Colour mixing LEDs with short microsphere doped acrylic rods

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Abstract: The output colour distributions from red, green and blue (RGB) LEDs mixed with cross linked PMMA micro particle doped PMMA mixing rods is compared to output from a plain PMMA mixing rod. Distinctive patterns with clear colour separation result with the undoped rod. These are homogenised by our mixers, resulting in white light. Light output has been photographed, measured and computer simulated at a distance of 10 cm from the output end of the rods.

OCIS codes: (330.1710) Color measurement; (230.3670) Light-emitting diodes; (080.2720) Geometrical optics, mathematical methods; (350.4990) Particles; (220.4830) Optical systems design; (230.2160) Photodetectors

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1. Introduction

Light sources using mixed red, green and blue (RGB) LEDs were recently judged superior to halogen, incandescent and phosphor white LED sources as reading and task lights [1]. PMMA guides have been utilized in colour mixing applications due to almost zero losses from total internal reflection (TIR) [2]. It was reported in a previous study that acrylic light guides utilizing TIR only provided no significant improvement in illuminance, color, or beam uniformity compared to a bare LED array [3]. These systems also require long mixing lengths, particularly for systems with few LEDs in the source array [2]. Mixing rods using transparent refractive index matched micro particles (TRIMM) incorporated into a polymer result in low loss light mixing with short rod lengths due to high forward transport and low backscatter [4]. TRIMM requires a refractive index (RI) mismatch between matrix and particles under ~0.04.

2. Experiment

PMMA rods 12.7 mm in diameter doped with TRIMM particles were extruded by combining PMMA granules and granules containing particles in a commercial extruder. Two

Received 16 June 2004; revised 9 July 2004; accepted 9 July 2004

concentrations were prepared: one low, containing 0.45 % TRIMM particles (labeled 15K) and the other 3.0 % TRIMM particles (labeled 100K). The average diameter of the particles is 35 µm [5]. Measured RI values at 589 nm are 1.490 for PMMA and 1.507 for the particles, giving a relative RI of 1.011. All rods are 10 cm long, except one 100K rod is 8.84 cm long.

The experimental set up is shown in Fig. 1(a). A triad of red, green and blue 3 mm LEDs were mounted as close as possible to one end of the mixing rod. (3 mm LEDs were used because of the limited diameter of the available mixing rods.) The centre point of the LED array was aligned with the rod’s axis. A frosted glass screen was positioned 10 cm from the exit end of the light guide. Photographs of the output light distributions transmitted through the screen were taken with an Olympus C-4000 ZOOM digital camera. For quantitative observations, the screen was removed and replaced with a translational stage, carrying the detector of a Hagner S3 photometer. The detector size was reduced to ~1 mm diameter with a cover. The illuminance of each LED was measured every millimetre in a horizontal direction through the centre axis of the guide, to form a strip 80 mm long. Each measurement corresponds to one pixel. The source luminous flux of each of the LEDs was measured using the Hagner meter coupled to an Oriel 70491 integrating sphere.

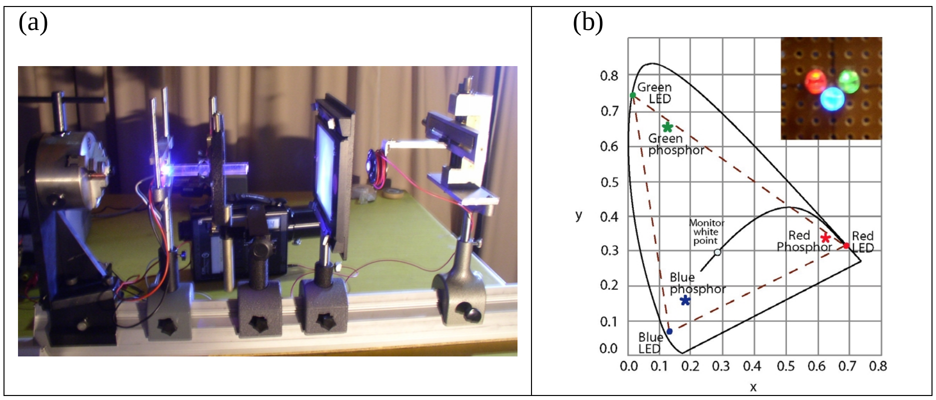

Fig. 1. (a) Experimental setup, showing (from left): alignment laser, LED array, acrylic mixing rod, frosted glass screen and the translational stage with photometric detector. (b) 1931 CIE diagram showing LED source chromaticity coordinates, and the coordinates of the computer monitor’s phosphors. Inset: 3 mm LED array.

Colour distribution for the horizontal ‘strip’ was obtained by measuring the intensity of the R, G, and B LEDs at each reading point (I_{Ri}, I_{Gi}, I_{Bi}). Each triplet was then combined to form a pixel, via calculations using Eq. (1) below. Spectra for each LED were obtained via an Ocean Optics SD2000 fiber optic spectrometer coupled to the Oriel 70491 integrating sphere, and associated software. CIE coordinates for each LED, (x_{LED}, y_{LED}, z_{LED}) were derived from the respective spectral power distributions.

3. Colour mixing calculations

The pixellated RGB data, both measured and modeled, are added together as a weighted sum to calculate the pixels’ 1931 CIE xyz components of colour from the 3 LEDs:

$$x_i = (I_{Ri}x_R + I_{Gi}x_G + I_{Bi}x_B)/(I_{Ri} + I_{Gi} + I_{Bi}) \tag{1}$$

and similarly for y and z. The tristimulus values (X_i, Y_i, Z_i) are calculated by

$$X_i = (x_i/y_i)Y_i \qquad Z_i = (z_i/y_i)Y_i \tag{2}$$

where firstly $Y_i = I_{Ri} + I_{Gi} + I_{Bi}$ are normalised so that the Y_i maximum is equal to 1.

Received 16 June 2004; revised 9 July 2004; accepted 9 July 2004

4. Computer modeling

Ray tracing simulations involving TRIMM particles have been described previously [4,5]. The angular intensity distribution of each of the LEDs was measured using a photogoniometer [4] and the distribution for the red LED was used as the light sources in all the computer models (Fig. 2(b)). Details on source algorithms and circular ray tracing systems are left for a future paper. Measurement based models of LED sources have the advantage of high accuracy in ray tracing since all source characteristics are incorporated [6]. Note that the angular profile of the red LED is somewhat narrower and more symmetric than that of the other LEDs, which will affect the computed green and blue pixel maps and hence the computed colours.

Rays exiting the end of the rod were traced to predefined detector planes which simulate square 'screens'. Each screen is divided into a matrix of pixels, and each pixel is incremented when hit by a ray. Simulations of 1 million rays were performed for each of the LEDs. Rays originate from a circular source, the centre of which is a specified coordinate for each LED corresponding to its position in the array. Each pixel in the matrix for each of the RGB LED simulations are normalised to the photopic response of the eye by dividing by y_{LED}, and is weighted by the intensity fraction of the source LED. The RGB matrices for a simulated screen are then added together to form a complete colour map (Eqs. (1) and (2).)

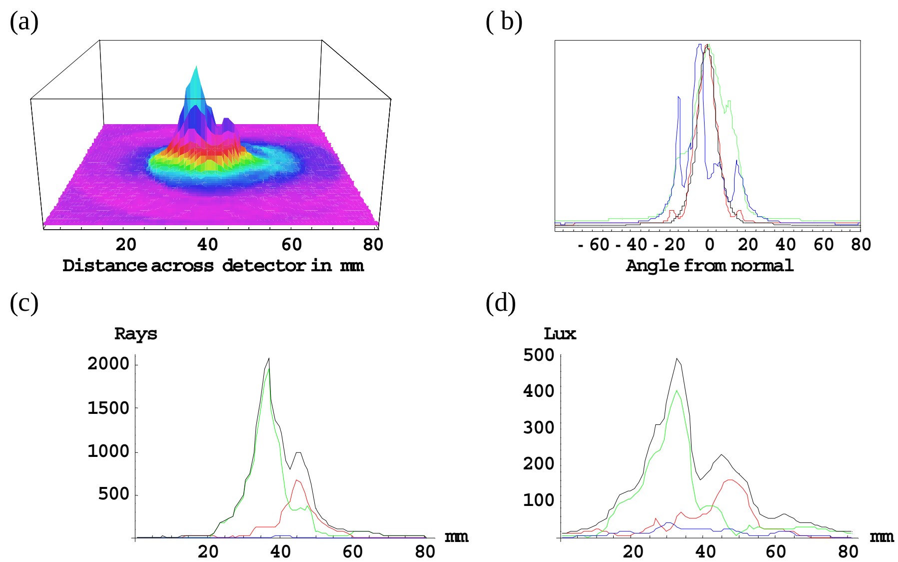

Fig. 2. (a) Modeled illuminance falling on detector 10 cm from end of the undoped 10 cm acrylic mixing rod. Source diameter is 2 mm. (b) Measured angular distribution of the source R, G and B LEDs. The black line, closely following the red profile, shows the functions used in the computer source modeling. (c) Cross-section through the centre of a), showing computed R, G and B components, and the total in black. (d) Corresponding measured illuminance.

To display the resultant colour map, the X,Y,Z data is converted to R,G,B using a matrix [7]. This matrix requires the white point of a computer monitor, which was calculated from photometer measurements of the RGB primaries displayed filling a monitor screen, and the CIE coordinates of the RGB monitor phosphors. A calculated RGB component of a colour map pixel occasionally falls outside of the colour gamut of the monitor (refer Fig. 1(b)), and exceeds 1. If this occurs, the relevant matrix is scaled so that its maximum component is 1. For colour map display, the final values are converted to a log (base 10) scale.

5. Results

5.1 Undoped rod

Coloured patterns are formed due to caustic effects dependent on rod aspect ratio, LED size, LED radial distance from the center of the rod, and screen distance from the rod's end. Figure 3 shows modeled, photographed and measured colour distributions at a distance 10 cm from the exit end of the rod. Notice the excellent qualitative agreement between modeled data (Fig. 3(a)) and photograph of experiment (Fig. 3(d)), although some colour in the white, slightly overexposed parts of the photographs may be hidden. It is interesting to note that the visual pattern is strongly dependant on the viewing angle: Figs. 3(b), (c), (d) and (e) are the same set up photographed from slightly different angles. This considerable colour variation with viewing angle shows that undoped PMMA light guides are not suitable as LED mixers.

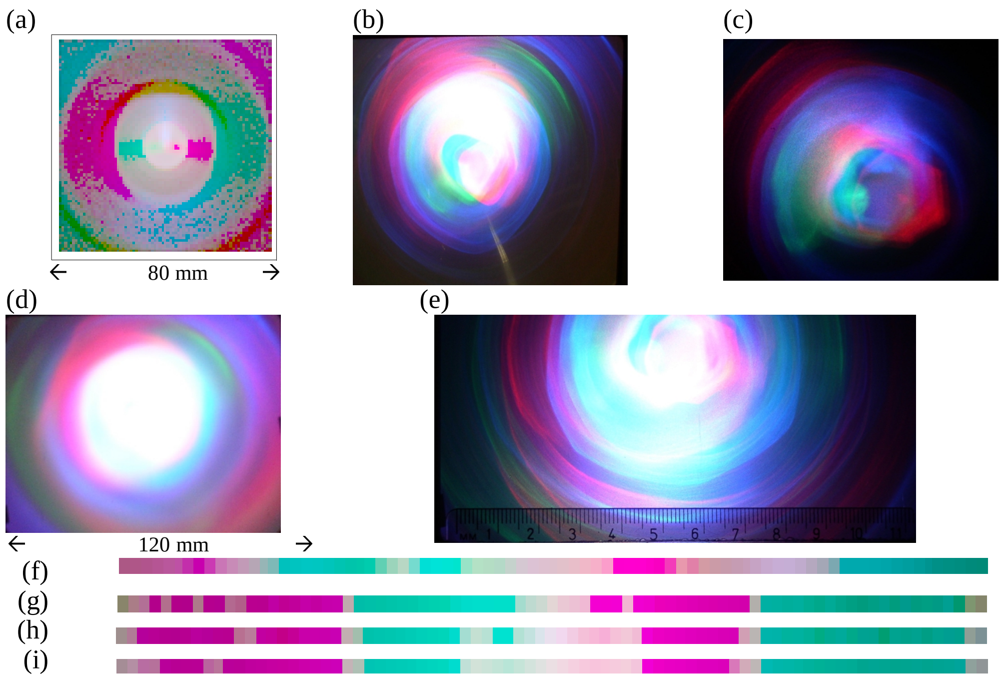

Fig. 3. (a) Modeled output colour mix falling on detector 10 cm from end of 10 cm acrylic rod. Pixel size is 1 mm. Source diameter is 2 mm. (b-e) Photographs of experimental results modeled in (a), taken at varying viewing angles. (f) Measured colours in a horizontal strip through the centre, which has been converted to RGB via calculations. (g-i) modeled strip, using source diameters of 1, 2 and 3 mm, respectively.

Variations in modeled output with size of the modeled source are evident in Figs. 3(g), (h) and (i). This is significant because although the angular distribution is known, it is difficult to determine exactly over what area the light originates. Sensitivity to slight variations in source distribution is amplified by the small rods used here, which also makes homogenization much more difficult.

5.2 Doped rods

Measurements and simulations performed for the 15K 10 cm rod were made using the same ratio of luminous fluxes as for the undoped rod (R:G:B = 1 : 1.24 : 0.379). It can be seen that the mixing is nearly complete for this configuration, although the relative intensity of the red has been set too high (Fig. 4).

Received 16 June 2004; revised 9 July 2004; accepted 9 July 2004

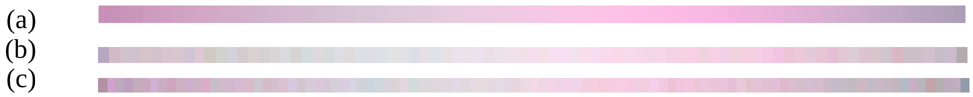

Fig. 4. Output colour falling on detector 10 cm from end of 10 cm long 15K rod. Pixel size is 1 mm. (a) Measured horizontal strip through the centre, converted to RGB. (b-c) modeled strip, using source diameters of 1 and 2 mm respectively.

The relative amount of red source light was reduced for the 100K 10 cm rod measurements. Source luminous flux ratios were (R:G:B = 1 : 1.66 : 0.462). The photographed and simulated results are shown in Fig. 5(a), (b) and (c). For Fig. 5a the camera was positioned about 1 cm from the screen while for Fig. 5(b) the distance was ~30 cm.

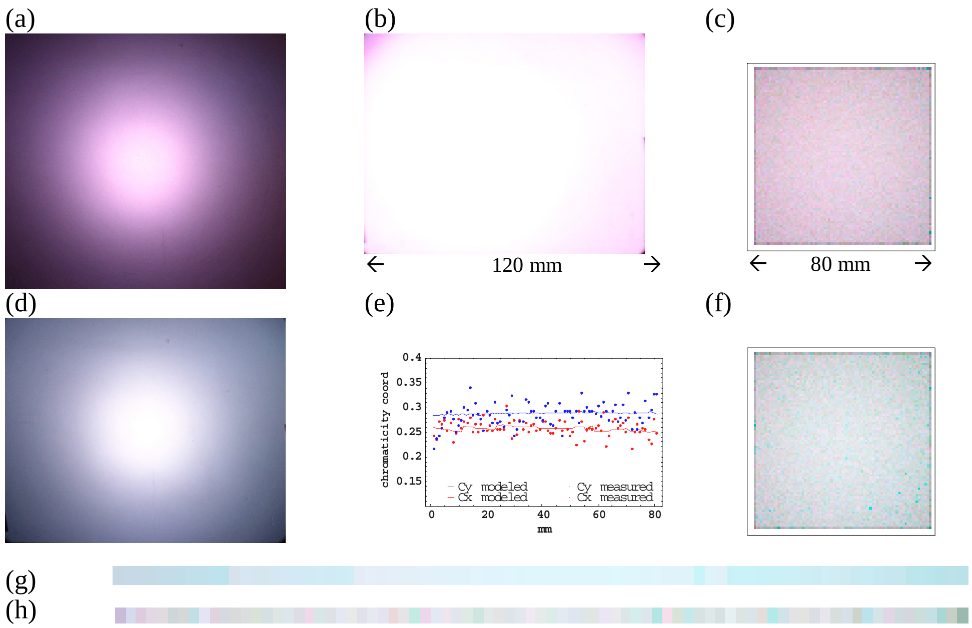

Fig. 5. Projected light 10 cm from the end of 100K rods. (a-c) 10 cm rod length. (a, b) photographed results, (c) computer simulation. (d-h) 8.84 cm rod length. (d) photographed results. (f) computer simulation. (g, h). measured and modeled strips through center cross-section. (e) CIE coordinates corresponding to (g) and (h).

Figs. 5(d), (f-h) show the output 10 cm from the end of a 8.84 cm 100K rod. Source luminous flux ratios were (R:G:B = 1 : 2.77 : 0.569). Uniform mixing is achieved with a shorter rod for higher TRIMM particle concentration. The computer simulation shows uniform colour across a 80 cm detector width. Although the measured and modeled appear blue (Figs. 5(f), (g) and (h)), the actual appearance of the light output is white with a blue halo (Fig. 5(d)). This is not surprising, as the blue LED source angular profile is the widest (Fig. 2(b)). The colour variance across the centre of the screen are represented as CIE coordinates, and measured and modeled values compared quantitatively, in Fig. 5(e).

5.3 Modeled varying screen distance

Simulated colour projected onto screens 1 cm and 100 cm from the output end of the 10 cm mixing rods are shown in Fig. 6. The source intensities are the same as for Fig. 5(a-c), so the output is pinkish/white, nevertheless it is clear that very good mixing is achievable. The colour variation across the screen 1 cm from the end is shown quantitatively in the form of CIE x and y coordinates in Fig. 7.

#4622 - $15.00 US
Received 16 June 2004; revised 9 July 2004; accepted 9 July 2004

6. Discussion

The colours of the measured and modeled results in Fig. 5 appear to differ because of display differences between camera and simulated images. Measured and modeled output colour are compared using CIE coordinates, avoiding artifacts due to factors such as limited camera contrast range. Figure 5(e) shows the agreement. Scatter in the modeled data is from statistical fluctuations.

Variation of RI with wavelength was not taken into account for this modeling, and will be discussed in a later paper. However, preliminary modeling trials have shown that there is little visual effect on the colour mixing results within the variation of RI that is expected.

The modeled results indicate that transmittance including Fresnel end loss is ~0.93. The extruded samples used here gave lower transmittance as they contain small air bubbles. Larger diameter or longer rods make mixing easier, but TRIMM doped systems allow a much wider variety of geometrical configurations.

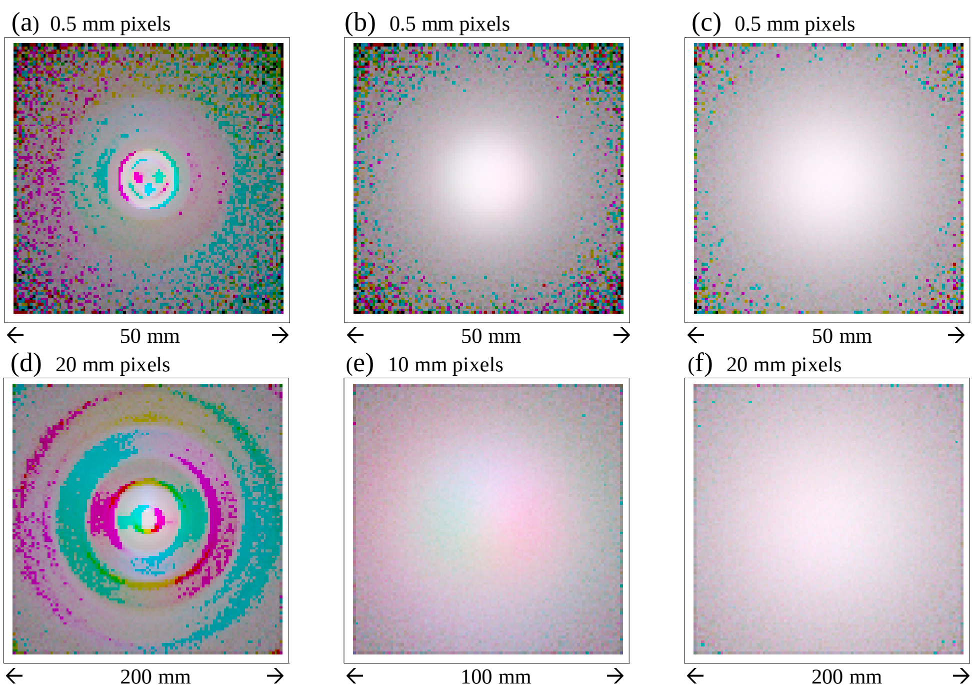

Fig. 6. Modeled colour distribution for 10 cm mixing rods. (a-c) 1 cm from the rod's end. (a) PMMA, (b) low concentration, (c) high concentration TRIMM. (d-f) 100 cm from the rod's end. (d) PMMA, (e) low concentration (15K) TRIMM, (f) high concentration (100K) TRIMM.

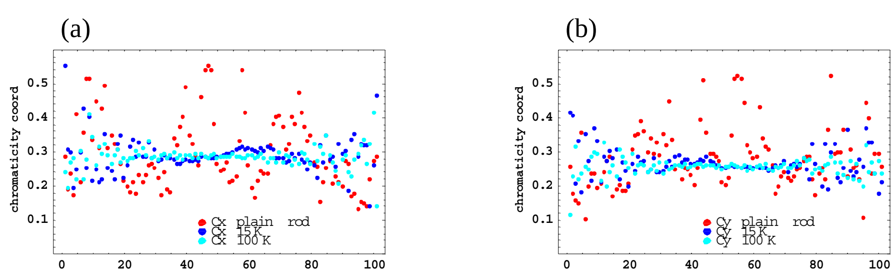

Fig. 7. Chromaticity coordinates; (a) CIEx, (b) CIEy for simulations 1 cm from the end of the three 10 cm mixing rods shown in Fig. 5. (a-c)

7. Conclusions

Complete homogeneity in colour mixing can be achieved using short PMMA rods doped with TRIMM particles. The output is diffuse, which reduces source glare and creates uniform illuminance for good quality lighting. The TRIMM particle concentration, source arrays and screen distance from the output end of the rods can be tailored to suit the desired application.

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Received 16 June 2004; revised 9 July 2004; accepted 9 July 2004