Flicker Suppression of AC Driven White LED by Yellow Persistent Phosphor of Ce^3-Cr^3 Co-doped Garnet

Asami, Kazuki; Ueda, Jumpei; Tanabe, Setsuhisa

Asami, Kazuki ...[et al]. Flicker Suppression of AC Driven White LED by Yellow Persistent Phosphor of Ce^3-Cr^3 Co-doped Garnet. Journal of Science and Technology in Lighting 2017, 41: 89-92

Journal of Science and Technology in Lighting Vol.41, 2017

J-STAGE Advanced published date: June 23, 2017, doi: 10.2150/jstl.IEIJ160000599

Paper

Flicker Suppression of AC Driven White LED by Yellow Persistent Phosphor of Ce^{3+}–Cr^{3+} Co-doped Garnet

Kazuki ASAMI †, Jumpei UEDA and Setsuhisa TANABE

Kyoto University, Graduate School of Human and Environmental Studies

Received December 6, 2016, Accepted March 1, 2017

ABSTRACT

The alternative current driven light emitting diode (AC-LED) lighting system has attracted a great deal of attention because of the high luminous efficiency and the simple electric circuit. However, this system causes the unacceptable flicker due to rapid fluctuations in the voltage of the power supply. In order to compensate the flicker effect in AC-LED, we proposed the use of yellow persistent luminescent garnet phosphors. The time evolution of luminescence intensity measurement of Ce^{3+} and Cr^{3+} co-doped $Gd_3Al_2Ga_3O_{12}$ phosphor using a modulated blue laser diode was performed. From this measurement, the flicker percent of Ce^{3+} and Cr^{3+} co-doped $Gd_3Al_2Ga_3O_{12}$ phosphor is calculated and showed to be about 60%. This result demonstrated that persistent phosphor is expected to solve the problem of flicker caused in AC-driven LED lighting system.

KEYWORDS: flicker, AC driven LED, persistent luminescence, cerium, garnet phosphor

1. Introduction

Nowadays, white-LEDs driven by direct current (DC) are widely used in the commercial LED market. In order to use a DC-LED, the alternating current (AC) grid supply should be converted into DC. There are some converting methods, such as a transformer system and a switching system. However the transformer generates massive heat, which would cause degradation of embedded organic resins and phosphors on the LED chip[1]. In the switching system, while the heat generation can be reduced, some other problems such as the noise of frequency and complexity of electric circuit arise. Recently, AC driven LED (AC-LED) system attracts the industry attention because of the possibility to overcome these disadvantages[2, 3]. This device can operate directly by the grid power without the AC to DC converter. AC-LED system consists of two strings of diodes that are connected to the power in parallel with opposite polarity. On the half-cycle of AC frequency, one line of the diode strings conducts and generates light, while on the other half-cycle the other line of LEDs works. The AC-LED lighting system has tremendous advantages (e.g., lower cost, higher energy utilization efficiency, compact volume and longer service life), however, it causes unacceptable flicker when powered from AC line current[4]. In the psychophysics of vision, the concept of flicker fusion threshold is defined as frequency at which an intermittent light stimulus appears to be completely steady to the observer. The human flicker fusion threshold is usually taken between 60 Hz and 90 Hz[5, 6]. Therefore, the human visually recognizes the flicker effect under the AC-LED device illumination driven by frequency below 90 Hz. The effect may cause photosensitive epilepsy, migraines, and headaches for certain human beings. In this context, the suppression of flicker effect in the AC-LED device is a challenge.

Many different solutions were proposed to reduce flicker from AC-LED system such as the designing of the circuit[7], increasing the output frequency with a light ballast[8] and applying multiphase power system[9]. Recently, the flicker suppression using persistent phosphors of $Gd_3Al_2Ga_3O_{12}$: Ce^{3+} garnet and $Mg_3Y_2(Ge,Si)_3O_{12}$: Ce^{3+} inverse garnet have been reported by Lin et al.[10, 11]. Persistent luminescence is an optical phenomenon in which phosphor exhibits emission of light for long time after ceasing of the excitation light. It is used for luminous paints, emergency signs and clock dials. Using persistent phosphors for the AC-LED devices instead of non-persistent phosphors, the decrease of the light output by the periodic change of the AC voltage can be suppressed by steady persistent luminescence.

Recently, we successfully developed orange and long persistent luminescence in Ce^{3+} and Cr^{3+} co-doped $Gd_3Al_2Ga_3O_{12}$ phosphor based on the crystal field and bandgap engineering[12–14]. Generally, Ce^{3+}-doped garnet phosphors such as $Y_3Al_5O_{12}$: Ce^{3+} (YAG: Ce^{3+}) show visible luminescence of few tenths nanosecond lifetime due

---

[†] Corresponding Author: Kazuki Asami asami.kazuki.68m@st.kyoto-u.ac.jp

doi: 10.2150/jstl.IEIJ160000599

to the 4f–5d allowed transition of Ce^{3+} 15). In the case of persistent phosphor such as $Gd_3Al_2Ga_3O_{12}$: Ce^{3+}–Cr^{3+}, the electrons can be excited to the traps formed by impurity ions (e.g., Cr^{3+}) by blue light, and then trapped electrons are released gradually and the luminescence continues for long durations from several minutes to hours.

In this study, we measured the time evolution of luminescence intensity in $Gd_3Al_2Ga_3O_{12}$: Ce^{3+}–Cr^{3+} persistent phosphor (GA2G3*G*: Ce–Cr) using a modulated blue laser diode (LD) and investigated the suppression of flicker effect from the AC-driven LED lighting system.

2. Experimental

2.1 Fabrication of samples

Ceramic phosphor of $Gd_3Al_2Ga_3O_{12}$ doped with 0.2 mol% Ce^{3+} and 0.03 mol% Cr^{3+} (GA2G3*G*: Ce–Cr) was fabricated by a solid-state reaction method using high-purity chemicals of Gd_2O_3, Al_2O_3, Ga_2O_3, CeO_2 and Cr_2O_3 as starting materials. These mixed powders were compacted to form a ceramic tablet (ϕ10 mm×2 mm thickness) under uniaxial pressing of 50 MPa. The tablets were sintered at 800°C for 60 h in air for calcination and at 1600°C for 10 h in air. The sample was identified as a single phase of garnet structure by X-ray powder diffraction12). As reference material, 0.2 mol% Ce^{3+} singly doped $Gd_3Al_3Ga_2O_{12}$ phosphor (GA3G2*G*: Ce) was also prepared by the same method. GA3G2*G*: Ce has high quantum efficiency in $Gd_3(Al,Ga)_5O_{12}$ system and hardly shows persistent luminescence16).

2.2 Time evolution of luminescence intensity measurement

The schematic diagram of the set-up used for the time evolution of luminescence intensity measurement is shown in Figure 1. As excitation source, a 442 nm laser diode (LD) was used. Irradiance of the blue LD was adjusted to 100 μW/cm² using a ND filter. The phosphors were irradiated by the modulated blue LD which was also modulated by a function generator. For the persistent luminescence decay measurement, the modulation frequency was set to 10 Hz with a duty cycle of 1:9. For the measurement of the suppression of the AC flicker effect, the modulation frequency is 50 Hz with a duty cycle of 5:5. The time evolution of luminescence was measured by a silicon detector with a 455 nm short-cut filter to collect Ce^{3+}: 5d–4f luminescence and monitored by an oscilloscope.

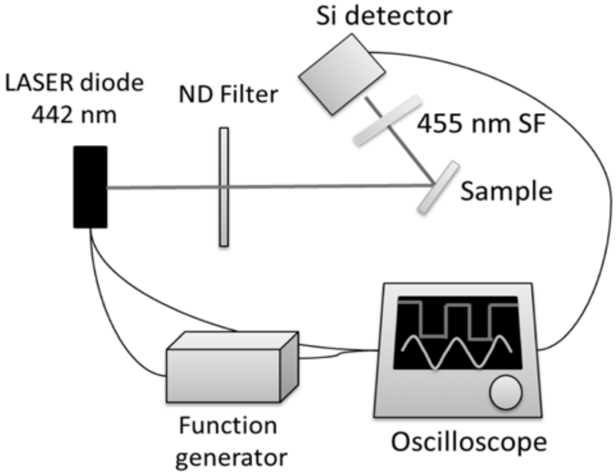

Figure 1 Schematic diagram of the set-up used for the time evolution of luminescence intensity measurement system.

3. Results and discussion

3.1 Persistent luminescence decay curve in millisecond range

Figure 2 shows the persistent luminescence decay curves of GA2G3*G*: Ce–Cr and GA3G2*G*: Ce samples of in millisecond range. During blue light irradiation for 10 ms (i.e., blue area in Figure 2, both samples show the visible photoluminescence. The photoluminescence intensity of GA3G2*G*: Ce sample is much stronger than that of GA2G3*G*: Ce–Cr samples. However, after ceasing blue light (i.e., white area in Figure 2), the persistent luminescence intensity of GA2G3*G*: Ce–Cr sample becomes stronger than that of GA3G2*G*: Ce sample. This result shows that the GA2G3*G*: Ce–Cr sample is a good persistent phosphor in the millisecond range for flicker suppression as well as the hour range for emergency

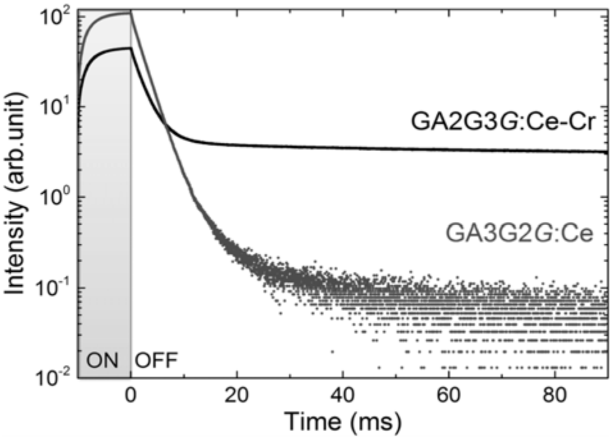

Figure 2 Persistent luminescence decay curves in millisecond order of GA3G2*G*: Ce and GA2G3*G*: Ce–Cr samples. The time range colored by blue shows the blue light irradiating phase.

Table 1 Fitting parameters of luminescence decay curves of GA3G2*G*: Ce and GA2G3*G*: Ce–Cr samples.

Sample	A_1	τ_1 (ms)	A_2	τ_2 (ms)
GA3G2*G*: Ce	100.6	2.19	3.14	7.7
GA2G3*G*: Ce–Cr	39.4	2.31	3.97	353.9

doi: 10.2150/jstl.IEIJ160000599

signs[12]. From the persistent decay curves, the curves are composed of two decay components. Therefore, the decay curve was fitted by a biexponential function expressed as Eq. (1).

$$y = A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right) \tag{1}$$

The fitting parameters of GA3G2*G*: Ce and GA2G3*G*: Ce–Cr were summarized in Table 1. The first term of Eq. (1), the value of A_1 is related to photoluminescence intensity of each sample whereas the values of τ_1 in GA3G2*G*: Ce and GA2G3*G*: Ce–Cr are almost the same. From these parameters, this term is inferred to be the rapid decay of persistent luminescence. In the second term, the parameter A_2 of GA2G3*G*: Ce–Cr is slightly larger than that of GA3G2*G*: Ce. In addition, the parameter τ_2 of GA2G3*G*: Ce–Cr is about 46 times longer than that of GA3G2*G*: Ce due to persistent luminescence. The second term is inferred to contribute the suppression of flicker.

3.2 Time evolution of luminescence intensity measurement

In Figure 3, the time evolution of luminescence intensity of blue-LD with GA2G3*G*: Ce–Cr and GA3G2*G*: Ce samples in AC periodic cycles is reported. During the blue light irradiation (blue area in Figure 3), the maximal intensity of GA3G2*G*: Ce is about twice stronger than that of GA2G3*G*: Ce–Cr because of different quantum efficiency[16]. However, when blue-LD irradiation was ceased (white area in Figure 3), the minimal intensity of GA2G3*G*: Ce–Cr sample is about 7.5 times stronger than that of GA3G2*G*: Ce.

This is because that Ce^{3+} persistent luminescence of GA2G3*G*: Ce–Cr is much stronger than that of GA3G2*G*: Ce. From these results, it is concluded that GA2G3*G*: Ce–Cr persistent phosphor can suppress the flicker effect of the AC-driven LED device. In order to discuss the efficiency of suppression, the flicker percent (δ) was calculated using Eq. (2), where $I_{\max}$ and $I_{\min}$ represent the maximal and minimal luminescent intensity, respectively[17].

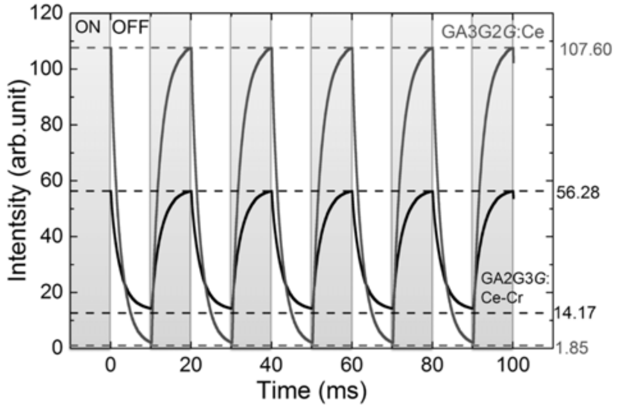

Figure 3 The time evolution of luminescence intensity of a blue LD with GA3G2*G*: Ce and GA2G3*G*: Ce–Cr samples in AC periodic cycles. Blue/White areas correspond to the on/off phases of a blue LD, respectively.

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \times 100 \tag{2}$$

In the AC-LED lighting with non-persistent phosphors, the flicker percent can be expected to be 100% because of $I_{\min}=0$. From the values of $I_{\max}$ and $I_{\min}$ of samples in Figure 3, the flicker percent of GA3G2*G*: Ce and GA2G3*G*: Ce–Cr samples are calculated and showed to be 96.6% and 59.8%, respectively. Based on the flicker percentage, it is found that the GA3G2*G*: Ce does not suppress the flicker. On the other hand, the flicker percent of GA2G3*G*: Ce–Cr (59.8%) is much lower than 100%, so that it is concluded that GA2G3*G*: Ce–Cr strongly suppressed the flicker by the intense persistent luminescence. In addition, compared with the previous reports of the flicker percentage in the system of YA*G*: Ce^{3+} and $Gd_3Al_2Ga_3O_{12}$: Ce^{3+} phosphors in glass (69.0%) and the system of $Mg_3Y_2(Ge,Si)_3O_{12}$: Ce^{3+} phosphor in silicone (71.7%) by Lin et al.[10, 11], our GA2G3*G*: Ce–Cr shows the higher performance for the flicker suppression. Therefore, GA2G3*G*: Ce–Cr phosphor possesses a potential for suppression of the flicker effect in the actual AC-driven LED lighting system.

4. Conclusions

The time evolution of luminescence intensity in $Gd_3Al_2Ga_3O_{12}$: Ce^{3+}–Cr^{3+} phosphor using a modulated blue LD was investigated. When blue-laser excitation was ceased, the minimal intensity of $Gd_3Al_2Ga_3O_{12}$: Ce^{3+}–Cr^{3+} is about 7.5 times stronger than that of $Gd_3Al_3Ga_2O_{12}$: Ce^{3+}. The flicker percent of $Gd_3Al_2Ga_3O_{12}$: Ce^{3+}–Cr^{3+} phosphor was calculated and showed to be about 60%. The suppression of flicker effect in $Gd_3Al_2Ga_3O_{12}$: Ce^{3+}–Cr^{3+} is much larger than that of $Gd_3Al_3Ga_2O_{12}$: Ce^{3+}. This result demonstrated that persistent phosphor might be a good candidate to suppress the flicker effect caused in AC-driven LED lighting system.

References

(1) Zhang, R., Lin, H., Yu, Y., Chen, D., Xu, J. and Wang, Y.: A new-generation color converter for high-power white LED: Transparent Ce^{3+}: YAG phosphor-in-glass, Laser Photonics Rev., 8-1, pp. 158–164 (2014).

(2) Onushkin, G. A., Lee, Y. J., Yang, J. J., Kim, H. K., Son, J. K., Park, G. H. and Park, Y. J.: Efficient alternating current operated white light-emitting

doi: 10.2150/jstl.IEIJ160000599

diode chip, IEEE Photonics Technol. Lett., 21-1, pp. 33–35 (2009).

(3) Yen, H. H., Yeh, W. Y. and Kuo, H. C.: GaN alternating current light-emitting device, Phys. Status Solidi., A Appl. Mater. Sci., 204-6, pp. 2077–2081 (2007).

(4) Schottky, W.: Small-shot effect and flicker effect, Phys. Rev., 28-1, pp. 74–103 (1926).

(5) Farrell, J. E., Benson Brian, L. and Haynie Carl, R.: Predicting flicker thresholds for video display terminals, Proc. SID., 28, pp. 449–453 (1987).

(6) Davis, J., Hsieh, Y. H. and Lee, H. C.: Humans perceive flicker artifacts at 500 Hz, Sci. Rep., 5-1, p. 7861 (2015).

(7) Tan, J. and Narendran, N.: An approach to reduce ac led flicker, J. Light & Vis. Env., 38, pp. 6–11 (2014).

(8) Mulay, A., Tribedi, M., Vijayalakshmi, R. and Shennai, K.: Switching dynamics of power bipolar transistor in high-frequency electronic ballast, IEEE Ind. Applicat. Conf., 3, pp. 2130–2136 (1998).

(9) Doshi, M. and Zane, R.: Control of solid-state lamps using a multiphase pulse width modulation Technique., IEEE Trans. Power Electron., 25-7, pp. 1894–1904 (2010).

(10) Lin, H., Wang, B., Xu, R. J., Zhang, R., Chen, H., Yu, Y. and Wang, Y.: Phosphor-in-glass for high-powered remote-type white AC-LED, ACS Appl. Mater. Interfaces, 6-23, pp. 21264–21269 (2014).

(11) Lin, H., Xu, J., Huang, Q., Wang, B., Chen, H., Lin, Z. and Wang, Y.: Bandgap tailoring via si doping in inverse-garnet $Mg_3Y_2Ge_3O_{12}$: Ce^{3+} persistent phosphor potentially applicable in AC-LED, ACS Appl. Mater. Interfaces, 7-39, pp. 21835–21843 (2015).

(12) Asami, K., Ueda, J. and Tanabe, S.: Trap depth and color variation of Ce^{3+}–Cr^{3+} co-doped $Gd_3(Al,Ga)_5O_{12}$ garnet persistent phosphors, Opt. Mater., 62, pp. 171–175 (2016).

(13) Ueda, J., Kuroishi, K. and Tanabe, S.: Bright persistent ceramic phosphors of Ce^{3+}–Cr^{3+}-co-doped garnet able to store by blue light, Appl. Phys. Lett., 104-10, pp. 3–7 (2014).

(14) Ueda, J., Dorenbos, P., Bos, A. J. J., Kuroishi, K. and Tanabe, S.: Control of electron transfer between Ce^{3+} and Cr^{3+} in the $Y_3Al_{5-x}Ga_xO_{12}$ host via conduction band engineering, J. Mater. Chem. C, 12-22, pp. 5642–5651 (2015).

(15) Blasse, J. and Bril, A.: Investigation of some Ce^{3+}-activated phosphors, J. Chem. Phys., 47-39, pp. 5139–5145 (1967).

(16) Ogiegło, J. M., Katelnikovas, A., Zych, A., Jüstel, T., Meijerink, A. and Ronda, C. R.: Luminescence and luminescence quenching in $Gd_3(Ga,Al)_5O_{12}$ scintillators doped with Ce^{3+}, J. Phys. Chem. A, 117-12, pp. 2479–2484 (2013).

(17) Illuminating Engineering Society of North America. In The IESNA Lighting Handbook, 9th ed., Rea, M. S., Eds., Illuminating Engineering Society, New York (2000).

All or part of this work was presented at 15th International Symposium on the Science and Technology of Lighting (LS15), May 2016, Kyoto, Japan.