Improving the Performance of Mixed-Color White LED Systems by Using Scattered Photon Extraction Technique

Huiying Wu, Nadarajah Narendran, Yimin Gu, and Andrew Bierman

Lighting Research Center
Rensselaer Polytechnic Institute, Troy, NY 12180
www.lrc.rpi.edu

Improving the Performance of Mixed-Color White LED Systems by Using Scattered Photon Extraction Technique

Huiying Wu, Nadarajah Narendran*, Yimin Gu, and Andrew Bierman

Lighting Research Center, Rensselaer Polytechnic Institute;
21 Union St., Troy, NY, 12180 USA

ABSTRACT

One of the methods for creating white light with light-emitting diodes (LEDs) is mixing radiations from several different colored LEDs. Mixed-color LEDs are expected to have greater luminous efficacy because they do not undergo down-conversion losses like phosphor-converted white LEDs. However, in reality mixed-color LED systems require extra optical elements to reduce spatial color variation and create uniform white light. Optical diffusing techniques commonly used for these purposes cause light loss, because some portion of the light is scattered back toward the LEDs where it is absorbed and lost. In 2004, a technique known as scattered photon extraction (SPE) was used to extract backscattered light from the phosphor layer of phosphor-converted white LEDs to increase overall light output. In this study, it was hypothesized that by using similar SPE optics with optical diffusers, the spatial color uniformity of mixed-color white LED systems could be improved without sacrificing the overall luminous efficiency. With this new approach, both a microsphere-doped diffuser and SPE optics were utilized. The experiments showed that the proposed setup did increase the spatial color uniformity of the mixed-color LED system with more than 79% overall optical efficiency. This study also demonstrated the effects of microsphere size, concentration, and diffuser thickness on spatial color uniformity and optical efficiency.

Keywords: mixed-color white LEDs, color uniformity, luminous efficiency, diffuser, scattered photon extraction

1. INTRODUCTION

Light-emitting diode (LED) technology has attracted great attention from the community interested in general lighting, primarily because of its potential to save energy and reduce maintenance costs.[1-3]

With LEDs, there are basically two main approaches to create white light. One method is to mix monochromatic radiations from several different colored LEDs (e.g., red, green and blue) in appropriate proportions. By carefully controlling the radiation from each LED, the mixed light will exhibit a spectrum that is perceived as white light by the human eye. The other method is to combine a short-wavelength LED with down-conversion phosphor(s).[4-7]

Comparing the two methods, the mixed-color approach could provide greater luminous efficacy because the LEDs do not undergo losses caused by the phosphor down-conversion process. Moreover, the mixed-color LEDs provide flexibility in color. Therefore, mixed-color LEDs could be the preferred method in the long term for producing high-quality white light.[4] In reality, for mixed-color LED systems to achieve high luminous efficacy, they have to overcome some challenges, including higher efficacy for green emission, and reduced optical losses when using extra optical elements to eliminate spatial color variations.

The optical components previously adopted for color mixing include transmissive optics, reflective optics, or diffusing optics.[8-12] Among them, the commonly utilized are optical diffusers; however, their low optical efficiency, due to light scattered back toward the LEDs, remains an issue. A technique known as scattered photon extraction (SPE) provided a possible solution for reducing losses caused by the backscattered light from the phosphor layer.[13] Past studies have also shown that transparent refractive-index-matched microparticle (TRIMM)-doped diffusers exhibit good color mixing capabilities with high transmission.[14-17] However, these studies did not systematically quantify how the TRIMM-doped diffusers affected the spatial color uniformity.

Therefore, in this study the SPE technique and the microparticle-doped diffuser were applied together to build a mixed-color LED system that could create uniform white light with high optical efficiency.

* E-mail: narenn2@rpi.edu; Tel: 518-687-7100; Web: www.lrc.rpi.edu

2. METHODOLOGY

In this study, we proposed an optical setup consisting of a red, green and blue (RGB) mixed-color LED with a TRIMM-doped diffuser added to the top surface of an SPE optic, as shown in Figure 1, to increase the spatial color uniformity of the mixed-color LED system with high optical efficiency. The TRIMM-doped diffuser is supposed to increase the chances of color mixing; the SPE secondary optic is designed to extract the backscattered light, thus ensuring a high optical efficiency.
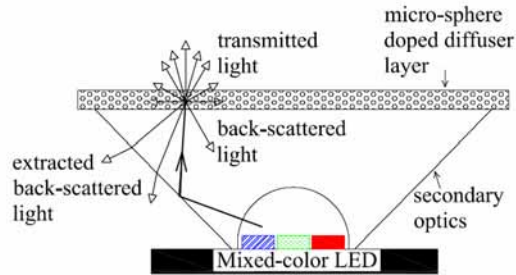

Figure 1: Schematic of microsphere-doped diffuser with SPE technology for RGB LED.

Laboratory experiments and computer simulations were carried out to understand the performance of the proposed optical setup.

2.1 Laboratory Measurements

The LED system was built as shown in Figure 1. A commercial RGB LED composed of 6 chips (2 red, 2 green and 2 blue) was utilized, on top of which was placed the SPE optics, an off-the-shelf secondary optics for this type of LED. Fourteen microparticle-doped diffuser samples were created, as listed in Table 1. (The shape of each microparticle is a sphere.) Each diffuser sample could be easily attached to and then removed from the top of the SPE optics. These diffusers were made of a cured mixture of epoxy resin and polymethyl methacrylate (PMMA) microspheres. Four different-sized PMMA microspheres (diameter 1.5 μm, 6.5 μm, 15 μm and 83 μm) were used with concentrations ranging from 0.02 mg/mm^3 to 0.18 mg/mm^3. In the end, the diffusers' thickness ranged from 0.6 mm to 1.8 mm.

Table 1: Microsphere-doped Diffusers

No.	Microsphere Size (μm)	Microsphere Concentration (mg/mm^3)	Diffuser Thickness (mm)
1	1.5	0.05	1.0
2	1.5	0.13	0.7
3	1.5	0.15	1.3
4	6.5	0.03	0.6
5	6.5	0.08	1.2
6	6.5	0.16	1.2
7	15	0.02	1.1
8	15	0.09	1.2
9	15	0.16	1.3
10	83	0.02	1.1
11	83	0.09	1.1
12	83	0.18	1.1
13	6.5	0.08	0.6
14	6.5	0.08	1.8

Note: Thickness of Diffuser Nos. 1, 3, and 5-12 was considered as 1 mm in later analysis.

The spatial color uniformity and the optical efficiency of the LED system with each diffuser sample were measured and compared.

2.1.1 Spatial Color Uniformity

The spatial color uniformity characterization of the proposed RGB LED system was based on a CCD camera system, as shown in Figure 2. The CCD camera system can be applied to capture images and quantitatively analyze the radiometry, photometry, and colorimetry of the images.[18]
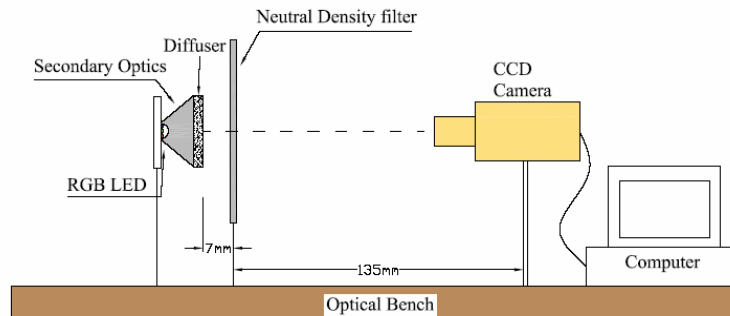

Figure 2: Experimental apparatus to measure spatial color uniformity.

The captured images were analyzed by a method similar to the "Frequency Accumulation Method".[9] Accordingly, each image was first divided into small bins, each composed of 2×2 adjacent pixels. For each bin, chromaticity coordinates (u',v') were defined as the averaged chromaticity values of all the enclosed pixels. Then, the chromaticity coordinates of all bins were plotted in a CIE 1976 diagram. The plotted points would appear as a group of dots conglomerated in a small region, as seen in Figure 3. To specify the color uniformity across the whole image, a parameter called "mean-r" was introduced, which was the average distance between each individual dot to their average center, also shown in Figure 3. A larger mean-r corresponds to worse color uniformity and vice versa. If the color of an image is perfectly uniform, the mean-r value should be zero.
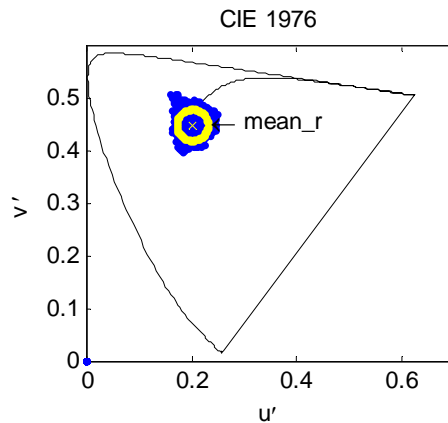

Figure 3: Illustration of spatial color uniformity evaluation.

2.1.2 Optical Efficiency

The optical efficiency of the RGB LED system was measured with an integrating sphere system, as shown in Figure 4. The light output of the bare RGB LED without additional optics was considered as 100% efficient. Firstly, the total light output from the RGB LED system in Figure 1 was measured. Secondly, the light exiting through the sidewall of the SPE lens was blocked by a black holder, as shown in Figure 4, so that the integrating sphere collected only the light transmitted through the diffuser layer. In the end, the amount of light exiting through the sidewalls of the SPE lens was obtained by subtracting the transmitted light from the total light.
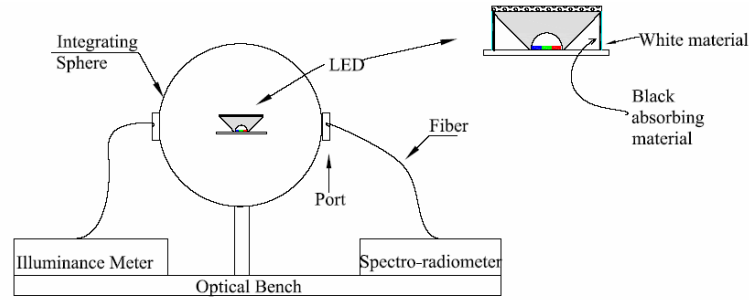
Figure 4: Experimental apparatus to measure optical efficiency (top right is the detailed LED structure for measuring the transmitted light).

2.2 Computer Simulation

Computer simulations were also carried out by a commercial software product, LightTools, whose algorithm is based on Monte Carlo ray tracing. In addition, its algorithm for the microsphere-doped diffusers is established on Mie theory.[19]

The computer model was built according to the physical geometry and characteristics of each component in the mixed-color LED system. The model also included a far-field spherical receiver to collect the output light and a flat receiver located 7 mm away from the light source, like the neutral density filter in Figure 2, to collect the spatial color distribution information.

3. RESULTS

3.1 Spatial Color Uniformity

The CCD camera images of the RGB LED systems with different diffusers are shown in Figure 5. These images provide some visual evidence that: (1) for diffusers with smaller microspheres, the spatial color uniformity is better than for diffusers with larger microspheres, as seen from images of diffuser Nos. 4, 7 and 10; (2) a higher concentration of microspheres also produced better color uniformity (e.g., images for diffuser Nos. 10, 11, and 12); and (3) increasing diffuser thickness also showed improved color uniformity, as shown in images for diffuser Nos. 13, 5 and 14.
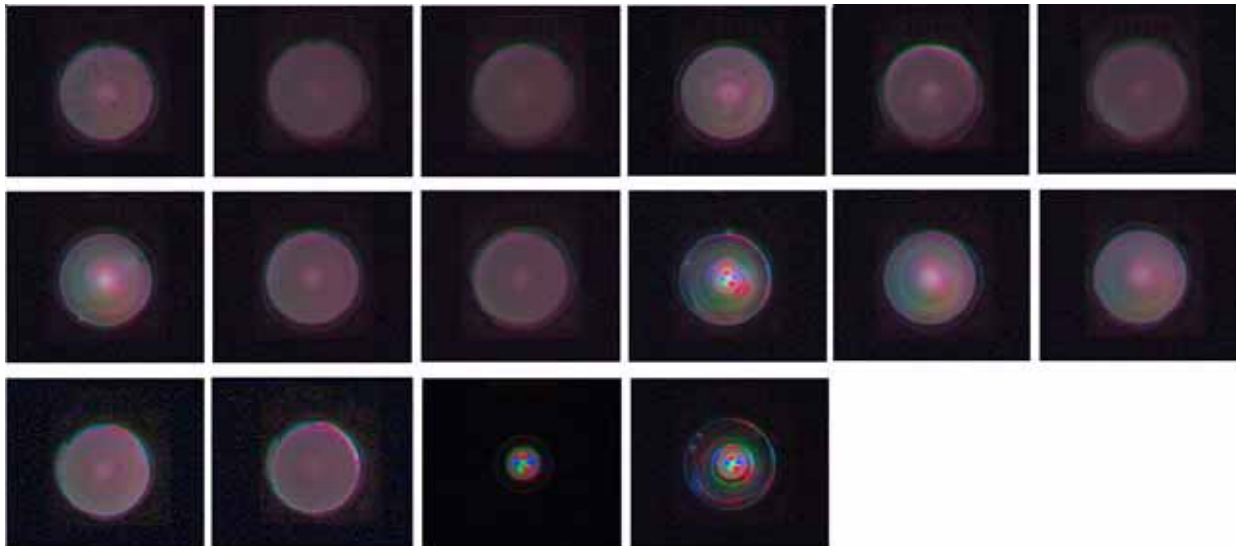
Figure 5: CCD camera images: Top row (left to right): RGB LED with SPE lens and diffuser No.1, No.2, No.3, No.4, No.5, and No.6; Central row (left to right): No.7, No.8, No.9, No.10, No.11 and No.12; Bottom row (left to right): No.13, No.14, Bare RGB LED, RGB LED with SPE lens but without a microsphere-doped diffuser

To quantitatively evaluate the results, the spatial color uniformities of all above images were expressed by their mean-r values.

Figure 6 shows that the mean-r value of the bare RGB LED is much higher than that of the Led with SPE lens and microsphere-doped diffusers, which means the proposed setup did improved spatial color uniformity.
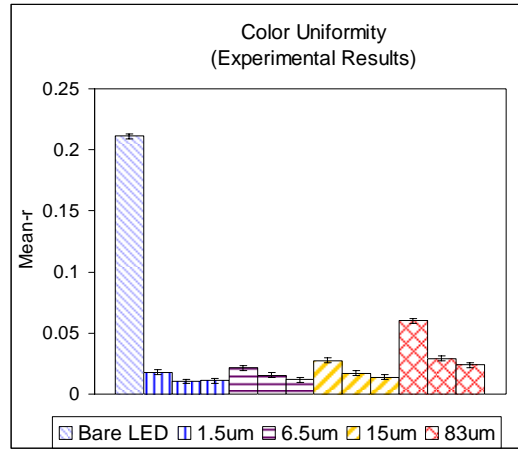

Figure 6: Color uniformity of the bare RGB LED vs. RGB LED with SPE lens and microsphere-doped diffusers (No.1 to No.14).

Figure 7(a) shows the relationship between spatial color uniformity and microsphere size, while keeping the microsphere concentration and diffuser thickness constant. An exponential best-fit curve through the data points resulted in very high regression (R) values. Therefore, exponential fits were used in this study because to our best knowledge, no previous literature has shown the relationship between microsphere size and spatial color uniformity. (We wish to caution that without further exploration, this exponential relationship cannot be directly extended to wider ranges other than those used in this study.) The curves show that the mean-r values decrease with decreasing microsphere sizes (i.e., smaller sized microspheres produced lower mean-r values, meaning better color uniformity). Figure 7(a) also shows another set of data from a different concentration. This curve also shows a similar trend—smaller microspheres resulting in better color uniformities. This result is reasonable because Mie theory asserts that for smaller particles, the scattered beam angle becomes wider, increasing the chances for the different colored beams to mix.[20]

Figure 7(b) shows the relationship between optical efficiency and microsphere size. As stated before, no previous literature has shown any formula between them. Since power function resulted in high regression (R) values, it was used as the best-fit curves. (Again, we wish to caution that without further exploration, this exponential relationship cannot be directly extended to wider ranges other than those used in this study.) Figure 7(b) also shows another set of data from diffusers with a different concentration. This curve also shows a similar trend—smaller microspheres result in lower efficiencies.

Figure 8(a) shows the relationship between microsphere concentration and spatial color uniformity for four different-sized microspheres. The data were also fitted with power curves for the same reason given in the previous cases. All four curves exhibited similar trends—that higher microsphere concentrations produce smaller mean-r values, meaning better color uniformity, which is consistent with the results from Smith et al.[14] and Deller et al. [16]

Figure 8(b) shows the relationship between microsphere concentration and optical efficiency, with four different-sized microspheres. Their relationship could be explained by Beer-Lambert's Law, which states there is an exponential relationship between transmitted light and microsphere concentration. Therefore, the data in Figure 8(b) were fitted with exponential curves. The four curves all exhibited similar trends—higher concentrations lead to lower system efficiency.

Figure 9(a) shows that spatial color uniformity was slightly improved when the thickness of the diffusers increased from 0.6 mm to 1.8 mm. The data were fitted to an exponential curve, also due to the high regression value from this type of curve. The results show decreasing mean-r values with increasing thickness, which agree with the results from Smith et al. [14]

Figure 9 (b) shows the relationship between optical efficiency and diffuser thickness. The data points in Figure 9 (b) were fitted to an exponential curve according Beer-Lambert's Law. The figure reveals that the system efficiency decreased by 5% when diffuser thickness increased from 0.6 mm to 1.8 mm, which is consistent with Beer-Lambert's Law.
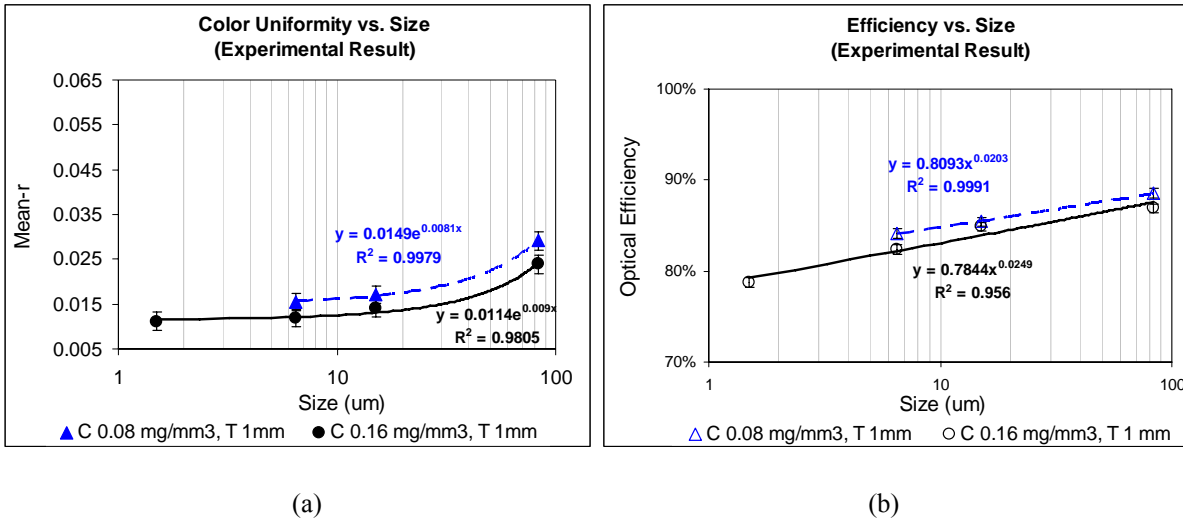

(a)

(b)

Figure 7: (a) Color uniformity vs. microsphere size; (b) Efficiency vs. microsphere size (experimental result, "C" means concentration, "T" means thickness)
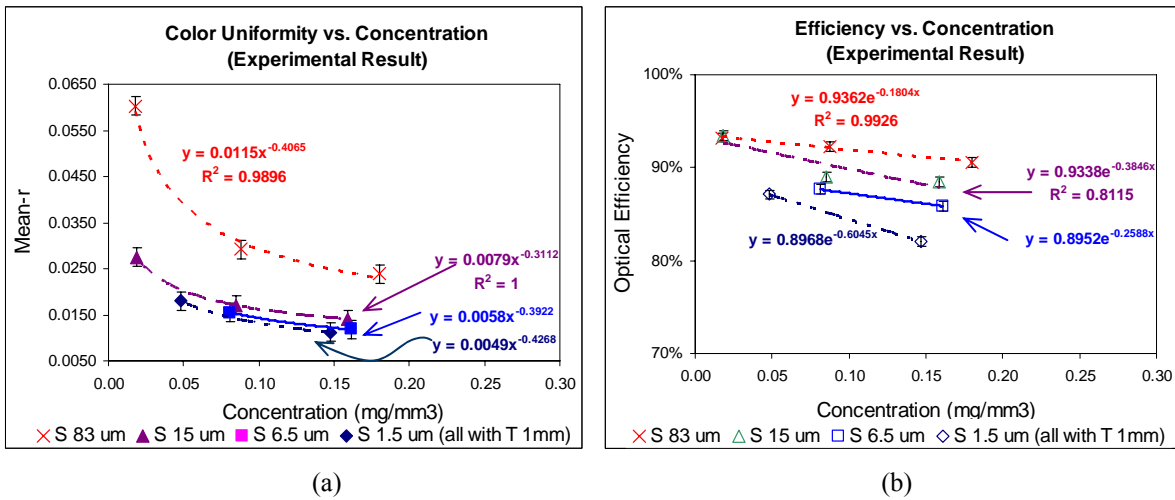

(a)

(b)

Figure 8: (a) Color uniformity vs. microsphere concentration; (b) Efficiency vs. microsphere concentration (experimental result, "S" means size, "T" means thickness)

**Color Uniformity vs. Thickness
(Experimental Result)**

Mean-r

$y = 0.0225e^{-0.2659x}$
$R^2 = 0.9431$

0.065
0.055
0.045
0.035
0.025
0.015
0.005

0.0   0.5   1.0   1.5   2.0
Thickness (mm)
◆ S 6.5um, C 0.08 mg/mm3

**Efficiency vs. Thickness
(Experimental Result)**

Optical Efficiency

$y = 0.8784e^{-0.0319x}$
$R^2 = 0.9676$

100%
90%
80%
70%

0.0   0.5   1.0   1.5   2.0
Thickness (mm)
◇ S 6.5um, C 0.08 mg/mm3

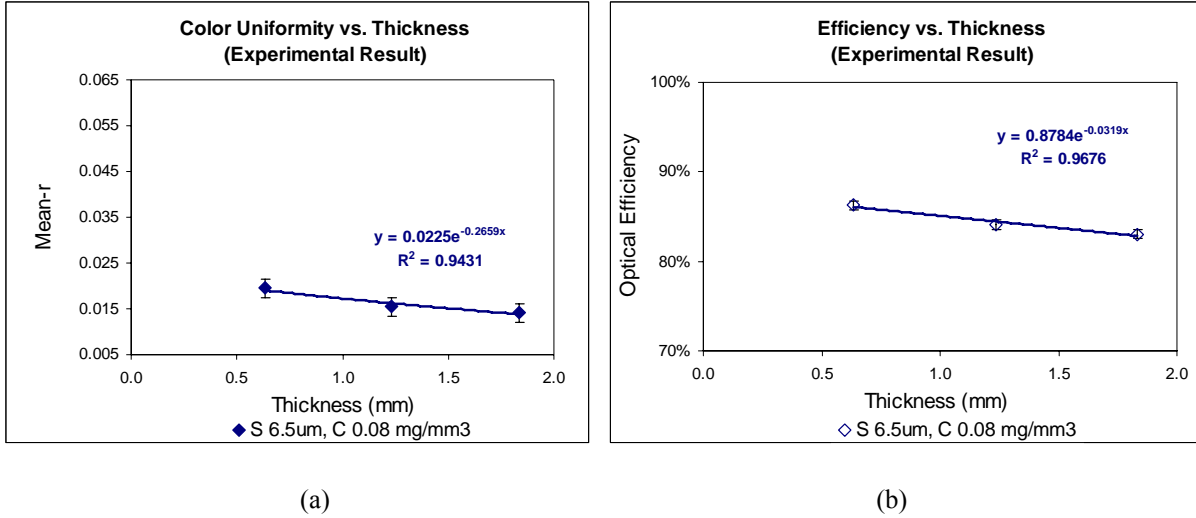(a)   (b)

Figure 9: (a) Color uniformity vs. diffuser thickness; (b) Efficiency vs. diffuser thickness (experimental result, "S" means size, "C" means concentration)

3.2 Computer Simulation Results

The computer simulation results are shown in Figure 10, Figure 11, Figure 12, and Figure 13

Regarding spatial color uniformity, from Figure 10 it was discovered that the mean-r value for the bare RGB LED is higher than those for the RGB LED with different diffusers, regardless of microsphere size, concentration, and diffuser thickness. This implies that microsphere-doped diffusers augmented the spatial color uniformity for the RGB LED system. The trend also confirms the experimental results in Figure 6. However, the simulated mean-r value of the bare RGB LED is much lower than its peer experimental result. The discrepancy between simulation result and experimental result was attributed to the depth of focus of the CCD camera. The CCD camera has a depth of focus, while the receiver in the computer models does not. Specifically, the depth of focus makes the CCD camera collect information not only from the neutral density filter, but also from other adjacent objects, such as the LED chips. Therefore, the CCD camera result showed less color uniformity than the simulation result for the bare RGB LED.

**Spatial Color Uniformity
(LightTools Simulation Result)**

Mean-r

0.10
0.08
0.06
0.04
0.02
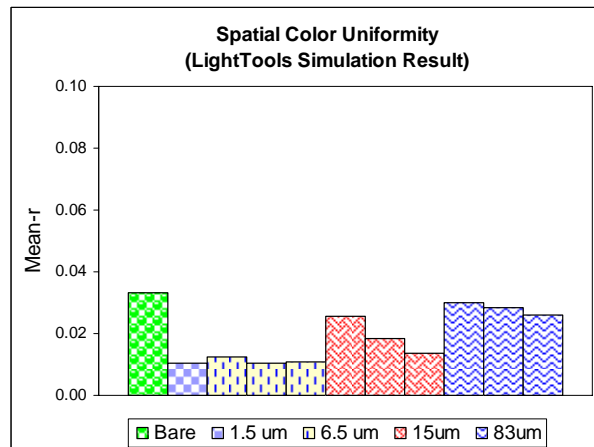0.00

□ Bare   ■ 1.5 um   ▨ 6.5 um   ■ 15um   ▨ 83um

Figure 10: Color uniformity of RGB LED vs. RGB LED with SPE lens and different microsphere-doped diffusers (left to right: diffuser No.3, No.5-No.12, and No.14).

The simulation results in Figure 11(a) show similarity to the peer experimental results [Figure 7(a)]. They all indicate that better spatial color uniformities are obtained by diffusers using smaller-sized microspheres. On the other hand, the simulation results also show that these diffusers with smaller-sized microspheres produce lower system efficiencies, as seen in Figure 11(b), which exhibits similar curve shapes to the peer experimental results [Figure 7(b)]; however, their absolute values are not similar. The simulated optical efficiencies are always 10% higher than the results from the experiments. This discrepancy could be because the SPE lens was not perfectly cemented to the LED in the experiments; the air gap in between introduced 5%-10% extra energy loss. This guess was confirmed by experimental measurement results. Another possible reason could be the indices of refraction provided by the manufacturer's data sheet could be different from the actual values of the materials used in the experiments, which would also result in a discrepancy between simulation results and experimental results. In short, the simulation results, based on Mie theory, showed similar trends to the experimental results but with slightly different absolute values.
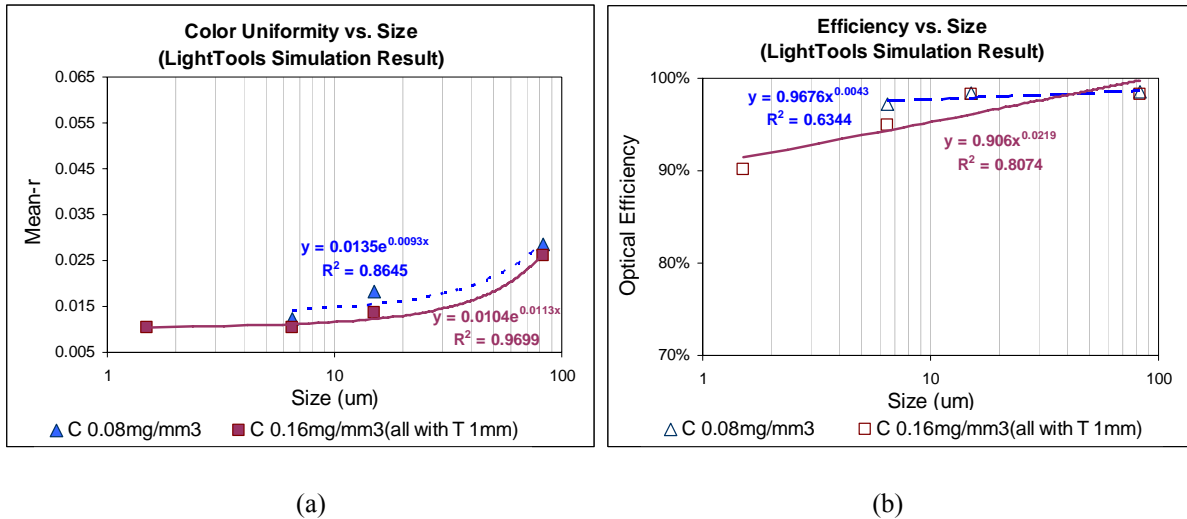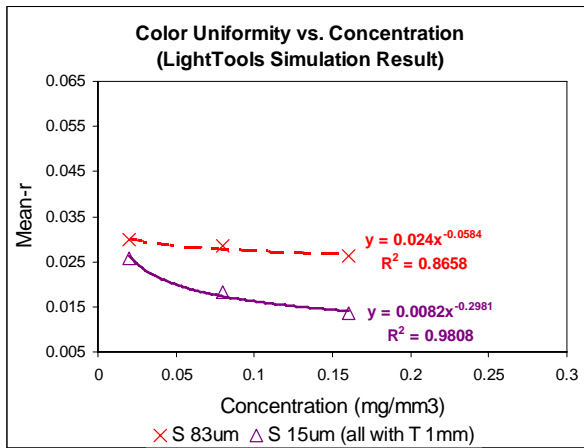

| (a) | (b) |

Figure 11: (a) Color uniformity vs. microsphere size; and (b) Efficiency vs. microsphere size (simulation result, "C" means concentration, "T" means thickness)

Figure 12 shows the simulated characteristics of diffusers with different microsphere concentrations. Figure 12(a) shows that higher microsphere concentrations produce lower mean-r values (i.e., more uniform color distribution). The simulation results agree well with experimental results in Figure 8(a).

On the other hand, Figure 12(b) shows that higher microsphere concentrations produce lower optical efficiencies. The simulation results in Figure 12(b) share similar trends with the experimental results [Figure 8(b)], but with about 10% higher absolute values due to the reason explained above. In summary, the simulation results exhibit similar trends to the experimental results for diffusers with different microsphere concentrations.

Figure 13 illustrates the simulation results for diffusers with different thickness but with similar microsphere sizes and concentrations. Due to limited time, only two data points were calculated and shown in Figure 13 (a). The graph shows that color uniformity was slightly improved with increasing thickness from 1 mm to 2 mm, which is very similar to the peer experimental results in Figure 9(a). At the same time, the system efficiencies drop from 97.2% to 94.7% when the diffuser thickness increases from 1 mm to 2mm, as shown in Figure 13 (b), which is similar to the experimental results shown in Figure 9(b). Likewise, the simulation results are about 5%-10% higher than the experimental results due to the reason explained previously.
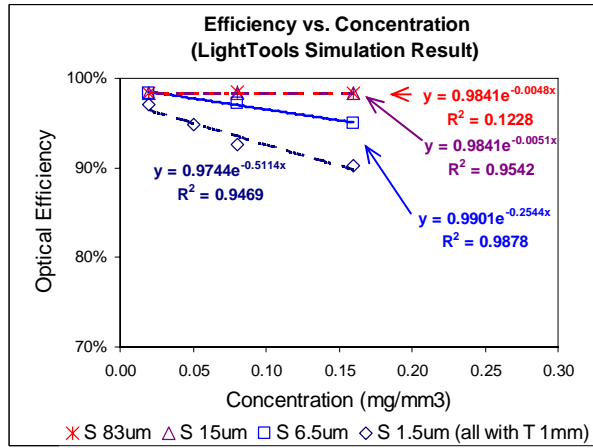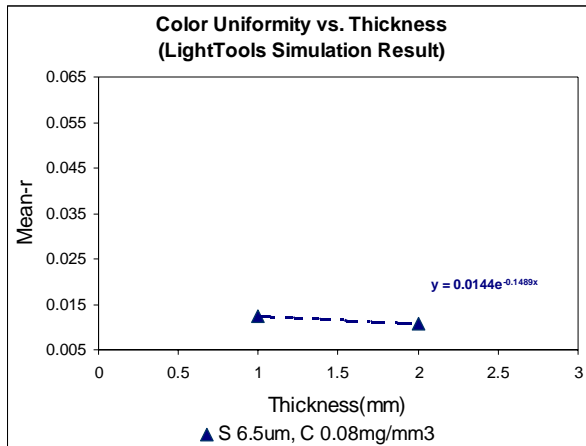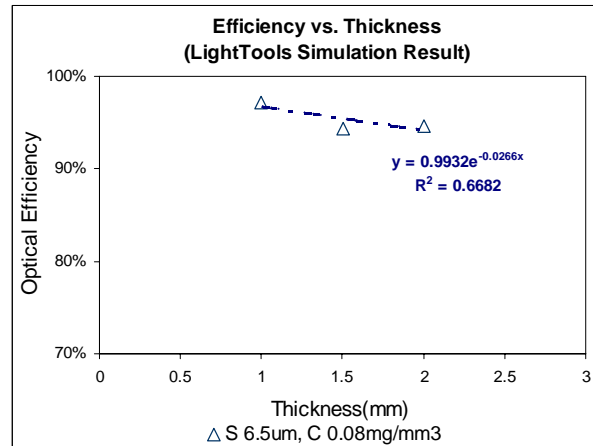
Figure 12: (a) Color uniformity vs. microsphere concentration; and (b) efficiency vs. microsphere concentration (simulation results, "S" means size, "T" means thickness)

Figure 13: (a) Color uniformity vs. thickness; and (b) Efficiency vs. thickness (simulation results, "S" means size, "C" means concentration)

4. DISCUSSION

4.1 Spatial Color Uniformity

The fact that spatial color uniformities improved with smaller-sized microspheres could be for two reasons. One is that smaller-sized microspheres produce wider beam angles than larger-sized microspheres according to Mie theory.[20] The other reason is that the overall surface area of the smaller microspheres is larger than that of the bigger microspheres, under the circumstance that they have the same concentration (volume fraction). This means larger overall cross sections for smaller microspheres than bigger microspheres if they have the same concentration; therefore, the light rays have more chances to be diffused. The combination of these two effects results in better color uniformity from smaller microspheres.

That spatial color uniformity improved with increasing microsphere concentration could be because the mean free path (the average distance a ray will travel before encountering a scattering particle) of a ray decreases with increasing microsphere concentration. Therefore, the optical rays have more chances to be diffused before exiting by the microspheres with higher concentration. In the end, the color-mixing effect is enhanced, which results in more uniform spatial color distribution.

The color uniformity increased with increasing diffuser thickness could be because when the thickness of a diffuser is increased, the ray also has more chances to be diffused by microspheres before exiting the diffuser, which also will produce a more uniform color distribution.

4.2 Overall Optical Efficiency

If we compare image (a) with image (b) of Figure 7, Figure 8, Figure 9, Figure 11, Figure 12 and Figure 13, we find that lower mean-r values (better color uniformity) are always associated with lower efficiency. There are two reasons contributing to this phenomenon: one is related to the backscattered light absorbed by the LED chips; the other is related to the absorption of materials.

Basically, all the light from the LED chips is divided into several portions after encountering the diffuser layers: the first is the light transmitted through the diffuser; the second is the light trapped and absorbed by the diffuser materials; and the remainder is the backscattered light from the diffuser, which could be subdivided into two portions. One portion will be absorbed by the LED chips and the other components inside the LED package, while the other portion will be extracted through the sidewall of the SPE lens. The total light output measured by the integrating sphere is the summation of transmitted light and the extracted backscattered light.

Figure 14 shows the transmitted light from the diffuser top and the backscattered light extracted through the sidewall of the SPE lens. Among all the output light, roughly 70%-80% of light was transmitted from the top of the diffuser layer, while the other 20%-30% of light was extracted through the sidewall of the SPE lens. This means that by using the microsphere-doped diffuser, most of the light is projected in a forward direction, which is preferable in many applications. It also means that the SPE lens did help to extract the backscattered light.

Figure 14 also reveals that the proportion of transmitted light decreases with decreasing microspheres size, while the extracted backscattered light increases with decreasing microspheres size. Further, the proportion of transmitted light decreases with increasing microsphere concentration; while the extracted backscattered light increases with increasing concentration.
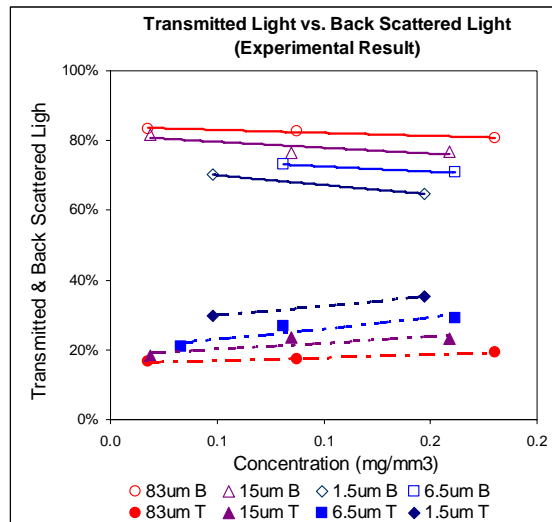

Figure 14: Transmitted light vs. backscattered light extracted from the sidewall of the SPE lens (experimental result). (100% means the total light output for the RGB LED with SPE lens and a certain microsphere-doped diffuser; "83um T" means transmitted light from the diffuser made by 83 μm microspheres; "B" means extracted backscattered light; others follow this rule)

5. SUMMARY

The main experiments demonstrated that the proposed SPE optics with a microsphere-doped diffuser on its top surface:

- Increases the spatial color uniformity of the mixed-color LED system with more than 79% overall optical efficiency.

- Produces more uniform spatial color distribution with smaller microspheres than with larger microspheres at the same concentration (volume fraction), although the optical efficiency of systems with smaller microspheres is lower.

- Produces more uniform spatial color distribution with higher concentrations of microspheres than with lower concentrations, although the optical efficiency is lower for systems with higher microsphere concentrations.

- Produces better spatial color uniformity with thicker diffusers than with thinner diffusers, although the optical efficiency is lower for systems with thicker diffusers.

ACKNOWLEDGMENTS

REFERENCES

[1] Optoelectronics Industry Development Association, *Light Emitting Diodes (LEDs) for General Illumination, An OIDA Technology Roadmap Update*, 2002.

[2] Uchida, Y. and Taguchi, T., "Lighting theory and luminous characteristics of white light-emitting diodes," Optical Engineering **44(12)**, p. 124003, 2005.

[3] Lighting Research Center, LED Lighting Institute Handout, 2007.

[4] Optoelectronics Industry Development Association, *The promise of solid state lighting for general illumination: Light Emitting Diodes and Organic Light Emitting Diodes*, 2001.

[5] Mueller-Mach, R. and Mueller, G.O., "White light emitting diodes for illumination," In Light-Emitting Diodes: Research, Manufacturing and Applications IV, Proc. of SPIE, **Vol. 3938**, pp. 30-41, 2000.

[6] Narendran, N., et al., "Characterizing LEDs for general illumination applications: Mixed-color and phosphor-based white source," Solid State Lighting and Displays. Proceedings of SPIE, **Vol. 4445**, pp. 137-147, 2001.

[7] Hoelen, C., et al., "Multi-chip color variable LED spot modules," Fifth International Conference on Solid State Lighting, Proceedings of SPIE **Vol. 5941**, p. 59410A, 2005.

[8] Zhao, F., et al., Optical elements for mixing colored LEDs to create white light, Proceeding of SPIE, Vol. 4776, pp.206-214, 2002.

[9] Zhao, F., *Optical elements for mixing colored LEDs to create white light*, Master's thesis, Rensselaer Polytechnic Institute, 2003.

[10] Yang, Y. and Yin, S., "An investigation on the light uniformers based on liquid guide," Fifth International Conference on Solid State Lighting, Proc. of SPIE, **Vol. 5941**, p. 59410R, 2005.

[11] Conway, K. and Zhou, Y. LED lamp with reflector and multicolor adjustor, US Patent 6,149,283, 2000.

[12] Van Kemenade, J.T.C. and Van Der Burgt, P.J.M., "An application overview of ceramic discharge metal halide lamps," IESNA Annual Conference Technical Papers, pp. 141-158, 1996.

[13] Narendran, N. et al, "Extracting phosphor-scattered photons to improve white LED efficiency," phys. stat. sol. (a) **202(6)**, pp. R60-R62, 2005.

[14] Smith, G.B., et al., "Spectral and global diffuse properties of high-performance translucent polymer sheets for energy efficient light and skylights," Applied Optics, **42(19)**, pp. 3981-3991, 2003.

[15] Deller, C.A., et al., "Uniform white light distribution with low loss form colored LEDs using polymer doped polymer mixing rods," Fourth International Conference on Solid State Lighting, Proc. of SPIE, **Vol. 5530**, pp. 231-240, 2004.

[16]   Deller, C., et al. "Colour mixing LEDs with short microsphere doped acrylic rods," Optics Express, **Vol. 12(15)**, pp. 3327-3333, 2004.

[17]   Jonsson, J., et al., "Angle-dependent light scattering in materials with controlled diffuse solar optical properties," Solar Energy Materials & Solar Cells, **84**, pp. 427-439, 2004.

[18]   Radiant Imaging Inc., *ProMetric 7^{TM} User's Manual*, 2002.

[19]   Optical Research Association, *LightTools User's Manual*.

[20]   Bohren, C.F. and Huffman D. R., *Absorption and Scattering of Light by Small Particles*, John Wiley & Sons, Inc., 1983.

Correction to SPIE Paper 6669-59
Improving the Performance of Mixed-Color White LED Systems by Using Scattered Photon Extraction Technique

An inconsistency was found between Figure 7(b) and Figure 8(b) in the original published paper. An explanation of the error and a corrected Figure 8(b) are given below.

Table 1 lists the experiment results of the research.

Table 1: Main Experimental Results

No.	Size (µm)	Volume Concentration (mg/mm3)	Thickness (mm)	Mean-r	Overall Extraction Efficiency – (Normalized to Bare LED) (%)	Overall Extraction Efficiency – (Normalized to LED With Secondary Optics) (%)
		Bare LED		0.2112	**100%**	
		Bare LED & secondary optics		0.1511	**96.0%**	**100%**
1	1.5	0.0481	1.04	0.0180	81.5%	85.0%
2	1.5	0.1321	0.76	0.0105	83.6%	87.1%
3	1.5	0.1472	1.36	0.0112	78.7%	82.0%
4	6.5	0.0328	0.61	0.0214	88.1%	91.9%
5	6.5	0.0810	1.23	0.0155	84.1%	87.7%
6	6.5	0.1614	1.24	0.0118	82.4%	85.9%
7	15	0.0185	1.08	0.0274	89.7%	93.5%
8	15	0.0850	1.18	0.0171	85.4%	89.0%
9	15	0.1588	1.26	0.0140	84.9%	88.5%
10	83	0.0176	1.14	0.0602	89.5%	93.2%
11	83	0.0877	1.14	0.0291	88.6%	92.3%
12	83	0.1802	1.11	0.0239	86.9%	90.6%
13	6.5	0.0791	0.63	0.0195	86.3%	89.9%
14	6.5	0.0818	1.83	0.0142	83.0%	86.5%

The overall extraction efficiencies listed in the sixth column of Table 1 were calculated with the light output from the bare RGB LED as 100%, while the efficiency numbers listed in the seventh column take 100% as the light output of the RGB LED with clear secondary optics, as shown in Figure 1 of the original paper. After attaching the clear secondary lens on top, there is a 4% efficiency loss due to imperfect cement between the secondary lens and the dome of the RGB LED package, which could be eliminated with better sealing of the epoxy. This imperfection has no effect on the characteristics of the micro-sphere-doped diffuser layer.

Due to an oversight, Figure 7(b) and Figure 9(b) use data from the bare LED efficiency (sixth column) of Table 1, while Figure 8(b) uses data from the secondary lens efficiency (seventh column) of Table 1. This is why the data in Figure 8(b) are inconsistent with the data in Figure 7(b) with the same condition (Figure 8(b) data are ~4% higher). The corrected Figure 8(b) is shown below:
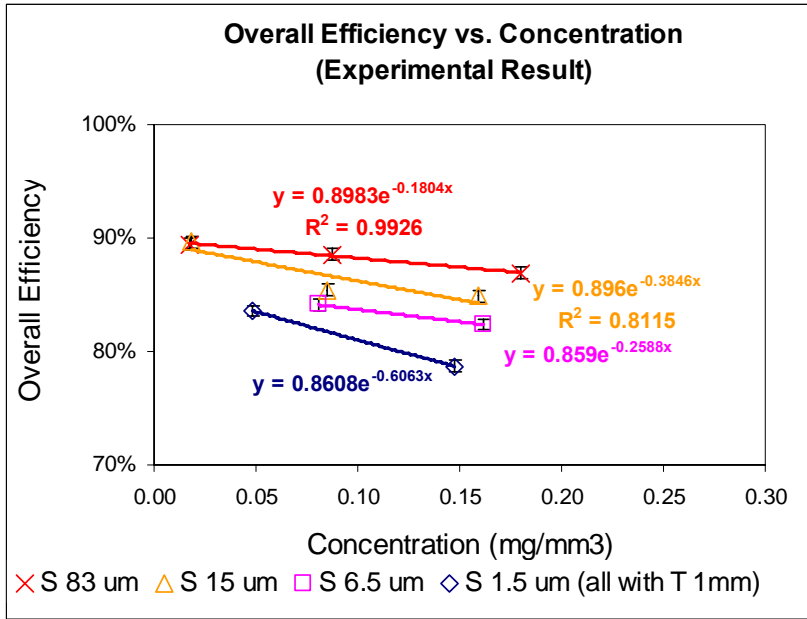
Figure 8(b): Efficiency vs. microsphere concentration (experimental result, "S" means size, "T" means thickness)

With the data correction, the parameters of the fitted curves in Figure 8(b) are also slightly changed; however, the trends of these curves still remain the same since the 4% efficiency loss does not affect the nature of the micro-sphere-doped diffusers. Therefore, the final conclusion of the paper does not change.