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Enhancing the Optical Efficiency of Near-Eye Displays with Liquid Crystal Optics

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Abstract: We demonstrate a light efficient virtual reality (VR) near-eye display (NED) design based on a directional display panel and a diffractive deflection film (DDF). The DDF was essentially a high-efficiency Pancharatnam-Berry phase optical element made of liquid crystal polymer. The essence of this design is directing most of the display light into the eyebox. The proposed method is applicable for both catadioptric and dioptric VR lenses. A proof-of-concept experiment was conducted with off-the-shelf optical parts, where the light efficiency was enhanced by more than 2 times.

Keywords: liquid crystal; Pancharatnam-Berry phase; near-eye display; light efficiency; virtual reality

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1. Introduction

After rapid development in the past decade, virtual reality (VR) headsets have become more powerful, and they can offer a relatively comfortable and immersive experience for users [1]. In the meantime, the continuous evolution of near-eye displays (NEDs) inside VR headsets is also remarkable [2]. About five years ago, mainstream VR headsets still required a smartphone screen to function as the display panel. Nowadays, most VR devices are integrated with one or two custom-built high-resolution display panels, such as liquid crystal display (LCD), organic light-emitting display (OLED), or micro-LED display [3]. In parallel, VR optics is gradually evolving from simple dioptric singlets to catadioptric "pancake" lenses [4]. Thanks to their folded optical path, VR NEDs using polarization-based pancake lenses allow the display to be significantly closer to the lens and therefore manifest a more compact form factor than those employing conventional singlets. However, a big tradeoff is that the total light efficiency is limited to 12.5% and 25% for an unpolarized and polarized display light source, respectively [5]. As a result, the peak brightness of pancake VR headsets is usually lower than that of conventional ones, and the display module needs to drain more power for maintaining the same brightness. This issue is more critical for a standalone VR headset powered by an internal battery. Thus, there is an urgent need to enhance the optical efficiency of VR headsets for higher brightness and extended battery life.

From an optical system perspective, light efficiency can be enhanced by improving the display panel or the VR optics or making them coupled better with each other. The display panels in current VR headsets are adopted from those in direct-view electronics, such as smartphones, with limited modification in the optical architecture. This adoption is doable, but there is still much room for improvement because direct-view display panels are not originally designed and optimized for VR applications. In most direct-view displays, continuous efforts have been made to maintain decent display quality within a large viewing angle. For example, multi-domain vertical alignment (MVA) and in-plane switching (IPS) technologies were invented for wide-view and high contrast LCDs [6]. Additionally, in OLED displays, there is often a tradeoff between light extraction efficiency and angular color uniformity due to micro-cavity effects [7,8], so the light efficiency is not usually maximized. It should be mentioned that the circumstance is different in VR headsets, where the display panel is fixed relative to the eye, and a magnifying lens is also placed between them, as illustrated in Figure 1.

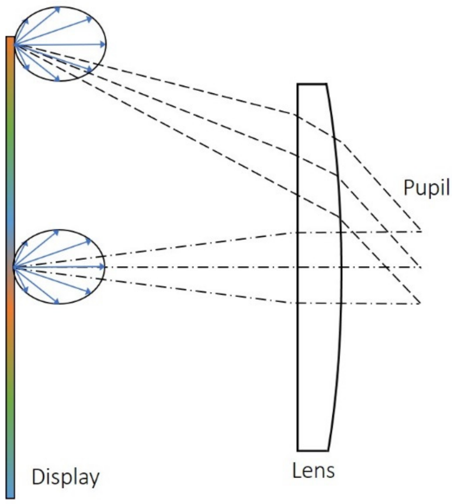


Figure 1. Illustration of a typical virtual reality (VR) display module with a wide-view display.

From the system viewpoint, applying a direct-view display panel in VR headsets may result in several issues that affect users' experience. Firstly, direct-view display panels emit light within a large solid angle, while in VR headsets, only the light rays radiating from a small solid angle can reach the pupil, as depicted in Figure 1. As a result, a considerable amount of display light is wasted. This issue is more critical in VR headsets with catadioptric (pancake) optics where the lens transmittance is already lower than 25%. Secondly, the stray rays outside the effective solid angle cannot enter the exit pupil. These rays may bounce back and forth between the VR lens and the display panel, causing background noise and reducing the contrast ratio of front-of-screen imagery. In addition, direct-view display panels usually manifest higher luminance in the direction normal to the panel surface, which leads to a relatively darker peripheral field, i.e., vignetting. The spatial varying size and orientation of the effective solid angle also exaggerate the luminance variation across the field of view (FOV). Last but not least, for OLEDs, the microcavity utilized in RGB pixels can narrow the emission spectra but may also cause color shift across the viewing angle due to the variance in RGB Fabry–Perot resonance [6]. In a VR headset, this angular color shift can lead to apparent color variation across the FOV. Because of the abovementioned issues, the wide-view display panel is not an ideal choice for VR displays.

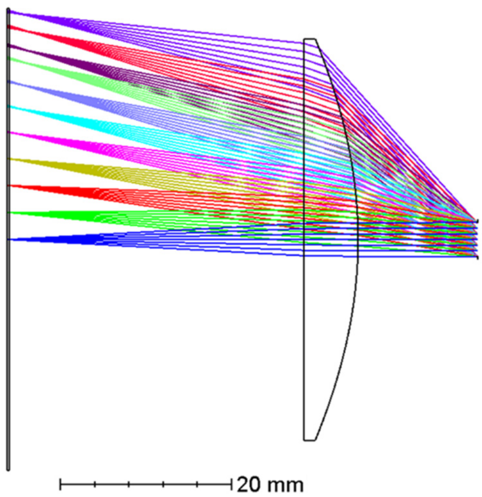
In this paper, we propose to tailor the VR display panels for better coupling with the VR lens and achieve a higher light efficiency at the system level. The essence of this design is to use a directional display to narrow the emitting angle and a diffractive deflection film (DDF) to direct more light toward the eyebox. Such an arrangement serves two important reasons: the first being the small etendue of the directional display, which matches better with the small etendue at the eyebox. The other reason is that the DDF can correct the orientation of emitting solid angle based on the lens design and alleviate potential vignetting. In Section 2, we demonstrate the design and simulation process using nonsequential ray-tracing analysis. This is followed in Section 3 by a proof-of-concept experiment that can validate the light efficiency enhancement with our proposed design. The limitations and further improvements of the proposed method are thoroughly discussed before the conclusion.

2. Method

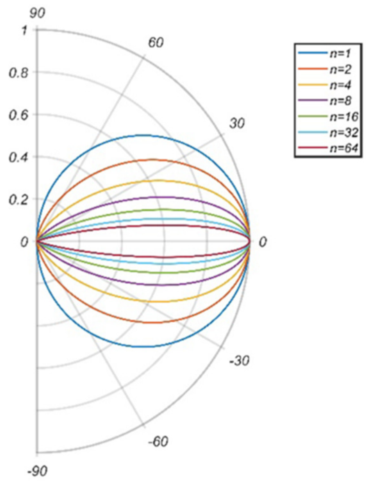
As mentioned above, direct-view displays' emitting solid angle is usually larger than the effective solid angle determined by the VR optical system, which is the primary cause of light efficiency issue for both dioptric and catadioptric VR display modules. In this section, we demonstrate a VR optical design where the display panel and the lens are better coupled with each other to boost the system-level efficiency.

2.1. Directional Display

The first part of our design is a directional display panel with a narrower emitting angle than conventional direct-view displays. Figure 2a depicts the cross-section view of an exemplary VR display module using a singlet with a Fresnel surface and an aspheric surface [9]. This polymethyl methacrylate (PMMA) lens has a focal length of 35 mm, and the FOV of the VR display module is ~100°. Similar to most commercial VR headsets, this example has spatial-varying effective solid angle sizes and orientations across the display panel, as depicted in Figure 2a.



(**a**)



(**b**)

Figure 2. (**a**) Optical layout of the VR display module used in the simulation; (**b**) Exemplary angular intensity profiles of the display panel described in Equation (1).

After finishing the sequential design in Zemax OpticStudio (Seattle, WA, USA), we reconstructed the same optical layout in Synopsis LightTools (Mountain View, CA, USA) to conduct the nonsequential light efficiency analysis. For simplicity yet without losing generality, the angular intensity profiles were set as Lambertian and its exponentiations in the simulation, as represented by Equation (1):

$$I(\theta) = I_0 \cos(\theta)^n, \tag{1}$$

where θ is the incident angle on the panel surface. Figure 2b displays the angular profiles in a 2D polar coordinate system, where the 0° direction is normal to the panel surface. In the nonsequential simulation, the circular receiver is located at the exit pupil and has a diameter of 9.5 mm. Only a single pixel is turned on at each simulation, and the luminous efficiency of each pixel is defined as:

$$\eta = L_{eyebox}/L_{pixel}, \tag{2}$$

where L_{pixel} is the luminance power emitting from each pixel, and L_{eyebox} indicates the luminous flux received by the circular receiver at the eyebox. One million rays were traced in each simulation to provide a decent accuracy. Figure 3 displays the simulated light efficiency of pixels located across the display panel. Five different angular intensity distributions described by Equation (1) were applied. It is not surprising that only <10% of the light from wide-view display panels (n = 8) can reach the receiver, which is inefficient and power-consuming for the VR system. Notably, the use of a highly directional display panel (n = 128) allows much higher light efficacy, and the enhancement can be as high as >6 times at center field. Although applying a directional display panel makes better use of light, the perceived brightness across the FOV may manifest a more considerable variation. This is because the effective solid angle of each field has a distinct orientation. Therefore, direct narrowing down the emitting angle may lead to apparent vignetting in the perceived imagery, especially in the fields where the chief ray is not perpendicular to the panel surface. Furthermore, it is also worth mentioning that utilizing a directional display may render the imagery more dependent on the eye location and demand users to adjust the headset position for the best performance.

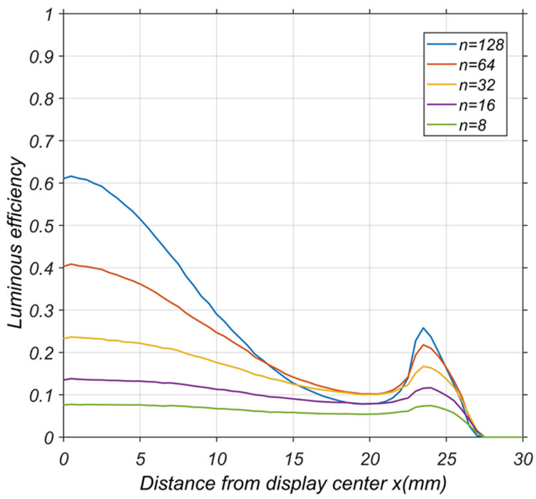


Figure 3. Simulated luminous efficiency of a single pixel in the VR optical module depicted in Figure 2a with the angular luminance distributions shown in Equation (1) and Figure 2b.

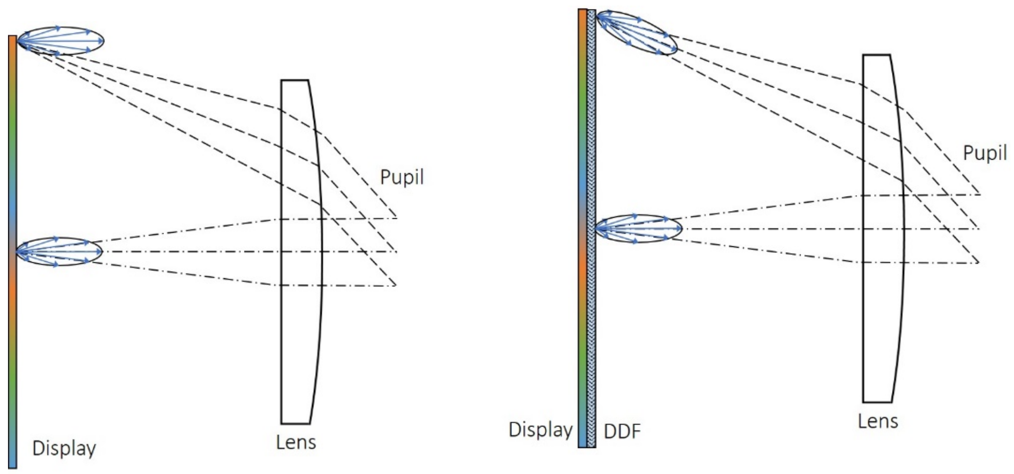
2.2. *Diffractive Deflection Film (DDF)*

One step further, to achieve a higher light efficiency and a smaller vignetting simultaneously, we propose to attach a DDF on the directional display panel for manipulating the orientation of the emitting solid angles, as illustrated in Figure 4. The DDF is a type of Pancharatnam-Berry phase optical elements (PBOEs) [10–12] made of liquid crystal (LC) polymer, which can be considered as a dielectric metasurface or a patterned half-wave plate with in-plane spatial-varying orientation. Its working principle can be explained by Jones calculus in the paraxial approximation. With a circularly polarized input, the output Jones vector can be expressed as:

$$J_{out} = R(-\psi)W(\pi)R(\psi)J_{\pm} = -je^{\pm 2j\psi}J_{\mp}, \tag{3}$$

$$J_{\pm} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ \pm j \end{bmatrix}, \tag{4}$$

where $R(\psi)$ is the rotation operation matrix, $W(\pi)$ represents the half-wave retardation of the half-wave plate, and $J_{\pm}$ stands for the left- and right-handed circular polarization. It is shown that the PBOE can convert the handedness and offer a phase delay that is proportional to the local liquid crystal orientation angle. As a result, arbitrary two-dimensional phase plates can be achieved based on this principle. Compared to conventional metasurfaces based on the Pancharatnam-Berry phase, LC-based PBOEs can offer nearly unit diffraction efficiency over the entire display spectrum [13,14] and have a cost-effective fabrication process [15–17]. These are the reasons why we chose PBOE over other compact optical elements for this application.

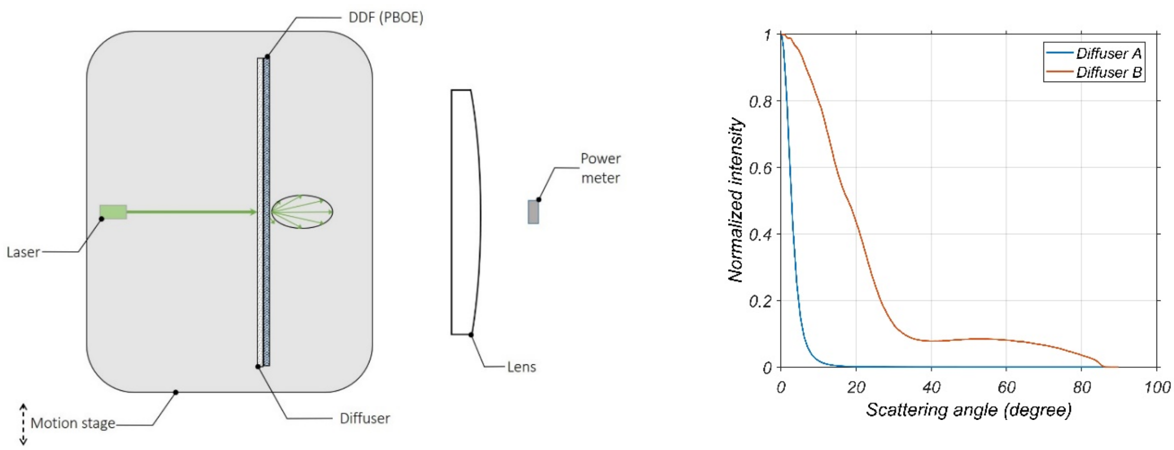


(**a**) (**b**)

Figure 4. (**a**) Illustration of the directional VR display module; (**b**) Illustration of the directional VR display module with a laminated diffractive deflection film (DDF) on the display panel.

3. Experiment

To prove the feasibility of the proposed design, we present below the result of a proof-of-concept experiment using commercial off-the-shelf components. The experiment setup is depicted in Figure 5a. Instead of using a directional display panel, a plastic diffuser film was utilized as the display panel and illuminated with a laser line (532 nm) to mimic the light emitting from a single pixel. The laser diode, diffuser film, and DDF were placed on a motion stage that could move in a direction perpendicular to the optical axis. By changing the position of the motion stage and collecting the light at the eyebox with a power meter, the light efficiency of pixels at different locations on the display panel could be measured. The scattering angular distribution of the diffusers at normal incidence is shown in Figure 5b.



(**a**) (**b**)

Figure 5. (**a**) Schematic illustration of the experimental setup; (**b**) Scattering angular distributions of the diffusers used in the experiment. Diffuser A represents a directional display, while diffuser B represents a conventional LCD.

As Figure 5b depicts, Diffuser B (Brightview Technology, C-HE55, Durham, NC, USA) behaved like a typical LCD, while diffuser A (Brightview Technology, C-HE05, Durham, NC, USA) represented the proposed directional display. At each pixel location in the measurement process, the relative position of the PBOE (Edmund Optics, #34-463, Barrington, NJ, USA) to the laser line was adjusted to maximize the intensity shown on the power meter (Thorlabs, PM100D, Newton, NJ, USA).

Figure 6 shows the measured luminous efficiency using three different configurations: diffuser A, diffuser B, and diffuser A with DDF. These results match well with our simulations, showing that a directional display (diffuser A) showed higher light efficiency than a wide-view display (diffuser B). However, this advantage came at the cost of stronger intensity variation across the FOV. The use of a DDF on top of the display allowed a significant alleviation of this side effect and allowed higher average efficiency over the entire display panel.

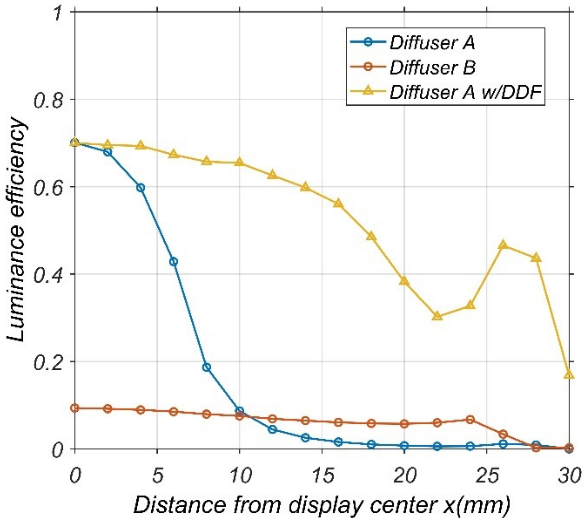


Figure 6. Measured luminous efficiency in the exemplary VR display module.

4. Discussion

Although the proof-of-concept experiment presented above shows the proposed approach is highly promising to deal with the light efficiency issue in a VR optical system, there are still some concerns that cannot be ignored in practical applications.

A common issue of using diffractive optical components in display systems is their chromatically dispersive optical response over the display spectrum [18]. In the proposed application, the PBOE-based DDF may possibly result in an angular color shift that is substantial enough to affect the front-of-screen imagery. The significance of this issue depends on the maximum angle of the chief rays on the display panel. Since the DDF here was not involved in imaging but only angular profile shaping, a small deflection angle did not induce perceivable color variation across the FOV. In VR lenses with large chief ray angles on the display panel, the DDF period needs to be smaller, and the directionality of the display should be limited to keep the angular color shift at an acceptable level. Additionally, in this case, other achromatic flat optics such as lithography-based metasurfaces [19,20] can be a better choice than the LC-based DDF.

Using a directional display panel is another demanding requirement of the proposed approach because most display panels in mass-production are not directional. Although directional displays are not as popular as the wide-view ones, it is actually not that hard to produce them by modifying the current manufacturing process. Firstly, for LCDs, numerous directional backlight designs have been proposed and employed to enhance the contrast and transmittance of LCD [21,22]. These are naturally suitable for the proposed approaches. Secondly, in OLED display panels, there is usually a tradeoff between angular color shift and light extraction efficiency [7]. Since the angular color shift is not a big concern in our approaches, it is feasible to apply strong cavities for a high-intensity directional OLED emission [23]. Furthermore, RGB micro-LEDs with nanowire structure have shown promise for exhibiting low dislocation densities and improved light extraction efficiency, and the emission divergence angle can be as small as ±5° [24]. Last but not least, metasurface can be fabricated on top of the LED chips to control the light emission [25], which can also be a neat option for the proposed concept.

5. Conclusions

We proposed a light-efficient VR display module and experimentally demonstrated the feasibility of this design with a proof-of-concept experiment. The proposed design mainly consists of a directional display pane and a PBOE-based DDF made of liquid crystal polymer. We used the directional display to confine the emitting solid angel of light and the DDF to direct more light into the eyebox. The light efficiency of the proposed VR display module can be >2× higher than conventional ones. Given the advantages demonstrated in this study, we expect the proposed concept and design to emerge as a useful technology for next-generation VR displays and to become one of the most practical applications of flat optics.

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