Projection LCD backlighting for improved VR display contrast through a pancake lens while using much less power

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ABSTRACT

Over 80% of the light produced by today's VR headsets using either emissive (OLED, µLED, etc.) or diffuse-backlit Liquid Crystal Displays (LCD) never directly reaches the user's eye and therefore represents not only wasted power but also represents the primary scattered light responsible for low contrast through a pancake lens. This paper discloses a simple, relatively compact approach to propagate the light from an array of light sources through the LCD and pancake lens so that an exit pupil is created only large enough for typical headset usage, thereby dramatically reducing the light outside that exit pupil for noticeably increased visual contrast while providing a 65% reduction in power and heat generation.

Keywords: Pancake lens, LCD, contrast, VR headset, LCD backlight, exit pupil, near-eye display

1. INTRODUCTION

A conventional VR headset Near-Eye Display (NED) includes a magnifier lens (pancake, Fresnel, etc.) which collects and directs light from a flat panel array of self-emitting (OLED, µLED, etc.) or diffuse-backlit LCD display pixels toward the eye of a user whose eye pupil intercepts a portion of that light to form a real image on the eye's retina for interpretation as a distant virtual image. Problems with such conventional headsets include a) over 80% of the light from such display panels misses the relatively small area which the eye scans through when viewing the virtual image, representing a waste of energy, increased heat management, and a source of scattering (both internal to the magnifier but also from the user's face) which significantly reduces image contrast; b) the light entering the user's eye includes optical aberrations both from the magnifier lens and the user's eye lens which further reduces clarity; and c) disparity between the user's eye lens focus and the user's binocular interpretation of the distance to content within the virtual image leads to vergence-accommodation conflict (VAC).

The above problems can be substantially reduced by replacing the conventional diffuse backlight of an LCD with an array of light sources, arranged in a compact optical assembly to form an image of the light source array at the magnifier exit pupil, and wherein eye tracking is used to turn on only that light source corresponding to the center of the eye pupil as determined through eye pupil tracking.[1] Such an approach not only substantially reduces stray light leading to contrast loss, but given a small enough image of the light source at the exit pupil, Maxwellian optical principles will apply to reduce optical aberrations and to increase depth of focus. This solution is achieved through two cooperating imaging systems. The first imaging system is simply the conventional magnifier such as a pancake lens forming a virtual image of a display panel. The second imaging system, effectively the lighting system, includes the array of light sources, the light from which is imaged through a transparent LCD panel now serving as the aperture stop of that second imaging system, then through the magnifier to form a real image of that array of light sources at the exit pupil where the user's eye is located. Each light source therefore corresponds to a small region or "subpupil" of the exit pupil, with all subpupils corresponding to their respective light sources therefore making up the entire exit pupil. Operationally, that subpupil corresponding to the user's eye pupil center location as determined by eye pupil tracking is turned "on" by turning on its corresponding light source while the remaining light sources are turned off. However, while this approach represents more of an ultimate solution in a product development roadmap, recent evolutions in Projection BackLighting (PBL) have demonstrated that simply reducing the size of a static optical system exit pupil by limiting the total size of the extended light source forming that exit pupil delivers a significant power savings and contrast improvement without the need for eye tracking due to at least 65% of light passing through current headset displays being turned off.

Despite the distinct advantages and simplicity of PBL, the second optical system nonetheless requires space behind the LCD panel to properly project light from the light source through the display panel and magnifier to form the exit pupil. A new form of folded optical system discussed below combines an off-axis aspheric concave mirror with polarization elements to provide proper illumination to the display panel to form such an exit pupil within an average distance of only 16mm behind the display panel for a 2.56” LCD panel, providing for a compact solution to deliver the contrast and power benefits explained herein.

2. CONVENTIONAL DIFFUSE BACKLIGHTING IN A NEAR-EYE DISPLAY

Figure 1 illustrates a typical catadioptric or “pancake” optical magnifier positioned with an image display panel of 56mm diagonal dimension to form a virtual image (not shown) approximately 2.5 meters from a typical position of a user’s eye through a 20mm diameter exit pupil, with a nominal distance from the exit pupil to the magnifier, or eye relief, of 15 millimeters. Other forms of optical magnifier can similarly serve as examples, including Fresnel lenses, compound lenses, mirrors, or any other arrangement of optical components that serve to form a virtual image of an image display panel. There are also myriad variations of catadioptric magnifier designs but the example used herein is representative.[2]

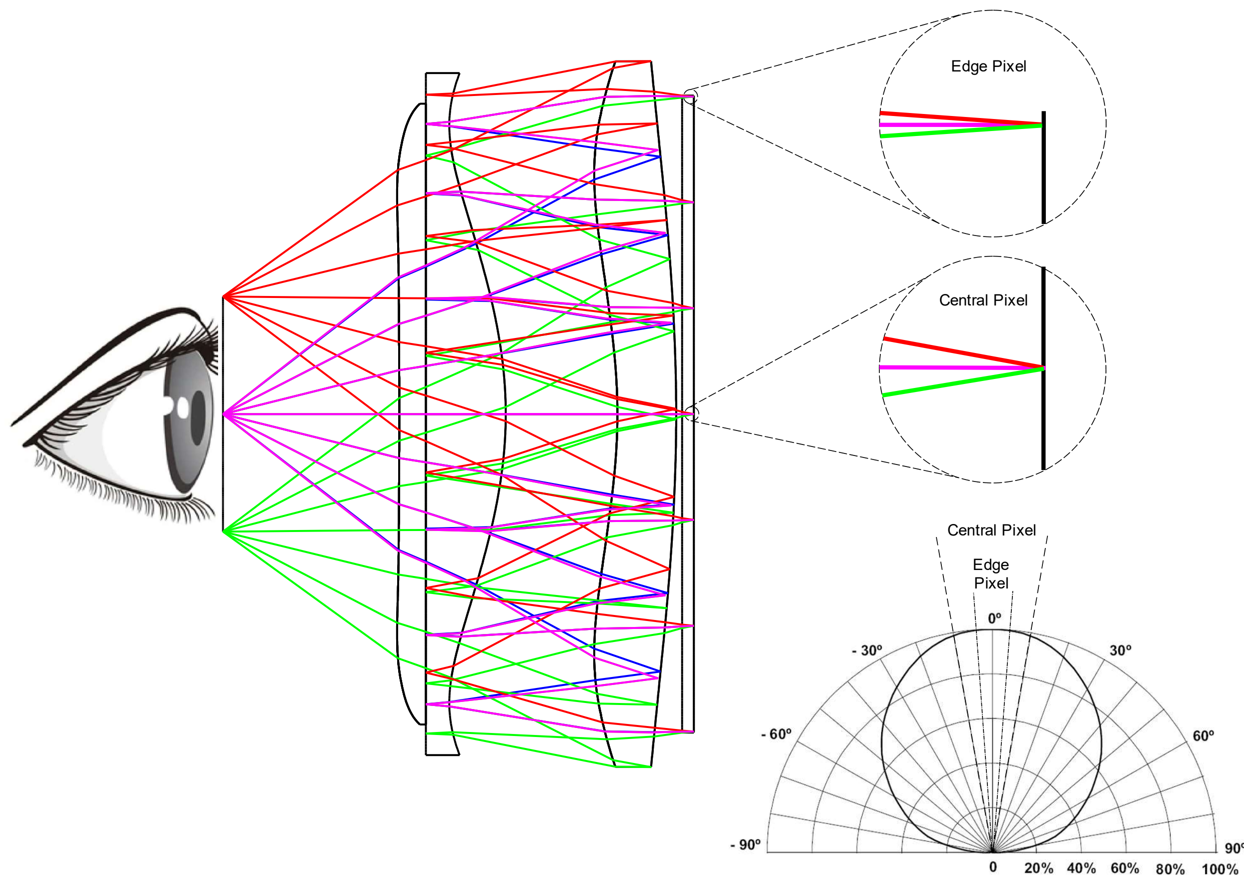

Figure 1. Ray tracing (right to left) from a display panel through a typical catadioptric pancake lens to a 20mm exit pupil with magnified views to show the angular subtense of light from a central and edge display pixel filling that exit pupil. Plotting these angular subtenses against a Lambertian angular light distribution typical of an emissive or diffusive-backlight pixel shows that there is a substantial amount of light from such displays which passes outside the exit pupil.

Further included in Figure 1 are ray traces from center pixel and edge pixel locations on the display panel propagated through the pancake lens with its catadioptric reflections to the eye location. Now referring to the magnified illustrations in Figure 1, the ray traces from the two example pixel locations are enlarged to more clearly show the full angle formed by the two rays propagating from the pixel location through the pancake lens to the edges of the exit pupil, such angles measured to be approximately 20 degrees for the central pixel and 9 degrees for the edge pixel. Any light exiting those pixel locations beyond these respective angles does not contribute to light through the exit pupil and is therefore both a waste of power and a source of light scattering.

The exit pupil should be large enough to provide light to the user's eye without vignetting of the virtual image both throughout the possible rotation angles of the eye and with moderate transverse and longitudinal misalignment of the eye with the exit pupil. In other words, the user should be able to be somewhat closer or farther from the exit pupil in addition to having some lateral misalignment without finding regions of the virtual image disappearing. Based on a general estimate of a relatively large field of view NED and general human eye parameters, the exit pupil diameter of 20mm diameter was selected to support such a non-vignetted environment.

Both diffuse-backlit LCD pixels and self-emissive pixels typically emit light with decreasing intensity as the angle from the LCD surface normal increases. While LCD backlights further include Brightness Enhancement Films (BEF) to concentrate light more into a forward angle, any diffractive scattering through a high-resolution LCD panel effectively broadens that angle back out. Accordingly, an assumption is made herein that the normalized radiation intensity as a function of angle from normal from both emissive and backlit LCD pixels can be approximated as Lambertian.

Referring now to the lower right portion of Figure 1, a normalized two-dimensional Lambertian plot is overlayed with full emission angles of 9 and 20 degrees, again corresponding to how much light from each pixel location fills the 20mm exit pupil. One can readily estimate from this plot that well over half the light from an average pixel location does not pass through the exit pupil. Assuming such a plot is valid for both axes, a corresponding three-dimensional solid angle comparison therefore suggests that over 80% of the light from an emissive or diffuse-backlit LCD panel does not directly reach the exit pupil. Instead, such light scatters and reflects within the NED or off the user's face and back into the NED where ultimately it partially scatters into the exit pupil to reduce contrast.

Therefore, more ideally, the light leaving each pixel location of a NED display panel should have a narrow, directed forward angle in accordance with the properties of the magnifier that allow that light to only fill the desired exit pupil. While one may consider some type of microlens array proximate the display panel to better collimate and direct the light from each display pixel, such a microlens array can easily show artifacts in the image in a NED environment, does not provide good directionality for pixel structures having non-point profiles, and further creates an additional diffractive scattering mechanism since each microlens would need to be very small to support a high-resolution display panel.

The challenge therefore becomes: given a magnifier optimized for creating the desired virtual image of a display panel through a desired exit pupil, how can a light source be arranged in a low-cost, compact, relatively simple optical configuration to provide light through each pixel that fully fills the desired exit pupil through the magnifier while significantly minimizing light passing outside that exit pupil?

3. COMPACT LCD PROJECTION BACKLIGHT FOR A NEAR-EYE DISPLAY

Figure 2 illustrates a new LCD projection-based backlight system as a solution to this challenge. An extended light source or array of light sources produces light which is reflected from a relatively angled, concave, off-axis first surface mirror toward a second surface proximate the back of the LCD panel. The second surface is comprised of a quarter-wave plate followed by a reflective linear polarizer, and then the LCD itself. Linearly polarized light reflected by the reflective polarizer is therefore immediately converted to circular polarization by the quarter-wave plate and thereafter is reflected yet again by the concave first surface mirror. Such second reflection from the concave first surface mirror reverses the orientation of the circular polarization so that upon reaching the second surface, the quarter-wave plate converts the light to that linear polarization which now passes through the linear polarizer to the LCD panel. One will note that light from the light source is likely to be randomly polarized, so that upon first striking the linear polarizer there will be a substantial amount of unwanted light that passes through the reflective linear polarizer. It is therefore beneficial to first convert the light leaving the light source to the appropriate circular polarization so that, upon arriving at the linear polarizer the first time very little unwanted light will pass through.

The polarization elements are selected to provide the desired input polarization of the LCD panel. In fact, because today's LCD panels often employ a reflective linear polarizer to recycle light of the wrong polarization state within a diffuse backlight, it is a relatively simple operation to add the quarter-wave plate to such an LCD panel, while leaving off the diffuse backlight so that the LCD panel itself provides the substrate for both the linear polarizer and the quarter-wave plate as a single component.

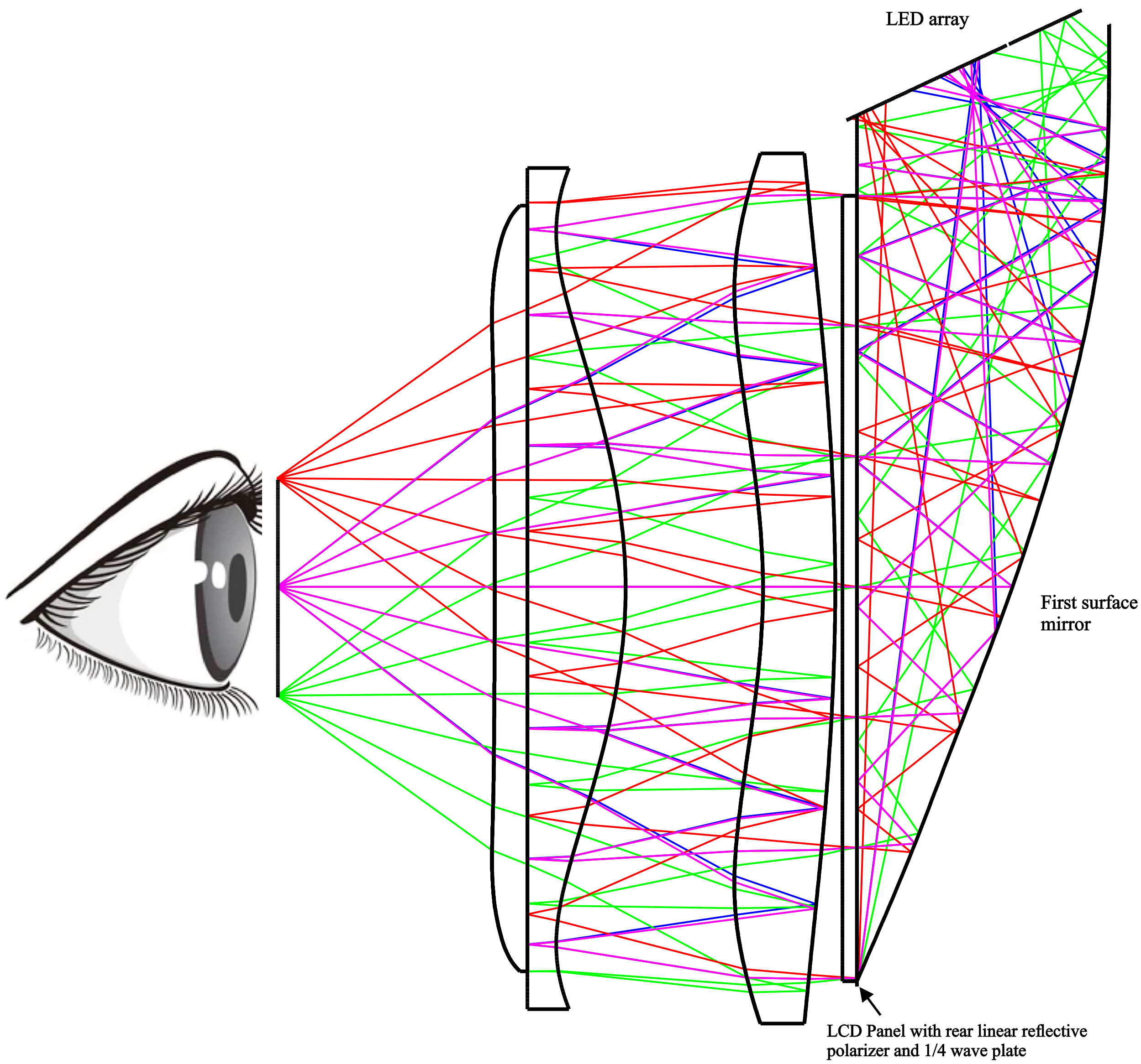

Figure 2. Ray tracing (left to right) from a 15mm exit pupil through a typical catadioptric pancake lens, through an LCD panel (acting as the aperture stop) and then through three reflections including polarization changes to arrive at the location of a light source array.

One will note that Figure 2 includes an exit pupil of only 15mm diameter instead of the initial 20mm diameter of Figure 1. It is assumed that diffractive scattering from the high resolution LCD panel will naturally expand the exit pupil to approximately achieve the originally targeted 20mm diameter.

4. OPTICAL DESIGN OF THE LCD PROJECTION BACKLIGHT

Again, the objective of this new backlight system is to provide a compact arrangement of optical components providing light to the LCD panel so that light thereafter leaving any display pixel fills the desired exit pupil with much less light passing outside the exit pupil. While a flat first mirror surface is sufficient to provide some benefit, a concave first surface mirror, specifically an off-axis aspheric mirror surface, serves to provide greater optical design parameters for optimization. One can similarly allow the second surface to be of a non-flat geometry for better design flexibility. However, there is such a great practical benefit in providing such second surface as part of a single LCD component that constraining that second surface to be flat to conform to the typically flat LCD panel is particularly desirable.

There are a number of methods to ultimately determine the best LCD backlight configuration through typical merit function optimization using optical design software. The most direct method, emphasizing the desired properties of the 15mm exit pupil and shown in Figure 2, is to propagate ideal optical rays from that exit pupil, through the magnifier, through the LCD panel now treated as the optical system aperture stop, and thereafter through the new LCD projection backlight to form an image of the exit pupil at the location of the light source array. By the reciprocity of optical rays, if the image of the exit pupil is formed at the location of the light source, then that exit pupil can similarly be considered as the image of that light source through the LCD backlight, LCD panel and pancake lens.

Such an optical design ultimately includes an optimization merit function in accordance with well-established optical design practices to examine variations in the locations and angles of the light source and concave first surface relative to the flat second surface at the LCD panel; an appropriate weighting of the image quality formed at the light source location; variations in the optical parameters of an off-axis, aspherical, concave first surface mirror; appropriate constraints to ensure each component does not interfere with other components or the beam path; and finally, weighted parameters to minimize the overall size of the LCD backlight. The resulting merit function was then minimized, again in accordance with standard optical design practices, to result in the design of Figure 2.

One will understand that while the LCD backlight described herein includes a cavity of air between the light source, the concave first mirror surface and the LCD panel (with polarizer and quarter-wave plate), such a cavity may also be comprised of a transparent optical material such as low-birefringent acrylic. However, any benefit of such a solid cavity may not be worth the additional mass.

Note that not all rays from a given exit pupil location arrive at a single, concentrated light source location, resulting in some amount of blur in the image of the exit pupil formed at the light source location. However, it is important to also note in Figure 2 that all rays from the ideal exit pupil arrive at the light source location in a confined area. This means that if a light source were to completely fill that confined area while providing light along all rays arriving thereon, the exit pupil itself will be completely filled. Of course, one cannot assume that all light from such a light source will fall within the exit pupil. But because of the imaging relationship between the light source and the exit pupil, even a poorly formed exit pupil will still confine light to a much smaller region within and around the exit pupil compared to light flooding the eye area such as from a diffuse-backlit or emissive display.

While the LCD backlight described herein does not form an ideal image at the exit pupil, the fact that such an image is blurry and will be additionally blended by diffractive scattering from the LCD panel means that any localized change in intensity as a function of spatial location within the light source will be blended to make a more uniformly illuminated exit pupil. Such blurring and blending therefore allows for spatial structure in the light source illumination profile, such as may be caused by using an array of discrete light sources or a microlens array in front of such light sources, rather than a single extended light source. Accordingly, there is additional design flexibility in employing a light source with as much directionality as possible to minimize light falling outside the exit pupil while maximizing the light within.

5. RESULTING IMPROVEMENTS IN CONTRAST FROM AN LCD PROJECTION BACKLIGHT VERSUS TYPICAL DIFFUSE BACKLIGHTING

A commercially available 56mm RGB LCD panel of 2160 x 2160 resolution and with included diffuse backlight was mounted as the left-eye side of a binocular, 3D-printed demonstration NED of fixed 70mm interpupillary distance (as constrained by the supplied LCD driver board) and fitted with an off-the-shelf, left-eye pancake lens to form a virtual image. An identical 56mm LCD panel was mounted as the right-eye side of the binocular NED with the right-eye version of the same pancake lens. However, this right-eye LCD panel was disassembled to allow light to transmit therethrough, with the back the LCD panel being fitted with a reflective linear polarizer and quarter-wave film properly oriented to allow the appropriate linearly polarized light through the LCD panel after the second reflection from the concave first surface mirror.

An array of 17 LED light sources each having a curved lens and each with power rating of 20mW, was oriented relative to the LCD panel as illustrated in Figure 2. This light source array was further covered with a linear polarizer and quarter-wave film to produce circularly polarized light.

As a result of the optimized design shown in Figure 2, a concave, off-axis, first surface mirror was injection molded from ABS. To save on cost, the mold was simply CNC generated and hand polished. The part was then chrome plated to provide a reflective surface.

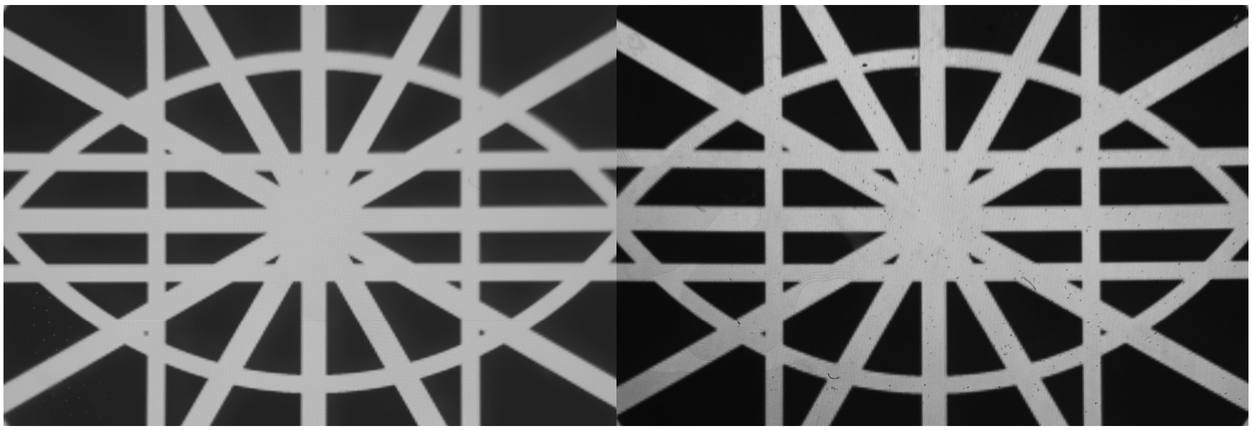

Figure 3. Digital camera images through the left (standard diffusive backlight) and right (projection backlight) pancake lenses showing the significant improvement in visual contrast due to the reduction of stray light.

Both displays were driven with identical test pattern images. A digital camera was used to produce zoomed-in images through each pancake lens. One will note the debris in the right image due to residual dust on the added polarization films. The left image was slightly modified to account for moderate scattering from the face area around the eye (which camera modifications could not easily replicate) so that the resulting images are proper representations of visual results. These results clearly show the contrast enhancement when using PBL.

The size of the array of light sources used in this demo was sufficient to provide a large enough exit pupil for comfortable, unvignetted viewing throughout the entire field of view. As expected, positioning one's eye away from the optical axis of the NED, thereby leaving the exit pupil, caused a very significant fall-off in visual brightness. This is an added benefit because such a departure necessarily results in significantly aberrated image quality and it is a better user environment to require the user's eye to be within the exit pupil to be able to see the best quality image.

No brightness modifications were applied to the above results. While the power specified for the diffusive LCD backlight is over 1000mW, the 17 20mW LEDs therefore represent a power reduction of approximately 65%.

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