Tuning of Chromaticity Coordinates for Ce:YAG Single Crystals by Laser Excitation

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ABSTRACT
Phosphor-converted light sources excited by a blue laser have attracted attention. There are few phosphor variations for such lasers and thus the color temperature variation of white is limited. Here, laser light sources are evaluated under various excitation conditions. It is found that the color temperature can be controlled.

1 Introduction
Solid-state light sources are commonly used in various applications, such as projectors, headlights, outdoor lights, and display backlights. Phosphor-converted light sources excited by a blue laser have attracted attention as high-power light sources for automotive headlights and outdoor lights due to their high intensity and energy efficiency [1]. However, few phosphors can endure laser irradiation as high excitation density causes damage, a temperature increase, and subsequent quenching of their emission [2]. Ce:Y3Al5O12 (Ce:YAG) is a phosphor that can endure laser excitation but it lacks emission intensity in the red light region, which restricts white light color expression. Ce:YAG can reproduce daylight (correlated color temperature (CCT): 5700-7100 K) and natural light (CCT: 4600-5500 K), but emission intensity in the red light region is necessary to produce white (CCT: 3800-4500 K), warm white (CCT: 3250-3800 K), and incandescent light (CCT: 2600-3250 K). Other phosphors that can endure laser irradiation have been developed, but their durability is not as high as that of Ce:YAG [3-4].

We previously extended the applicability of laser light sources by evaluating laser light source systems and preparing laser excitation phosphors and devices [5-6]. We prepared laser excitation light sources that can control the CCT for the emitted white light and evaluated these sources under various excitation conditions to increase the white color variety.

In the present study, Ce:YAG single crystals are evaluated as transmission-type laser excitation light sources. The phosphor thickness and excitation conditions are varied to arbitrarily control the chromaticity coordinates and CCT. It is found that it is difficult to control the chromaticity coordinates by changing the thickness of the Ce:YAG plates due to the nonuniform distribution of Ce ions, but varying the excitation density by tuning the excitation spot size allows precise control to be achieved. In addition, a red laser is combined with a blue excitation laser to enhance the intensity of the red color region. The CCT for the emitted white light can be tuned by adding suitable red laser intensity.

2 Sample preparation and light source system configuration
Ce:YAG single crystals were prepared using the Czochralski method. The charge-in quantity of Ce ions was 0.4 wt% relative to Y ions. The solidification ratio was 70% and thus the Ce ion concentration was about 0.1 mol%. The samples had a length of 5 mm, a width of 5 mm, and a thickness of 1 to 4.5 mm (in increments of 0.5 mm). The samples were cut from the Ce:YAG single crystal boule (the cut position was randomly selected), and the optical input and output surfaces were polished.

The emission spectrum of a representative Ce:YAG single-crystal sample measured using a spectrophotometer (FP-8550, Jasco) is shown in Fig. 1.

Fig. 1 Emission spectrum of Ce:YAG single-crystal sample (thickness: 2.5 mm)

The samples were placed in a transmission-type laser excitation light system with a simple configuration (Fig. 2) and excited by blue laser light at 443 nm and a power of 1.3 W. The temperature of the sample mount was controlled at 35 °C. The luminescence and transmitted blue light were measured using a spectral illuminance meter (CS-2000, KONICA MINOLTA Corp.).
Fig. 3 shows the blue light spectrum obtained without the sample and Fig. 4 shows a representative transmission spectrum of a sample with a thickness of 3 mm.

The integrated intensity in the blue color region (380–464 nm) in Fig. 3 was defined as the incident intensity. The integrated intensity in the blue region (380–464 nm) and that in the luminescence region (465–780 nm) in Fig. 4 were defined as the transmission and luminescence intensity, respectively. The blue light intensity ratio was calculated by dividing the transmission intensity by the incident intensity, as shown in equation (1).

\[
\text{Blue light intensity ratio } B(\%) = \frac{\int_{380}^{464} I_{\text{trans}} \, d\lambda}{\int_{380}^{464} I_{\text{in}} \, d\lambda} \quad (1)
\]

The conversion efficiency was calculated by dividing the luminescence intensity by the incident intensity, as shown in equation (2).

\[
\text{Conversion efficiency } C(\%) = \frac{\int_{465}^{780} I_{\text{lum}} \, d\lambda}{\int_{380}^{464} I_{\text{in}} \, d\lambda} \quad (2)
\]

3. Control of chromaticity coordinates using phosphor thickness

Fig. 5 shows the relationship between the thickness and the blue light intensity ratio and that between the thickness and the conversion efficiency. Fig. 6 shows the chromaticity coordinates calculated from the spectrum of each sample. As can be seen, the intensity ratio decreases linearly with increasing thickness, following Lambert's law.

In contrast, the conversion efficiency is proportional to the thickness. The chromaticity coordinates vary greatly with phosphor thickness and the coordinates are not near the blackbody locus.

The absorption coefficient and the ratio of the conversion efficient to thickness were calculated from Fig. 5. Based on these values, the thickness that yielded chromaticity coordinates near the blackbody locus was calculated. It was found that phosphors with a thickness of 2.5 to 3.5 mm were close to the locus for blackbody radiation.

3. Control of chromaticity coordinates using phosphor thickness

Fig. 5 shows the relationship between thickness and blue light intensity ratio B (%) and conversion efficiency C (%)

Fig. 6 Chromaticity coordinates calculated from spectrum of each sample

Based on these results, the phosphor thickness was set to 2.5 to 3.5 mm in 0.1-mm increments and the measurements were repeated. Fig. 7 shows the results.

As shown, the conversion efficiency is almost proportional to the thickness. The blue light intensity ratio data are relatively dispersed. Based on these results, 12 samples (nos. 1-12) with a phosphor thickness of 2.6 mm
were prepared. The blue light intensity ratio and conversion efficiency for these samples were measured using the configuration shown in Fig. 8. Fig. 9 shows the results.

Fig. 8 Configuration of light power measurement system

Fig. 9 Blue light intensity ratio B (%) and conversion efficiency C (%) measured using light power measurement system (sample thickness: 2.6 mm)

As shown, the conversion efficiency is almost constant but the blue intensity ratio data are relatively dispersed even though the phosphor thickness was fixed. This dispersion is caused by the nonuniform distribution of Ce ions in the YAG single-crystal boule. It is thus difficult to control the chromaticity coordinates for a Ce:YAG single crystal via the phosphor thickness.

4. Control of chromaticity coordinates using phosphor excitation density

Fig. 10 shows the beam density for the blue laser in the measurement system shown in Fig. 2. By changing the distance between the condenser lens and the focal point from 0 to 8 mm in increments of 1 mm, the excitation density for the phosphor could be controlled from 3.8 to 0.09 W/cm². Single-crystal samples nos. 2, 6, 8, and 11 were excited using various lens positions to evaluate the influence of excitation density on the illuminating light color. Fig. 11 shows the blue light intensity ratio versus lens position.

Fig. 10 Relationship between beam density for blue laser in measurement system shown in Fig. 2 and lens position.

Fig. 11 Relationship between blue light intensity ratio and lens position (lens position controls blue excitation density) for various samples

As shown, the blue intensity ratio is proportional to the lens position. The chromaticity coordinates can thus be finely and systematically controlled by adjusting the lens position (Fig. 12).

Fig. 12 Chromaticity coordinates at each lens position and predicted chromaticity coordinates at 0.01-mm intervals of phosphor thickness (shown as dots in figure)

The chromaticity coordinates for various phosphor thicknesses (interval of 0.01 mm) were calculated from the predicted spectra based on the approximated linear dependence of the blue light intensity ratio and conversion efficiency on thickness shown in Fig. 7. The chromaticity coordinates can be shifted by also adjusting the lens position in intervals of 0.01 mm. Accordingly, by adjusting the excitation density for the phosphor, the chromaticity coordinates can be continuously, minutely, and arbitrarily controlled.

5. Red laser assist effect

Although the chromaticity coordinates can be controlled by adjusting the excitation density for the phosphor, the coordinates still deviated from the blackbody locus. To move them closer to the blackbody locus, a red laser (635 nm) was combined with the blue excitation laser. The previous tests were repeated with the intensity of the red laser varied from 0 to 26 mW.

Fig. 13 shows a representative spectrum of sample no. 8 irradiated by blue and red laser light. Fig. 14 shows the chromaticity coordinates for various lens positions and red laser intensities for samples nos. 2, 6, 8, and 11. Fig.
15 shows that the CCT for each sample was close to the blackbody locus (within Duv ± 5).

In contrast, adjusting the excitation density for the phosphor allowed arbitrary and fine control of the chromaticity coordinates. In addition, the chromaticity coordinates could be moved closer to the blackbody locus by adding a red laser. For the prepared Ce:YAG samples, the CCT ranged from about 2600 to 7000 K.

With a uniformly transparent phosphor, the chromaticity coordinates and CCT can be more continuously, minutely, and arbitrarily controlled by tuning the excitation density and red laser intensity.

The proposed method is limited to transmission-type laser excitation light sources. However, the results demonstrate the possibility of obtaining an arbitrary color temperature by adjusting the excitation density for the phosphor and the laser intensity. This method could be applied to a laser light system in which the CCT could be adjusted without the need to physically change the phosphor.

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**References**


