# AR Glasses with Single Microdisplay and Optics Based on Polarization Volume Hologram (PVH)

*Darwin Hu*, Jianghao Xiong***

***Phasereality Laboratory, Sysview Technology, Inc. , San Jose, CA 95120 USA**

****Beijing Engineering Research Center of Mixed Reality and Advanced Display, School of Optics and Photonics, Beijing Institute of Technology, Beijing, China.**

## Abstract

***A new compact AR/VR display glasses with single imager combined with optics based on multiple polarization volume hologram (PVH) of flat phase elements [1] as ultrathin surface lens integrated with a transparent flat plastic lens to reduce cost, weight, and volume is proposed. With specific optical characteristics of design and method of the PVH to diffract light beams at predefined via total internal reflection (TIR) emulating conventional freeform technique in the embodiment is described and simulated to achieve high optical efficiency at 50% up to 100% (if double layers of PVH used) of glasses light engine. It is significantly shifting the paradigm of the present AR or VR optical designs potentially benefiting the general consumers.***

## Author Keywords

polarization volume hologram; PVH; total internal reflection; TIR; freeform; cholesteric liquid crystal; CLC; left-handed circular polarization; LCP; right-handed circular polarization; RCP; birdbath; BB; microdisplay; microOLED; augmented reality; AR; virtual reality; VR.

## 1. Introduction

With rapid recent advancements of large language model (LLM), the enthusiasm for next-generation human-AI interface platform is surging. Augmented reality (AR) stands out as one of the most promising candidates due to its ability to deliver real-time digital images and natural interactions in addition to virtual reality (VR) head-mount display (HMD) devices have been well accepted in visualized imaging simulation and gaming industry in the virtual worlds. Despite the volume of market demand could be explosive but now there is a lack of sales which is unmatching the consumers' expectations and potential buying power, there still exist many obstacles commercially and barriers technically to be overcome. Hype against interests seems to remain controversial status for prevailing in the AR/VR emerging market for the time being:

- The social aspects of real-world activities are important. Augmented reality is better closer to reality with AR glasses than VR head-mount display (HMD).
- VR is felt more isolated than immersive, it is more virtual but distracting from reality.
- VR hardware is bulky, heavy, and cumbersome with physically uncomfortable. Sometimes it makes users sick.
- The cost of entry is still too high for most consumers to be afforded, particularly Apple Vision Pro.
- The existing technological integration and implementation, such as AR, VR, MR and XR products, are not mature to be acceptable for general consumer's requirements.
- Price-Performance is recognized as the essential matter in consumers' expectation to reach potential buying power.
- AR / VR display optical module in size, resolution, field of view(FOV), weight, heat dissipation, lack of killer application software and other functional capabilities are all crucial factors.
- For AR glasses to replace smartphones is still a long way to go! However, the market has been looking for a low cost, light weighted, simple plug and play AR glasses as a smartphone replacement in the future. Is that real or just hype?

Many optical architectures are currently under development, but few have succeeded in large-scale commercialization like smartphones. The two main reasons are: 1) not easily accessible price, and 2) failure to deliver a good image while maintaining a lightweight glasses form.

Bearing those two reasons in mind, many analyses of how to build such an AR optics with available technologies have been conducted. Two main approaches for AR combiners are waveguide and geometric combiners. For waveguide combiners, it uses the principle of multiple total internal reflections (TIRs) to fold the light path into a thin waveguide plate (~1mm thickness) and can therefore achieve a compact glasses-like form. The mainstream surface relief grating (SRG) route, although developed for almost 10 years since its representative of Hololens 1 in 2016, still faces the problems of excessive cost and image issues like color non-uniformity, rainbow, low brightness, etc. While Meta's latest release of Orion addresses some image issues like rainbow and limited field-of-view despite applying Silicon Carbide (SiC) material, its unaffordable price prevents its wide commercialization soon. On the other hand, the ideal light engine built-in of microdisplay for waveguide, micro-LED, is still far from mature, e.g., Orion uses three separated 640×480 RGB micro-LEDs from Jade Bird Display, while ideally resolution of more than 2K panel is required no matter what they are microOLED, LCoS, microLED or laser scanning.

From the above analysis, we can conclude that waveguide-based optical architecture is not suitable for a widely affordable glasses-like AR in the short term.

As for geometric combiners, currently birdbath (BB) optics is the mainstream scheme due to its simplicity and low cost. However, the disadvantages are the low image brightness and bulky form. The low brightness comes from the multiple transmission and reflection by the beam splitter and semi-reflective curved mirror. The bulky form of BB combiner is larger than the display panel, which is typically more than 2 centimeters and therefore not compact enough.

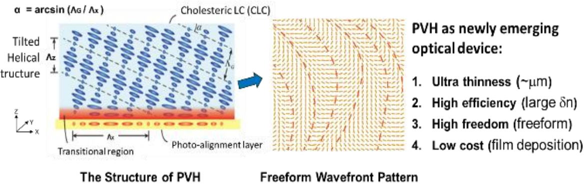


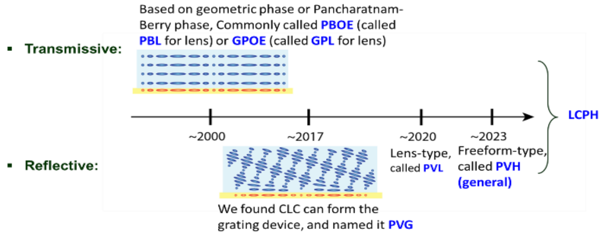
**Fig. 1**. The structure of polarization volume hologram.

ISSN 0097-996X/25/5601-0313-$1.00 © 2025

## 2. New Display Design Techniques and Method based on Single Microdisplay and PVHs Optics

To combine the advantages of waveguide (compactness) and geometric combiner (low cost), we propose to use PVH in traditional TIR-based geometric combiner to produce a compact and highly efficient optical combiner with potentially low cost [2]. The sketch is shown on Fig.1 and is also shown the physical design transformed from traditional freeform to flat optics as shown in Fig.3. PVH optics emulates the freeform type of optic to achieve high optical efficiency but less complication in injection molding of manufacturing. It is a newly emerging holographic optical element (HOE) based on photo-alignment and self-assembly cholesteric liquid crystal (CLC) as shown in Fig. 1, the bottom sinusoidal photo-alignment pattern provides a local periodic pattern, which makes the helical CLC structure tilted to form the bulk tilted helical structure. The tilted helical structure can establish efficient Bragg diffraction, like SRG and traditional hologram. The structure of PVH has a period of Λx in X–Y plane and a period of Λz in Z axis direction. Periodical refractive index planes have a period of ΛG. It depicted means the period of periodical refractive index planes, which should be calculated by the Bragg equation after determining the center wavelength. The LC director rotation plane could be slanted to the X-Z plane and along the Y axis.

**2.1 What is PVH?** It has evolved from the original optical devices applied to liquid crystal (LC) to become a key optical element. [3] At the very first stage, researchers used nematic liquid crystal to form transmissive devices. The working principle of such transmissive devices is based on geometric phase, or Pancharatnam-Berry phase (PBP). Such a type of device, depending on the functionality (take lens for example), is therefore often called geometric phase optical element (GPOE, or GPL for lens), or Pancharatnam-Berry optical element (PBOE, or PBL for lens) [4]. Later, we found cholesteric liquid crystal (CLC) can also form the grating device [5,6]. It only responds to one circular polarization state of light and has a volume slant structure, like volume holographic grating (VHG). Therefore, this type of reflective grating is called polarization volume grating (PVG). Then, we successfully fabricated a reflective lens device. This means arbitrary wavefront function can be achieved with reflective device. At this stage, the name becomes complicated. Sometimes the general reflective device is called chiral liquid crystal optical elements (CLCOE) due to its usage of chiral liquid crystal. However, a more appropriate way to call this general reflective device may be as PVH, which manifests its polarization dependency, volume structure and arbitrary wavefront functionality. The summarized graph is illustrated as follows:



- The transmissive device does not possess the volume structure but has polarization dependency.
- Both transmissive and reflective devices accommodate arbitrary wavefront functionality, we deem it appropriate to call as Liquid Crystal Polarization Hologram (**LCPH**).

It was indeed determined as the research deepened step by step from PBL (or GPL) to PVG to PVL then to PVH or LCPH.

**2.2 Fundamental Operation Principle:** It started with the simple transmissive polarization diffraction device, like the PBP device as an example to discuss. In the LC research community, researchers have explored the concept of using PBP for planar optics since 1984 [7] and have pointed out the importance of half-wave conditions for diffraction efficiency. The basic idea of the PBP can be explained by the Jones Matrix shown below:

Consider the PBP as diffraction gratings. The diffraction angle can be calculated by the grating equation:

$$sin\theta_{out} = \frac{m\lambda}{\Lambda} + sin\theta_{in}$$

With the normal incident, $\theta_{in}$=0, consider +-1 order diffraction, using paraxial analysis, we got the relation between input light and output light:

$$[E_{out}] = [M(\Gamma,\varphi)][E_{in}]$$

Where $[M(\Gamma,\varphi)] = [R(-\varphi)]\begin{bmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{bmatrix}[R(\varphi)]$

In the equation above, φ is the angle between the optical axis and the y axis, [R(φ)] is the rotation matrix. The grating works for circularly polarized light, with the circularly polarized incident along the Z axis. The grating is on the X-Y plane. We assume that an incident circularly polarized (CP) light can be written as

$$J_{\pm} = \begin{bmatrix} E_{y-in} \\ E_{x-in} \end{bmatrix} = \begin{bmatrix} 1 \\ \pm i \end{bmatrix}$$

Where, **J+** and **J-** represent left-handed circular polarization (LCP) light and right-handed circularly polarization (RCP) light, respectively.

We have output:

$$\begin{bmatrix} E_{y-out} \\ E_{x-out} \end{bmatrix} = cos\frac{\Gamma}{2}\begin{bmatrix} 1 \\ \pm i \end{bmatrix} - i\, sin\frac{\Gamma}{2} e^{-i(\mp 2\varphi(x))}\begin{bmatrix} 1 \\ \mp i \end{bmatrix}$$

If the retardation of layer meets with half wave condition, $\Gamma = 2\pi\Delta nd/\lambda = \pi$, $\Delta n = n_e - n_o$ is birefringence, the output can be simplified as:

$$\begin{bmatrix} E_{y-out} \\ E_{x-out} \end{bmatrix} = -i\, e^{-i(\mp 2\varphi(x))}\begin{bmatrix} 1 \\ \mp i \end{bmatrix}$$

This equation clearly shows that incident light with circular polarization would have a phase shift related to angle φ in output, which is the angle of the liquid crystal director in X-Y plane from X axis. In the director's configuration of PBP, φ(x)=180°x/Λ (a linear function of x). The equation also tells us that the half-wave condition will change the chirality of the outgoing light, yield maximum diffraction efficiency, and make the phase shift which is called the Pancharatnam–Berry (PB) phase or geometric phase twice the azimuth angle. [8]

A nematic liquid crystal and CLC can be used to prepare PBL. The former yields transmissive PBL, and the latter will be a reflective PBL. A transmissive PBL is considered as a waveplate with different orientations of crystal molecules at various positions on the alignment layer. Refer to the Fig.2 as below:

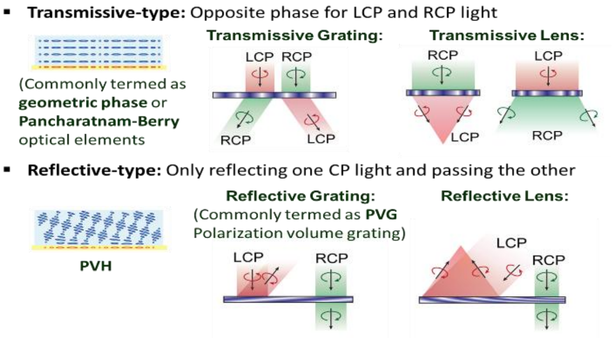


**Fig 2** Diagram of Polarization Responses of Various LCPHs

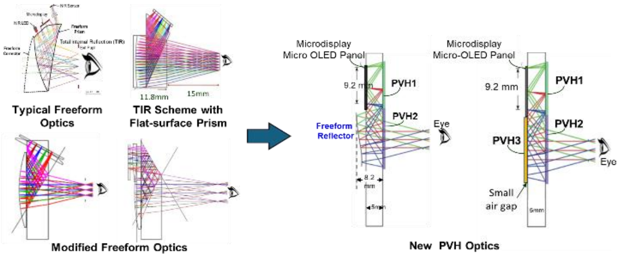


**Fig. 3**. AR glasses designed with a single imager & PVHs optics transformed from traditional freeform optic design.

**2.3 PVH Optics:** As the new PVH optics shown from Fig. 3, the light from microOLED image panel is diffracted by PVH1 to enter TIR process. Then the light encounters PVH2 and gets diffracted again. After the second diffraction, it exits the TIR and propagates in free space. Then the light is reflected by the third PVH3 lens (or can be a freeform reflector optional design) and finally enters the user's eye. Fabricating PVH for mass production (also good for PBL) are under development. The proprietary technology uses sputtering-like technique for thin-film deposition, enabling extremely uniform and high-quality multi-layer LC film. It is suitable for fabrication of gradient-pitch PVH.

The general fabrication procedure is illustrated as Fig. 4. It shows the overall workflow of PVH fabrication. The sample undergoes steps of spin-coating Brilliant Yellow (BY) solutions, photoalignment exposure and humidity treatment, inkjet printing LC mixture, heating, and UV polymerization.

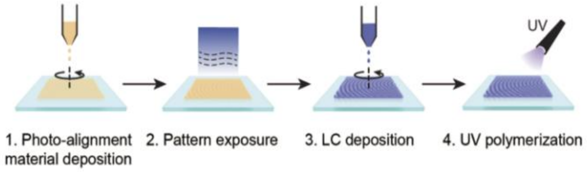
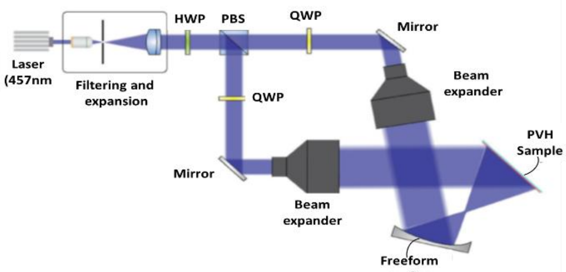
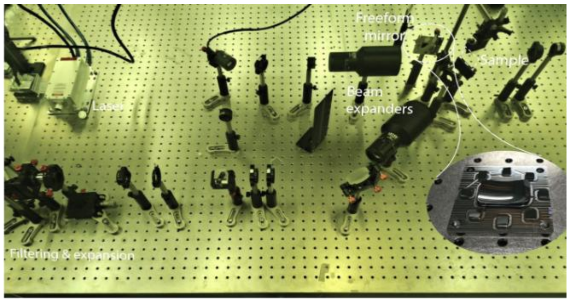


**Fig. 4** Schematic illustration of fabrication procedure.



(a) Diagram of exposure interferometer setup



(b) Physical optical setup in laboratory

**Fig.5** Setup of exposure interferometer: **(a)** Diagram**; (b)** Lab Setup**,** to calibrate a sample with unique molecular arrangement of PVH lens like freeform wavefronts.

From Fig.5 (a) & (b), it shows a diagram of exposure interferometer set up to calibrate a sample of PVH lens naming unique molecular arrangement depending upon a specific required application of the PVH lens. Here, to ensure high image quality, the PVHs adopt freeform wavefronts, which can be achieved by freeform surface exposure [3]. Because the microOLED panel is placed vertically (z direction), the combiner can be much thinner than BB scheme. Here in the preliminary result, we use a 5mm substrate, which resembles a glasses form factor. In terms of cost, PVH can be fabricated by large-scale optical replication and thin-film deposition method. The potential cost is much lower than SRG, which requires expensive semiconductor processes like etching. The laser light, after filtering and expansion, is modulated by a half wave polarizer (HWP) and split by a Polarized beam splitter (PBS) into two beams. Each beam is modulated by a quarter wave polarizer (QWP), reflected by a mirror, and expanded by a 3X beam expander, before being modulated by the freeform surface (recording beam) or directly reaches the sample (reference beam).

Based on the alternative freeform reflector or PVH3 design shown in Fig.3, we can see the total thickness of combiner can be as small as 5 mm and could potentially shrink further with improvement of optical design. This is significantly smaller than the BB scheme, which is typically around 25mm due to the size of horizontally placed display panel as mentioned.

## 3. Simulations of PVHs Optical Characteristics and Performance

Preliminary simulation results are achieved based on the design of AR glass with the desired parameters listed as Table 1. has been conducted successfully.

**Table 1. Desired performances of AR optical imaging**

| | |
|---|---|
| Substrate thickness | <5mm |
| MicroOLED 0.71" panel | 16x9mm |
| Efficiency | >40% |
| Field of view | >54° |
| Eye Relief | >15mm |
| Eye Box | >6mm |

The PVH1 and PVH2 planar thin lens design and their simulation result are illustrated in Fig.6. in accordance with the system design of PVH-based AR optical combiner shown in Fig.3. The AR system simulation with Modulation Transfer Function (MTF) performance is plotted and illustrated as Fig.7 achieved at remarkably high diffractive efficiency. Resulting a complete AR glasses system based on single microOLED imager at smaller size from 0.44" to 0.71" diagonal of high resolution at least 1920 x 1080, having a good acceptable color quality, integrated with PVHs lenses becomes as an optical module which can achieve as compact, comfortable and affordable light-weight AR glasses. Another merit of our designated AR glasses can achieve the high brightness of optical efficiency at 50% or 100% if double PVHs are used. For the traditional BB scheme, the efficiency is around

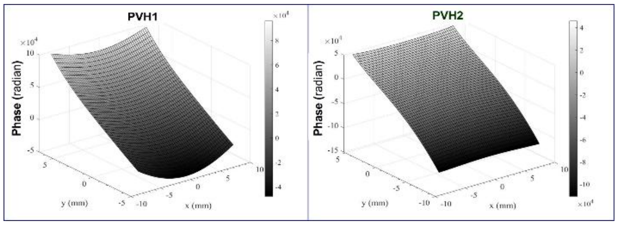


**Fig. 6** Simulation of PHH1 and PVH2 phase diagram

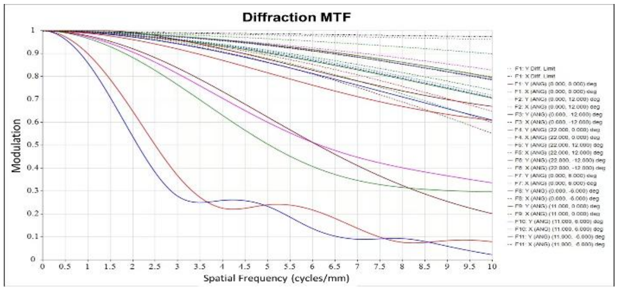


**Fig.7** Simulation of Diffraction MTF on AR with PVH optics.

25% max. because light must pass the half mirror two times. While for waveguide, the efficiency is significantly lower, around ~2-3% for two-dimensional (2D) Exit Pupil Expansion (EPE) scheme or around ~10% for 1D EPE scheme. For the 2D EPE scheme, ideally micro-LED should be used. But currently single-panel full color RGB micro-LED imager is far from mature. Using individual R, G, & B monochrome panel assembly would increase the overall light engine size. Also, increasing the resolution to around 1920x1080 would also enlarge according to the size of panel and light engine. Therefore, the 2D EPE waveguide is currently not ready. While for the 1D EPE scheme, a more appropriate light engine is micro-OLED. But even for micro-OLED with the highest brightness of 5,000 nits, the output image brightness would be around 500 nits, which is still inadequate for daily outdoor use.

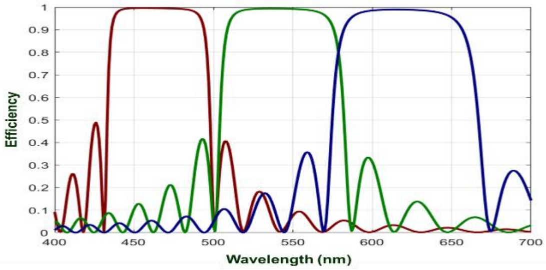
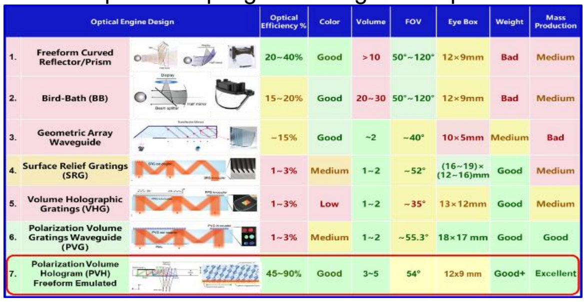


**Fig.8** Simulation of diffraction efficiencies of RGB PVHs.

The efficiency of PVH can theoretically reach 100%. As shown in Fig.8, we simulate three PVHs corresponding to RGB channels with thickness at 3µm by using Rigorous Coupled-Wave Analysis (RCWA) method. [9] The average efficiencies of PVHs at 450nm, 532nm and 633nm are higher than 99% at overall optical efficiency in addition to polarization sensitivity. For a PVH with single handedness, only one circular polarization is diffracted.

**Table 2.** Optical coupling technologies comparison.



| Optical Engine Design | | Optical Efficiency % | Color | Volume | FOV | Eye Box | Weight | Mass Production |
|---|---|---|---|---|---|---|---|---|
| 1. | Freeform Curved Reflector/Prism | 20~40% | Good | >10 | 50°~120° | 12×9mm | Bad | Medium |
| 2. | Bird-Bath (BB) | 15~20% | Good | 20~30 | 50°~120° | 12×9mm | Bad | Medium |
| 3. | Geometric Array Waveguide | ~15% | Good | ~2 | ~40° | 10×5mm | Medium | Bad |
| 4. | Surface Relief Gratings (SRG) | 1~3% | Medium | 1~2 | ~52° | (16~19)×(12~16)mm | Good | Medium |
| 5. | Volume Holographic Gratings (VHG) | 1~3% | Low | 1~2 | ~35° | 13×12mm | Good | Medium |
| 6. | Polarization Volume Gratings Waveguide (PVG) | 1~3% | Medium | 1~2 | ~55.3° | 18×17 mm | Good | Good |
| 7. | Polarization Volume Hologram (PVH) Freeform Emulated | 45~90% | Good | 3~5 | 54° | 12x9 mm | Good+ | Excellent |

This means the overall optical efficiency of our proposed system is around 50%. However, we can combine two PVHs with both RCP & LCP together to reach around 100% efficiency due to each PVH having micrometer-level thickness, such a stacking would not increase the system thickness. So, if we use a microOLED panel at 0.71" with, say, 3000 nits, we can already achieve an image with around 1500 nits ideally without stacking, and 3000 nits with stacking. Such a high brightness display would be eligible even for use in bright sunlight environment.

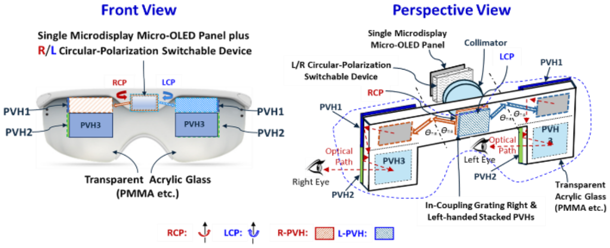


**Fig.9** AR glasses with single microOLED & PVHs optics

## 5. Conclusion

The conceptual design of an AR glasses based on one single microdisplay and optics of PVH are illustrated in Fig. 9. with a 3D perspective view [10]. It is very feasible to achieve low-cost, compact, and light weight. However, it remains practical work and detailed challenges to overcome as well as a wonderful opportunity with significant potential to improve further to be perfect. In addition, many other display devices might also be able to apply such planar PVH technologies as proposed to enhance or create a new breed of displays. Prospectively, the dream of a low-cost and high-performance AR glasses design for consumers is foreseeable soon, not that far away!

## 5. References

[1] Tong Yang, Dewen Cheng & Yongtian Wang, Optics Express Vol. 26, Issue 19, pp. 25347-25363 (2018). https://doi.org/10.1364/OE.26.025347

[2] Jianghao Xiong and Shin-Tson Wu, *eLight*, 1(1), 3 (2021). https://doi.org/10.1186/s43593-021-00003-x

[3] Jianghao Xiong & Shin-Tson Wu, "Liquid crystal polarization hologram for near-eye displays", Liquid Crystals Today Jan 2, 2025. https://doi.org/10.1080/1358314X.2024.2448399

[4] Tao Zhan, YH Lee, Guanjun Tan, JH Xiong, ST Wu et al. Journal of the Optical Society of America B Vol. 36, Issue 5, pp. D52-D65 (2019). https://doi.org/10.1364/JOSAB.36.000D52

[5] ]Lee Y-H, He Z, Wu S-T. Optical properties of reflective liquid crystal polarization volume gratings. J Opt Soc Am B. 2019;36(5):D9-D12. https://doi.org/10.1364/JOSAB.36.0000D9

[6] Xiong J, Chen R, Wu S-T. Device simulation of liquid crystal polarization gratings. Opt Express. 2019; 27(13):18102-18112. https://doi.org/10.1364/OE.27.018102

[7] Jianghao Xiong et al. PhotoniX (2023) 4:35. https://doi.org/10.1186/s43074-023-00111-6

[8] Feng, Xiayu. "Liquid Crystal Polarization Volume Hologram for Augmented Reality Applications." Doctoral dissertation, Kent State University, 2021. http://rave.ohiolink.edu/etdc/view?acc_num=kent1619646439873892

[9] Jianghao Xiong and Shin-Tson Wu, Optics Express Vol. 28, Issue 24, pp. 35960-35971 (2020). https://doi.org/10.1364/OE.410271

[10] Darwin Hu US Pat. App. No. 18/959034, "Display glasses using single imager and planar optical engine", Nov. 2024.