Study on laser-based white light sources

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ABSTRACT

We reported on the design, demonstration, and analysis of white lighting systems based on GaN laser diodes. Compared to light-emitting-diodes (LEDs), lasers have been proposed for the development of high-power light sources for many potential advantages, including circumventing efficiency droop, reduced light emitting surface, directional beam characteristics. Laser-based white light sources are also attractive for visible light communication (VLC) applications that enabling lighting and communication dual functionalities. In this work, we detailed the color-rendering index (CRI), correlated color temperature (CCT), and luminous flux analysis of laser white light sources by using the GaN laser diode exciting color converters at various driving conditions. By using a blue-emitting laser exciting a yellow YAG phosphor crystal, a luminous flux greater than 600 lm has been achieved with a moderate CRI of 67.2. By constructing a white lighting system using phosphor crystal array based on a reflection configuration, an improved CRI of 74.4 and a luminous flux of ~400 lm with a CCT of 6425 K was obtained at 3A. Using a novel ceramic phosphor plate as color converter, the CRI for the white light source has been further improved to ~84.1 with a CCT of ~4981 K, which suggests that the laser-based white light source is capable of high-quality illumination applications. The CCT of the white laser sources can be engineered from 5000 K to 6500 K and a potential approach to use laser array for high power white lighting is discussed.

Keywords: Gallium Nitride, laser diode, semiconductor laser, solid state lighting, light emitting diodes.

1. INTRODUCTION

Solid-state lighting (SSL) technology uses semiconductor light emitters, such as light emitting diodes (LEDs), offering a versatile and energy-efficient light source with high color stability and growing lumen efficacy [1-3]. White LED bulbs based on GaN LEDs have been successfully commercialized with the potential to be the dominant standard for general lighting since the cost of LED chips drops in the past decade [4-6]. Eventually, LEDs will likely take over many if not all indoor and outdoor lighting. Besides, LEDs are used for backlighting, display, and visible light communications. Recently, GaN-based laser diode (LD) has attracted increasing attention for enabling novel white light sources [7]. One of the critical driving forces is the potential to build compact, high intensity light bulb using lasers as LDs are not associated with “efficiency droop” effect. In LEDs, a significant drop in external quantum efficiency (EQE) is observed as operating current increases, which is known as “efficiency droop” [8, 9]. Since the carrier clamping in the cavity after threshold point of lasing [10], the EQE of LDs linearly increases with increasing operating current [11]. In addition, laser based white light source has many other potential advantages such as minimized light emitting surface, directional beam characteristics, and ultra-fast operation speed, making it promising for future smart lighting applications.

In 2013 and 2014, Wierer et al. and Tsao presented a detailed discussion and review on the advantage and potential of laser-based SSL. Since then, the utilization of laser for white light generation for various applications has been reported. For example, laser based solid-state light source for etendue-limited applications [12], automotive lighting applications [13], indoor lighting and communication (Li-Fi) [14] have been discussed. In particular, since GaN-based LDs have much higher modulation bandwidth than LEDs, LDs are becoming attractive to serve as the light emitter and signal transmitter in visible light communication systems [15-20]. More recently, LD based white light sources have been used for underwater lighting and wireless data communication [21]. Therefore, the study of high-intensity laser-based white lighting systems becomes an important topic for many emerging applications.

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In general, there are two approaches to generate white light using LDs, by directly mixing the light from three (or more) monochromatic sources, such as red, green and blue (RGB) LDs, or using violet-blue LD integrated with phosphors. Both approaches have advantages and challenges, but the later scenario is more widely studied due to its relatively simple structure and low cost.

1.1 Combination of RGB lasers

By combining red, green and blue laser beams, white light can be generated as illustrated in Figure 1. For smart lighting, the integration of RGB lasers offers great flexibility and enhanced lighting quality for display applications. Yang et al. reported a highly uniform white laser lamp based on RGB lasers [15]. By mixing RGB LDs to generate a white light beam with a correlated color temperature (CCT) of 6500K, Huang et al. demonstrated a white-light communication system with divergent diffuser optimization [22]. The potential to use RGB laser white light source for high-speed WDM communications in free space and underwater channels were also reported [16, 23]. However, white light based on combining RGB lasers are costly, partly due to the relatively low efficiency in green LDs and high cost in high power red LDs.

Figure 1. By combining the blue, green and red laser beam, white light source can be built. A diffuser was placed in front of the output to diffuse the white laser beam.

1.2 Blue laser with phosphors

Similar to the white LED or SLD lamp, a more practical approach to generate white light is using blue laser to excite yellow phosphors or mixture of two or more phosphors as color converters, as shown in Figure 2 [11, 24]. In 2015, Lee et al. presented a system that uses a blue gallium nitride LD to excite YAG:Ce phosphors to produce white light that has a CRI of 58 and the CCT of the produced light was found to be 4740 K [25]. Later, a number of research demonstrations have been reported for general illumination, projector, automotive and Li-Fi applications [20, 26-29]. Since the laser based white light bulb has the great potential for high intensity applications, there are growing research in developing color converters for laser based white lighting as the excitation power density is orders of magnitude higher than those in LED white lamps [27, 30-33].

In this work, we designed and demonstrated compact laser-based white light modules and discussed the approaches towards high quality and high power laser light sources. The presented laser white light modules can be configured as narrow beam emitter for long distance spot lighting and have promising potential to enable high-speed visible light communication links.

Figure 2. White light generated using blue LD exciting yellow phosphors. Part of the blue light is converted into the yellow portion of the white light after passing through the phosphor material while the unconverted blue light contributes to the blue portion of the white light spectrum.

2. EXPERIMENTS

Device 1 (SNWL-1) contains a 450 nm blue laser diode mounted on brass heatsink with a glass diffuser and a circular YAG:Ce crystal as color converter. The phosphor crystal was installed in front of the laser beam output and the generated white light, which is the combination of the transmitted blue light and the converted yellow emission, was directly emitted out of the device. Device 2 (SNWL-2) is constructed with the same blue laser and an array of square phosphor plates mounted on a brass heatsink with a 45° inclined plane as reflector. The 2*2 phosphor plate array was mounted on the surface of the slope reflector so white light can be generated in a reflecting configuration. Device 3 (SNWL-3) features a blue laser exciting the ceramic phosphor plate mounted on the brass heat sink using a reflecting configuration. The ceramic phosphor plate contains two phosphor materials, which emitting at green and red bands. Device 4 (SNWL-1a) contains 3 blue lasers mounted in one module with the circular YAG:Ce phosphor crystal. All the devices were tested without active cooling. A current source (Keithley 2420) is used to driver the laser. The testing was done using a 0.5m diameter integrating sphere connected to a lamp testing system (HOPOO HP8000). To evaluate the system's performance as an SSL lighting source, the factors considered are Color-Rendering Index (CRI) and Correlated Color Temperature (CCT). CRI evaluates the ability of the produced light to reveal colors while CCT describes the appearance of the white light. The luminous flux, power consumption and optical spectrum are measured at the same time. All the measurements were done at room temperature.

3. RESULTS AND DISCUSSIONS

The emission spectrum and CIE chromaticity diagram for device 1 at 3A is shown in Figure 3. The generated cool white light has a CRI of 67.2, CCT of 6391 K and a total luminous flux of 625 lm. In order to study the consistency of CRI and CCT at different injection currents, the changes of CRI and CCT at increasing injection currents are plotted in Figure 4. Since the laser has a threshold current of approximately 450 mA, the device was measured with injection ranging from 500 mA to 3A. The variation of CRI and CCT, i.e. the difference between maximum value and minimum value, is ~ 7.3 and ~ 550 K, respectively. The luminous flux at different injection currents can be found in Figure 5.

Figure 3. Emission spectrum and the CIE chromaticity diagram for device 1 at a driving current of 3A.

Figure 4. Changes of CCT and CRI as a function of driving current in device 1 (SNWL-1).

Figure 5. Luminous flux as a function of driving current in device 1 (SNWL-1).

We performed similar measurements for devices 2 and 3. The emission spectrum and CIE chromaticity diagram for device 2 at 3A is shown in Figure 6. Device 2 has a CRI of 74.4, CCT of 6425 K and a total luminous flux of 401 lm at 3A. In this configuration, the CRI has been increased at the cost of lower total luminous flux achieved compared with device 1. The variation of CRI and CCT is ~ 5.8 and ~ 530 K, respectively, which is slightly improved compared with device 1. For device 3, the CRI has been increased to 84.1 with a CCT of 4981 K at 2.5 A. The device shows a very stable CRI performance with a CRI variation as little as 2.9, making it very promising for high quality neutral white lighting applications. The luminous flux of 283 lm is measured at 2.5 A, which is lower than that of 357 lm in device 2.

Figure 6. Emission spectrum and the CIE chromaticity diagram for device 2 at a driving current of 3A.

To achieve high intense laser lighting system, we integrated 3 laser diodes in one device (SNWL-1a). At injection current of 3A, the device emits a total flux of 1606.8 lm. The measured CRI and CCT are 63.9 and 4179 K, respectively. The luminous efficacy at 3A is calculated to be 32.6 lm/W. This result indicates high intensity white light sources can be achieved using integrated GaN laser array configuration. The high-power white laser light sources presented in this work can also serve as the transmitter for high-speed data communications. Utilizing the devices studied, we have achieved a wireless data communication over 1 Gbps using on-off keying modulation technique, suggesting its attractive property for outdoor Li-Fi and long distance underwater optical communication applications.

4. CONCLUSIONS

In this paper, the recent progress in laser-based white lighting devices and systems have been discussed. Different designs towards high CRI, high intensity laser white lighting devices are demonstrated and measured. The CRI of laser-based white lighting system can be engineered from 67.2 to 84.1 and the CCT can be tuned from 5000 K to 6500 K. The luminous flux for a single laser based white lighting device can be as high as 600 lm and by integrating multiple laser diodes to assemble the laser array, a high-power white lighting system with a total flux exceeding 1600 lm can be achieved. Such white laser device as a high intensity light source will be useful for many emerging applications, such as outdoor lighting, projection, and high-speed visible light communications.

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