A Light Pipe Based Recycling Scheme for LED Brightness Enhancement

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Abstract

As a follow-up to our previous work we present in this paper some experimental results on LED light recycling. Specifically we demonstrate for the first time that screen brightness can be increased using our light pipe based light recycling scheme for real-life projection display applications.

1. Introduction

The advent of LED-based light sources for projection display systems has prompted an increased interest in light recycling[1,2,3]. Contrary to conventional light sources such as arc lamps and filament lamps, LEDs are well suited to recycling techniques due to the presence of flat emitting surfaces where significant light reflection can occur. In addition to projection dispay systems, light recycling may also prove to be useful to small-etendue, edge-emitting LED backlight sources, where higher brightness is desirable.

Beeson et al from Goldeneye recently developed a cavity-based recycling system with multiple LEDs[1] which resulted in brightness enhancement of approximately 1.3x-2.0x. Following a similar approach we propose in our previous work an alternative type of recycling schemes, namely, recycling light through the use of light pipes and light tunnels[2,3]. The main advantage of our approach is that, in contrast to the cavity configuration of the Goldeneye system, off-the-shelf, standard packaged LEDs can be used directly in our system.

Besides offering higher screen brightness, the availability of a brighter light source also affords optical designers the opportunity to trade-off part of the brightness for reduced LED drive current, which in turn leads to longer lifetime and reduced heat-sinking requirements.

2. Results and discussion

Light recycling can be classified as angular, spatial, or mixed based on the angular filtering characteristics of the recycling process[2,3]. Spatial recycling configuration in general is the simplest to implement and best suited to real world display applications, which explains why all experimental results presented in this section are based on this configuration.

It can be shown, after some assumptions and simple algebra, that recycling is governed by the following equation[2,3]:

$$P_{out} = \frac{1-\alpha}{1-\alpha+\alpha\beta} P_{in} \quad (1)$$

where

α = Per cent power recycled

β = Per cent round trip power loss

and P_{in} and P_{out} are the input and output power respectively.

For spatial recycling, the brightness enhancement factor takes a especially simple form[2,3]:

$$B_{out} = \frac{1}{1-\alpha+\alpha\beta} B_{in} \quad (2)$$

LED Brightness enhancement has already been demonstrated in our previous work using PhlatLight™ devices. Fig. 1 shows one such setup where a tapered light pipe is used for spatial light recycling:

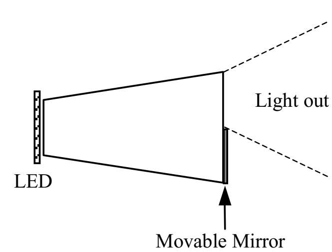
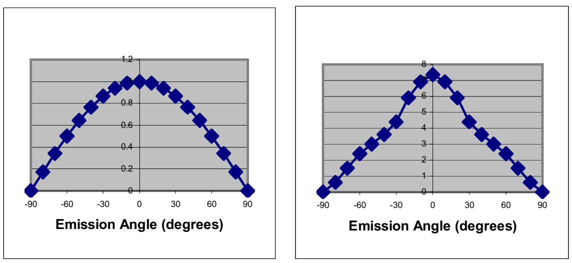


Fig. 1. Spatial recycling with tapered out light pipe.

Two different kinds of LED chips are used in this experiment: one is a Lambertian emitter (specifically a PhlatLight^{TM} PT120 red device) and the other is a PhlatLight^{TM} PT120 green device which emits light with its own characteristic angular distribution pattern[4]. Both emission patterns are given here for reference:



(a) (b)

Fig. 2. LED angular emission profiles. (a) Lambertian; (b) PhlatLight^{TM} device (green or blue)

The brightness enhancement factor as a function of mirror blockage is plotted as follows:

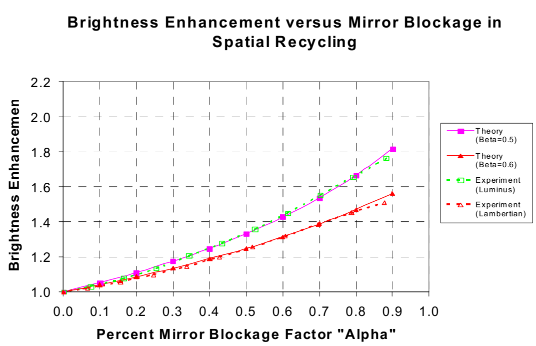
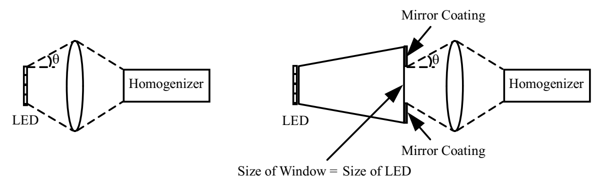


Fig. 3. Brightness enhancement plot for the setup in Fig. 1. Note for spatial recycling the mirror blockage factor "alpha" in this plot is the same as the power recycling factor "alpha" used in equations (1) and (2).

In a real-world commercial application such as RPTV, optical designers however are concerned not so much with chip brightness as with lumen count within a given acceptance angle θ, which in turn is related directly with the brightness on the screen. In that case, a tapered-out light pipe can be used to both reduce the ray angles and provide spatial recycling. This idea is illustrated in the following set-up, replicated from a commercially available LED RPTV:



(a) (b)

Fig. 4. Spatial recycling with a tapered-out light pipe. (a) Original system; (b) Modified system with spatial recycling after insertion of a tapered-out light pipe. The opening on the exit face of the light pipe is of the same size as the LED and hence the modification is transparent to subsequent optics. The LED used here is a PhlatLight^{TM} green device.

With the insertion of the tapered-out light pipe, the total number of lumens collected within the acceptance angle of roughly 40˚ is increased by approximately 15%. It is also worth noting that the tapered-out light pipe, if designed properly, could replace the homoginizer and the condenser lens(es), as the light pipe itself is capable of homogenizing the light and narrowing down the cone angle at the same time (the setup in Fig. 4 is only meant to be a preliminary testcase, intended for minimal modification to the original system. It is by no means the final or the optimal design). This means that the total gain in screen brightness could potentially reach 25-30%, assuming a 10%-15% total loss in the condenser lens(es) and the homogenizer. In addition, PhlatLight^{TM} green devices are known to outperform traditional Lambertian LED emitters in the low angle range due to the presence of an emission peak (see Fig. 2(b)). Current light pipe as shown in Figure 4 does not take advantage of this emission peak as it reflects and recycles light of all angles evenly. It is possible to design a light pipe with more complex geometry (e.g. one for mixed recycling) that could preserve the brighter center spot and potentially increase the brightness gain by another 10-15%. These numbers match well with the estimated 40+% brightness enhancement that one would expect from the green curve in Fig. 3.

3. Future work

Whereas the light pipe based spatial recycling scheme is easy to implement by itself, it was also noted in the last section that, to take full advantage of its potential in enhancing brightness, the recycling light pipe should also serve as a light homogenizer for the whole system and hence any existing light homogenizer would need to be removed. This would require quite a bit of modification to the original system, a commitment that we find most optical designers are hesitate to make.

To address this concern and to reduce the required modification to a bare minimum, we introduce yet another Wavien patented recycling configuration:

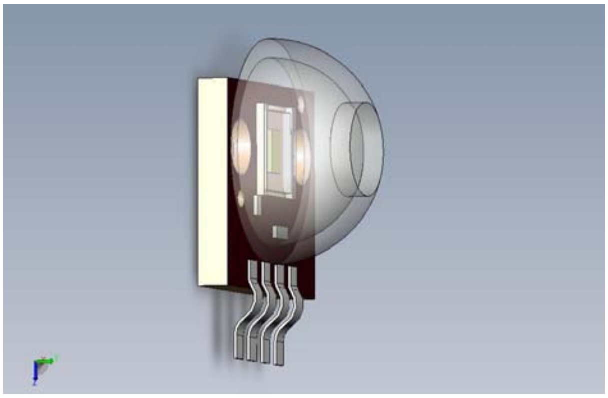


Fig. 5. Recycling dome scheme.

In this new configuration, a recycling dome which is really a spherical mirror reflector with its top cut off, replaces the recycling light pipe. The angle subtended by the opening at the top of the dome defines the collection angle, which should also match the acceptance angle of subsequent optics. All rays below the collection angle would pass through the opening unhindered, whereas all high angle rays would reflect off the dome wall and back toward the chip surface. The chip surface in general possesses some roughness and a considerable portion of the recycled high angle light will be scattered into the low angle collection cone and hence would escape through the opening during the next forward trip. As a result brightness within the collection cone is increased.

A very preliminary experiment has been performed on a PhlatLight^{TM} green device with dimensions of 3.9x2.19mm. The radius of the recycling dome is arbitrarily chosen to be 20mm. For a collection anlge of 22° (corresponding to an "alpha" factor of 0.86 in Fig. 3) we measured a brightness increase of 40%. Since this is our very first attempt at characterizing this type of recycling configuration, none of the system parameters has been optimized (e.g., the radius of the dome is arbitrarily chosen, the equatorial plane of the dome may not be aligned with the emitting surface of the LED, and the reflective coating on the inner surface of the dome may not be of high quality). As a result, the measured bright enhancement factor falls short of 70% estimate that one would expect from the green curve in Fig. 3. It is our belief that, with all the parameters optimized in the new configuration, we should be able to achieve comparable brightnees enhancement as in Fig. 3.

4. Conclusion

For the first time brightness enhancement effect for light recycling schemes is demonstrated in a real life projection display set-up. The result at this point is notable but sub-optimal. Significant brightness gain is expected when system is optimized in the near future.

5. References

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