A method for evaluation of the optical uniformity distribution in the white LEDs-based visible light communication applications

Quang-Khoi Nguyen,*[1,3] Anh-Tuan Pham, [2,3] Van-Tuan Huynh,[1,3] Thi-Hanh-Thu Vu, [1,3] and Huynh-Tuan-Anh Nguyen [1,3]

[1]*Faculty of Physics and Engineering Physics, VNUHCM-University of Science, Hochiminh City, Vietnam*
[2]*Faculty of Electronics and Telecommunications, VNUHCM-University of Science, Hochiminh City, Vietnam*
[3]*Vietnam National University Hochiminh City, Hochiminh City, Vietnam*

Received December 12, 2023; accepted December 22, 2023; published December 31, 2023

Abstract—The uniformity characteristic of emitted radiation in VLC applications is a factor that can affect the efficiency of a detector and the overall efficiency of the VLC system. In this paper, we theoretically investigate the optical uniformity characteristic of using LEDs in VLC applications in terms of the parameter of the emission angle of LEDs and the spatial distribution of LEDs. The result indicates that the optical uniformity can be controlled at a high level by controlling the emission angle of the LED or distributing the LEDs in the room's space.

Light emitting diode-based white light sources have been extensively used in lighting for their advantages, such as energy saving, fast response, environment-friendly, high color performance, and compact size [1–3]. These sources can be fabricated by coating a yellow phosphor on a blue LED chip called a phosphor-converted white light emitting diode (pcW-LEDs) [4]. White light generation and its emission spectrum are illustrated in Fig. 1.

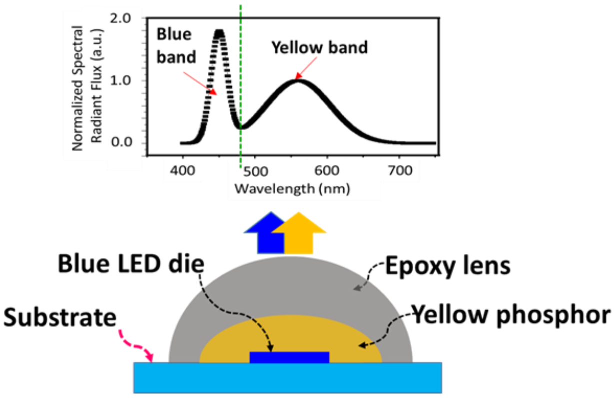

Fig.1. Illustration of white light generation method (bottom) and its emission spectrum (top).

Besides the application in lighting, it is interesting that the extension of pcW-LEDs in visible light communication (VLC) has attracted much attention from researchers [5–14]. Burton *et al.* presented a numerical evaluation of the illumination within a room using white LED lighting located in set positions on the ceiling [6]. Gismalla *et al.* have proposed a new optical photocell configuration model (i.e., model 3) in the room to provide uniformity [7]. Wang *et al.* reported a uniform power distribution by optimizing the beam angle and power weight of the light-emitting diode sources [8]. Bhalerao *et al.* reported a line-of-sight model for visible light communication using the Lambertian radiation pattern of LED and photodiode [9]. Zang *et al.* reported the relationship between optimal strategies of the light source. They received optical power, which has been discussed to attain high luminosity as a lighting source and high-quality transmission for an optical wireless system [10]. Oliveira *et al.* analyzed an LED lamp's communication and illumination performance [11]. Ding *et al.* introduced the typical commercial non-Lambertian beams to enhance VLC transmission performance [12]. Zhang *et al.* have considered the new factor of first reflected light and have proposed a way to determine the optimal layout of channel quality [13]. Kaewpukdee *et al.* studied the characterization of Line-of-Sight (LOS) optical performance in an Outdoor Wireless Visible Light Communication (OWVLC) system [14]. In general, evaluating the uniformity of visile light is still a research direction that needs more proposed new ideas.

The VLC principle is illustrated in Fig. 2, where the light source is simultaneously used for illuminating and communication purposes. The information is modeled and transmitted utilizing the radiation from the light source. In the receiving process, this radiation hits the receiver and demodules through a system to give out the information. The receiver is placed so the collecting incident light has the highest efficiency. The main disadvantage of having low uniformity in LED-based visible light communication is that it causes a higher chance of data loss and communication errors. High uniformity of radiation distribution is an important fact that needs to be optimized to ensure reliable and efficient data transmission. Furthermore, addressing the uniformity problem in LED-based visible light communication systems helps ensure consistent data flow between devices.

* E-mail: nqkhoi@hcmus.edu.vn

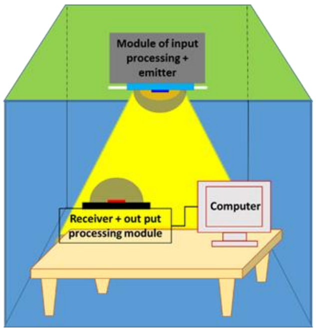

Fig. 2. Illustration for pcW-LEDs based visible light communication principle.

The mathematical model of the spatial power distribution of LED can be described as: $I = I_o\cos^m(\theta)$, where m is the power factor which depends on the emission angle of LED; θ is the emission angle relative to the normal axis of the emission surface; I_o is the luminous intensity corresponding to the emission angle θ of zero degrees [5, 7]. The light pattern of LED varies depending on factors such as packaging configuration, the encapsulant material, or the LED dimension /geometrical parameters. The LED's luminous distribution curve corresponds to different m values, as shown in Fig. 3. Higher m value is, the narrower the emission angle of the LED is. This property of LED causes a different light distribution when used in lighting and VLC applications, as illustrated in Fig. 4.

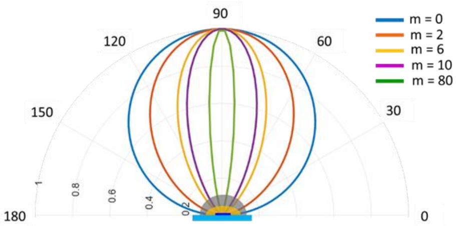

Fig.3. The luminous distribution curve of LED with different values m.

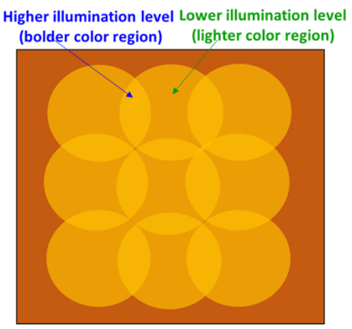

Fig. 4. Illustration of un-uniform light distribution caused by LED light source on the floor.

Figure 5 shows the illustration of modeling using 4 LEDs. In the simulation, the parameter is described as follows: The height, length, and width of the room are 5, 5, and 5 meters, respectively. Four LEDs are set at the top of the ceiling. The variable parameter is the emission angle of the LED. The radiation distribution on the floor is recorded and further analyzed. The simulation is programmed in the MATLAB software. Figure 6 shows the uniformity characteristics of the case using the LEDs with a semi-emission angle at half power of 5 degrees. In Fig. 6(a), the uniformity characteristics are shown in the 3D view, which clearly separates four peaks. The farther separation of peaks indicated a higher different light intensity on the floor. In Fig. 6(b), 2D light distribution showed a dark and white position in the light pattern. The darker level means a lower distribution of incident light, and vice versa. For more institutive sensing, the contour of light distribution on the floor is visualized as shown in Fig.6(c). In general, the case of using the LEDs with a semi-emission angle at half power of 5 degrees showed poor uniformity on the floor.

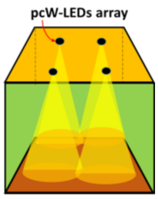

Fig. 5. Illustration of modeling with using 4 LEDs.

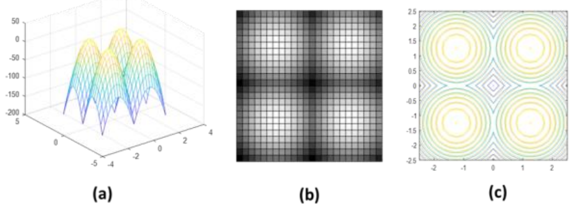

Fig. 6. Uniformity of case using the LEDs with semi-emission angle at half power of 5 degrees. (a) 3D view., (b) 2D of light distribution., (c) contour of light distribution on the floor.

To investigate the effect of the emission angle on uniformity, the simulation is conducted for cases using the LEDs with a higher semi-emission angle value at half power. Larger values of semi-emission angle at half power of 30, 50, and 70 degrees are used in the simulation. Figure 7 shows the 3D view of light distribution for different values of LED emission angles of 30 degrees, 50 degrees, and 70 degrees, respectively.

The corresponding 2D of light distribution for the case using the value of semi-emission angle at half power of 30, 50, and 70 degrees are shown in Fig. 8. As increasing the angle, the four hot spots in Fig. 8a gradually disappear, then become a relative uniform more prominent spot which ushered in the Figs. 8b and 8c. This behavior indicated the dependence of uniformity of light distribution on the used LED emission angles.

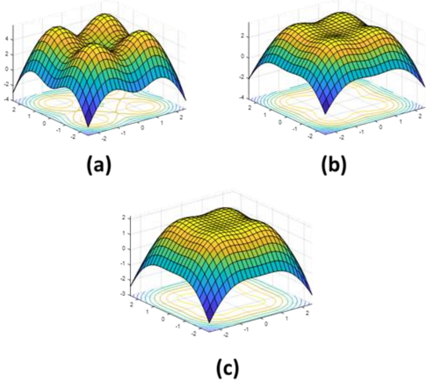

Fig. 7. The 3D view of light distribution for different values of LED emission angle: (a) 30 degrees, (b) 50 degrees, and (c) 70 degrees.

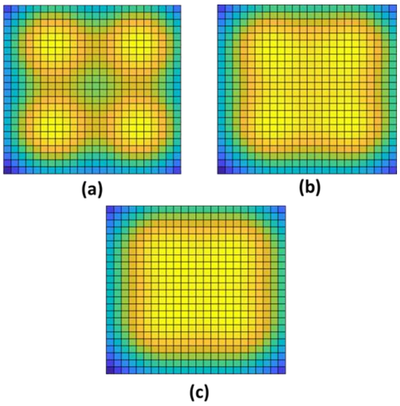

Fig. 8. The 2D view of light distribution for different values of LED emission angle: (a) 30 degrees, (b) 50 degrees, and (c) 70 degrees.

The principle of quantitive is described as follows. If we want to know the uniformity improvement, we need to compare different 2D light patterns to that of a worse case. If the result is similar, the uniformity is still not improved. If the similarity is decreased, then the uniformity is enhanced. In this study, the poor case of the 2D-light pattern is that of the case having an emission of 5 degrees. The 2D light distribution in Figs. 8a–c will be compared to the 2D light distribution shown in Fig. 6b. Then, the similarity level will be analyzed. The similarity of the 2D light distribution of cases shown in Figs. 8a–c to case of 5 degrees shown in Fig. 6b can be quantitively calculated by the normalized cross-correlation (NCC) algorithms. The mathematical description of the algorithm NCC is expressed as follows:

$$NCC = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \bar{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \bar{B})^2\right)}}$$

where $\bar{A}$, $\bar{B}$ are the mean values of the light intensity distributed on the floor for each case under comparison, respectively. A_{mn}, B_{mn} are the values of light intensity distributed on the floor at position having coordinates (m, n) for each case under comparison, respectively. The result of the NCC calculation indicated that the changing of NCC's value versus the LED emission angles, the higher the value of the emission angle, the lower the NCC's value. It indicated the similarity of the 2D light distribution of cases shown in Figs. 8a–c to that of case 5 degrees shown in Fig. 6b is decreased. When the emission angle increases from 30 to 50 or 70, the decrease in NCC becomes more significant. NCC decreased from a value of 11 to 9 and 8.4, respectively. The percentage of relative decrease of NCC is 18.2% and 23.6%, respectively. Generally, the result is that better uniformity improvement can be obtained using a higher emission angle of LED of 50 to 70. In other words, a significant improvement can be achieved for a larger emission angle (e.g., 70 degrees)

In summary, we proposed the new idea to calculate the uniformity improvement quantitively using normalized cross-correlation (NCC) algorithms. If we want to know the uniformity improvement, we need to compare different 2D light patterns to a worse case. If the comparison result is similar, the uniformity is still not improved. If the similarity is decreased, then the uniformity is enhanced. Based on the proposed method, when increasing the emission angle from 30 to 50 and 70, NCC decreased from 11 to 9, and 8.4, corresponding to the percentage of reducing of NCC is 18.2%, and 23.6%, respectively. The result indicated that using a higher emission angle of LED of 50 to 70 can provide a better uniformity improvement. Notably, a significant improvement can be achieved for a larger emission angle (e.g., 70 degrees). These obtained results are meaningful for impove the efficiency LED applications for lighting and communication purposes.

References

[1] E.-F. Schubert, J.- K. Kim, Science **308**, 1274 (2005).
[2] N. Narendran, Y. Gu, J. Display Technol. **1**, 167 (2005).
[3] E. Schubert, *Light-Emitting Diodes* (Cambridge, Cambridge Univ. Press 2006).
[4] C.C. Sun, Q.K. Nguyen, T.X. Lee, S.K. Lin, C.S. Wu, T.H. Yang, Y.W. Yu, Sci. Reports **12**, 12433 (2022).
[5] Z. Ghassemlooy, W. Popoola, S. Rajbhandari. *Optical Wireless Communications System and Channel Modelling with MATLAB* (Florida, CRC Press, Taylor & Francis Group, 2013).
[6] A. Burton, H. Le Minh, Z. Ghasemlooy, S. Rajbhandari, IEEE 2012 Int. Workshop on Opt. Wireless Comm. (IWOW), Pisa, Italy, 2012.
[7] M.S.M. Gismalla, M.F.L. Abdullah, M.I. Niass, B. Das, W.A. Mabrouk. Int. J. Commun Syst. **e4349** (2020).
[8] C. Wang, J. Wang, J. Zhang, J. Wang, H. Du, J. Wang, SPIE Proc. **12062**, AOPC 2021: Optoelectronics and Nanophotonics (2021).
[9] M.V. Bhalerao, M. Sumathi, S.S. Sonavane. Int. J. Comm. Systems (2016).
[10] J.F. Zang, Y. Piao. SPIE Proceedings **10255**, (2016).
[11] M. Oliveira, F.C.B. Tosta, D.E.F. Guillen, P.P. Monteiro, A.A.P. Poh, Wireless Personal Communications **125**, 3461(2022).
[12] J.P. Ding, C. Lin, J.T. Wang, H. Yang, Sensors **22**, 216 (2022).
[13] X. Zhang , N. Zhao, F. Al-Turjman, M.B. Khan, X. Yang. Sustainability **12**, 9006 (2020).
[14] A. Kaewpukdee, P. Uthansakul, Materials Continua **74**, 1026 (2023).

