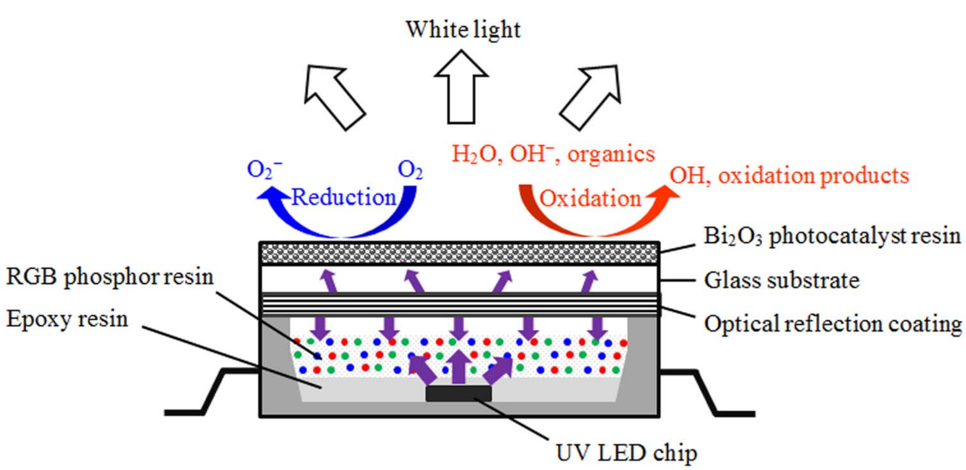
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Improved Design of UV- and Blue-Light-Inhibited White Light-Emitting Diode

Volume 7, Number 4, August 2015

Yen-Chang Chu
Gang-Juan Lee
Chin-Yi Chen
Shih-Hsin Ma
Jerry J. Wu
Tzyy-Leng Horng
Kun-Huang Chen, Member, IEEE
Yi-Wen Huang
Li-Ya Lai
Jing-Heng Chen, Member, IEEE



DOI: 10.1109/JPHOT.2015.2458989

Improved Design of UV- and Blue-Light-Inhibited White Light-Emitting Diode

Yen-Chang Chu,[1] Gang-Juan Lee,[2] Chin-Yi Chen,[3] Shih-Hsin Ma,[4] Jerry J. Wu,[2] Tzyy-Leng Horng,[5] Kun-Huang Chen,[6] *Member, IEEE*, Yi-Wen Huang,[6] Li-Ya Lai,[6] and Jing-Heng Chen,[4] *Member, IEEE*

[1]Ph.D. Program of Electrical and Communications Engineering, Feng Chia University, Taichung 40724, Taiwan
[2]Department of Environmental Engineering and Science, Feng Chia University, Taichung 40724, Taiwan
[3]Department of Materials Science and Engineering, Feng Chia University, Taichung 40724, Taiwan
[4]Department of Photonics, Feng Chia University, Taichung 40724, Taiwan
[5]Department of Applied Mathematics, Feng Chia University, Taichung 40724, Taiwan
[6]Department of Electrical Engineering, Feng Chia University, Taichung 40724, Taiwan

DOI: 10.1109/JPHOT.2015.2458989

Manuscript received June 19, 2015; revised July 4, 2015; accepted July 17, 2015. Date of publication July 21, 2015; date of current version August 3, 2015. This work was supported by the Ministry of Science and Technology, Taiwan, under Contract NSC 100-2632-E-035-001-MY3 and Contract MOST 103-2221-E-035-035. Corresponding author: J.-H. Chen (e-mail: jhchen@fcu.edu.tw).

Abstract: This paper proposes the improved design of an ultraviolet (UV)- and-blue-light-inhibited white light-emitting diode for use as a safe and practical light source. Covered with a glass substrate coated with a photocatalyst resin on one side and a reflectance film on the other side, wavelengths below 400 nm are reflected back to re-excite the red–green–blue phosphors and, consequently, enhance luminous efficiency. The absorption spectrum of bismuth oxide photocatalysts is below 521 nm, and the leaked UV and blue light can be absorbed, thereby exciting electron–hole pairs and producing the photocatalytic effect. Thus, blue light and UV leakage can be suppressed appreciably, and the luminous efficiency can be increased markedly. Experimental results showed a UV suppression ratio of 88.43% and a visible light increasing ratio of 21.66%. The Commission International de L'Eclairage chromaticity coordinates (x, y) were (0.343, 0.404), the correlated color temperature and the deviation from de Black-body locus were (5201 K, 0.0250), and the color rendering index was 93.16. In addition, the photocatalyst coating layer can act as a diffuser to provide a comfortable visual experience and facilitate environmental purification.

Index Terms: Bismuth oxide, phosphor, photocatalyst, ultraviolet (UV) leakage, white light-emitting diode (LED).

1. Introduction

White light-emitting diodes (LEDs) are considered to be the optimal candidate for next-generation light sources because of their several advantages such as low energy consumption, small size, compactness, light weight, high durability, and high reliability; moreover, they are mercury-free. Therefore, in the past few decades, LEDs have become a frequently researched topic in lighting applications. Meanwhile, shorter wavelength-excited for long wavelengths phosphor-converted to create white light are the most common methods. Blue light-excited yellow-phosphor-converted white LEDs have a high luminous efficiency which is the preferred solution for all the current options in the market. By contrast, ultraviolet (UV)-excited red–green–blue (RGB)-phosphor-converted white LEDs have a higher color rendering index [1]. Several researchers have improved the luminous efficiency, color temperature, and color rendering index of LEDs, and the luminous efficiency and color rendering index of currently available commercial LED products exceed 120 lm/W and 90, respectively [1]–[5]. Although technological progress has led to the rapid increase in LED applications—display, electronics, car headlights, and other lighting applications—and to LEDs gradually replacing traditional light sources, a trade-off exists between the luminous efficiency and the color rendering index. Despite the high number of LED applications, the high temperature of blue light, UV leakage, and glare are commonly encountered problems when current phosphor-converted white LEDs are used. Many medical reports have suggested that long-time exposure to blue or UV light can damage the skin, eyes, and endocrine system of humans [6]–[9]. Therefore, if LEDs are to be promoted as a next-generation light source, problems related to the safety of these devices must be solved. Using omnidirectional reflectors with a layer of diffuser for suppressing UV leakage and increasing light extraction ratio has been proposed [10]–[13]. However, omnidirectional reflectors are essentially a periodic stack of three-layer structures of 1-D photonic crystals, and the fabrication process of these crystals is complex and costly. The authors of the current study proposed an alternative method based on the blue and UV light absorption characteristics of a bismuth oxide photocatalyst for solving the problem of short wavelength leakage in white LEDs [14]. The proposed UV-excited RGB-phosphor-converted white LEDs provide the additional function of decomposing environmental organic molecules. However, the UV suppression ratio was only 52%, consequently reducing luminous efficiency.

For developing a safe light source, this paper proposes the improved design of an RGB-phosphor-converted white LED. In the design, the LED package is covered with a substrate that has an optical reflection coating on the underside and a bismuth oxide photocatalyst coating on the topside. Compared with the omnidirectional reflector, the optical reflection coating involves a maturely commercial fabrication process, is low cost, and reflects light in the UV spectrum below 400 nm to re-excite the RGB phosphors, thereby increasing luminous efficiency. The blue and UV light residually leaked through the optical reflection coating is absorbed by the coating layer of the bismuth oxide photocatalyst. In addition, the bismuth oxide photocatalyst excited by blue and UV light can decompose organic molecules in the environment. Therefore, a safe and environmentally friendly LED light source can be obtained. To show the feasibility of the design, a UV-excited RGB-phosphor-converted white LED was packaged and covered with a substrate coated on both sides. The results indicated that the LED showed excellent performance, with a UV suppression ratio of 88.43% for the UV spectrum from 360 nm to 420 nm, and an improvement of 21.66% in the luminous efficiency for visible light from 420 nm to 780 nm. The Commission International de L'Eclairage (CIE) color coordinates (x, y) were (0.343, 0.404) at a dominant wavelength of 559 nm, the correlated color temperature was 5201 K, the deviation from de Blackbody locus Duv was 0.0250, and the color rendering index was 93.16 $(\text{R9} = 97.3)$. In addition, the photocatalyst coating served as an optical diffuser to provide a comfortable visual experience and decompose organic molecules in the environment.

2. Principles

Fig. 1 shows a schematic representation of the proposed UV-excited RGB-phosphor-converted white LED covered with a glass substrate coated on both sides. The substrate was coated with a Bi_2O_3 photocatalyst resin on the topside and an optical reflection coating on the underside. A UV-LED chip mounted on a surface-mounted device (SMD) lead frame was used as the exciting light source for the RGB phosphors. Inside the LED lead frame, the bottom layer and superstratum were filled with epoxy resin and RGB phosphor resin, respectively.

The optical reflection coating consisted of 30 stacked coatings of Ti_3O_5/SiO_2 material with a total thickness of 18.843 kÅ. The transmission spectrum under normal incidence is shown in

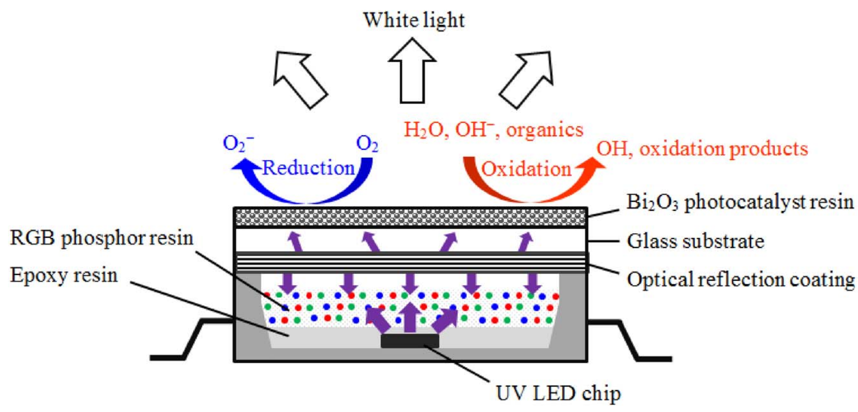


Fig. 1. Schematic representation of the proposed white LED.

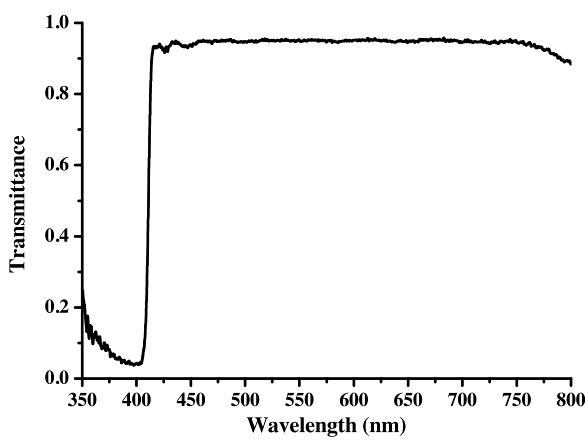


Fig. 2. Transmission spectrum of the optical reflection coating.

Fig. 2, in which the UV spectrum below 400 nm is almost reflected, and the reflected UV light is recycled to re-excite the RGB phosphors. Consequently, luminous efficiency can be considerably increased. The Bi_2O_3 photocatalyst resin was prepared by mixing the Bi_2O_3 photocatalyst and an adhesive at a weight ratio of 1 : 15. The absorption spectrum of the Bi_2O_3 photocatalyst is shown in Fig. 3 [14]. The inset shows the $(\alpha h\nu)^2$ plots, where α is the absorption coefficient, as a function of the photon energy and light frequency. The corresponding energy bandgap is 2.38 eV. Consequently, leaked UV light below 521 nm with slant incidence can be absorbed by the Bi_2O_3 photocatalyst to excite electron–hole pairs and produce the photocatalytic effect. Therefore, the Bi_2O_3 photocatalyst coating also provides an optical diffuser for a comfortable visual experience, and the functions of decomposing organic molecules in the environment.

3. Experimental Results and Discussion

To demonstrate the feasibility of the design, a UV-LED chip (HU1165W, TEKCORE) mounted on an SMD-LED lead frame was used as the light source for exciting the RGB phosphors; the spectrum of the LED chip was 380–385 nm. Inside the LED lead frame, the bottom layer and superstratum were filled with epoxy resin and RGB phosphor resin, respectively. The RGB phosphor resin was prepared by mixing red phosphor (RU-R6006S, NANTEX), green phosphor (RU-G503, NANTEX), blue phosphor (RU-B403, NANTEX), and epoxy resin at a weight ratio of 1 : 1.47 : 4.18 : 59.83, and was baked in a vacuum oven at 80 °C for 3 h. A substrate coated with an optical reflection coating (provided by BOHHEN Optronics, Inc.) and a Bi_2O_3 photocatalyst

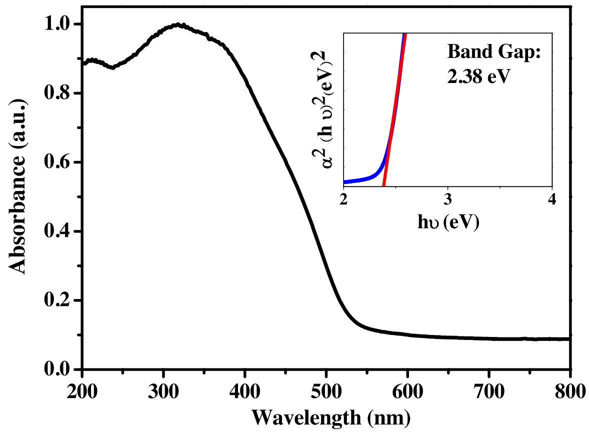


Fig. 3. Absorption spectrum of the Bi_2O_3 photocatalyst [14].

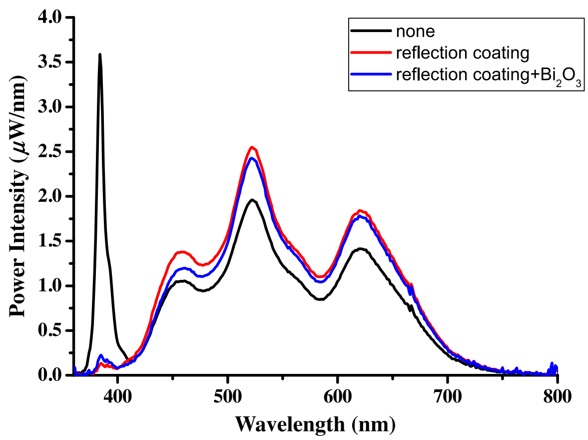


Fig. 4. Spectral comparison of LED packages 1) without a substrate cover, 2) with a substrate cover with a single optical reflection coating, and 3) with a substrate cover with optical reflection and Bi_2O_3 photocatalyst coatings.

resin was used to cover the LED package. The fabricated white LEDs were driven (SourceMeter 2400, KEITHLEY) at a forward voltage of 3.48 V and a current of 20 mA, and they were tested using an LED characterization system (LCS-100, SphereOptics) and luminous intensity measurement system (IS-LI TE, Radiant Vision Systems).

Although, in the demonstration of the proposed design, a low-power UV-LED chip (@20 mA) was applied for exciting the RGB phosphors with a high color rendering index, it can get rid of some of the thermal problems in high power LEDs. The proposed method can also applied in high power blue light-excited yellow-phosphor-converted white LEDs. The thermal problem of color shifts could be moderated with properly modifying the parameters of optical reflection and Bi_2O_3 photocatalyst coatings. For comparison, Fig. 4 shows the spectra of three types of LED packages: 1) without a substrate cover, 2) with a substrate cover with a single optical reflection coating, and 3) with a substrate cover with optical reflection and Bi_2O_3 photocatalyst coatings. Apparently, the proposed design successfully suppresses UV light (360–420 nm) while considerably enhancing visible light (420–780 nm). The luminous efficiencies for the three cases are 1.315 lm/W, 1.701 lm/W, and 1.619 lm/W, respectively. Therefore, the proposed design is suitable for LED packages with a thinner phosphor resin or a lower phosphor density to save the cost. For case 2, the increased luminous efficiency is 29.35%, in which the UV suppression ratio is 86.38%, and the visible light increasing ratio reaches 30.09%. The CIE chromaticity

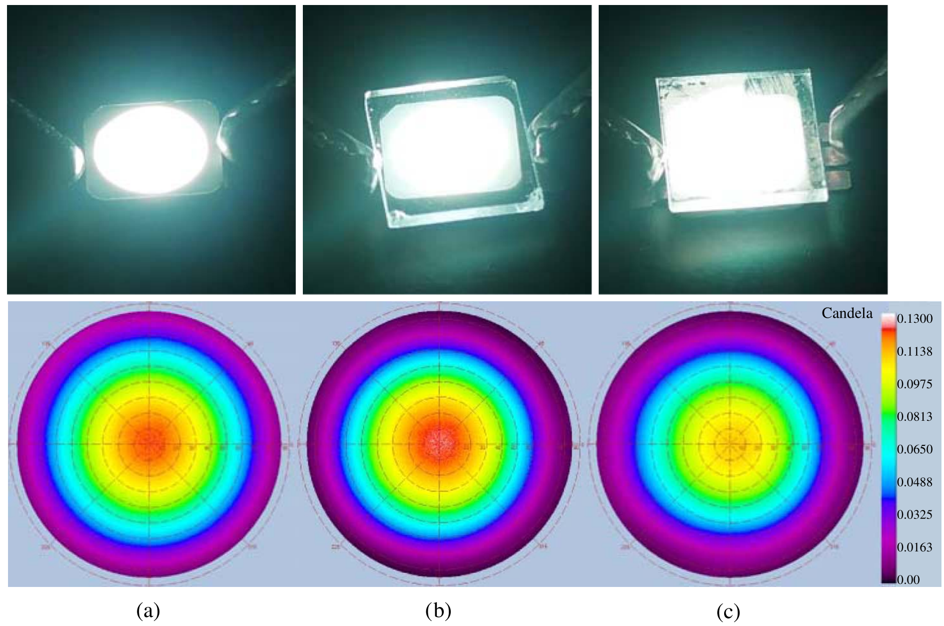


Fig. 5. Visual experience and luminous intensity distribution comparisons between LED light sources. (a) Without a substrate cover, (b) with a substrate cover with a single optical reflection coating, and (c) with a substrate cover with optical reflection and Bi_2O_3 photocatalyst coatings.

coordinates (x, y) are (0.336, 0.394), the correlated color temperature and the deviation from de Blackbody locus (CCT, Duv) are (5388 K, 0.0230) at a dominant wavelength of 556 nm, the color purity is 19%, and the color rendering index is 93.49 $(R9 = 95.3)$. By contrast, in case 3, the increased luminous efficiency is 23.12% in which the UV suppression ratio is enhanced to 88.43% and the visible light increasing ratio decreases by a small amount to 21.66% because of the introduction of the Bi_2O_3 photocatalyst. Because the energy gap of Bi_2O_3 is 2.38 eV corresponding to a wavelength of 521 nm, bismuth oxide is suitable for suppressing the blue light and UV in white LEDs. A thicker coating of Bi_2O_3 photocatalyst or a higher weight ratio of photocatalyst resin owns a higher inhibition for UV and blue light but at the cost of a lower extraction for visible light. However, the decay of visible light exchanges additional function of decomposition of organic molecules in the environment [14]. It was shown that 70% degradation of formaldehyde in the air mixture in a closed system was achieved within 2 hours. This indicates the effectiveness of using such a device for residential or industrial indoor environments. Therefore, it will definitely work out by providing oxidation mechanisms in the environment especially for trace quantities of gaseous organic pollutants. A trade-off exists between the luminous efficiency and the photocatalyst decomposition efficiency. Therefore, the photocatalyst-preparing ratio should depend on the functional demand. Fig. 5(a)–(c) shows comparisons of visual experience and luminous intensity distribution from the aforementioned three types of LED packages. Apparently, the luminous intensity distribution is relatively uniform with photocatalyst coating which provides comfortable visual experiences. In addition, the CIE chromaticity coordinates (x, y) are (0.343, 0.404), the correlated color temperature and the deviation from de Blackbody locus (CCT, Duv) are (5201 K, 0.0250) at a dominant wavelength of 559 nm, the color purity is 24%, and the color rendering index is as high as 93.16 $(R9 = 97.3)$.

4. Conclusion

This study proposes an improved design for a UV-excited RGB phosphor-converted white LED package. The package was covered with a substrate coated on both sides. The topside was coated with a layer of a bismuth oxide photocatalyst, whereas the underside was coated with an optical reflection coating. To show the feasibility of the design, practical white LEDs were fabricated and tested. The spectra and related colorimetric parameters of packaged LED samples both without and with coated substrate covers were compared. The UV suppression ratio reached 88.43%, i.e., from 360 nm to 420 nm, and the visible light increasing ratio was 21.66%, i.e., from 420 nm to 780 nm. The CIE chromaticity coordinates (x, y) were (0.343, 0.404), the correlated color temperature and the deviation from de Blackbody locus were (5201 K, 0.0250) at a dominant wavelength of 559 nm, and the color rendering index reached 93.16. In addition, the photocatalyst coating could also serve as an air purifier and as a diffuser for providing a comfortable visual experience. Thus, the experimental results demonstrated that the white LED light source with the proposed design was characterized by high color rendering index and high safety, in addition to being environmentally friendly and practical.

Acknowledgements

The authors thank C.-C. Yang of BOHHEN Optronics, Inc., for providing useful comments and optical reflection coating samples, as well as Associate Prof. C.-F. Lai of Feng Chia University for his assistance and discussion in this work.

References

[1] T. Nishida, T. Ban, and N. Kobayashi, "High-color-rendering light sources consisting of a 350-nm ultraviolet light-emitting diode and three-basal-color phosphors," *Appl. Phys. Lett.*, vol. 82, no. 22, p. 3817, Jun. 2003.
[2] R. Mirhosseini *et al.*, "Improved color rendering and luminous efficacy in phosphor-converted white light-emitting diodes by use of dual-blue emitting active regions," *Opt. Exp.*, vol. 17, no. 13, pp. 10 806–10 813, Jun. 2009.
[3] M. K. Lee, C. L. Ho, and C. H. Fan, "High light extraction efficiency of gallium nitride light emitting diode with silicon oxide hemispherical microlens," *Appl. Phys. Lett.*, vol. 92, no. 6, 2008, Art. ID. 061103.
[4] O. Yoshi, "Spectral design considerations for white LED color rendering," *Opt. Eng.*, vol. 44, no. 11, Nov. 2005, Art. ID. 111302.
[5] T. S. Kim, S. M. Kim, Y. H. Jang, and G. Y. Jung, "Increase of light extraction from GaN based light emitting diodes incorporating patterned structure by colloidal lithography," *Appl. Phys. Lett.*, vol. 91, no. 17, 2007, Art. ID. 171114.
[6] Anses Press Kit: Lighting Systems Using Light-Emitting Diodes: Health Issues to be Considered, 2010, to be published. [Online]. Available: https://www.anses.fr/en/content/lighting-systems-using-light-emitting-diodes-leds-health-issues-be-considered
[7] G. C. Brainard *et al.*, "Action spectrum for melatonin regulation in humans," *J. Neurosci.*, vol. 21, no. 16, pp. 6405–6412, Aug. 2001.
[8] S. M. Pauley, "Lighting for the human circadian clock: Recent research indicates that lighting has become a public health issue," *Med. Hypotheses*, vol. 63, no. 4, pp. 588–596, 2004.
[9] D. E. Blask, "Melatonin, sleep disturbance and cancer risk," *Sleep Med. Rev.*, vol. 13, no. 4, pp. 257–264, Aug. 2009.
[10] J. C. Su, C. L. Lu, and C. W. Chu, "Design and fabrication of white light emitting diodes with an omnidirectional reflector," *Appl. Opt.*, vol. 48, no. 26, pp. 4942–4946, Sep. 2009.
[11] J. C. Su and C. L. Lu, "Color temperature tunable white light emitting diodes packaged with an omni-directional reflector," *Opt. Exp.*, vol. 17, no. 24, pp. 21 408–21 413, Nov. 2009.
[12] C. Shen, H. Feng, Z. Xu, and S. Jin, "GaInN light-emitting diodes with omni-directional reflector using nanoporous SnO2 film," *Chin. Opt. Lett.*, vol. 6, pp. 152–153, 2008.
[13] S. W. Chen, J. C. Su, C. L. Lua, S. F. Song, and J. H. Chen, "Phosphors-conversion white light LED with omni-directional reflector," in *Proc. SPIE*, 2008, vol. 7138, pp. 1–8.
[14] Y. C. Chu *et al.*, "Preparation of bismuth oxide photocatalyst and its application in white-light LEDs," *J. Nanomater.*, vol. 2013, Jan. 2013, Art. ID. 596324.