High-efficiency slim LED backlight system with mixing light guide

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Abstract
We have developed a novel optical system for an edge-lit LED backlight. The system uses high-power red, green and blue LEDs and has a minimum thickness despite the arrangement for color mixing. The components of the system have been optimized enabling high optical efficiency while maintaining low cost and good manufacturability. Furthermore, conceptually the system is very close to the existing CCFL backlights and allows re-use of the existing components and infrastructure.

1 Introduction
LED backlight for LCD has numerous advantages, including wide color gamut, tunable white point, high dimming ratio and long lifetime [1][2][3]. The use of LEDs in backlight has been demonstrated both in edge-lit configuration, suitable for desktop monitors [1], [2] and in direct configuration usable for larger display sizes (e.g., LCD-TV).

If a string of high-brightness red, green and blue LEDs is used as a light source in an edge-lit backlight system, additional arrangements are required to allow the light of different colors to mix before it can be used as the light source for LCD. Previously proposed solution [1] was to perform the mixing in a part of the main light guide. This part must be free from the light extraction structures (white paint dots or microprisms). To illuminate the whole display, two of such light guides need to be combined in such a way that mixing parts and optically active parts are complimentary to each other. This has some disadvantages, including higher thickness and weight of the backlight and difficulty with matching the brightness and color points of the two parts of the display. The backlight concept described in this paper addresses the above issues.

2 Backlight design
The wide color gamut of the RGB LED backlight comes at a price: light of the individual LEDs needs to be mixed before it can be used for illuminating the LCD screen. Several solutions for this mixing problem have been proposed [1], [2]. In essence, they all require the light to travel some distance in a clear medium before it may be coupled out towards the LCD screen. Because of tight space constraints, a light guiding solution is the obvious choice. Such a light guide can either be an air-filled cavity bounded by reflective walls or a piece of transparent refractive material (e.g. PMMA) guiding the light by total internal reflection (TIR). We have found experimentally that PMMA light guide solution offers the best efficiency due to almost zero losses by TIR.

The second issue is the placement of the color mixer. In earlier attempts [1] two light guide plates were used on top of each other, both having a mixer area and an area where light is coupled out.

We have chosen another approach. In our backlight a separate color mixing light guide is used in combination with the conventional light extraction light guide.

The principle of operation of the system is depicted in Figure 1 and its exploded view is shown in Figure 2.

Figure 1. Light source and color mixing optics of the LED backlight

The LED backlight consists of an LED light source (1), a separate mixing light guide (3) and a main light guide panel (6). The light from the source is coupled into the mixing light guide by a cylindrical elliptical mirror (2). The light emerging from the mixing light guide is mixed to a homogeneous white color. It is coupled into the main light guide with a cylindrical elliptical mirror (4). The main light guide panel (6) is a PMMA slab with a screen-printed pattern optimized for the light distribution of the LED light source. A diffuse reflective foil (5) is applied at the back of the main light guide and a stack of collimating an polarization control foils (7) is placed in front of the main light guide.

Figure 2. Exploded view of LED-based backlight optical system with a mixing light guide. (1) LED light source; (2) first elliptical mirror 90°; (3) mixing light guide; (4) second elliptical mirror (180°); (5) reflective foil; (6) main light guide; (7) collimating foil stack; (8) mounting frame; (9) heat sink.
2.1 Color mixing and color control

The light source consists of a series of high-power Luxeon™ LEDs placed at a metal-core PCB with a pitch of 9 mm. For illuminating 15” LC displays a string of 34 LEDs is typically used. The numbers of red, green and blue LEDs are selected to have an optimal combination of luminous flux in order to achieve the required color point. At the same time, the sequence of placement of the LEDs of different color on the PCB is carefully optimized in order to avoid color variations.

We have found experimentally that for such a light source the mixing light guide length should be around 75 mm.

In order to improve color uniformity even further a strip of microprism foil (e.g. BEF™ from 3M) can be applied to the entrance edge of the main light guide. The function of this BEF strip is illustrated in Figure 3. Outside the light guide the angular distribution of light is approximately Lambertian. In the light guide the angular distribution is bounded by the TIR angle. The microprism foil strip widens the angular distribution in the light guide thus improving the color mixing.

Figure 3. Schematic representation of angular distributions in the two neighboring LEDs in the light guide with and without the BEF strip at the entrance aperture.

Overall color stability is ensured by use of an optical feedback system that automatically adjusts duty cycles of LEDs of different color in response to variations of their luminous output flux over time and temperature range (for details see [3]).

2.2 Optical design

The design of the two coupling elliptical mirrors appears to be very important to achieve high coupling efficiency. Extensive ray tracing simulations (ASAP) were performed to optimize the shape of the mirrors. The drawings of the mirrors are depicted in Figure 4.

The coupling cavity mirror is designed as an ellipse having one of its foci at the line passing through the dies of all the LEDs of the light source. The other focus is placed at the center of the mixing light guide entrance aperture. Optical axes of the LEDs are turned 90º with respect to the light guide plane making the construction very compact.

The second mirror, coupling the light from the mixing to the main light guide, is also elliptical. Its foci are placed at the inner edges of the aperture of the two light guides (see Figure 4).

The mirrors were manufactured from highly reflective aluminum sheets (MIRO material from Alanod). To improve the efficiency even further a highly reflective tape (ESR™ foil from 3M) has been applied to the surface of the mirror.

3 Performance

3.1 Optical efficiency

We have studied the optical efficiency of the LED backlight system (luminous flux output/input ratio) using a photogoniometer with a tunnel length of 8 m. Prior to the measurements in the backlight the LED light source was characterized in the same photogoniometer and the dependence of its output flux on the temperature was established using an external temperature controller. During the measurements both the temperature and the forward voltage of the LEDs was monitored. In this way we could account for the flux reduction of the LEDs due to the warming up of the light source when it is mounted in the backlight system. The results of the measurements are summarized in Table 1.

The total system (excluding brightness enhancement foils) achieves luminous efficiency of 40% for MIRO reflectors and 50% for ESR reflectors. One should bear in mind that at each air-PMMA transition causes about 8% of light to reflect back towards the light source (Fresnel reflections). These reflection losses can
be reduced by applying antireflection coatings to the light guide apertures.

<table>
<thead>
<tr>
<th>Element</th>
<th>MIRO mirrors</th>
<th>ESR mirrors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling cavity mirror</td>
<td>91%</td>
<td>97%</td>
</tr>
<tr>
<td>Mixing light guide output</td>
<td>75%</td>
<td>80%</td>
</tr>
<tr>
<td>Mixing-to-main light guide coupling</td>
<td>70%</td>
<td>82%</td>
</tr>
<tr>
<td>Efficiency backlight with single diffuser</td>
<td>40%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 1. Efficiency analysis results of the LED backlight.

3.2 Backlight performance

Backlight performance was studied using the color-filter-based CCD ProMetric camera from Radiant Imaging in combination with a spectrophotometer PR 650 from Photo Research. For these measurements brightness enhancement foil was added. A 15” backlight with 34 Luxeon™ LEDs driven at full power achieved peak brightness of the order of 4300 nits while power consumption remained below 45 Watt.

Figure 6. Brightness and color uniformity distribution of 15” RGB LED backlight with MIRO reflectors. Peak luminance is 4000 nits, color uniformity Δu’v’<0.01 over whole area.

4 Discussion

The optical system with the mixing light guide has optical efficiency comparable with that of the previously proposed dual waveguide system [1] but has numerous advantages. The backlight has smaller thickness and weight and is more robust with respect to variation of the light source properties.

Another important advantage of this system is its compatibility with the existing backlight technology and manufacturing infrastructure. An LED backlight with the mixing light guide can simply be viewed as white light source. It can be combined with a variety of light guide panels, including slabs screen printed dot patterns, molded wedges with microprism structures etc.

The system can easily be scaled upwards (for 18”, 19” and 20” displays) and downwards (for 10” and smaller). The emitter pitch and the length of the mixing light guide will remain constant.

Furthermore, this concept can also be easily adapted for future developments in LED technology. The flux output per LED will be increasing steadily. That means that less LEDs are necessary to achieve a given display brightness and, consequently, the pitch of the emitters on the light source will increase. Better color mixing required for these new light sources can be achieved simply by increasing the length of the mixing light guide.

5 Conclusions

We have developed an optical system for an edge-lit backlight using RGB high-power LEDs as a light source. This system provides a good color mixing of the colored LEDs and an optical efficiency of 50% and a color uniformity Δu’v’<0.01. It is very compact, easily manufacturable and cost-effective easily fitting in the existing infrastructure of backlighting industry. It is expected that it will become widely adopted by the manufacturers and within 1 year will find its way into the LCD display products.

6 Acknowledgements

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7 References


