IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 2, April 2018

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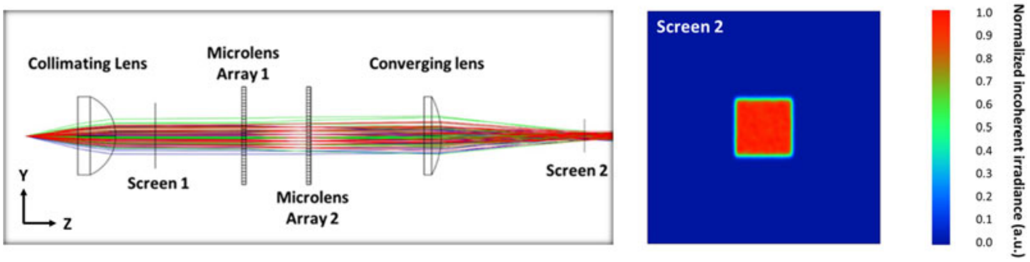

DOI: 10.1109/JPHOT.2018.2802933
1943-0655

IEEE photonics SOCIETY
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Highly Uniform White Light-Based Visible Light Communication Using Red, Green, and Blue Laser Diodes

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DOI:10.1109/JPHOT.2018.2802933

Manuscript received December 24, 2017; revised January 29, 2018; accepted February 2, 2018. Date of publication February 15, 2018; date of current version February 21, 2018. This work was supported by the National Key Research and Development Program of China under Grant 2017YFB0403803. Corresponding author: Zhe Liu (e-mail: liuzhe@semi.ac.cn).

Abstract: With the development of wireless optical communication and solid-state lighting, the high efficiency, large bandwidth, and high uniform white light source becomes more and more important. In this paper, a white light source generated by red, green, and blue laser diodes (RGB LDs) was synthetized according to the calculated power ratio of RGB LDs based on the chromaticity theory. The high coherence of the lasers normally leads to the nonuniform white light. Thus, it is to improve the illumination quality of the lighting source by employing micro lens for the purpose of homogenization. The simulation results showed that the uniformity of the white light incoherent radiation was above 90% which proves that the coherence of the lasers was destroyed. In addition, the photoelectric parameters of the RGB-LD mixed white light after homogenization was characterized. Meanwhile, the modulation bandwidth of RGB LDs before and after homogenization was analyzed, respectively, and it shows that the bandwidth was more than 1 GHz, which is limited by the photodetector cut-off frequency. Such a high-uniformity and high-speed RGB-LD mixed white light can be deployed for illumination and wireless communication simultaneously.

Index Terms: Laser diode, white light, beam homogenization, modulation bandwidth, visible light communication.

1. Introduction

People's demand for high-speed wireless communication is getting higher and higher with the popularization of mobile Internet, smart city and other emerging service. However, wireless spectrum resources become more and more deficient and the electromagnetic spectrum below 10 GHz has been occupied by a variety of wireless communication technology exhausted. Nitride LEDs (Light Emitting Diodes, LEDs)-based VLC (visible Light Communication, VLC) technology combines lighting and communication together. It has the advantages of environmental friendly, high security and privacy, without electromagnetic interference and appropriate licensing bands compared with the existing radio communication. Therefore, VLC technology is generally considered to have good scientific research value and application prospects [1]–[3].

However, the modulation bandwidth of traditional LEDs is a few hundred MHz which is limited by carrier lifetime and parasitic RC effects [4]–[8]. On the other hand, the LEDs exhibit a decrease in optical power at high current density——efficiency droop [9], which leads to the low data rate and low operating current density of VLC. Therefore, scientists are trying to find a new generation high-quality light source. Currently the most suitable choice is the nitride LDs-based white light source. The modulation bandwidth of the LDs is determined by the photon lifetime rather than the carrier lifetime, and their inherent bandwidth can reach several GHz [10]. Many research institutions have reported that LDs-based VLC can achieve several-Gbps data rate [11]–[15]. What's more, LDs do not show the phenomenon of "sudden droop in efficiency" under lasing. Therefore, LDs-based VLC can be a supplement for LEDs-based VLC at high current density [16].

At present, the main stream approach of solid-state lighting is to utilize blue light to excite yellow phosphors to synthesize white light. However, such approach would require good thermal stability of the phosphor if the LED is replaced by LD due to the much higher optical power density of the laser. Once the yellow phosphors fail, the blue light will leak out which is harmful to human retina and circadian rhythm. In addition, there exists Stokes shift loss during wavelength conversion in the phosphor and the luminous efficiency of the phosphor-conversion white LDs is limited by the quantum efficiency of the phosphor [17]. Hence, new phosphors of high thermal stability and high quantum efficiency need to be further researched. On the other hand, RGB LDs is another effective approach to synthesize white light. Compared with the phosphor conversion-LD white light it has less blue light component which is safer to the human eye. Furthermore, complex modulation methods and wavelength division multiplexing technology can be employed to improve the data transmission rate. Laser beam with high brightness and strong directivity is directly applied to lighting will do harm to the human eyes. Thus, laser beam needs to be homogenized before applying for illumination. The main factors that limit the synthesis of high brightness uniform RGB-LD white light include: 1) In order to accurately control and drive the RGB LDs the optical elements and complex circuits are needed; 2) The light field distribution and the photometric parameters of the three primary colors is different, which will result in nonuniform chromaticity coordinates of the synthesized white light; 3) The laser light intensity distribution is Gaussian distribution, and the white light synthesized by the three-color LDs is still Gaussian distribution rather than the flat top beam distribution. In this paper, the beam combination and beam homogenization were studied. In recent years, laser based lighting with the advantages of high luminous efficiency, high response speed, high plasticity, small size and so on attract people's attention. For example, there are many concept cars using LDs as headlamps [18]. However, some unique issues need to be considered among which the color performance is one of the important aspects. Its own physical properties determine its luminous characteristics-coherent light, which results in nonuniform spatial color. Research shows that drivers in the nonuniform light color driving will be uncomfortable which will lead to security risks [19]. So, the spatial color uniformity of LD white light becomes extremely important. In order to achieve uniform flat top type light field distribution, laser beam needs to be shaped through the optical system. Micro-lens array has the characteristics of beam homogenization, small volume, light weight, low transmission loss and so on. The structure of the shaping system is simple and flexible. Schreiber *et al.* conducted a theoretical analysis of the micro lens-based shaping system and obtained a high uniformity spot by illuminating the micro lens array with LEDs [20], [21].

Up to now, the research on laser lighting is focused on improving the CRI (color rendering index, CRI) and the CCT (correlated color temperature, CCT) (such as adding yellow LED or yellow single crystal phosphor), improving the communication rate (such as using complex modulation method and equalization technology) and so on. But the method of laser beam homogenization and the effect of homogenization are less studied.

In this study, according to the existing laser diode parameters, the power ratio of RGB LDs required to synthesize standard white light is calculated based on the solar color coordinates (0.33, 0.33) (CCT: 5500 K). The standard white light was homogenized through employing the micro lens array as the homogenizer. Finally the photoelectric parameter of the RGB-LD white light were characterized by Spectro-Radiometer. Meanwhile the bandwidth of RGB LDs were measured before and after homogenization to verify the promising applications of LDs in communication and illumination.

2. Experimental Details

In this experiment, the red, green and blue lasers are used as the light source, and the wavelength of the three diodes are 638 nm, 520 nm and 450 nm, respectively. Assume that the three primary colors each have a unit that can match standard white light of a unit. Take sunlight as an example:

$$1\,[R_L] + 1\,[G_L] + 1\,[B_L] \equiv 1\,[D_{sun}] \tag{1}$$

where "≡" expresses visually equal, that is, color matching. The tristimulus values of the standard white light should be equal to the sum of the tristimulus values of RGB LDs:

$$\begin{cases} X_{D_{sun}} = X_{R_L} + X_{G_L} + X_{B_L} = \frac{x_{R_L}}{y_{R_L}} L_{R_L} + \frac{x_{G_L}}{y_{G_L}} L_{G_L} + \frac{x_{B_L}}{y_{B_L}} L_{B_L} \\ Y_{D_{sun}} = Y_{R_L} + Y_{G_L} + Y_{B_L} = L_{R_L} + L_{G_L} + L_{B_L} \\ Z_{D_{sun}} = Z_{R_L} + Z_{G_L} + Z_{B_L} = \frac{1 - x_{R_L} - y_{R_L}}{y_{R_L}} L_{R_L} + \frac{1 - x_{G_L} - y_{G_L}}{y_{G_L}} L_{G_L} + \frac{1 - x_{B_L} - y_{B_L}}{y_{B_L}} L_{B_L} \end{cases} \tag{2}$$

where L represents the brightness,

$$\begin{cases} x = \frac{X}{X+Y+Z} \\ y = \frac{Y}{X+Y+Z} \\ z = \frac{Z}{X+Y+Z} \end{cases}$$

represents color coordinates. Since $x + y + z = 1$, color coordinates are usually expressed by (x, y). The color coordinate of the standard white light is (0.33, 0.33) (CCT: 5500 K), and the color coordinates of RGB LDs are (0.71716, 0.28281), (0.07430, 0.83380), and (0.15664, 0.01771), respectively [22]. Substitute the above data into (2) and get:

$$L_{RL} : L_{GL} : L_{BL} \approx 15.182 : 34.21 : 1 \tag{3}$$

So the power ratio is:

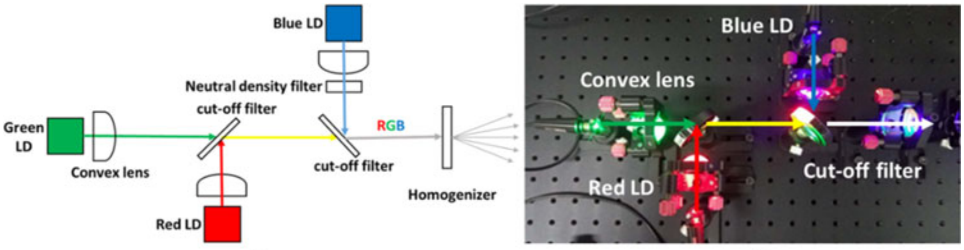
$$P_{R_L} : P_{G_L} : P_{B_L} = \frac{L_{R_L}}{v\,(638\text{ nm})} : \frac{L_{G_L}}{v\,(520\text{ nm})} : \frac{L_{B_L}}{v\,(450\text{ nm})} \approx 3.018 : 1.8309 : 1 \tag{4}$$

where $\nu(\lambda)$ is the visual function under bright conditions. For the general purpose of indoor lighting, the RGB-LD mixed/diffused white light source can also provide a luminous flux of 400-600 lm, as required for indoor lighting. According to the luminous flux calculation formula:

$$\Phi_\nu = K_m \int_{380}^{780} \Phi_e(\lambda) \cdot \nu(\lambda) d_\lambda \tag{5}$$

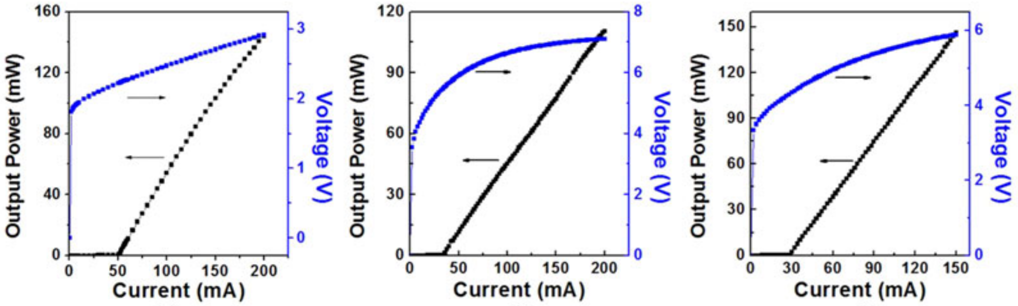
where K_m is the maximum value of spectral luminous efficacy, equal to 683 lm/W; (λ) is the standard spectral light efficiency function specified by the International Commission on Illumination (CIE); $\Phi_e(\lambda)$ is the spectral density of the radiation flux, to meet the requirement of the indoor lighting at least 0.92305 W red LD, 0.55998 W green LD and 0.30585 W blue LD needed.

The experimental setup is shown in Fig. 1. A plano-convex lens (LA1951-A) is placed in front of each emitting device to collimate the laser beams. In order to obtain white light, the beams are aligned in a single path with the help of two cut-off filters. A neutral density filter (NE04A) is placed in blue-ray path not only to reduce the blue light intensity to obtain good color temperature but also to ensure the high modulation bandwidth of the blue LD. Finally a homogenizer is employed to form uniform white light due to the high coherence of the laser. In order to obtain high uniform RGB-LD white light, a micro lens array-beam homogenization optical system as the homogenizer was designed based on the micro lens array beam homogenization principle.



(a) (b)

Fig. 1. The experiment setup diagram (a) and experiment set up (b) of the white light source synthesized by RGBLDs.



(a) (b) (c)

Fig. 2. Light output power-Current-Voltage (L-I-V) curves of (a) red laser diode, (b) green laser diode and (c) blue laser diode at 10 °C.

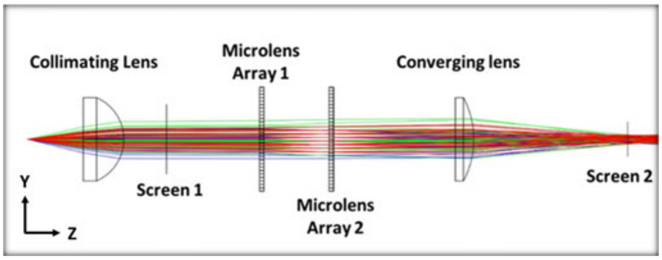


Fig. 3. Employ the micro lens array as the diffuser to homogenize the white light synthesized by RGB LDs.

3. Results

The LDs, red LD (Hitachi HL63603TG), green LD (Osram PL520B) and blue LD (Osram PL450B) exhibit a nominal spectral linewidth/center wavelength of 2 nm/638 nm, 2 nm/520 nm and 2 nm/450 nm, respectively. The beam divergence $\theta_{//} \times \theta_{\perp}$ of RGB LDs are 8.5 × 18, 7 × 22 and 7 × 21, respectively. Fig. 2(a)–(c) shows the light output power– current – voltage (L-I-V) characteristics of the RGB LDs having threshold current of 50 mA, 35 mA and 29 mA and P-I slope of 1.0 W/A, 0.7 W/A and 1.2 W/A, respectively.

As shown in Fig. 3, beam homogenization can be realized by applying micro lens array based on the division of the laser beam. The micro lens array is formed by a series of small lenses which could divide the wide beam into many fine beams. Every fine laser beam through converging lens focused and superimposed on the focal plane. The area of the split beam is so small that intensity distribution can be considered to be uniform [23]–[25]. Therefore, the superposition of all small laser beam is homogeneous. The optical path includes two micro lens arrays, the first one is used to produce the uniform white light spot, while the second one is used to transform the white light spot into space uniform white beam. In this paper, ZEMAX software was used to simulate the

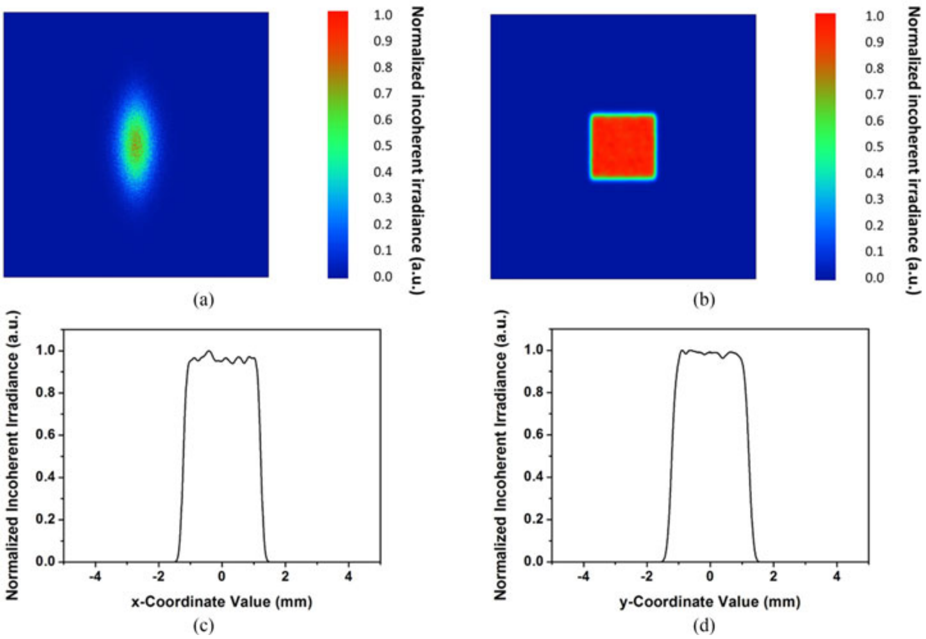


Fig. 4. Normalized incoherent irradiance of the light spot in the entire space (a) before (Screen 1) / (b) after (Screen 2) homogenization; Normalized incoherent irradiance of the light spot after homogenization in the (c) x / (d) y axes.

whole illumination system, and the uniformity of spatial illumination of synthetic white light spot was analyzed. The incoherent radiation of the light spot before/after homogenization and the incoherent radiation of the light spot in x/y axis were shown in Fig. 4.

In order to analysis the uniformity of the incoherent irradiance, the following parameters are defined [26]–[28]:

$$A = \frac{E_i}{E_p} \tag{6}$$

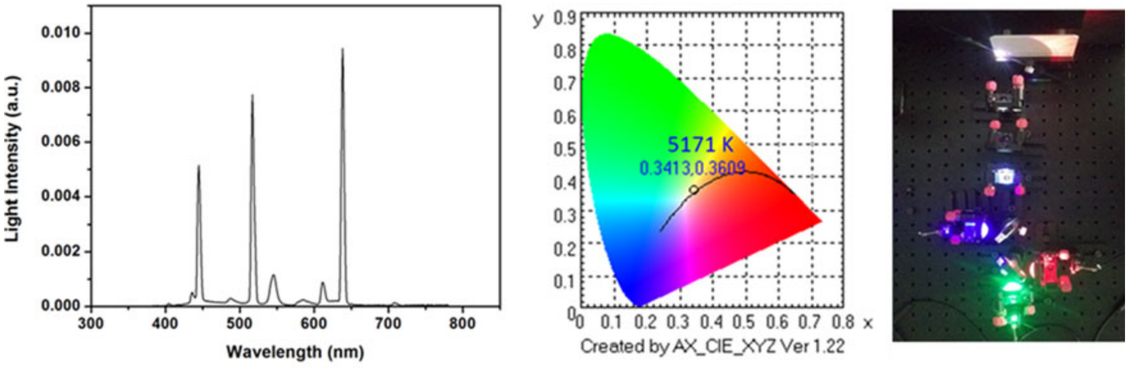
$$E = \frac{S_e}{S} \tag{7}$$

where E_i represents the light intensity of one point on the lighting screen, E_p represents the peak light intensity in the spot, and A is the uniformity of the illumination system which generally should be controlled more than 85%; S represents the total area of the spot on the illumination screen and S_e is the uniform light region where $A \geq 85\%$. In the same optical spot, the larger the A is, the higher the uniformity is. The larger the E is, the better the uniformity of the light distribution of the spot is.

As illustrated in Fig. 4(a) and (b), the coherence of the laser beam is substantially eliminated by the homogenization of the micro lens array. According to (6) and (7), it can be estimated that the illumination uniformity of the optical spot on the illumination screen in both directions of x and y is more than 93.64% and 96.18%, respectively. This is because the micro lens array divides the laser beam into a number of fine beams, and the non-uniformity in the vertical direction between these fine beams which damages the coherence of the laser. More importantly, the beams located in the symmetry position on the illumination screen will superimpose on each other so that the non-uniformity in the vertical direction could be compensated. Therefore uniform and incoherent white light spot will appear on the lighting screen. The white light synthesized by RGB LDs is indeed homogenized, but its uniformity in x axe is lower than that in y axe. The reason is that the inequality of the divergence angle of laser diodes in the fast and slow axes. It needs further optimization in future. Table 1 shows the parameters of the micro lens array in the simulation and experiment.

TABLE 1
Simulation Parameters of Micro Lens Array (mm)

X Half-Width	Y Half-Width	Thick	Radius	Material	Focal Length
0.3	0.3	1.3	8.6	N-BK7	18.6

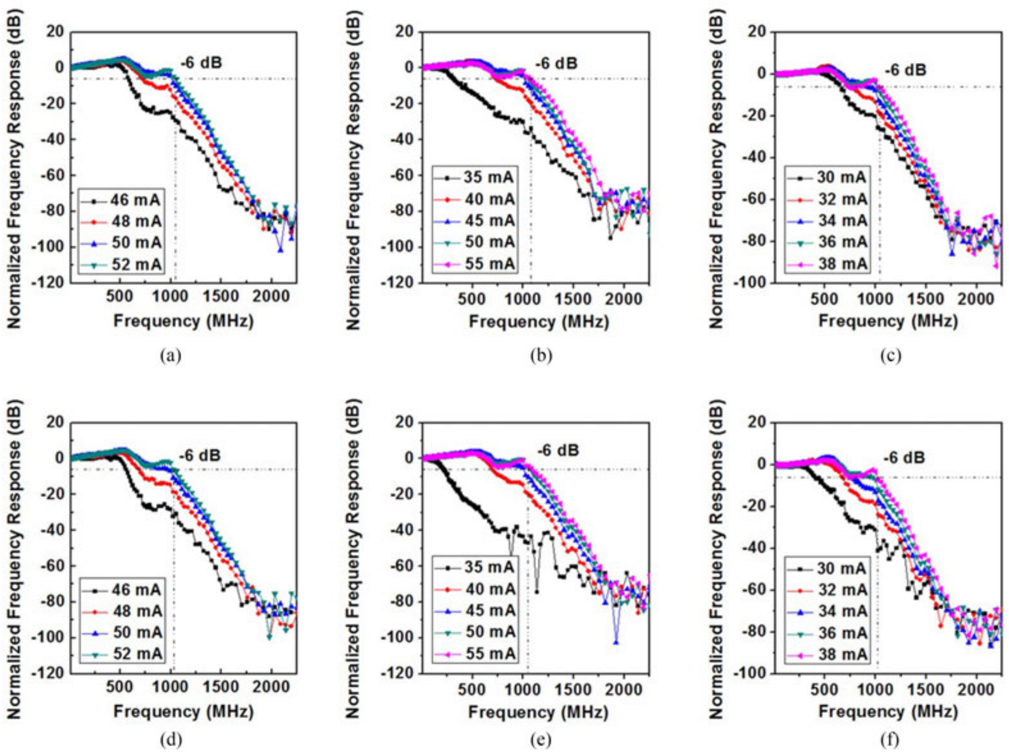


(a) (b) (c)

Fig. 5. (a) The spectral distribution of the white light synthesized by RGB LDs; (b) The characteristics of the white light; (c) RGB-LD mixed white light source.

The spectrum distribution of the white light synthesized by RGB LDs as shown in Fig. 5(a). The power ratio of red, blue and green LDs in the experiment approximates the theoretical calculation. Furthermore the CCT, CRI, CIE coordinate and illuminance of the white light homogenized by micro lens array are 5171 K, 64.8, (0.3413, 0.3609) and 1.415×10^4 lx, respectively. The corresponding bias current of RGB LDs is 92.8 mA, 83.8 mA and 80 mA, respectively. The relatively low color temperature benefits from the neutral density filter (NE04A) in the blue light path. But the CCT and CRI of the white light synthesized by RGB LDs need further optimization. The reason is that the relatively high power of blue light and the small FWHM (full width at half maximum, FWHM) of laser spectrum. Dursun *et al.* employed yellow phosphors or yellow LEDs to control the CCT below 5000 K and enhance the CRI above 80 [29]–[32]. The homogenized white light spot according to our simulation results is shown in Fig. 5(c). The interference effect of the laser is destroyed, which proved the feasibility of laser lighting.

In the bandwidth measurement experiment [7], the S21 parameter of the network analyzer presents the ratio between the input electric power of the LD and output electric power of the receiver. Modulation bandwidth of the LD is obtained from the S21 parameter falling by −6 dB (electrical −6 dB bandwidth), which is also named as the optical −3 dB bandwidth. Fig. 6(a)–(c) shows the normalized frequency response of the non-uniformed RGB LDs having the bandwidth of 1.045 GHz, 1.058 GHz and 1.027 GHz at a distance of 17 cm, respectively. Fig. 6(d)–(f) shows the normalized frequency response of the uniformed RGB LDs having the bandwidth of 1.032 GHz, 1.053 GHz and 1.023 GHz at a distance of 17 cm, respectively. When the injection current is around threshold current, the modulation bandwidth of RGB LDs obviously increases as the injection current increases. However, the modulation bandwidth of uniformed LDs decreased compared with the non-uniformed one. As shown in Fig. 6(d)–(f), the normalized frequency response curves of the uniformed LDs fluctuate greatly. This is because in the vicinity of the threshold current, the output power of LDs is so small that the influence of the environment noise becomes significant. In addition, the scattering effect of the optical elements on the laser beam during the homogenization



(a) (b) (c)

(d) (e) (f)

Fig. 6. The normalized frequency response of (a) red laser diode, (b) green laser diode and (c) blue laser diode at different currents before homogenization at 10 °C; The normalized frequency response of (d) red laser diode, (e) green laser diode and (f) blue laser diode at different currents after homogenization at 10 °C.

process could reduce the laser power received by the detector. When the injection current is larger than the threshold current, the modulation bandwidth of RGB LDs basically remain the same and saturate at 1 GHz which is limited by the cut-off frequency of the photodetector (MenloSystems APD 210).

Intensity modulation can be utilized to encode data on the LDs for incoherent visible light communication. The data rate of RGB LDs-based VLC module can reach several or even dozens of Gbps through sophisticated modulation scheme [15].

4. Conclusion

In this study, a high uniform white light mixed by RGB-LD was demonstrated. The power ratio of RGB LDs were calculated according to the colorimetry to make the white light close to the standard sunlight. Also a micro lens array-beam homogenization optical system was designed to homogenize the white light generated by RGB-LD. And the uniformity of the white light incoherent radiation in x and y axe was 93.64% and 96.18%, respectively. The difference between x and y axes results from the inequality of the divergence angle of laser diodes in the fast and slow axes. After the homogenization the CCT, CRI, CIE coordinate and illuminance of the white light homogenized by micro lens array are 5171 K, 64.8, (0.3413, 0.3609) and 1.415×10^4 lx, respectively. In addition, the RGB LDs exhibit the modulation of 1.045 GHz, 1.058 GHz, 1.027 GHz and 1.032 GHz, 1.053 GHz, 1.023 GHz before and after homogenization at a distance of 17 cm, which indicates that the response speed of the RGB LDs is basically unchanged before and after homogenization. It is noted that a neutral density filter is needed in the blue-ray path to cooperatively optimize the communication and illumination of the blue LD. These results show the potential of RGB LDs based white lighting systems for high data rate VLC and high quality illumination.

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