Foveated Virtual-Reality Display Based on a Pancake Lens

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Abstract

A foveated virtual reality display based on pancake lens is proposed and demonstrated experimentally. The proposed system enhances the system efficiency due to its higher optical efficiency in the peripheral region. A shorter effective focal length can be achieved with reduced field of view in the foveated region.

Author Keywords

Foveated display; virtual reality; high efficiency; compact formfactor.

1. Introduction

Virtual reality (VR) display is regarded as next-generation display because it provides fully immersive experiences and has the potential to revolutionize the way we interact with the digital world (1–4). Tremendous efforts have been devoted to design and optimize the VR systems, aiming to a higher resolution density, wider field of view (FoV), higher brightness, and more compact formfactor, which are critical demands to enable uncompromised visual experiences (5,6).

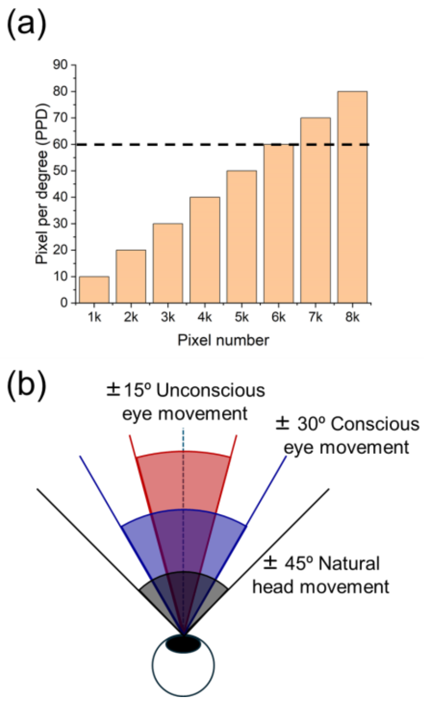

Figure 1. (a) Angular resolutions for different pixel numbers, given a 100º FoV, and (b) human eye movement range in the horizontal direction.

The visual acuity of a normal human eye, a measure of the ability to distinguish shapes and the details of objects, is approximately 1 arcmin, which is equivalent to 60 pixel per degree (PPD). A 6K by 6K display panel is required to achieve 100º FoV with such a high angular resolution as Fig. 1(a) shows, which poses a big challenge for the light engine. However, human visual acuity drops rapidly as the eccentricity angle increases, since cone cells (the image receptors in the retina) are concentrated in the ±5º fovea region (7). Moreover, previous research reveals that the conscious eye movement range is from −30º to +30º as illustrated in Fig. 1(b), indicating that high angular resolution is only required within a limited range (8). Therefore, foveated systems hold potentials for next-generation VR headsets (9–11).

In this paper, we propose a novel foveated VR display based on a commonly used pancake lens. The fovea region and peripheral region have different light paths due to the different circular polarization response of the pancake lens. A special circular polarizer is employed to control the different circular polarization states of the emitted light. The effectiveness of this novel system is validated by both experiment and simulation.

2. Method

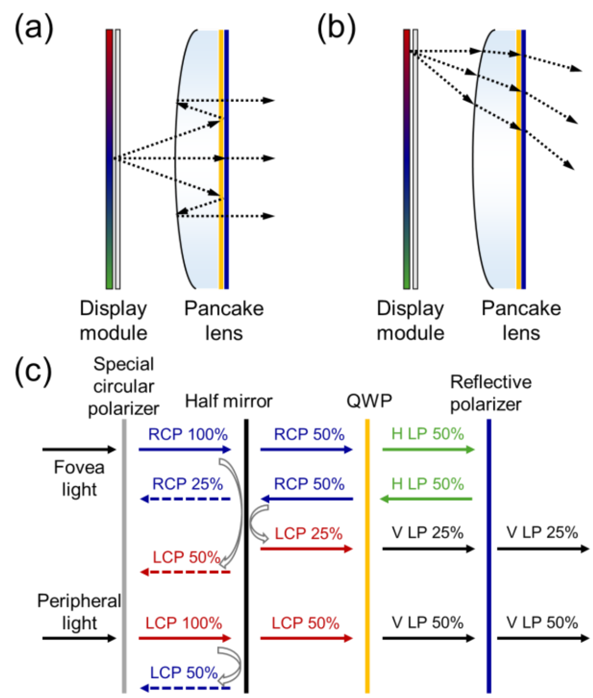

Figure 2. Light path of (a) fovea region and (b) peripheral region inside the pancake system, and (c) polarization conversion for incident light with different circular polarization states.

Pancake lens has been widely used in VR headsets due to its compact formfactor and excellent image performance. Figure 2(a) depicts the light path of the pancake VR system, which represents the fovea region of the proposed foveated system. The emitted light from the microdisplay module is folded inside the pancake lens before it exits. In contrast, the light path for the peripheral region is depicted in Fig. 2(b), where the light passes through the pancake lens without being folded. These two different light paths can be attributed to different polarization states of the emitted light as illustrated in Fig. 2(c).

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Half of the incident light with right-handed circular polarization (RCP) first passes through the half mirror and is then converted to horizontal linear polarization (LP) by the quarter-wave plate (QWP). However, such beam is reflected to the QWP because its linear polarization is orthogonal to the transmission axis of the reflective polarizer. The reflected light is converted to RCP by the QWP again and impinges on the half mirror. Only 25% light is converted to left-handed circular polarization (LCP) and reflected by the half mirror. The LCP light then passes through the QWP for the second time and is converted to vertical LP, which is parallel to the transmission axis of the reflective polarizer. Afterwards, the remaining 25% light transmits through the reflective polarizer and is perceived by the user's eye. Therefore, the system efficiency for the fovea region is 25% in an ideal case.

For the peripheral region with LCP incident light, 50% light transmits through the half mirror and is consequently converted to a vertical LP state by the QWP and passes through the reflective polarizer without being reflected. Thus, the optical efficiency is 50% for the peripheral region, which is 2x higher than that of the fovea region. Therefore, different light paths with different system efficiency for fovea and peripheral region can be achieved by controlling the polarization states of the emitted light.

3. Experimental demonstration

To demonstrate the effectiveness of the proposed foveated VR display, we build a simple experimental setup using a pancake lens. A specially designed circular polarizer is used to control the polarization states of the emitted light from the microdisplay panel as shown in Fig. 3(a).

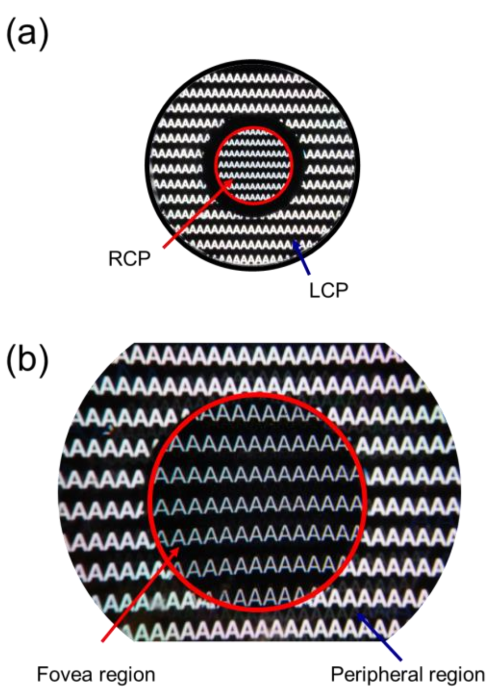

Figure 3. (a) Polarization states of fovea region and peripheral region, and (b) captured image with a pancake lens.

The light emitted from the pixels inside the red circle is converted to RCP while that outside the circle is converted to LCP. Different circular polarization states lead to different light paths as shown in Fig. 2. Figure 3(b) shows the captured image after adding a pancake lens over the display panel and the circular polarizer. The fovea region inside the red circle shows sharper images as the pancake lens is designed and optimized for the folded path. Additionally, the fovea region exhibits a reduced brightness due to the lower optical efficiency caused by the double interaction with the half mirror. In contrast, the peripheral region outside the red circle exhibits a lower image performance but higher brightness due to a different light path.

4. Simulation and discussion

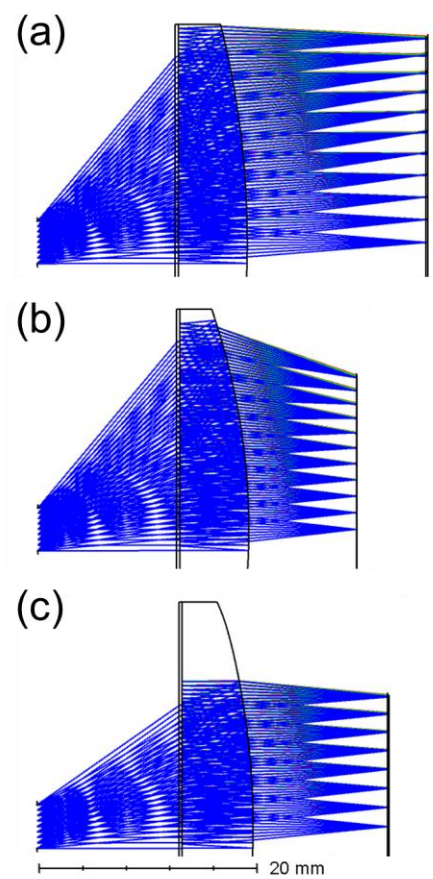

Figure 4. Pancake models with a 50º half FoV: (a) considering and (b) without considering the chief ray incident angle, and (c) a pancake model with a 35º half FoV, considering the chief ray incident angle. Eye relief = 13mm, lens thickness = 6.5mm. The effective focal length for (a), (b), and (c) is 25mm, 18mm, and 20mm, respectively.

The proposed foveated pancake VR display system does not provide a higher resolution compared to the current pancake VR display system but offers an improved efficiency for the peripheral region as demonstrated in Section 3. Therefore, the size of the peripheral region would be essential to evaluate the improvement of the overall system efficiency. A simulation model depicted in Fig. 4 (a) has been developed to investigate the size of fovea and peripheral regions. The conscious human eye movement is about ±30º and the fovea region is in the ±5º area. Therefore, 35º field angle is considered as the boundary between the fovea and the peripheral regions. The image height ratio of 35º field angle to 50º field angle is approximately 0.735, indicating that the size of the fovea region and the peripheral region account for about 54% and 46% of the entire display, respectively. As the theoretical efficiency of the peripheral region is doubled compared to that of the fovea region, the proposed foveated pancake VR display is expected to benefit from lower power consumption and longer operation time.

In addition to higher system efficiency, the proposed foveated system provides a more compact formfactor, which improves the wearing comfort of the VR headsets. The focal length of a conventional pancake length is limited by the restriction on the chief ray incident angle on the image plane in simulation, also the display panel in reality. To ensure higher input efficiency from the display, the chief ray incident angles on the image plan are expected to be as small as possible because the display panel provides the strongest emission in the normal direction. A shorter focal length can be achieved in Fig. 4(b) while resulting in large chief ray incident angles on the image plane, especially for large field angles, which finally leads to a lower efficiency. Fortunately, the proposed foveated pancake VR system only restricts the chief ray incident angle for the fovea region, which releases the burden of design requirements. An effective focal length of 20mm can be achieved in Fig. 4(c) for the 35º fovea region, shorter than the 25mm effective focal length in Fig. 4(a). The fovea region and peripheral region are fixed in the current configuration with a passive circular polarizer after the display. An active circular polarizer with the ability to switch the circular polarization state of different emission areas on the display can be considered with assistance of an eye tracking system, where the fovea region is smaller but can shift according to the saccade of the user's eye.

5. Conclusion

We proposed a foveated VR display system based on a pancake lens. The different light paths of the fovea region and peripheral region can be achieved by controlling the polarization states of the emitted light from different areas on the microdisplay panel. The effectiveness of the proposed system has been demonstrated with experiments. A higher efficiency for the peripheral region is observed. The simulation results help evaluate the size of the fovea region and peripheral region to investigate the overall efficiency improvement. The proposed foveated VR system also enables a shorter effective focal length for a more compact formfactor.

6. Impact

In addition to providing solutions to overcome the low efficiency and compact formfactor, both the urgent issues for the present VR headsets, our proposed foveated pancake VR system exhibits an almost identical configuration compared to the current pancake VR system, except for using a circular polarizer with two segmented regions: one for LCP and another for RCP.

7. References

1. Choi S, Jung K, Noh SD. Virtual reality applications in manufacturing industries: Past research, present findings, and future directions. Concurr Eng. 2015;23:40–63.
2. Xiong J, Hsiang EL, He Z, Zhan T, Wu ST. Augmented reality and virtual reality displays: emerging technologies and future perspectives. Light Sci Appl. 2021 Oct 25;10(1):216.
3. Zhang W, Wang Z. Theory and Practice of VR/AR in K-12 Science Education—A Systematic Review. Sustainability. 2021 Jan;13(22):12646.
4. van der Kruk SR, Zielinski R, MacDougall H, Hughes-Barton D, Gunn KM. Virtual reality as a patient education tool in healthcare: A scoping review. Patient Educ Couns. 2022 Jul 1;105(7):1928–42.
5. Park JH, Lee B. Holographic techniques for augmented reality and virtual reality near-eye displays. Light Adv Manuf. 2022;3:9.
6. Luo Z, Li Y, Semmen J, Rao Y, Wu ST. Achromatic diffractive liquid-crystal optics for virtual reality displays. Light Sci Appl. 2023 Sep 15;12(1):230.
7. Osterberg G. Topography of the layer of rods and cones in the human retina. Acta Ophthal. 1935;6:1–103.
8. Costa ALF de A, Santos VR dos. From vision to citizenship: types of tables to assess reading in special education. Revista Brasileira de Oftalmologia. 2018;77(5):296–302.
9. Tan G, Lee YH, Zhan T, Yang J, Liu S, Zhao D, et al. Foveated imaging for near-eye displays. Opt Express. 2018 Sep 17;26(19):25076–85.
10. Lee S, Wang M, Li G, Lu L, Sulai Y, Jang C, et al. Foveated near-eye display for mixed reality using liquid crystal photonics. Sci Rep. 2020 Sep 30;10(1):16127.
11. Yin K, He Z, Li Y, Wu ST. Foveated imaging by polarization multiplexing for compact near-eye displays. J Soc Inf Disp. 2022;30(5):381–6.