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Foveated imaging by polarization multiplexing for compact near-eye displays

Kun Yin, Student Member | **Ziqian He** | **Yannanqi Li, Student Member** | **Shin-Tson Wu, SID Fellow**

College of Optics and Photonics, University of Central Florida, Orlando, Florida, USA

Correspondence
Shin-Tson Wu, College of Optics and Photonics, University of Central Florida, Orlando, FL 32816, USA.
Email: swu@creol.ucf.edu

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Abstract
We demonstrate a multi-resolution foveated imaging system for virtual reality, which is enabled by a single display panel with polarization multiplexing to significantly increase the angular resolution without scarifying the frame rate. By using a polarization-dependent cholesteric liquid crystal reflector, we have achieved a 4.4× higher resolution density while maintaining a compact form factor.

KEYWORDS
liquid crystals, polarization multiplexing, resolution enhancement, virtual reality

1 | INTRODUCTION

Near-eye displays have found widespread applications in gaming, communication, healthcare, and education. At present, the visual experience provided by commercial virtual reality (VR) headsets is still substantially lower than that of human perception.[1–4] One of the reasons is inadequate angular resolution. The acuity of a normal person is around 1 arcmin, which is 60 pixels per degree (ppd), while most commercial VR displays can only offer 10 to 20 ppd, depending on the field of view.[5,6] Thus, the VR headset users can easily observe the screen-door effect, which significantly degrades the image fidelity.

A straightforward approach to match human-eye acuity is to increase the resolution density of the display panel. To achieve angular resolution ∼60 ppd and field of view >100° simultaneously, each eye needs a display panel with at least 6 K × 6 K pixels.[6] With panel makers' vigorous efforts, commercial VR display resolution has reached 4 K per eye. Recently, Pimax announced to release VR headsets with 6 K resolution per eye soon, but the cost remains relatively high at present stage. It's worth mentioning that the observed ppd is also affected by panel utilization and optical elements, meaning that even a 6 K resolution panel may still be insufficient to meet the requirement of 60 ppd with field of view >100°. In addition, it would be extremely challenging to render high-resolution images and videos in real time, and a more efficient image rendering pipeline must also be developed to support tremendous data transfer. Therefore, foveated imaging becomes a more favorable solution to provide ultra-high-resolution images by considering the panel fabrication and data transport difficulties.[7–12] Due to the 1-arcmin requirement being only for the narrow central region (< ±5°) defined by the cone cell distribution on retina, we may only need to provide high resolution for central fovea region instead of the entire field of view.[13] To achieve foveated VR display, current approaches employ two separate display panels to provide low-resolution and high-resolution images, respectively.[6,14] Aside from the two-panel requirement, a beam splitter cube/plate is required to combine the images of two panels, which will lead to a bulky system and high-power consumption. To reduce the form factor with a single panel, recently, Meta proposed a switchable pancake structure.[15] High-resolution images of the fovea and relatively low-resolution peripheral images are achieved by time multiplexing, which means the system needs to rapidly switch between two different magnifications. The advantage is to deliver foveated imaging without any beam splitter, but the disadvantage is the sacrificed frame rate.

In this paper, we demonstrate a foveated VR system implemented by only one display panel and polarization multiplexing without sacrificing the frame rate. The low-resolution image and the high-resolution image are encoded into two orthogonal polarization states, respectively, which are overlapped and displayed on the same display and then be separated by polarization-dependent components. One of the polarization images provides a wide field of view, just like a conventional VR display panel. The other provides an ultra-high resolution for the fovea through a polarization-dependent optical minification system, which increases the effective resolution. The proposed system can effectively suppress the screen-door effect, while reducing the system volume and power consumption of the VR headset.

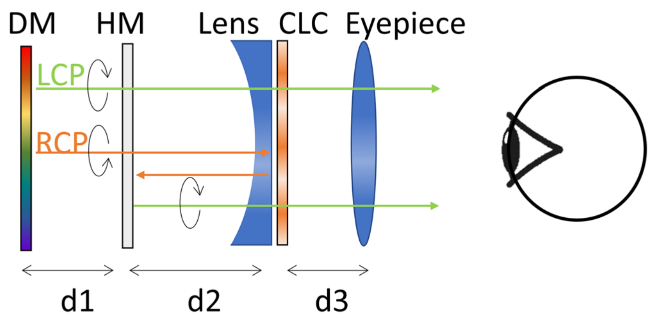

FIGURE 1 Schematic diagram of the proposed multi-resolution foveated display for a VR headset. CLC, cholesteric liquid crystal; DM, display module; HM, half mirror

2 | SYSTEM CONFIGURATION

Figure 1 depicts the system configuration of the proposed foveated display design enabled by polarization multiplexing. Briefly, this design consists of one display module, a half mirror, some optical lenses, and a polarization-dependent cholesteric liquid crystal (CLC) reflector. The peripheral image and the center image are displayed on the same panel and then be decoded into left- and right-handed circularly polarized (LCP and RCP) light, respectively.

The unfolded optical layouts of the proposed design are illustrated in Figure 2A,B. For one polarization state, say LCP, it passes through the system and enters the human eye, just like the conventional VR system. However, in our design, this polarization only delivers the image content for surrounding region or peripheral image.

For the opposite polarization state, say RCP, the light will pass through a folded optical path (Figure 1). As illustrated in Figure 2B, the RCP light displays the center image, and the light will enter the concave lens three

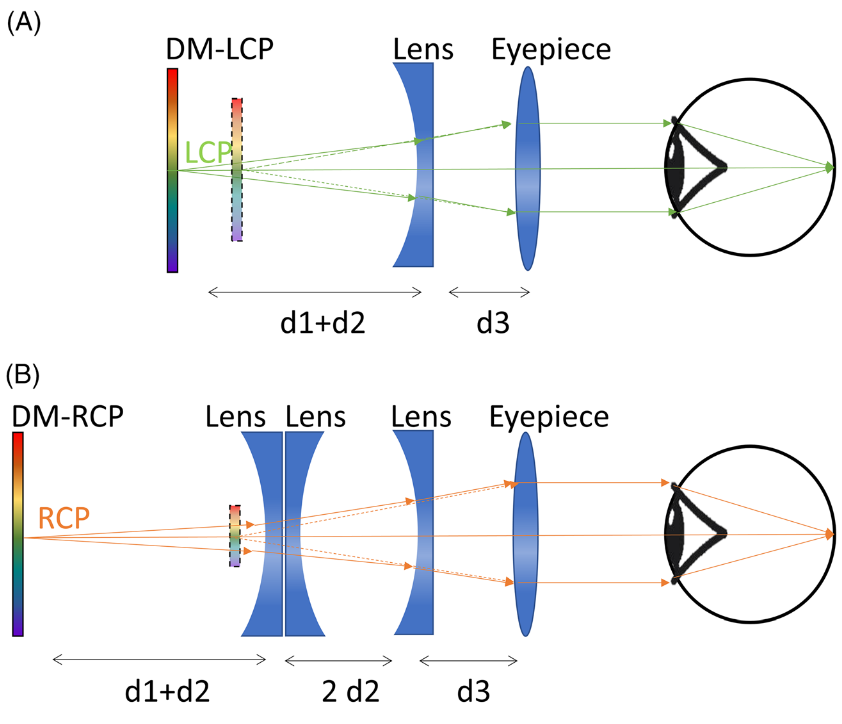

FIGURE 2 The unfolded layout of the optical paths for (A) peripheral image with low resolution and (B) center image with high resolution

times. The first time is the same as LCP light, then it is reflected by the CLC and arrives at the concave lens for the second time. After being reflected by the half mirror, the RCP will be converted to LCP, and the light will enter the concave lens for the third time. Finally, it passes through the CLC and enters the human eye. Compared to LCP, the RCP light goes through the concave lens two more times, so the image will be minified, thereby enhancing the resolution density.

If the focal length of the concave lens is denoted as $-f_c$ and the optical minification factor between peripheral and center images as M, then the spatial resolution enhancement ratio R can be expressed as

$$R = \frac{1}{M} = 1 + \frac{d_1 + d_2}{f_c/2}, \quad (1)$$

where d_1 is the distance between the display module and the half mirror, and d_2 is the distance from half mirror to CLC. According to Equation 1, the enhancement ratio R can be enlarged by reducing the focal length f_c of the concave lens or increasing the distance $(d_1 + d_2)$. In our following experimental demonstrations, the resolution enhancement can reach 4.4×.

In our proposed system, it is critical to display two images (peripheral and center images) on the same display panel while splitting them during the imaging process. Figure 3 depicts the configuration of our proposed polarization-multiplexed display module. The display module consists of three components: one display panel, one polarization modulator, and a broadband quarter-wave plate. The display panel can be a liquid crystal display which usually consists of two linear polarizers. Without losing generality, we can assume the display panel emits a linearly polarized light along the z-axis (0°). Then a pixelated polarization modulator is closely integrated and aligned to the display panel. The polarization modulator is designed to obtain full range between two orthogonal polarization states from 0° to 90° with continuous modulation including intermediate states. With a broadband λ/4 plate oriented at 45°, these two orthogonal linear polarizations would be converted to LCP and RCP beams to present peripheral and center images, respectively. With the help of a polarization-dependent reflector (CLC), the LCP and RCP lights will be sent to two different optical paths simultaneously.[16]

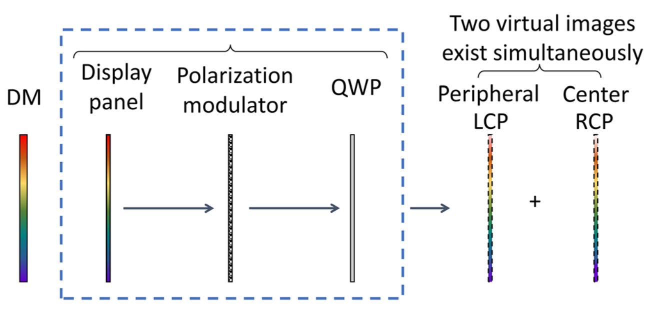

FIGURE 3 Schematic diagram of the proposed polarization-multiplexed display module, including a display panel (DM), a polarization modulator, and a broadband quarter-wave plate (QWP)

3 | EXPERIMENT

To prove concept, we carried out a simple experiment to demonstrate our proposed design discussed above. Our optical setup follows the layout depicted in Figure 1. In experiment, we used a 6.1-inch LCD (iPhone 11, with resolution 1792 × 828) as the display panel. To prepare a polarization modulator, we removed the polarizers of a commercial twisted nematic (TN) LCD panel (5.0 inch, 800 × 480 pixels) and used it as polarization modulator. One plano-concave lens with focal length $f_c = -35$ mm was adopted.

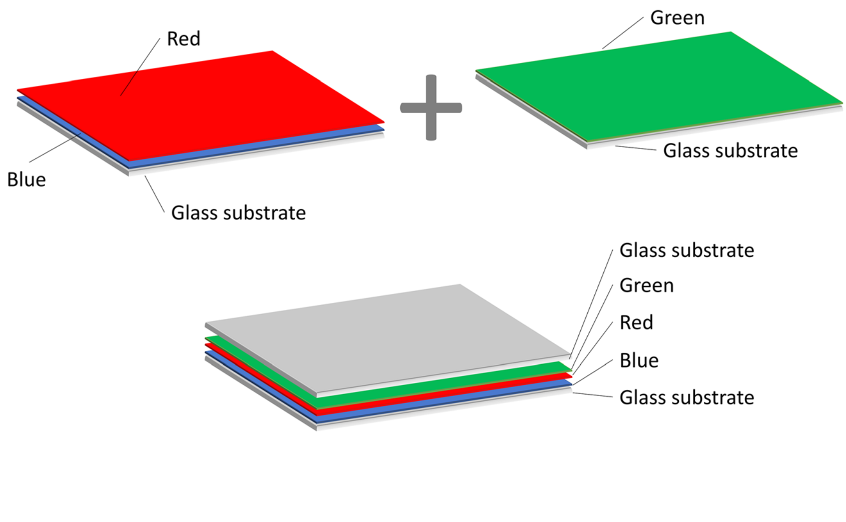

FIGURE 4 Three-layer CLC film structure

To obtain a polarization-selective reflector, we stack three CLC films together. Such a CLC film exhibits a helical structure; it reflects the circularly polarized light with the same handedness (e.g., RCP) but transmits the opposite polarization (LCP). The central wavelength (λ_0) of the Bragg reflection is jointly determined by the CLC helical pitch length (p) and average refractive index (n) of the employed LC material as $\lambda_0 = pn$.[17] To present a full color image, the CLC film consists of three layers, and each layer has the central wavelength located at red, green, and blue, respectively. The blue and green CLC layers were spin-coated on two separate 2-inch glass substrates, and the red one was spin-coated on top of the blue one as Figure 4 shows. Detailed fabrication process has been described in reference.[18]

Next step is to generate the image displayed on the panel. Since we only use one panel, the images of peripheral and center fovea areas need to be overlapped and displayed on the same panel but with different sizes. The peripheral image is shown in Figure 5A. The center image comes from the content that should be displayed in the blank area of the peripheral image. Because we will minimize the center image to increase the resolution in the following optical system, the center image here is enlarged by 4.4×, as shown in Figure 5B. After passing through the following optical system, the size of the center image will fit the blank in peripheral image and become a complete whole image again. Then we combine these two images together with designed ratio and generate the image that we need to display on the panel. Figure 5C is the computer-generated image for the display panel, in which the peripheral and the central areas overlap each other but can be clearly distinguished. Finally, we build the setup and all the optical elements we used are listed in Figure 6.

Figure 7 represents the experimental results. The center image area is minimized by the polarization-dependent optical system to fit the blank area with higher resolution. This complete image with multi-resolution is shown in Figure 7A. In Figure 7A,B, the displayed image region, enclosed by yellow dashed lines, exhibits a much higher angular resolution than that of the outside regions. When we zoom in the center area enclosed by the green rectangle, the apparent pixelation and screen-door effect can be observed in the outside

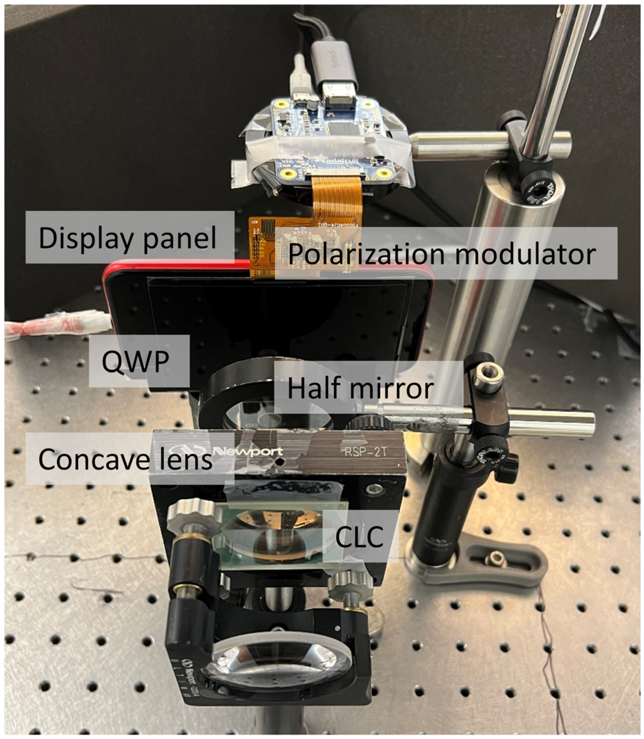

FIGURE 6 Picture of the optical elements used in the system. CLC, cholesteric liquid crystal; QWP, quarter-wave plate

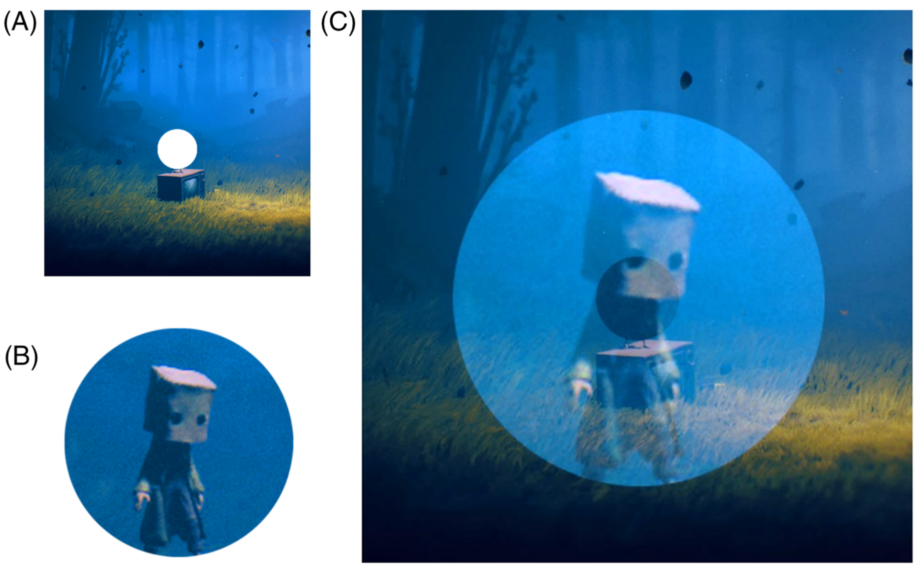

FIGURE 5 The displayed image: (A) peripheral image, (B) enlarged center image, and (C) combined image on the display panel

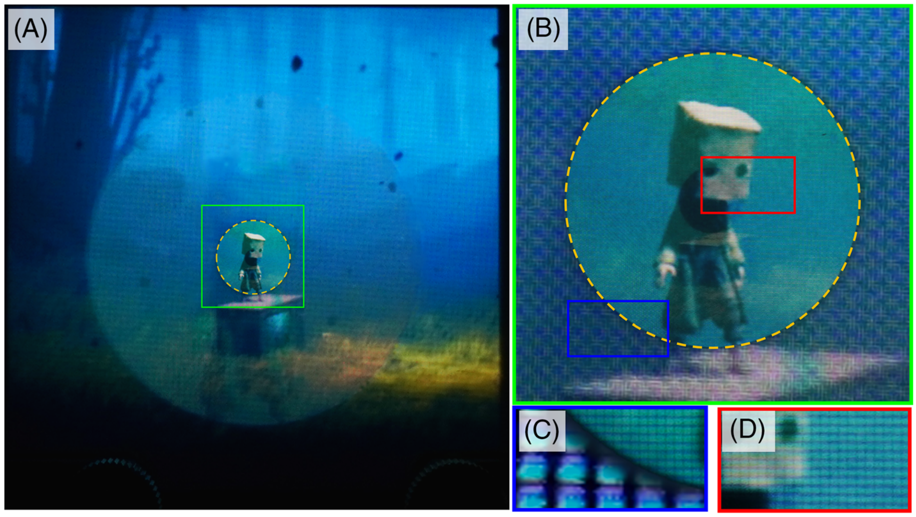

FIGURE 7 Experimental photographs of the proposed multi-resolution display with 4.4× resolution enhancement: (A) whole displayed image; (B) the magnified green square region in (A); (C) the magnified blue rectangle region in (B); and (D) the magnified red rectangle region in (B)

low-resolution region in Figure 7B. While inside the yellow dashed circle, the image is quite smooth. By further zooming in the photographs, the pixel size can be compared directly at the boundary, as depicted in Figure 7C, D. In addition to the obvious resolution enhancement, we can also observe a larger circle with slightly incorrect color and overlapped image outside the fovea in Figure 7A. The image is like the one we displayed on the panel in Figure 5C. This issue results from the depolarization generated by the optics in the system and the insufficient polarization conversion by the polarization modulator including the quarter-wave plate. The two orthogonal polarization states, corresponding to two images, are not fully separated by the polarization-selective system; therefore, we can still observe a very dim center image in the peripheral area.

For quantitative evaluations, we can easily measure the center image size before and after the minification system. Since the peripheral and center images are displayed on the same panel at the beginning, they possess the same resolution. Then, the center image passes through the polarization-dependent optical paths to accumulate different optical powers. By comparing the center image size in Figures 5C and 7A, the diameter of the image is reduced by 4.4×, which is corresponding to the resolution enhancement ratio. It should be clarified here that the enhancement is with respect to the polarization modulator. If the resolution of the TN modulator is 2 K pixel per inch, then we can obtain an 8.8 K for the fovea region. Besides, the resolution enhancement ratio of the central region can be easily tuned by changing the focal length of the concave lens or the distance $(d_1 + d_2)$ as Figure 2 depicts. A higher resolution is achievable, but the trade-off is increased system volume and more challenging lens design.

It is worth mentioning here that the concave lens in the optical path will decrease the power of the eyepiece, thereby increasing the volume of the system. One possible solution is to replace the concave lens and CLC reflector with an on-axis CLC lens with a built-in power. Under such condition, the volume of the system will be decreased, and the peripheral image will not be affected by the concave lens. Moreover, it will provide a wider field of view as compared to the current design.

4 | IMPACT

We have experimentally demonstrated a multi-resolution foveated display for VR applications. Compared to conventional foveated imaging systems, the proposed design only requires one display panel without the need for a beam splitter. By using the polarization multiplexing method, we encode the peripheral images and the center images into two orthogonal polarization states and then send them to two optical paths with different optical powers. As a result, an ultra-high resolution for the central fovea region can be obtained. The spatial resolution of the fovea area is enhanced by 4.4× by an optical minifying system. The proposed optical system can effectively reduce the screen-door effect while providing a compact system design for near-eye displays.

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ORCID

Kun Yin https://orcid.org/0000-0002-5624-4915
Ziqian He https://orcid.org/0000-0003-3560-2987
Shin-Tson Wu https://orcid.org/0000-0002-0943-0440

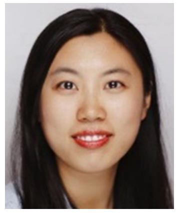
REFERENCES

1. Sherman WR, Craig AB. Understanding virtual reality San Francisco, CA: Morgan Kauffman; 2003.
2. Zhan T, Yin K, Xiong J, He Z, Wu ST. Augmented reality and virtual reality displays: perspectives and challenges. iScience. 2020;23(8):101397.
3. Maimone A, Wang J. Holographic optics for thin and lightweight virtual reality. ACM Trans Graph. 2020;39(4):67.
4. 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;10:216.
5. Bastani B, Turner E, Vieri C, Jiang H, Funt B, Balram N. Foveated pipeline for AR/VR head-mounted displays. Inf Disp. 2017;33(6):14–9.
6. Tan G, Lee YH, Zhan T, et al. Foveated imaging for near-eye displays. Opt Express. 2018;26(19):25076–85.
7. Kim J, Jeong Y, Stengel M, et al. Foveated AR: dynamically-foveated augmented reality display. ACM Trans Graph. 2019;38(4):1–5.
8. Akşit K, Chakravarthula P, Rathinavel K, et al. Manufacturing application-driven foveated near-eye displays. IEEE Trans vis Comput Graph. 2019;25(5):1928–39.
9. Yoo C, Xiong J, Moon S, et al. Foveated display system based on a doublet geometric phase lens. Opt Express. 2020;28(16):23690–702.
10. Lee S, Wang M, Li G, et al. Foveated near-eye display for mixed reality using liquid crystal photonics. Sci Rep. 2020;10(1):16127.
11. Fujii T, Kon C, Motoyama Y, et al. 4032 ppi high-resolution OLED microdisplay. SID Symp Dig Tech Pap. 2018;26(3):178–86.
12. Iwase Y, Tagawa A, Takeuchi Y, et al. A novel low-power gate driver architecture for large 8 K 120 Hz liquid crystal display employing IGZO technology. J Soc Inf Disp. 2018;26(5):304–13.
13. Brown PK, Wald G. Visual pigments of rods and cones in a human retina. Science. 1964;144(3614):45–52.
14. Hua H, Liu S. Dual-sensor foveated imaging system. Appl Optics. 2008;47(3):317–27.
15. Geng M. Oculus research: optics & displays for future VR: from perceptual testbeds to building blocks. Proc SPIE 11764, SPIE AVR21 Industry Talks II. 2021;11764:117640W. https://doi.org/10.1117/12.2597473
16. Tan G, Zhan T, Lee YH, Xiong J, Wu ST. Polarization-multiplexed multiplane display. Opt Lett. 2018;43(22):5651–4.
17. Yin K, He Z, Wu ST. Reflective polarization volume lens with small f-number and large diffraction angle. Adv Opt Mater. 2020;8(11):2000170.
18. Zou J, Hsiang EL, Zhan T, Yin K, He Z, Wu ST. High dynamic range head-up display. Opt Express. 2020;28(16):24298–307.

AUTHOR BIOGRAPHIES

Kun Yin received her BS degree in Opto-Electronics from Tianjin University, China, in 2016 and is currently working toward a PhD degree from the College of Optics and Photonics, University of Central Florida, Orlando. Her current research interests include optical gratings and augmented reality and virtual reality displays.

Ziqian He received his BS degree in Materials Physics from Nanjing University in 2016 and PhD degree from the College of Optics and Photonics, University of Central Florida. His current research interests include liquid crystal photonics, mini-LED LCDs, micro-LED displays, and near-eye displays.



Yannanqi Li received her BS degree in Optics from Sichuan University in 2018 and is currently working toward a PhD degree at the College of Optics and Photonics, University of Central Florida. Her current research interests include novel liquid crystal optical elements and AR/VR/3D display system designs.

Shin-Tson Wu is a Pegasus professor at College of Optics and Photonics, University of Central Florida. He is the recipient of Optica/IS&T Edwin H. Land medal (2022), SPIE Maria Goeppert Mayer award (2022), OSA Esther Hoffman Beller medal (2014), SID Slottow-Owaki prize (2011), OSA Joseph Fraunhofer award (2010), SPIE G. G. Stokes award (2008), and SID Jan Rajchman prize (2008). In 2014, he was inducted to the inaugural Florida Inventors Hall of Fame. He is a Charter Fellow of the National Academy of Inventors and a Fellow of the IEEE, OSA, SID, and SPIE. In the past, he served as founding Editor-In-Chief of the IEEE/OSA Journal of Display Technology, OSA Publications Council Chair, OSA Board of Directors, and SID honors and awards committee chair.

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