a	R_9	
1	5174	0.0014	1.20	0.96	0.91	82	60	314
2	5087	0.0010	1.20	0.96	0.94	82	68	316
3	5151	0.0008	1.14	0.80	0.98	84	92	322
4	5148	0.0007	1.14	0.81	0.98	84	93	322
5	5134	0.0007	1.14	0.81	0.98	84	92	322
6	5076	−0.0016	1.10	0.80	0.99	83	90	321
7	5060	0.0002	1.14	0.81	1.01	84	85	323
8	4842	−0.0005	1.20	0.96	1.04	84	92	321
9	4812	−0.0031	1.10	0.81	1.08	83	67	325
10	4810	−0.0030	1.10	0.81	1.08	83	65	325
11	4713	−0.0012	1.20	0.96	1.09	84	94	324
12	4774	−0.0033	1.10	0.81	1.09	83	65	325
13	4680	−0.0015	1.20	0.96	1.11	84	90	325
14	4599	−0.0019	1.21	0.97	1.15	84	86	326
15	4617	−0.0025	1.14	0.83	1.17	83	48	330
16	4511	−0.0093	0.95	0.64	1.20	78	−1	332
17	4356	−0.0055	1.11	0.83	1.29	81	26	335
18	4401	−0.0040	1.15	0.83	1.29	82	27	336
19	4337	−0.0096	0.95	0.62	1.31	75	−30	338
20	4343	−0.0038	1.14	0.81	1.32	81	18	338

In addition, the ratio of the output intensities of the three colors of green, red, and yellow (G/B, R/B, Y/B), which is the standardized output ratio of the four-color laser at the measurement point with the blue laser output

Table 2 CRI's values at $T_c = 5000$ K, duv = 0 in the BGYR CM-type laser illuminant



R1	R2	R3	R4	R5	R6	R7	R8	Ra
87	92	76	78	84	76	85	91	84

R9	R10	R11	R12	R13	R14
94	73	39	65	82	87

color rendering property and efficacy, could be maximized, which was in agreement with the experimental value. We found that the efforts of this research were effective. Furthermore, this initiative enables the production of high-quality white light sources for the general lighting field.

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