crystals

MDPI

*Article*

# Simultaneously Improve White LED Omni-Directional Package Efficacy and Spatial Color Uniformity on Scattered Photon Extraction Technology

**Tsung-Xian Lee * and Yun-Chieh Huang**

Graduate Institute of Color and Illumination Technology, National Taiwan University of Science and Technology, Taipei 10607, Taiwan; ychieh.huang@gmail.com

* Correspondence: txlee@mail.ntust.edu.tw; Tel.: +886-2-2737-6901

Received: 29 November 2018; Accepted: 26 December 2018; Published: 30 December 2018

check for updates

**Abstract:** The Scattered Photon Extraction (SPE™) based on the concept of TIR lens combined with remote phosphor is proven to be one of the effective solutions for improving white LED efficiency, and it provides the omnidirectional light distribution for luminaire design. Not only the light extraction efficiency (LEE) is important, but also the angular uniformity of correlated color temperature (CCT) is a critical index in the evaluation of high-quality white LEDs. A non-optimized SPE™ will cause an increase in the angular CCT deviation (ACCTD) and ultimately affect lighting quality. Two possible ways using lens design are proposed to reduce the ACCTD and even improve its efficiency. Among them, using the concept of light guiding to design the lens can minimum the deviation of forward and backward CCT from 2720 K to 657 K, and the overall efficiency can be further enhanced by 12% compared to typical SPE™ lens.

**Keywords:** white LEDs; remote phosphor; light extraction efficiency; spatial color uniformity

## 1. Introduction

As the awareness of the environment protection increases, the high-efficient Light-Emitting Diodes (LEDs) is gradually replacing traditional lights sources, such as the incandescent lamp, fluorescent lamp, and tungsten lamp because the traditional light source would cause pollution to the environment. However, even though LEDs pose lower risks to the environment, it still requires proper recycling and uses as what is done with regards to electronic wastes when handling the wastes of LED lighting products, as there exists a lot of metal and precious metal in them. In addition to being friendly to the environment and conserving energy, the LED has another characteristic that is different from that of the traditional light source. The LED uses cold light illumination and is brighter, a faster launch speed and a compact size. As a result, the development of the LED is robust in past years.

Currently, the packaging methods of the LED are divided into four major types: RGB tri-color LED mixed light, blue LED covered with yellow phosphor, blue LED covered with green and red phosphor and ultra-violet LED covered with RGB tri-color phosphor. The way that uses the LED to activate the phosphor is to mix the phosphor with the glue and cover the mixture on the LED dies. This method is called the "Phosphor-Converted White Light-Emitting Diodes (PC-WLEDs)". Such a packaging method accelerates the manufacturing process and lowers the cost, making it a relatively more popular option.

The idea to separate the phosphor layer and the LED dies was presented in 1990 [1]. However, as it is difficult to manufacture and is not supported by any theories, this idea did not attract mainstream attention. In 2005, Narendran presented a new packaging method for the PC-WLEDs. This method places a total internal reflection (TIR) lens on the dies and covers the phosphor evenly on the top surface of the TIR lens. As a result, there is a space between the phosphor and the dies. Such a structure is named as the "Scattered Photon Extraction (SPE™)". It emphasizes the effectiveness of penetrating into the backscattering ray behind the phosphor layer. Compared to the traditional packaging method, this idea effectively increases the light extraction efficiency (LEE) by 30–60% [2–4].

New results continue to emerge out of the researches on the SPE™ technology. Zhu and others presented the influences of different combinations of the red/yellow duo-color phosphor on the light output efficiency. As seen from the results, when the layer above is the red phosphor and the layer below is the yellow phosphor, the output light flux is better. The authors suggest two main reasons for this: (1) The bottom phosphor layer generates backscattering ray; (2) the forward scattering ray generated by the bottom phosphor layer can be absorbed and transformed by the top phosphor layer. The pre-condition of this is that the light spectrum of the positive scattering ray of the bottom phosphor layer must fall within the absorption spectrum of the top phosphor layer [5].

However, it is not true that there is no any disadvantage of the SPE™ solutions. This packaging method requires the design of a larger dimension and the size and amount of the phosphor that it covers is much more than those covered by the traditional packaging method. Therefore, such a technology is not suitable for a highly directional optical design or a compact optical system application. Omnidirectional lighting design will be the main development area. Figure 1 is an example of an omnidirectional light bulb designed using the SPE™ concept.

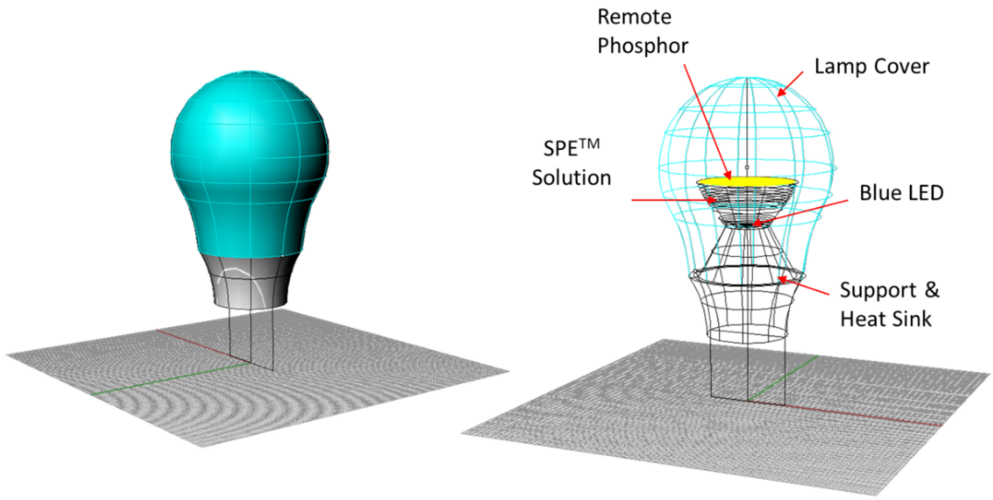



**Figure 1.** An example of omnidirectional light bulb designed using the SPE™ concept.

When evaluating a high-quality PC-WLED, the packaging efficacy is undoubtedly one of the important indicators [6,7]. Other than that, the spatial color uniformity (SCU) is also important for the lighting application. There have been many works of literature on the research on the SCU in the context of traditional packaging [8–16]. When the concept of the remote phosphor was brought up, the LEE was improved. Later, when the SPE™ technology came out, not only to further improve LEE, it also has the advantage of an omnidirectional light. As a result, it attracted more attention and researchers. But many of the literature in this field only focus on the characteristic which increases the LEE [17–23] while ignoring an important and indispensable indicator, the SCU.

SPE™ technology utilizes a secondary TIR optics between the phosphor and the die to increase LEE. However, if the design of the secondary optics is inappropriate, the uniformity of the spatial color distribution will be severely impacted. Therefore, for SPE™, it is necessary to redesign a new TIR lens can effectively control the forward and backward light output simultaneously. In this way, a perfect omnidirectional light with high LEE, high SCU and uniform light intensity can be truly achieved.

## 2. Omnidirectional ACCTD of Existing SPE™ Solution

Now existing SPE™ technology presents the idea of covering the phosphor evenly on the top surface of the collimation TIR lens. This structural design has been proven to increase the white light efficacy due to the backward scattering. However, there is rare research in terms of the angular correlated color temperature deviation (ACCTD). Therefore, we first analyze and discuss the omnidirectional ACCTD for the existing SPE™ design.

### *2.1. Optical Model and Simulation*

In this paper, the material of the TIR lens is set to use PMMA. The blue light excites the yellow phosphor to generate the white light will be accurately simulated. For the simulation of the blue light source, we use the XLamp XT-E Royal Blue LED manufactured by CREE. The emission wavelength was set at 450 nm. The phosphor that we select is the YAG:Ce yellow phosphor mixed with silicone. For detailed parameters of the optical model of the phosphor, please refer to the reference [24]. In this paper, the thickness and concentration of the phosphor are adjusted to allow the average CCT of each design case to fall within the target of 6500 K after the light is emitted.

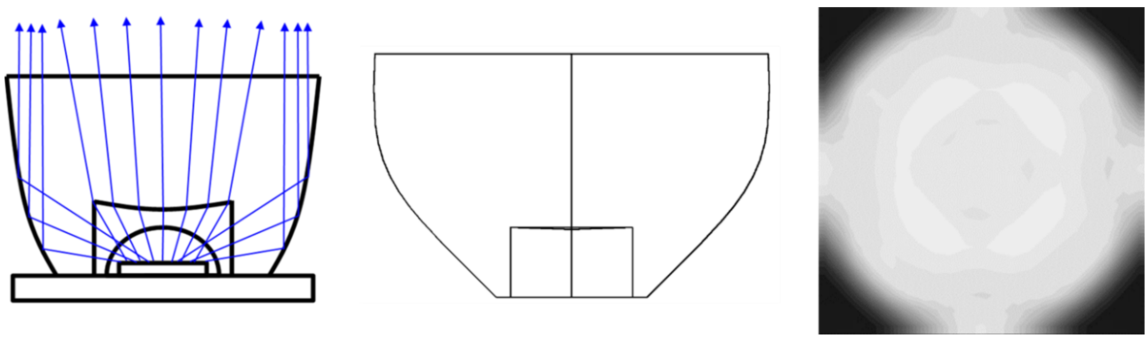
Since the white light emitted by the SPE™ is omnidirectional. In the optical simulation, we set up two far-field observers: forward and backward semi-sphere respectively to collect the forward and backward extracted light information separately. Here, we will try to achieve a target CCT of 6500 K for both the forward and backward CCT. In other words, it is necessary to narrow the average CCT difference between the two and get closer to 6500 K, so we propose two evaluation benchmarks:

$$\Delta \mathrm{CCT} = |CCT_{FW} - CCT_{BW}| \tag{1}$$

$$SD_{CCT} = \sqrt{\frac{1}{2}\left[\left(CCT_{FW} - CCT_{tgt}\right)^2 + \left(CCT_{BW} - CCT_{tgt}\right)^2\right]} \tag{2}$$

where $CCT_{FW}$ and $CCT_{BW}$ are the average CCT of all rays collected by the forward and observer, respectively. $CCT_{tgt}$ is the overall target CCT. In this study, the $CCT_{tgt}$ was set to 6500 K, and our design goal was to minimize both ΔCCT and $SD_{CCT}$.

We implemented a collimated TIR lens design for traditional SPE™ as shown in Figure 2. In the initial design, the lens collimates almost all the light, then the uniformity of illumination on the top surface, that is, on the phosphor, was further improved through optimization, so in fact, the final light distribution angle is no longer fully collimated. The uniformity on the phosphor is as high as 85%, based on the definition of the average illuminance divided by the maximum illuminance.



(**a**) (**b**) (**c**)

**Figure 2.** A collimated TIR lens designs for traditional SPE™. (**a**) Design concept and ray trajectory, (**b**) Layout of the final designed lens, (**c**) Illuminance distribution of blue pump on top surface of lens.

## *2.2. Simulation Results*

Based on the above lens design, and with the Mie scattering as the basis for the modeling of phosphor, we conducted the Monte-Carlo ray tracing simulation and SCU performance analysis for the traditional SPE™ structure. The weight percentage concentration and thickness of the phosphor were changed in the simulation to find the best condition for low ΔCCT and $SD_{CCT}$. The results of the forward and backward average CCT are shown in Figure 3. Among these results, we can clearly see that there is no condition that allows both to reach the target CCT of 6500 K at the same time. The forward CCT is mostly below target, while the backward CCT is much higher than the target CCT value. We attempt to find a better and stable result among them, wherein when the concentration and thickness of the phosphor are 30% and 0.5 mm, it is possible to obtain a minimum ΔCCT of 3589 K and a $SD_{CCT}$ of 1954 K. Figure 4 shows the spatial color distribution of this optimization result in simulation and experiment, respectively. It can be seen that the forward and backward white light are obviously different.

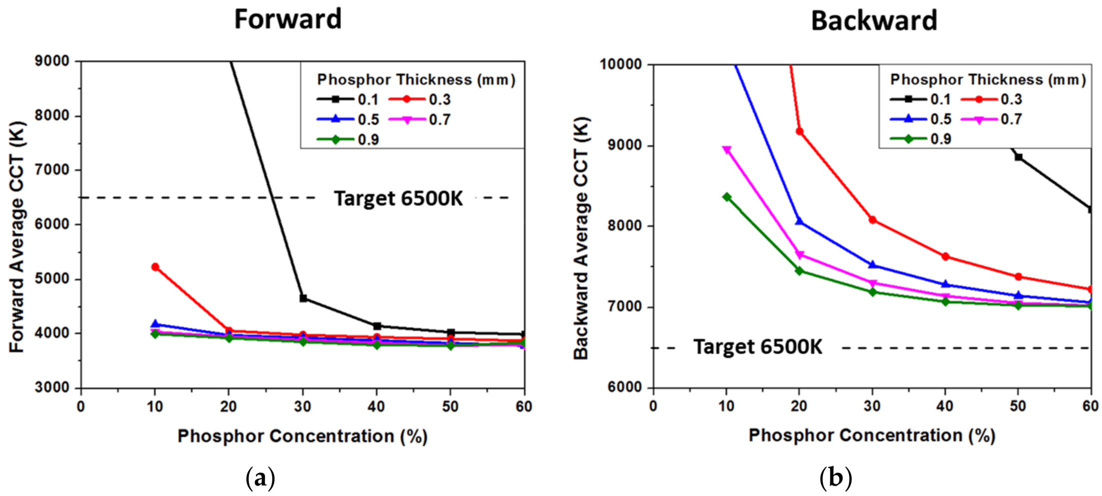



**Figure 3.** (**a**) Forward and (**b**) Backward CCT simulation with various phosphor concentration and thickness for traditional SPE™ structure.

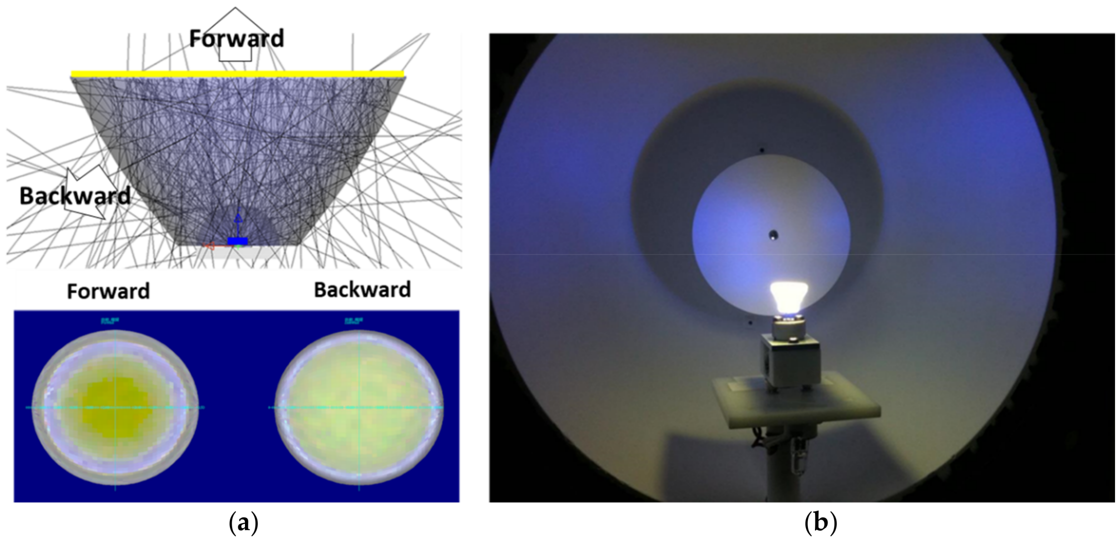
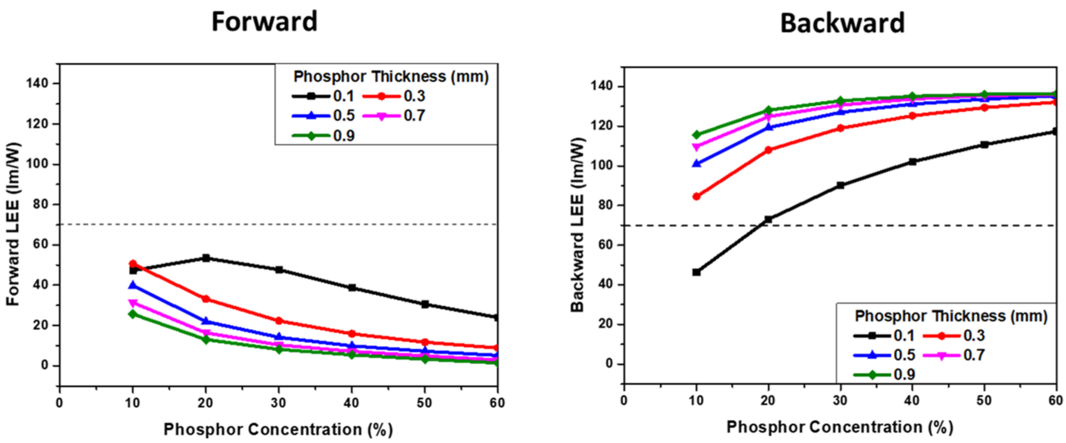



**Figure 4.** The spatial color distribution of SCU-optimized traditional SPE™ in (**a**) simulation and (**b**) experiment. The ACCTD between forward and backward is still significant.

In terms of the LEE, when the concentration of phosphor is higher, in theory, the forward LEE will drop and the backward LEE will increase. The data obtained from the simulation is presented in Figure 5 and the result matches the theory. The figure shows that the concentration and thickness of phosphor have to be 10% and 0.1 mm if we would like to approach the best balance between the forward and backward LEE. At this time, the forward LEE is 47.3 Lm/W and the backward LEE is 46.4 Lm/W. However, this result is unsatisfactory, as there exists a large gap from the optimized SCU. If we consider the SCU-optimized phosphor parameters shown in Figure 4, the difference between forward and backward LEE becomes significant, which is 14.2 and 127 Lm/W respectively. The total LEE is 141.2 Lm/W. As a result, existing SPE™ technology cannot provide both forward and backward balance while maintaining high LEE and SCU.




(**a**) (**b**)

**Figure 5.** (**a**) Forward and (**b**) Backward LEE simulation corresponding to the phosphor parameters of Figure 3.

## 3. Design Strategy for SPE™ Technology

The traditional SPE™ cover the phosphor on a collimator TIR lens to effectively increase the LEE. But it apparently lacks the uniform omnidirectional light and color distribution. The above simulation results show that we cannot simultaneously narrow the difference between the forward and backward CCT and LEE for the traditional SPE™. From this, we learn that we must let the blue light pumping the phosphor effectively to achieve the conversion of multiple excitations. In this paper, to allow the rays to bounce for multiple times on the phosphor, we present two novel TIR lens designs to achieve the goal.

### *3.1. Two-Way Structure Lens Design*

The first proposed lens design is to make good use of the double side of the phosphor layer. If the blue light can excite phosphor from both sides, it increases the utilization of the phosphor. A specific design case, we can place the top surface of the two collimator TIR lens in a position that allows them to face each other, with a phosphor layer between them. The layout is illustrated in Figure 6a.

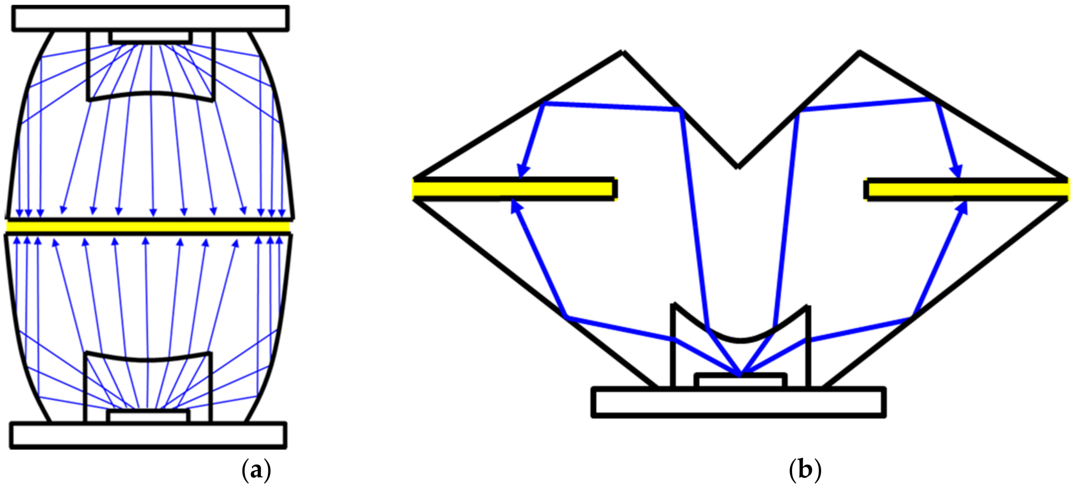
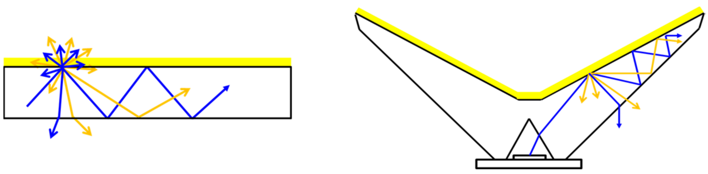



**Figure 6.** Two-way structure lens design. (**a**) Initial design concept, (**b**) Improved TIR lens idea.

By using the concept of the double collimator TIR lenses with a single phosphor layer in between, we can balance the forward and backward CCT easily and thus reduces ΔCCT. But the light source adopted by this design needs two blue LEDs. This is something that needs to be overcome and improved upon in terms of the circuit design and cost. We use the idea to design a TIR lens as shown in Figure 6b that will also serve this function. The purpose of such a two-way structure TIR lens design is to increase the chance of the interaction of the blue light on the phosphor. In this structure, the small-angle light will go through the two sloped sides designed on the top of the lens. Two total internal reflections will take place and then the ray incidents to the upper surface of the phosphor. The large-angle light is incident on the bottom surface of the phosphor by the sidewall of the TIR lens. Therefore, we can adjust the range of phosphor ring coverage. By adjusting the range, the ratio of blue light incident to the upper and bottom surface can be changed in order to bring the forward and backward CCT together to the target value.

### *3.2. Light-Guide Structure Lens Design*

In order to address the issue of the SCU, we further propose another TIR lens design that is based on the light guide concept as shown in Figure 7. The main design idea is to allow the rays to bounce on the phosphor for multiple times within the lens to increase the chance for it to interact with the phosphor. The method provides enough light-mixing space to produce more uniform yellow light to be mixed with the blue light. When conducting the design of the light-guide structure lens, we consider the light source from two perspectives. The first part is the blue light emitted from the LED die. We have to allow it to generate total internal reflected bounces for more times in the light-guide lens. The second part is the emerging light that is converted after the excitation of the phosphor and the scattering blue light that is not absorbed by the phosphor. These lights can be seen as re-emitting light from the phosphor in the Lambertian manner, which will allow most of the light to be excited, scattered and mixed again before being extracted from the lens.



(a) (b)

**Figure 7.** Light-guide structure lens design. (**a**) Initial design concept, (**b**) Improved TIR lens idea.

## 4. Results and Discussion

We have proposed two TIR lens design ideas try to enhance the SCU of SPE™, including two-way and light-guide structure lens. First, the two-way TIR lens design presents the idea to divide the rays into two sections and guide them to the upper and bottom phosphor to make good use of the phosphor. The layout of the final design is shown in Figure 8. In this structure, the width $W_p$ which the phosphor ring covers will be adjusted. The thickness of the phosphor layer in this design is fixed at 0.5 mm, and the concentration is optimized to achieve the overall average CCT closest to the target value of 6500 K. The simulated results of the SCU and LEE are shown in Figure 9. The best result is obtained when the width ratio $W_p/W_l$ is 0.8, and the corresponding concentration of the phosphor is 30%, the ΔCCT and $SD_{CCT}$ can be reduced to 560 K and 548 K respectively. However, the gap between the forward and backward LEE will widen slightly as the width of the phosphor ring increases.

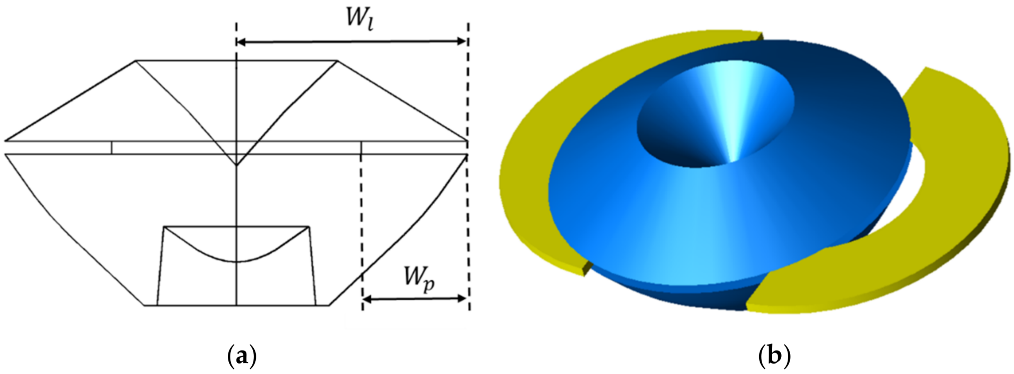



**Figure 8.** The final design of the two-way TIR lens. (**a**) side view, (**b**) 3D exploded view, the yellow part refers to the phosphor and the blue part to the lens.

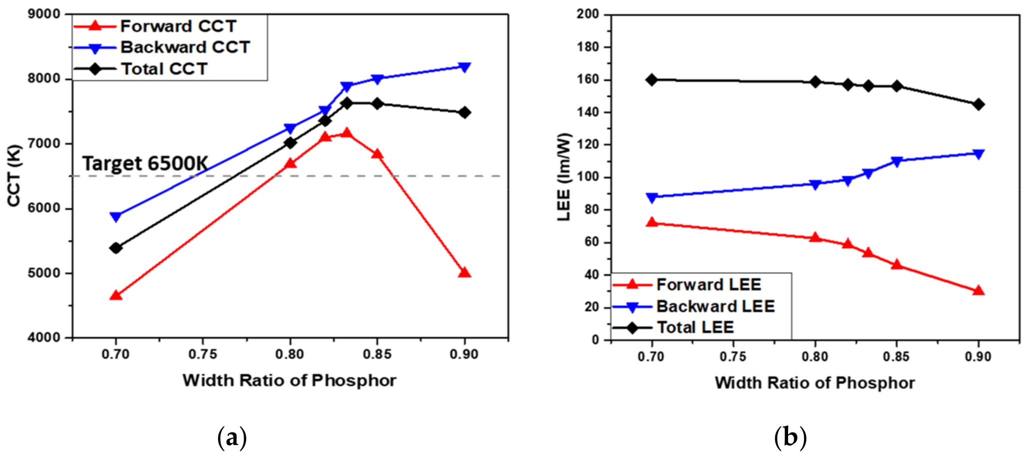
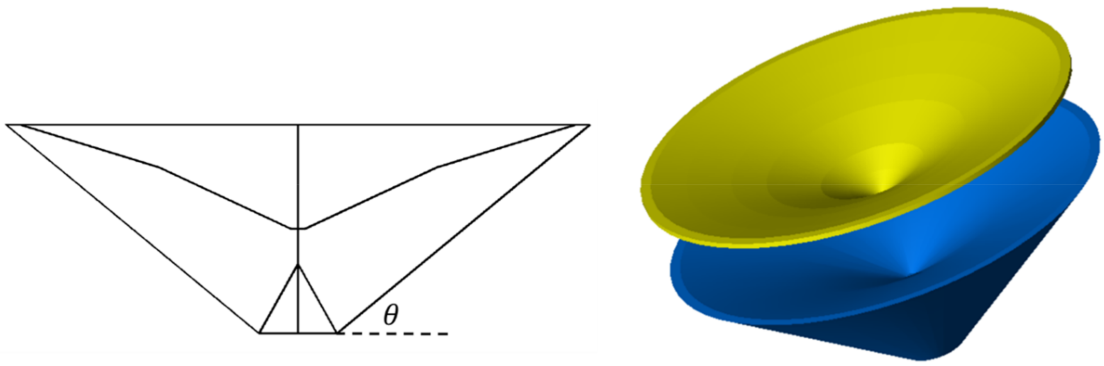


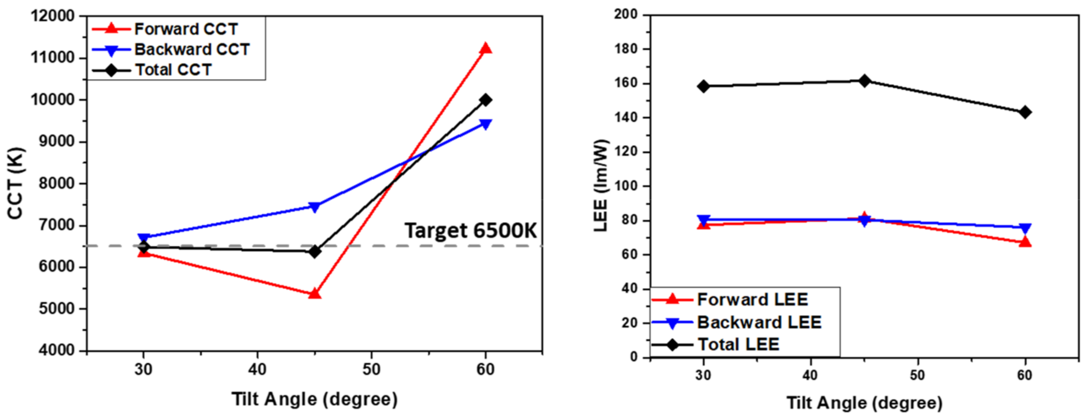

**Figure 9.** The simulated (**a**) SCU and (**b**) LEE for two-way TIR lens according to the width ratio of phosphor covers.

We present another concept for the TIR lens design, which can further increase the utilization of phosphor. This method introduces the light guide structure to allow the light to be guided along the lens through total internal reflection to increase the chance for it to convert with phosphor. Figure 10 shows one of the final design layouts. In the process of design, we found that the tilt angle θ of the light-guide lens will affects the final white light performance. Therefore, we fine-tune the lens shape for the tilt angle of 30, 45 and 60 degrees respectively. Here, the thickness of the phosphor is fixed at 0.5 mm, and the concentration is optimized accordingly. Figure 11 shows the CSU and LEE simulation results for lenses at different tilt angles. The data shows that when the angle is at 30 degrees, and the corresponding concentration of phosphor is 5%, the resulting ΔCCT and $SD_{CCT}$ can further be reduced to 375 K and 190 K compared to the two-way lens. In terms of the LEE, the difference between forward and backward is only 3.4 Lm/W, both are quite close to each other, and the overall LEE can reach 158.4 Lm/W, around 12% higher than traditional SPE™.




(**a**) (**b**)

**Figure 10.** The final design of the light-guide TIR lens. (**a**) side view, (**b**) 3D exploded view, the yellow part refers to the phosphor and the blue part to the lens.




(**a**) (**b**)

**Figure 11.** The simulated (**a**) SCU and (**b**) LEE for light-guide TIR lens at different tilt angles.

The comparison results are list in Table 1 show that our new SPE™ designs are much more efficient than traditional SPE™, whether it is performance in SCU and LEE. In addition, more detailed CCT information of the spatial distribution, the true color map and one-dimensional angular CCT distribution of the simulation are presented in Figure 12. This result shows more clearly that these two designed TIR lenses applied in SPE™ technology can provide a uniform and smooth white light distribution in omnidirectional directions.

**Table 1.** The comparison of phosphor parameters, as well as CSU and LEE performances for different SPE™ solution.

| | **Traditional** | **Two-Way** | **Light-Guide** |
|---|---|---|---|
| Phosphor Thickness (mm) | 0.5 mm | 0.5 mm | 0.5 mm |
| Phosphor Concentration (%) | 30% | 30% | 4% |
| Forward CCT (K) | 3932 K | 6691 K | 6342 K |
| Backward CCT (K) | 7521 K | 7251 K | 6717 K |
| **ΔCCT (K)** | **3589 K** | **560 K** | **375 K** |
| $SD_{CCT}$ **(K)** | **1954 K** | **548 K** | **190 K** |
| Forward LEE (Lm/W) | 14.2 Lm/W | 62.7 Lm/W | 77.5 Lm/W |
| Backward LEE (Lm/W) | 127.0 Lm/W | 96.1 Lm/W | 80.9 Lm/W |
| **ΔLEE (Lm/W)** | **112.8 Lm/W** | **33.4 Lm/W** | **3.4 Lm/W** |
| **Total LEE (Lm/W)** | **141.2 Lm/W** | **158.7 Lm/W** | **158.4 Lm/W** |

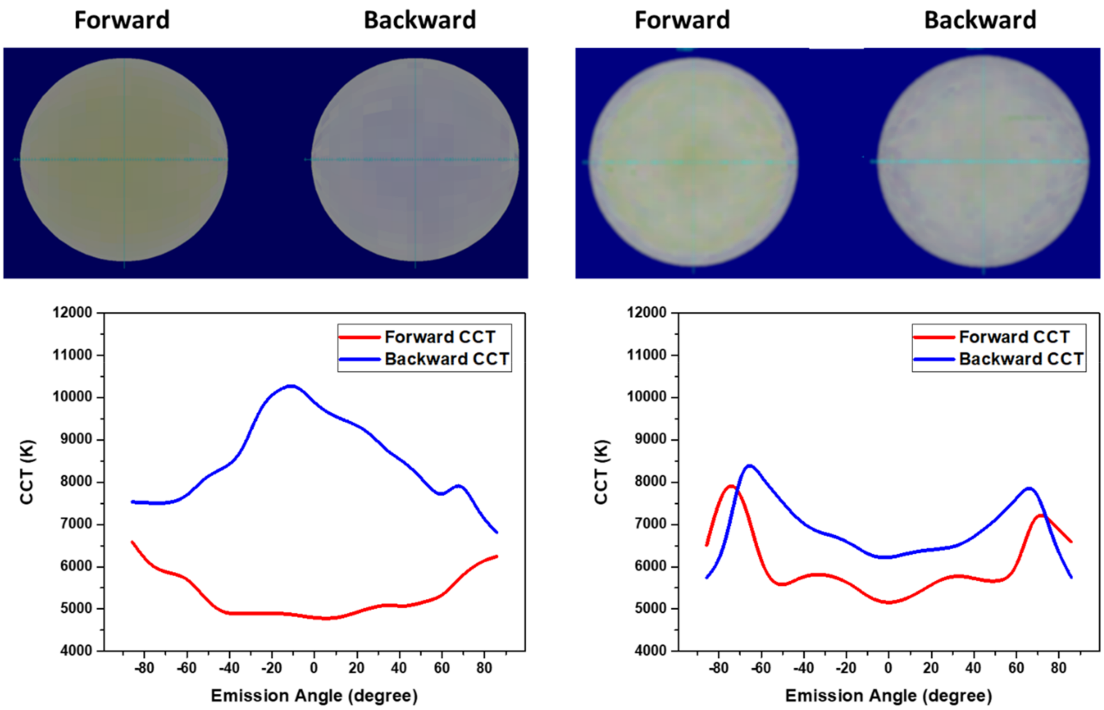



**Figure 12.** The simulated true color map and one-dimensional angular CCT distribution. The SPE™ technology with (**a**) Two-way TIR lens, (**b**) light-guide TIR lens.

## 5. Conclusions

We have proposed a TIR Lens design concept that can simultaneously improve white LED efficiency and spatial color uniformity by multiple phosphor excitations for SPE™. Design methods for the development of two proposed types of TIR lens, two-way and light-guided designs, both are easily implementable and offer great design for omnidirectional lighting. Compared to the traditional SPE™, both designed lenses can provide high SCU quality, which means low ΔCCT and $SD_{CCT}$, and effectively increase the overall LEE by 12%. Furthermore, the light-guide lens can also balance the forward and backward LEE to achieve the most uniform omnidirectional illumination, both in terms of light intensity and color.

**Author Contributions:** T.-X.L. conceived and designed the simulation methods and experiments, as well as analyzed the data and wrote the paper. Y.-C.H. implemented the optical design and analysis.

**Funding:** This study was sponsored by the Ministry of Science and Technology (MOST) of the Republic of China with the contract number 101-2218-E-011-034-.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Narendran, N. Improved performance white LED. *Proc. SPIE* **2015**, *5941*, 594108.
2. Chen, H. LED Structure with Ultraviolet-Light Emission Chip and Multilayered Resins to Generate Various Colored Lights. U.S. Patent 5,962,971, 5 October 1999.
3. -Narendran, N.; Gu, Y.; Freyssinier, J.P.; Zhu, Y. Extracting phosphor-scattered photons to improve white LED efficiency. *Phys. Stat. Sol.* **2005**, *202*, R60–R62. [CrossRef]
4. Zhu, Y.; Narendran, N. Optimizing the performance of remote phosphor LEDs. *J. Light Vis. Environ.* **2008**, *32*, 115–119. [CrossRef]
5. Zhu, Y.; Narendran, N. Investigation of remote-phosphor white light-emitting diodes with multi-phosphor layers. *J. Appl. Phys.* **2010**, *49*, 100203. [CrossRef]
6. Li, B.; Zhang, D.; Huang, Y.; Ni, Z.; Zhuang, S. A new structure of multi-layer phosphor package of white LED with high efficiency. *Chin. Opt. Lett.* **2010**, *8*, 221–223.
7. Liu, Z.; Liu, S.; Wang, K.; Luo, X. Measurement and numerical studies of optical properties of YAG: Ce phosphor for white light-emitting diode packaging. *Appl. Opt.* **2010**, *49*, 247–257. [CrossRef] [PubMed]
8. Shuai, Y.; He, Y.; Tran, N.T.; Shi, F.G. Angular CCT uniformity of phosphor converted white LEDs: Effects of phosphor materials and packaging structures. *IEEE Photonics Technol. Lett.* **2011**, *23*, 137–139. [CrossRef]
9. Wang, K.; Wu, D.; Chen, F.; Liu, Z.; Luo, X.; Liu, S. Angular color uniformity enhancement of white light-emitting diodes integrated with freeform lenses. *Opt. Lett.* **2010**, *35*, 1860–1862. [CrossRef] [PubMed]
10. Liu, Z.; Liu, S.; Wang, K.; Luo, X. Analysis of factors affecting color distribution of white LEDs. In Proceedings of the 2008 International Conference on Electronic Packaging Technology & High Density Packaging, Shanghai, China, 28–31 July 2008; pp. 1–8.
11. Li, S.; Chen, F.; Wang, K.; Zhao, S.; Zhao, Z.; Liu, S. Design of a compact modified total internal reflection lens for high angular color uniformity. *Appl. Opt.* **2012**, *51*, 8557–8562. [CrossRef] [PubMed]
12. Liu, Z.Y.; Li, C.; Yu, B.H.; Wang, Y.H.; Niu, H.B. Effects of YAG: Ce phosphor particle size on luminous flux and angular color uniformity of phosphor-converted white LEDs. *J. Disp. Technol.* **2012**, *8*, 329–335. [CrossRef]
13. Sun, C.C.; Chen, C.Y.; Chen, C.C.; Chiu, C.Y.; Peng, Y.N.; Wang, Y.H.; Yang, T.H.; Chung, C.Y. High uniformity in angular correlated-color-temperature distribution of white LEDs from 2800 K to 6500 K. *Opt. Express* **2012**, *20*, 6622–6630. [CrossRef] [PubMed]
14. Keppens, A.; Denijs, S.; Wouters, S.; Ryckaert, W.R.; Deconinck, G.; Hanselaer, P. Modelling the spatial colour distribution of phosphor-white high power light-emitting diodes. *Proc. SPIE* **2010**, *7717*, 77170J.
15. Sommer, C.; Krenn, J.R.; Hartmann, P.; Pachler, P.; Schweighart, M.; Tasch, S.; Wenzl, F.P. The effect of the phosphor particle sizes on the angular homogeneity of phosphor-converted high-power white LED light sources. *IEEE J. Sel. Top. Quant.* **2009**, *15*, 1181–1188. [CrossRef]
16. Sommer, C.; Reil, F.; Krenn, J.R.; Hartmann, P.; Pachler, P.; Tasch, S.; Wenzl, F.P. The impact of inhomogeneities in the phosphor distribution on the device performance of phosphor-converted high-power white LED light sources. *J. Light. Technol.* **2010**, *28*, 3226–3232. [CrossRef]
17. Kan, D.; Wu, E.; Wang, D. Design optimization and experimental verification of white-light-emitting diodes using multiple phosphor films. *Proc. SPIE* **2006**, *6669*, 63370.
18. Yu, R.; Jin, S.; Cen, S.; Liang, P. Effect of the phosphor geometry on the luminous flux of phosphor-converted light-emitting diodes. *IEEE Photonics Technol. Lett.* **2010**, *22*, 1765–1767.
19. Zhu, Y.; Narendran, N.; Gu, Y. Investigation of the optical properties of YAG: Ce phosphor. *Proc. SPIE* **2006**, *6637*, 63370S.
20. Kuo, H.C.; Hung, C.W.; Chen, H.C.; Chen, K.J.; Wang, C.H.; Sher, C.W.; Yeh, C.C.; Lin, C.C.; Chen, C.H.; Cheng, Y.J. Patterned structure of remote phosphor for phosphor-converted white LEDs. *Opt. Express* **2011**, *19*, A930–A936. [CrossRef]
21. Lin, M.T.; Ying, S.P.; Lin, M.Y.; Tai, K.Y.; Tai, S.C.; Liu, C.H.; Chen, J.C.; Sun, C.C. Ring remote phosphor structure for phosphor-converted white LEDs. *IEEE Photonics Technol. Lett.* **2010**, *22*, 574–576. [CrossRef]
22. Allen, S.C.; Steckl, A.J. ELiXIR-solid-state luminaire with enhanced light extraction by internal reflection. *J. Display Technol.* **2007**, *3*, 155–159. [CrossRef]

23. Allen, S.C.; Steckl, A.J. A nearly ideal phosphor-converted white light-emitting diode. *Appl. Phys. Lett.* **2008**, *92*, 143309. [CrossRef]
24. Lee, T.X.; Chou, C.F. Ideal luminous efficacy and color spatial uniformity of package-free LED based on a packaging phosphor-coated geometry. *Appl. Opt.* **2016**, *55*, 7688–7693. [CrossRef] [PubMed]


© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).