

A superior architecture of brightness enhancement for display backlighting

Oliver Dross^{*b}, William A. Parkyn^a, Julio Chaves^b, Waqidi Falicoff^a, Juan Carlos Miñano, Pablo Benítez^b, Roberto Alvarez^a

^aLight Prescriptions Innovators, 2400 Lincoln Ave., Altadena, CA 91001, USA;

^bLight Prescriptions Innovators, Marques de Urquijo, 14, 5D, 28008 Madrid, Spain

ABSTRACT

Brightness enhancement of backlighting for displays is typically achieved via crossed micro prismatic films that are introduced between a backlight unit and a transmissive (LCD) display. Prismatic films let pass light only into a restricted angular range, while, in conjunction with other reflective elements below the backlight, all other light is recycled within the backlight unit, thereby increasing the backlight luminance. This design offers no free parameters to influence the resulting light distribution and suffers from insufficient stray light control. A novel strategy of light recycling is introduced, using a microlens array in conjunction with a hole array in a reflective surface, that can provide higher luminance, superior stray light control, and can be designed to meet almost any desired emission pattern. Similar strategies can be applied to mix light from different colored LEDs being mounted upside down to shine into a backlight unit.

Keywords: Brightness enhancement, BEF, display backlight, color mixing

1. INTRODUCTION

An LCD display consumes almost negligible amounts of energy in comparison to the backlighting unit, which is the major power consumer in most applications as laptops and hand-held computers. The backlighting unit must be specifically designed to achieve very high efficiency and brightness. Typical backlight units produce approximately Lambertian radiation, so that most of the flux is emitted into angles where it is of no use to the end user. Brightness enhancing films (BEF) are used to increase the luminance in a particular angle range, normally perpendicular to the display surface. This is achieved via recycling illumination systems that, instead of emitting off-axis light where it is not needed, reflect the light back into the backlight unit where reflecting surfaces give this light another chance to be emitted in the desired angle range.

Standard BEF use linear prisms that recycle light by total internal reflection (here called RBEF). This technology has been widely adopted, although its optical efficiency and luminance increase are far from the theoretical limits.

2. OPTICAL ARCHITECTURE OF BACKLIGHTING

Where in the past almost all backlights have been equipped with small diameter (about 3 mm) cold cathode tubes, now the share of white (or RGB) LEDs is increasing. LEDs are readily available at sufficient flux levels, so that most new backlighting designs, especially for smaller devices, such as cellular phones, PDAs and digital cameras, now rely on LEDs, which eliminates the CCFL problems of high supply voltage, low-temperature difficulties, toxicity, low luminance, and lamp fragility.

Typical architectures for both CCFL and LED use side-lit (flat or tapered) acrylic light guides (see Figure 1). Their thickness depends on the source étendue, with typical values are as small as 0.5 for a small held device to 4 mm for larger devices. The light sources are arranged at one, two, or all 4 edges of the light guide. All but the emitting sides are surrounded by diffuse white reflectors. While materials of up to 98% reflectivity are commercially available, they are typically rather expensive. Generally 95% is achieved for injection-molded parts with titanium-dioxide pigment. As will

* odross@lpi-europe.com; phone +34 91 540 1044; fax +34 91 559 6082; <http://www.lpi-llc.com/>

be shown later, reflectivity is a very important parameter, since BEF may cause many reflections off those surfaces before a ray finally exits the device. A diffuse reflective coating operates on the microlevel through light-scattering by small transparent pieces of such high-refractive index material as titanium dioxide ($n \sim 2.5$). The actual surface of such a coating (typically white) will only reflect a portion of its 95 to 99% reflectivity, with deeper layers also scattering. A minimum thickness presumably must be tens of microns, with reflectivity being sacrificed for anything too thin, leaving some light to be transmitted instead. Commercial products are also available in the form of spray paints or inks (including silk-screenable inks), which can be deposited onto a suitable substrate by a wide range of processes known. For example, a 99% reflective paint material is available from Edmund Optics of New Jersey called “Munsell White reflectance coating”. The material is a composite of Barium Sulfate, binder and solvent. The minimum coating thickness to achieve a reflectance in the visible range above 99% is 0.64 mm.

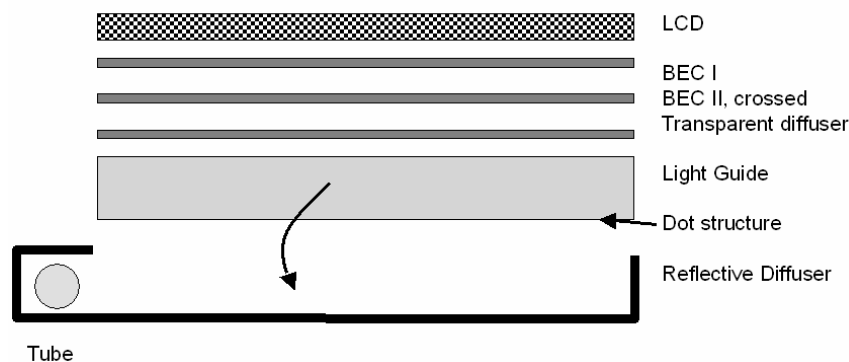


Figure 1 Structure of typical backlight with BEF

The lightguide is provided with extraction features at the bottom side that break the light guidance and scatter light randomly. Light incident at the exit surface below the critical angle exits upwards, while light emitted towards the back of the lightguide is reflected upwards by the white reflector, and then transmitted towards the front side. Scattered light emitted within the dielectric material's total internal reflection angle cone will be guided until it hits another scatter dot. The extraction features are either printed white dot arrays or injection molded shapes with high roughness. The density of such features is usually varied [10,11] across the light guide to compensate for the decreasing flux density in the light guide further away from the light source. If no BEF are employed, diffusers to reduce moiré effects are added. Color filters for each pixel and the LCD pixel array complete the LCD display.

The amount of light to illuminate a large TV screen makes so many LEDs necessary that for thermal and spatial reasons they cannot be placed at the rim of a light guide. Design-variations of air filled white “boxes” with many diffusing elements homogenize and color mix the light so that individual LEDs don't replicate as illuminance variations at the exit surface. However, the methods for brightness enhancement are similar for light guide back lit displays.

3. BRIGHTNESS ENHANCEMENT VS. ETENDUE CONSERVATION

The entire backlight can be viewed as a homogeneously emitting Lambertian source. Etendue conservation prohibits the increase of intensity or luminance while maintaining the aperture of a source [1]. However this doesn't hold for recycling systems. BEF lets part of the radiation escape into the desired angular range while returning rays from other directions back onto the source (see Figure 2). If the source behaves like a diffuse and highly reflective surface, the light is reflected again, getting a second chance to escape into the desired angular range, thereby increasing the brightness.

The majority of the backscattered light from the BEF does not fall on the scattering dots of the backlight, so that for those rays the reflectivity of the backlighting unit is basically the same as of the white diffuse reflector below the light guide. Backscattered light that hits the scatter dots behaves just like light originating from the light source; a large portion will be returned upwards. Since the backlight increases the etendue of the light sources dramatically, only a very small portion of the light travels back into the source, where it may experience increased absorption, even though a non black body light source can theoretically have reflectivity 1. Different brightness enhancement schemes have been used, mostly basing on micro spheres and prisms in conjunction to white reflective surfaces [2,3,4,5,6,7,8]

4. PRISMATIC BEF

Prismatic films [9] consist of linear 90-degree prisms, arranged on one side of a clear plastic film, of about 25 microns height and 50 micron pitch (smaller versions exist). With the flat side of the film facing the backlight (Figure 2), the prisms let pass light from a certain oblique angle range and emits into a range of about 50 deg full angle around the axis perpendicular to the film. Most other light is reflected back down, and, after hitting a diffuser or any other reflective element in the backlight, gets a second chance to pass the RBEF into the desired angle range. About $\frac{3}{4}$ of the light from a Lambertian source incident on the RBEF is turned back, recycled and used again.

Because of the linear symmetry, RBEF “compresses” the light in either the horizontal or vertical direction. In many devices two separate films in a 90 deg crossed configuration are being employed to compress the light in both directions.

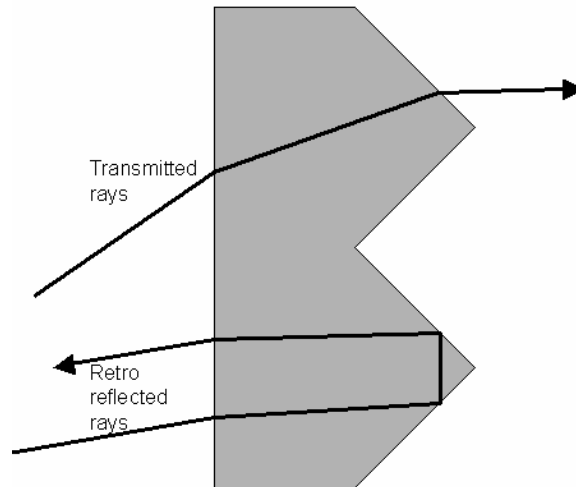


Figure 2 Linear prismatic films retro-reflect most light impinging on their flat surface via two total internal reflections in the prism. Only a small oblique angular range of rays is transmitted.

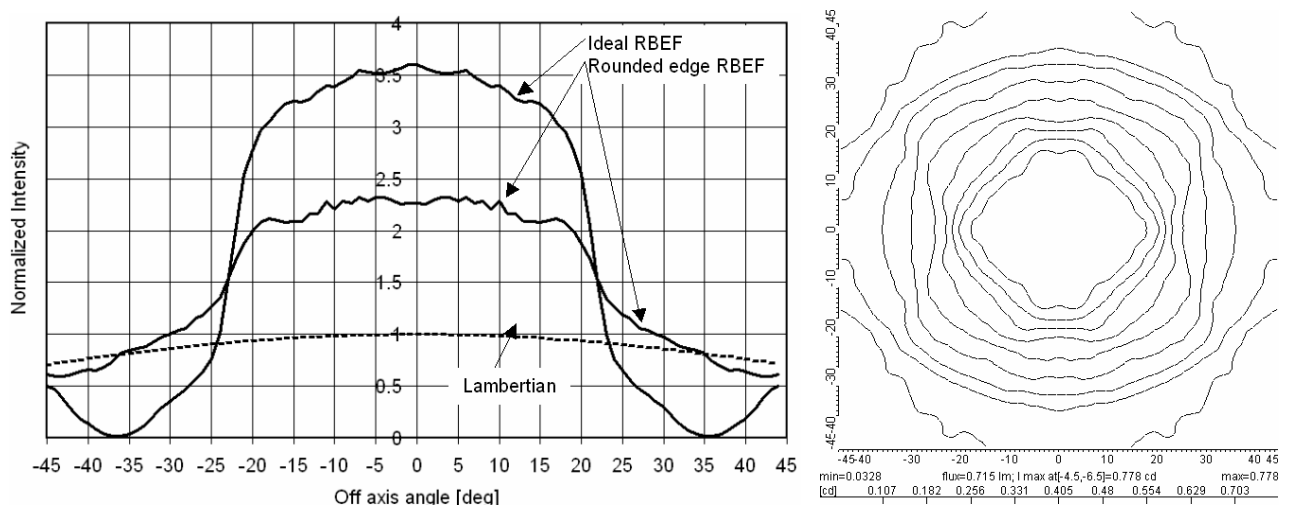


Figure 3 Left: The dotted curve represents the cosine intensity distribution of a bare Lambertian backlight. The ideal RBEF curve is the resulting intensity of two ideal crossed RBEF on top of a 95% reflecting diffuse backlight. The distribution for the same system but with rounded prism edges ($r=1/10$ of prism pitch) is included. Right: Intensity distribution of crossed RBEF with rounded edges (linear scale)

An ideal system with no absorption nor surface roughness, perfectly sharp edges, and two crossed prismatic films (90 deg prism angle made from PC) and a backlight with a global reflectivity of 95%, results in a theoretical brightness gain of 260% over the Lambertian backlight, while the efficiency of such a system, in a $\pm 45^\circ$ by $\pm 45^\circ$ square angular region, is 67% (Figure 3). However, edge radii of typical manufactured TIR teeth reduce the brightness gain to 135% for crossed

90 deg prisms and 5 micron edge radii, for both the convex and the concave prism edge. Commercially available RBEF produce on axis luminance increases of 50-90% for one film and 105- 120% for crossed films.

The 90 deg prism angle its optimal independent of the index of refraction of the film material, indeed small angle changes lead to large brightness gain losses compared to the 90 deg case. Prisms at that angle return more of the light of a light cone impinging perpendicularly on a prism film than for any other prism angle, so therefore the light recycling is more effective. At any other prism angle the light bundle flow line forms at either the first or the second reflection an angle with the prism surface-normal smaller than 45°, so that part of the light of the bundle is lost because the TIR condition fails. This light shows up in the far field at angles around 60° deg off axis (“side lobes”) and does not contribute to the emission wanted near normal, as it enables unauthorized viewers to see the information on the display from oblique angles. As there are no degrees of freedom for the design of an RBEF, the emission pattern is basically fixed (Figure 3) and can only be manipulated by adding more elements, such as diffusers.

5. LENSLET BEF

Lenslet BEF (LBEF) does not rely on TIR to reflect light back into the backlight unit. Figure 4 shows a backlight that has diffuse or specular reflecting surface on top. This surface has an array of holes that transmit the light from the backlight, represented in this figure by the “white” bottom surface.

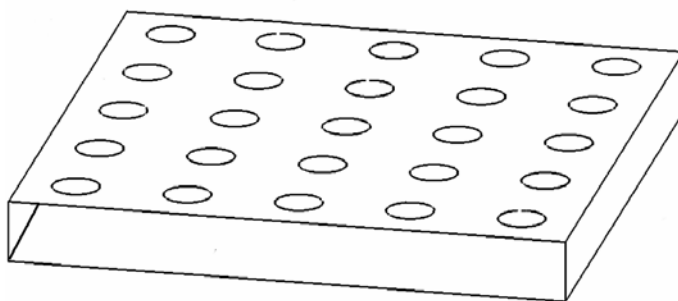


Figure 4: The top surface of the shown box (filled with a dielectric or air) is a white reflecting surface with holes (windows) in it that serves as a first element for a new BEF device. The bottom surface represents the backlighting unit.

The top surface shown is actually an intermediary surface that feeds another optical element, as explained later. Behind it, there may be many elements, such as a backlight light guide or air filled backlight unit, back reflector and diffusers. For our purposes now, the only data needed is the global effective reflectance of top surface (representing a reflecting surface with holes) and the bottom surface that takes into all the internal backlight components no matter their complexity. The high diffuse reflectance the top and bottom surface enables recirculation and mixing of the light to take place and eventually to exit through holes, typically after multiple bounces. The side walls of backlight are typically reflective to prevent leakage although the relative size in real backlights is much smaller than is shown in Figure 4. This figure is equally valid for another backlight type, formed by a white enclosure in which the LEDs are placed inside (not shown). In this case, these LEDs can face downward towards bottom surface and thereby illuminate it.

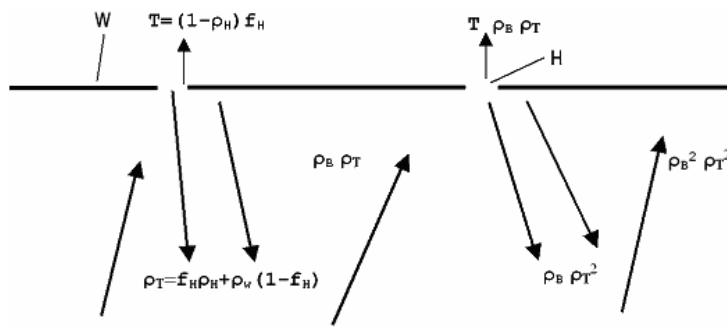


Figure 5 shows the mathematical modeling of light recirculation between the white top surface and the bottom (backlight) surface.

ρ_w = reflectivity of top surface (can be either diffuse or specular)

ρ_H = reflectivity of the holes H

ρ_T = effective reflectivity of the top surface

ρ_B = reflectivity of bottom surface (typically a diffuse reflector but can also be specular)

T = transmission of the top surface.

f_H = fraction of upper surface occupied by holes.

If d_H is the hole diameter (assumed constant in this analysis) and S_H is the hole spacing, then, for instance, for rectangular arrays $f_H = \pi d_H^2 / 4 S_H^2$

In Figure 5 the backlight is thin, indicating that for the sake of analytical clarity, edge-effects will not be considered. Successive stages in the recirculation within the backlight are shown. First, light is emitted upwards, as indicated by the long arrow on the left with unit flux. Part of this is transmitted, another part reflected by the hole, and the last portion by the white top surface. The reflected light off of the top surface is reflected again and the process repeats. The total escaping flux F_{out} is equal to

$$F_{out} = T(1 + \sum_{i=1}^{\infty} (\rho_B \rho_T)^i) = T/(1 - \rho_B \rho_T).$$

The reduced luminous output of the holes is emitted over their much small surface fraction f_H , resulting in their brightness being amplified, relative to the brightness of the backlight by the factor

$$\text{Brightness gain factor} = F_{out}/f_H$$

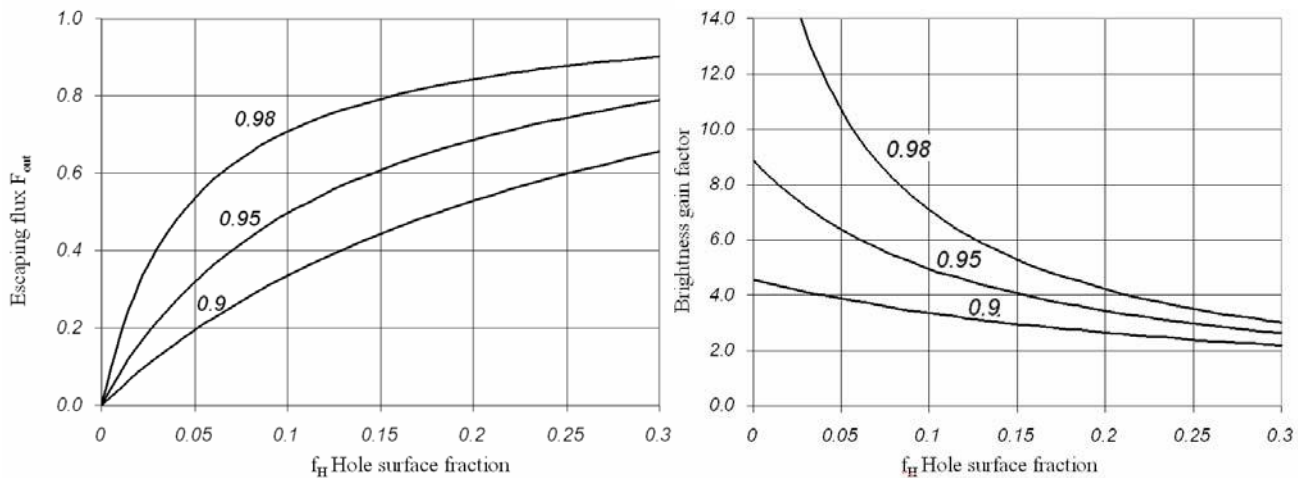


Figure 6 Left: The three different curves represent top and bottom reflectivities of $\rho_w = \rho_B = 90\%$, $\rho_w = \rho_B = 95\%$, and $\rho_w = \rho_B = 98\%$. All curves correspond to a hole reflectivity $\rho_H = 13\%$ (which corresponds to some embodiments that will be shown below). Right: Possible brightness gains for different hole surface fractions and 3 different top and bottom surface reflectivities.

In the limit of perfectly reflecting top and bottom surfaces, the escaping flux becomes unity and therefore the maximum brightness gain factor becomes $1/f_H$, independent of the hole reflectivity.

In order for the brightness gain factors to be useful, the light transmitted through the holes, whose illuminance is spatially non-uniform due to the fact that there is an opaque unlit surface surrounding the holes, needs to be transformed into a spatially uniform collimated light (with introducing any additional scattering processes). The hole array can be viewed as a Lambertian light source array with a distance between the holes that permits collimation of the light. While arrays of microreflectors, dielectric or air filled CPC's and other configurations are possible, a potent solution is a micro lenslet array: If the hole array in a white (or specular) diffusing surface is the entry surface of a dielectric film, the light emitted through the holes is confined within the critical angle cone within the material.

Depending on the hole spacing, the light cones will start to overlap at a certain film thickness- this is where a refractive lenslet surface can collimate the light. The microlenses can be designed to maximize the light throughput, to create certain intensity profiles, or to meet certain spatial constraints as the hole-pitch to hole-diameter ratio.

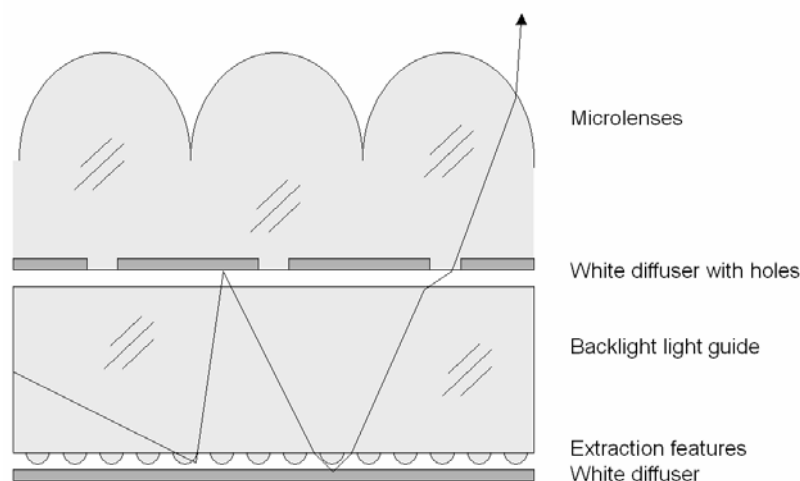


Figure 7. Schematic layout of Backlight and LBEF with a typical ray trajectory, not to scale. The backlight in reality is much thicker than the LBEF film on top.

The BEF has to be flashed completely to reach highest on-axis intensity. To ensure this, the microlenses will have highly sloped lens edges that can cause TIR for some rays and high Fresnel losses. The microlens array can have square, rectangular or hexagonal symmetry to avoid non flashed surfaces. The maximum achievable intensity equals the product of the lit aperture times the source luminance. In the ideal case (fully flashed surface, no losses) the brightness gain factor as defined above describes the on-axis intensity gain over the Lambertian source. Depending on the application one chooses the hole surface fraction to meet either high intensities, in other words a high brightness gain factor, in conjunction with a microlens that ensures that most of the surface is flashed, or for high efficiencies (wider intensity distribution).

Figure 8 depicts the optical behavior of some different LBEFs, with schematic architectures as shown in Figure 7. All designs are rotationally symmetric and cut to a hexagonal aperture for closest packing. LBEF 1 is designed to produce a flat-top pattern of very high intensity (brightness gain 530%, FWHM 15 deg) while LBEF 3 is designed to have a wide radiation pattern of FWHM of 80° with a brightness gain of 55%. Also shown is an ideal crossed prismatic RBEF. Note the side lobes of the RBEF design, seen as rising intensities at 45° off axis. This is in contrast to the LBEF, which shows almost no light outside of the main emission lobe.

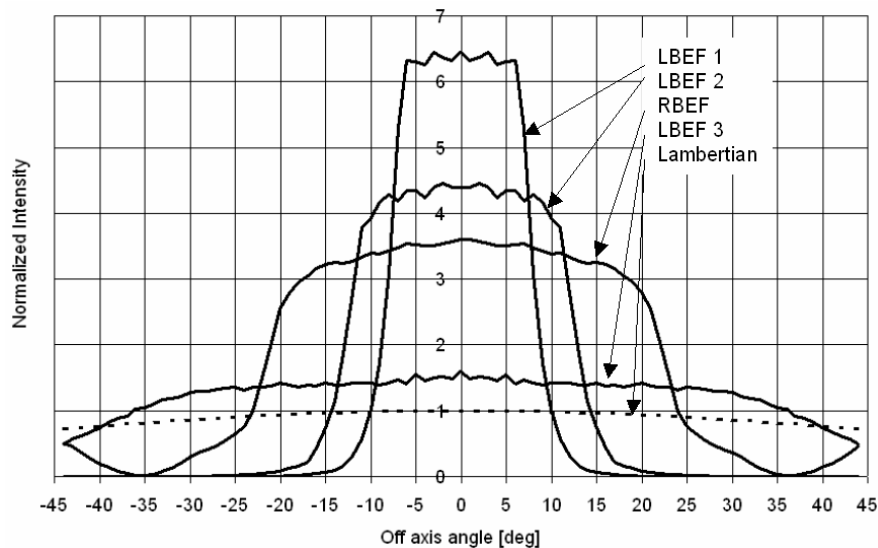


Figure 8 Ray traced intensity distributions of several BEFs. The dotted line represents the normalized cosine distribution of the naked backlight. All traced models use 95% reflective diffuse surfaces. Refractive surfaces are modeled with Fresnel losses, but without surface roughness and rounded edges.

Non rotational designs, here designed for a rectangular aperture, can produce oval (Figure 9, left) radiation of 65 x 40 deg at a brightness gain of 150%, with a full efficiency of 63%. A different configuration ((Figure 9, right) produces a horizontally broad and vertically very narrow pattern of about 100° by 35° with 150% brightness gain and a full efficiency of 83%. This pattern could be very beneficial for a multitude of observers that see a screen from a defined height but from a wide range of lateral positions, as in home theatres.

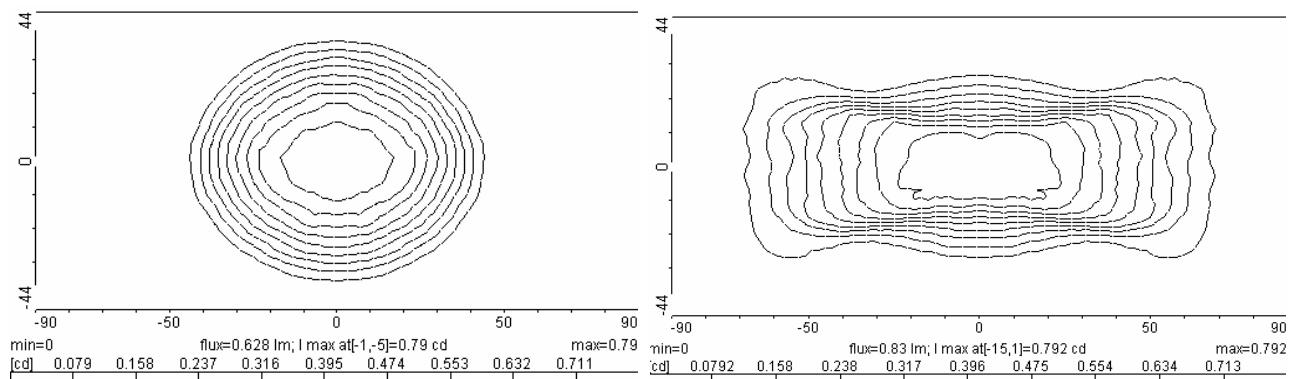


Figure 9 Two simulations of non rotational radiation patterns for LBEFs

6. UPSIDE DOWN DESIGN AND COLOR MIXING

The application of the LBEF concept is not restricted to any one type of backlight. The one in Figure 10 shows new possibilities, in that conventional backlights required totally transparent tops for light to come out of, so there is no way to mount the LEDs thereupon. Although this cannot be used in display backlighting, where the hole pitch should be in the few hundred micron level or less, this approach is interesting for more general backlighting in illumination. While architectures with LEDs shining upwards use numerous strategies to keep the LEDs from shining directly out the top aperture, there is no such problem with this 'upside-down' mounting of the LEDs in between the holes, making it possible for different colored LEDs to be mounted for full chromatic mixing.

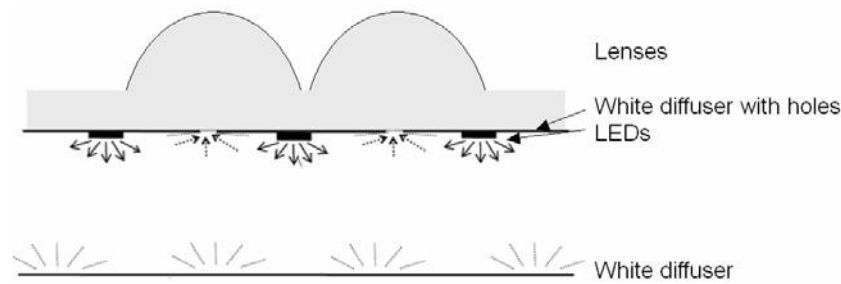


Figure 10 Schematic layout of an airfilled backlight with “upside down” LEDs. The LEDs are attached on the bottom surface of a dielectric lenslet array. A white diffuse layer hides the electrical contacts of the LEDs

It is theoretically possible for hole-luminance to approach chip luminance and even exceed it somewhat, but such high brightness would require the total area of apertures to be smaller than LEDs’ area. The design shown here can produce different radiation patterns with very good color mixing. Alternatively the collimator array could, instead of the shown dielectric version as in the top section of Figure 7, consist of metallic or metallized reflectors like CPC and similar architectures, offering the possibility to combine the LED light source heat sinking with the collimator device.

7. CONCLUSIONS

A new kind of brightness-enhancing film has been introduced, having superior efficiency and brightness gain over conventional designs. This new scheme relies on diffuse or specular reflection between a top surface with small holes in it and a continuous bottom surface of the backlight instead on TIR reflections as in conventional brightness enhancement films. The lensed versions of this novel design, known as LBEFs, can be applied to the same backlights as conventional retroreflective BEFs (RBEFs), but yielding higher brightness enhancement. LBEF also allow creating almost any kind of radiation pattern to achieve superior viewing in defined angular zones. LBEF systems with very narrow radiation patterns of more than 5x the backlight brightness have been simulated, as well as wider rotational and non rotational emission patterns showing very high efficiency.

Besides applications in (LCD-) display backlighting, general backlighting with lenslet or CPC type reflectors versions mounted over and integral the diffuse reflector may be used with top-mounted light sources shining directly down to prevent hot spots from being seen by the viewer, thereby homogenizing the radiation, and providing potentially perfect color mixing.

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