TITLE: Characteristics of High-Efficient InGaN-Based White LED Lighting

Characteristics of high-efficient InGaN-based white LED lighting

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ABSTRACT

The basic illumination characteristics of an efficient white LEDs lighting source, which is composed of cannon-ball type 10 cd-class InGaN-based white LEDs, are described. It is noted that the temperature and forward-bias current dependence under full wave rectification of AC 100 V gives a significant effect to both electroluminescence properties and luminous efficacy. We have obtained a maximum luminous intensity of 95000 cd/m^2 and a luminous efficacy of about 27 lm/W at an electric power of 20 W (at a constant current of 10 mA). The developed white LEDs lighting source indicates two injection electroluminescence peaks at 465 and 555 nm, which are originated from a blue LED and a YAG:Ce^{3+} phosphor, respectively. The illuminance distribution of the LED lighting source was analyzed using our "multi sources of LED light" theory. We have performed the design of a street lighting as the practical application using the 700 LEDs array lighting source.

Keywords: InGaN, white LED lighting, YAG phosphor, luminous efficacy, LED lighting theory

1. INTRODUCTION

Visible and white light-emitting diodes (LEDs) are ideal for a large number of applications including illumination, displays and signage, with advantageous properties such as high-brightness, reliability, long lifetime and low power consumption.[1] Recently, there is a growing interest in shorter wavelength blue and ultraviolet LEDs for high-brightness white–light LEDs together with phosphor coating.[2] A 10 Cd class white LED composed of a multiple quantum well (MQW) InGaN blue LED and a YAG:Ce phosphor has been developed.[3, 4] A structure of the white lighting source has been obtained by the integration of the blue InGaN LED die and the YAG phosphor into a single package. We have reported the improved luminous efficacy of about 40 lm/W using 700 LEDs lighting source at an electric power of 5 W.[3] It has been expected that extremely high-brightness white LEDs can significantly replace standard incandescent bulbs usually used in hospitals, hotels and airplanes. We have already demonstrated an energy saving type street lamp linked with a photovoltaic solar cell, using a 10 cd-class white LEDs array lighting source.[4, 5] These applications are extremely useful for saving electric power owing to lower energy consumption of LEDs.[1]

In this paper, we will describe for the first time the basic illumination characteristics of high-efficient InGaN-based white LEDs array lighting source. The temperature and forward-bias current dependence which gives a significant effect to both electroluminescence properties and luminous efficacy has extensively been investigated. In spite of strong polar and linear radiation intensity profiles from a cannon-ball type LED, we will analyze the distribution of illumination intensities from the LEDs array using the " multi sources of LED light" theory which has recently been developed by our group.[6]

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2. EXPERIMENTAL PROCEDURES

2. 1 White LED device

Table I shows the characteristics of the InGaN-based multiple quantum well (MQW) white LED together with YAG:Ce phosphor.[5] The white LED structure in a cannon-ball type consists of InGaN/GaN MQW LED and YAG:Ce phosphor in a single package. An external quantum efficiency is over 20 %. A luminous efficacy for a chip is estimated to be approximately 20 lm/W at a forward-bias current of 20 mA at room temperature. The operation lifetime is expected to be over 20000 hrs. The white LED used in the present experiment has a luminous intensity of 10 candela.

Table I Basic properties of a InGaN-MQW white LED

Output Powre	~10mW
External quantum efficiency	>20%
Luminous Efficacy	>20lm/W
Chromaticity coordinate	(0.31,0.32)
Color temperature	6500K
General color rendering index	Ra=85
Response time	120ns
Life time	>20000hr

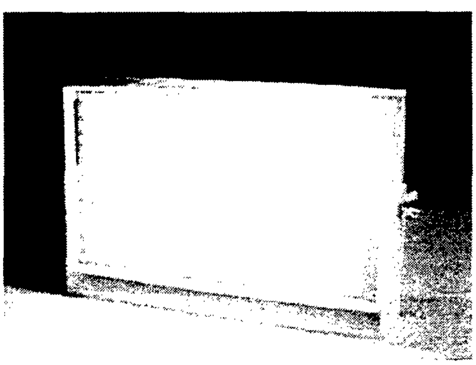

Fig. 1 A practical view of white LEDs lighting

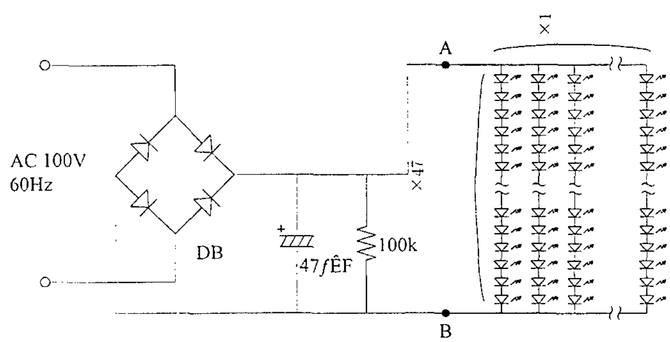

Fig. 2 A condenser-input type electric circuit

2. 2 White LEDs array lighting source and driving electric circuit

Figure 1 shows a typical example of a white LEDs array lighting source, where 705 pieces LEDs are composed by a 15 LEDs parallel connection with each 47 LEDs series connection block. Fig. 2 shows a typical driving electric circuit for the LEDs array lighting device, where a condenser-input type rectification circuit was used (AC 100 V supply and 60 Hz). A basic electric circuit consists of a diode bridge circuit, and a smoothing circuit with a 47 μF condenser and a 100 kΩ resistance in order to obtain full wave rectification voltages between 143 and 126 V at 120 Hz. The maximum and minimum current was then about 17 and 3 mA, respectively. We obtained a maximum luminance of about 95000 cd/m^2 at electric power of about 20 W, and obtained a maximum illuminance as high as 10000 lx at a distance of 30 cm from the present LEDs array. The size of LEDs array has a 230 × 180 mm^2 area.

2.3 Evaluation of lighting source

Temperature dependence of the emission spectra of a white LED under a forward bias DC or AC current of 20 mA was measured using a CCD camera in conjunction with a 50 cm single grating monochromator. A temperature variable cryostat was used for the measurement. A chromatic point in the CIE chromatocity diagram, luminous intensity and color temperature were evaluated by a luminance and illuminance meter using a Si photodiode.

3. RESULTS AND DISCUSSION

3. 1 Basic properties of a cannon-ball type white LED

Usually, a LED is operated under a forward-bias direct current (DC) and a cannon-ball type white LED has already been used as an indicator and displays in general. As mentioned in 2. 1, a white LED is made of a particular type of blue LED covered with a YAG:Ce phosphor. The white color is produced by a mixture of blue and yellow colors, which generate from an InGaN-MQW blue LED (465 nm) and a Ce^{3+} emission (555 nm), respectively. In spite of tremendous applications to optoelectronic devices using the white LEDs under the DC bias condition, there have been nothing reports on the characteristic of white LEDs under the AC and pulse-biased conditions.

3. 2 Temperature and forward-biased current dependence of illumination characteristics

Figure 3 shows the temperature dependence of the forward biased electroluminescence (EL) spectra of a cannon-ball type white LED between 20 and 160 ℃. An emission peak at 465 nm at room temperature (RT) originates from a blue LED. An yellow emission at 555 nm with a bandwidth of about 150 nm is generated by an excitation of a Ce^{3+} center whose excitation wavelength exists near 460 nm. It is thought that energy from the 465 nm excitation band can be trapped at the Ce^{3+} ion and emits as cerium yellow emission at 555 nm. With increasing temperature, the 465 nm peak moves towards longer wavelength, which is similar to the temperature dependence of band gap energy of InGaN semiconductor.[1] On the other hand, the 555 nm peak position did not change with temperature. Due to the change in the emission peak wavelength of the blue LED with temperature, the effective excitation efficiency for YAG phosphor is decreased. As a result, the emission intensity of the 555 nm band becomes weak at 160 ℃. It is therefore suggested that the emission properties of the InGaN white LED depends upon the temperature, and that an emission efficiency of the yellow band at 555 nm becomes weak above 50 ℃.

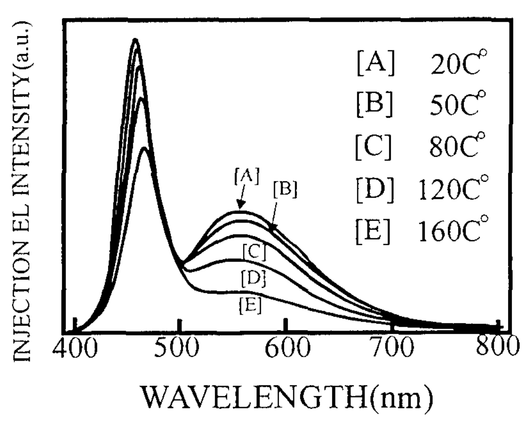

Fig. 3 Temperature dependence of EL spectra [A~D] of a white LED device between 20 and 160 ℃.

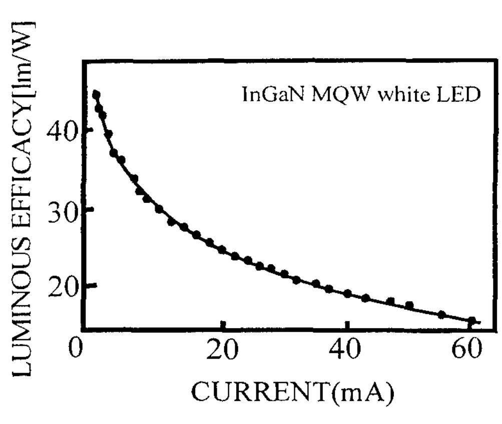

Fig. 4 Luminous efficacy of a white LED chip as a function of forward-bias current.

Figure 4 shows the characteristics of luminous efficacy of a 10 cd class white LED chip as a function of forward-bias current. The onset for the white emission starts from a forward-bias current of about 9×10^{-2} mA. At 1 mA, the luminous efficacy is estimated to be about 45 lm/W. However, the luminous efficacy is estimated to be about 27 and 23 lm/W at a constant forward-bias current of 10 and 20 mA, respectively. The evidence which indicates the high luminous efficacy at low currents is related to an increase in the internal quantum of the blue LED itself. This behavior is quite different from that of AlGaAs red and AlInGaP amber LEDs.[1] However, the detailed physical process is still unknown at present.

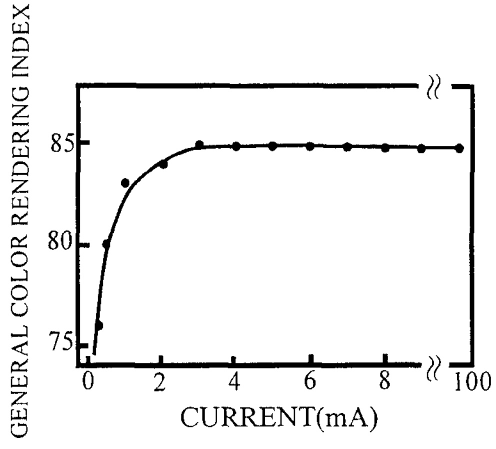

Fig. 5 General color rendering index of a white LED as a function of forward-bias current.

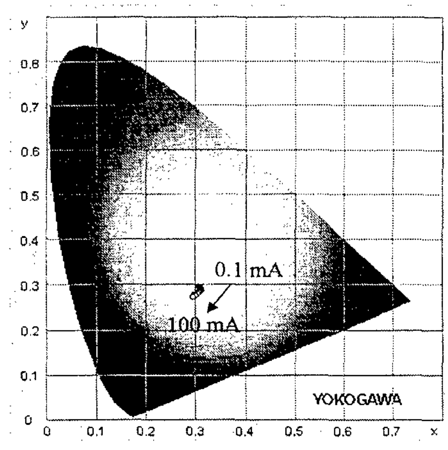

Fig. 6 Changes in (x,y) chromaticity coordinates of the chromatocity between 0.1 and 100 mA

Figure 5 shows the general color rendering index (Ra) of a white ED as a function of forward-bias current. Between 0.1 mA and 3 mA, the Ra gradually increases, but over 3 mA the Ra is nearly constant and kept to be 85, which is very good color index for all possible general lighting applications.

Figure 6 describes the experimental plots in (x,y) choromaticity coordinates of choromatocity between 0.1 and 100 mA. As seen in this figure, the changes in x- and y-coordinate lines are extremely small, so that the white LED indicates a good characteristic which is possible for high current operation.

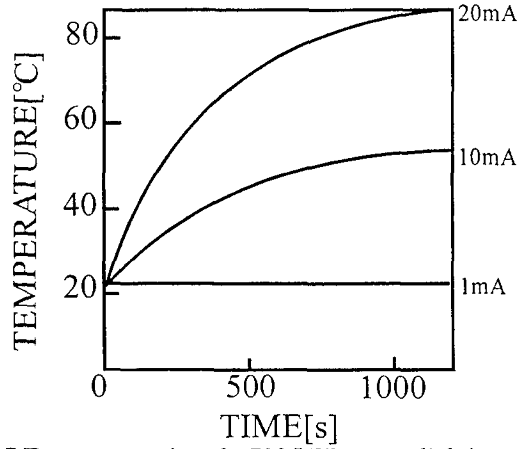

Fig. 7 Temperature rise of a 700 LEDs array lighting source at three different forward currents (1, 10 and 20 mA) as a function of driving time.

Figure 7 shows the temperature rise of a 700 LEDs lighting source at three different forward currents (1, 10 and 20 mA) as a function of driving time. At 1 mA, the temperature rise can not almost be observed with time. As has already been shown in Fig. 4, the luminous efficacy is high, so that the efficiency of the LED lighting device is extremely good. At 10 mA, the efficacy is decreased to be about 28 lm/W and the temperature rise gradually occurs with time. Finally, the temperature of the LED array rises up to 50 ℃ without cooling system after 3 hrs. When the forward current is 20 mA, the temperature rise is significant and after 2 hr the temperature of the LED array is over 80 ℃ without cooling system. Such situation is extremely worse for operating the LED lighting array during a long time and as a result degradation of the LED array may occur. The luminous intensity of the LED array at 20 mA for about 3 hrs operation is decreased by 20 % of the initial value as shown in Fig.8.

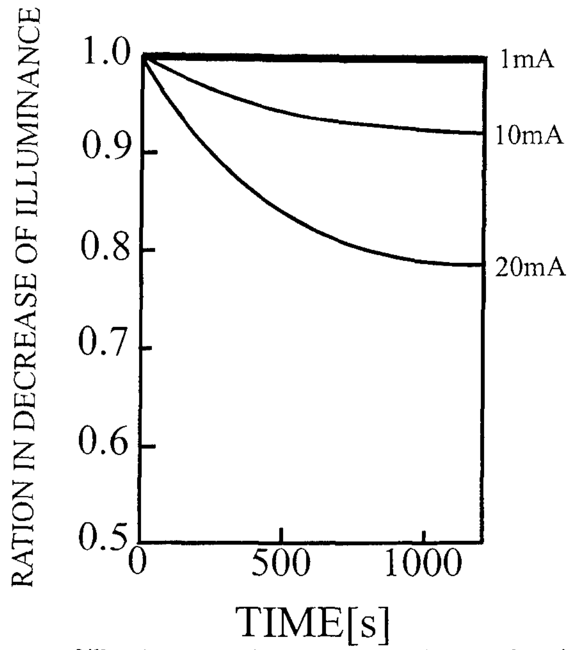

Fig. 8 Ratio in decrease of illuminance against the initial value as a function of time obtained at three different currents (1, 10 and 20 mA).

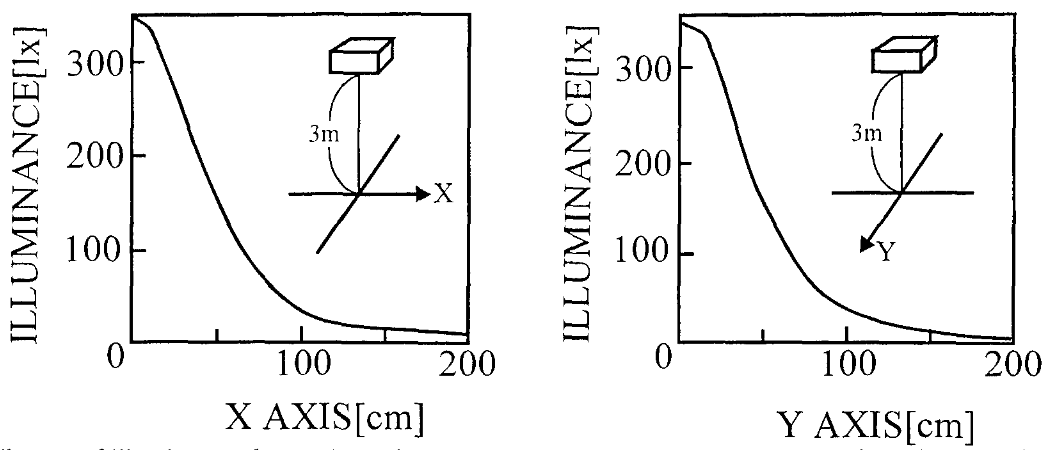

Fig. 9 Distribution of illuminance along x (a) and y (b) axial directions measured directly under a distance of 3 m from the white LED array source.

Figure 9 shows the distribution of illuminance along x (a) and y (b) axial directions measured directly under a distance of 3 m from the white LED array source (same as used in Fig. 7). This LED lighting device was operated at a constant current of 10 mA. At a center of (x , y) coordinates, the illuninance is estimated to be about 350 lx. At a 50 cm distance separated from the center, the luminous intensity is estimated to be 150 lx. The intensity distribution along x or y axis is equal and indicates the homogenous distribution character of the illumination intensity along x and y direction. This LEDs lighting source is applicable to the practical street lamp instead of white fluorescent lamp, and seems suitable for local lighting.

3. 3 A comparison between the experimental results and our theoretical LEDs lighting model

It is necessary to establish a new theory for calculating illuminance when an lighting array device constructed using many cannon-ball type LEDs is designed, because the LED is the exponential intensity source ($\cos^n \theta$ source).

As shown in Fig. 10, assuming that there are many LED light sources which are arranged by following the lattice- and circular- like configuration on the flat plate, the illumination at a search point of L in the (x, y, z) space can be calculated by the following equation,

$$E(x, y, z) = \sum_{i=1}^{n} \frac{I_i(\theta_i)}{r_i^2} \cos(\theta_i)$$

when i is a suffix for arbitrary position of LED light source and $r_i^2 = (x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2$. We can calculate a polar and linear intensity profile of many LEDs by the inverse square (r^{-2}) law, and the illuminance is expressed by a cos component for a vertical direction. In order to understand how to arrange suitable LED light sources between 1 and n, we developed a basic algorithm for LEDs arrangement.[6] Fig.11 shows a typical configuration for n = 4 including the lattice-and circular-like arrangement.

Fig. 12 shows the calculated result of illuminance of multi LED sources as a function of x and y distance from a center directly under a distance of 3 m from the LEDs lighting array used. The obtained results are in quantitatively good agreement with the experimental characteristics described in Figs. 8 (a) and (b).

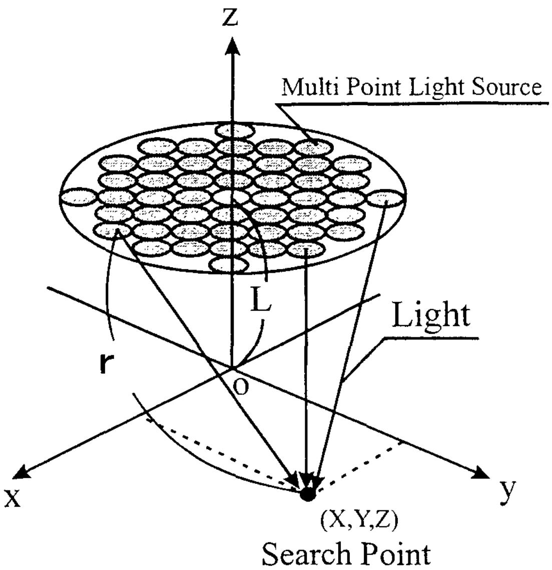

Fig. 10 A "multi source of LED light" model for the calculation.

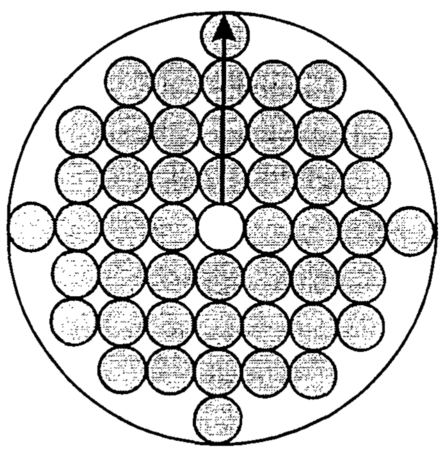

Fig. 11 A typical configuration of multi LED sources for n = 4

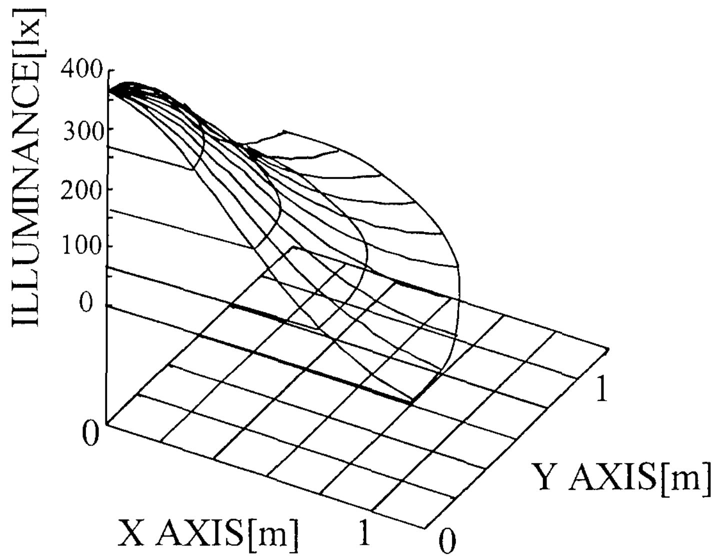

Fig.12 Calculated illuminance along x and y axial direction for a LEDs lighting source.

4. SUMMARY

The basic illumination characteristics of an efficient white LEDs lighting source, which is composed of cannon-ball type 10 cd-class InGaN-based white LEDs, have been extensively investigated. It is revealed that the temperature and forward-bias current dependence under full wave rectification of AC 100 V gives a significant effect to both electro luminescence properties and luminous efficacy. We have obtained a maximum luminous intensity of 95000 cd/m^2 and a luminous efficacy about 27 lm/W at an electric power of 20 W (at a constant current of 10 mA). The developed white LEDs lighting source indicates two injection electroluminescence peaks at 465 and 555 nm, which are originated from a blue LED and a YAG:Ce^{3+} phosphor, respectively. The illuminance distribution of the LED lighting source was analyzed using our theory on the basis of multi sources of LED light. We have constructed a street lamp as the practical application using the 700 LEDs array lighting source. The experimentally obtained illumination characteristics are well interpreted in terms of our LEDs lighting theory.

Acknowledgements

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