

Double-Path Pancake Optics with Wider FoV

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Abstract

We propose highly light efficient pancake Head Mounted Display (HMD) optics named “Double path (DP) pancake optics”, which has 1.8 times higher light efficiency than conventional one.

In previous works, we fabricated several prototypes with 90 deg Field Of View (FOV), focusing on compactness. However, the optics with wider FOV is necessary for application in various HMD products. DP pancake optics requires symmetric design, which seems a big burden for achieving wider FOV. Through optical simulation, we finally have found how to achieve wider FOV while maintaining high Modulation Transfer Function (MTF) properties. We introduce our 105 deg FOV prototype along with optical simulation and the evaluation result.

Author Keywords

HMD; Compact HMD; Virtual reality; Polarized pancake optics; Folded optics; Wide FOV.

1. Introduction

The HMD market is expected to grow by approximately 30% year on year [1]. The folded optics for HMD, commonly referred to as pancake optics, was proposed to achieve compact HMD [2]. Recently, the optics has been used in many products such as Quest 3 by Meta, Apple vision pro by Apple, and Pico 4 Ultra by Pico, which shows the optics becomes de facto standard. However, the conventional pancake optics has a big drawback of lowering light efficiency, because light goes through Half Mirror (HM) twice, then theoretical maximum light efficiency is only one-fourth (25%). Current HMDs are typically battery-powered; therefore, low light efficiency reduces usage time without power supply, which affects attractiveness of products.

To improve light efficiency of pancake optics, we propose “DP pancake optics” using two light paths. Our results show approximately 1.8 times higher light efficiency than conventional one [3]. Z. Luo et al. also propose DP pancake optics concept like ours [4]. They use Cholesteric Liquid Crystal (CLC) instead of a combination of Reflective Polarizer (RP) and Quarter Wave Plate (QWP). CLC can also realize the function of a concave mirror with a flat shape, commonly referred to as a Polarization Volume Hologram (PVH). However, it may exhibit low contrast due to imperfection of the polarization state and have large wavelength dependency depending on the incident angle. Y. Ding et al. also propose theoretically predicted 100% efficiency pancake optics using Faraday rotator [5]. It looks theoretically best way, however, even if the commercial Faraday rotator can be used, several issues must be addressed to be applied into a commercial HMD product, such as effective diameter, thickness, and cost. Thus, we believe that, at present, DP pancake optics is the most promising technology to improve light efficiency in thin HMD optics like current pancake optics, and we are progressively refining our optical designs with the goal of mass production [6-8].

From the viewpoint of FOV, our prototypes are designed with a 90 deg FOV to emphasize compactness. Current HMDs have FOVs

ranging roughly from 90 deg to 115 deg, therefore achieving a wider FOV is necessary for application in various HMD products. In this paper, we describe our approach to achieving DP pancake optics with a wider FOV and introduce our 105 deg FOV prototype.

2. Basic optical design with 90 deg FOV

In the previous works, we established 2 basic optical design. Here, we name these “Curved RP structure” [3, 6] and “Flat RP structure” [7], as shown in Fig. 1.

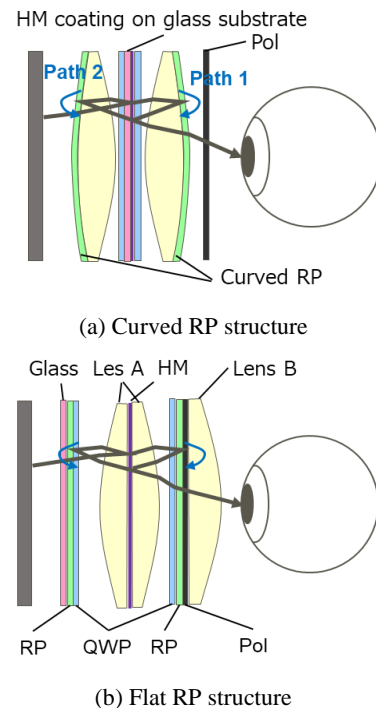
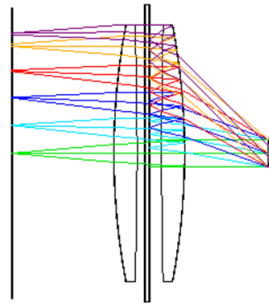


Figure 1. Basic optical design for DP

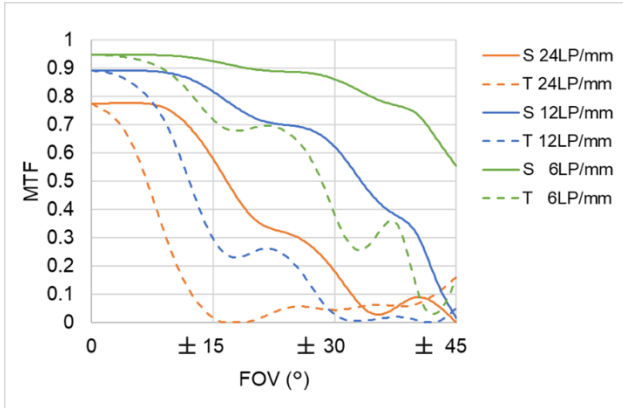
Curved RP structure is more effective to get better optical performance such as MTF, because reflection at curved RP surface enhances lens power without color aberration. On the other hand, Flat RP structure can be fabricated at a lower cost, because it does not require curved bonding or a HM coated glass substrate, which tend to increase cost.

The ray diagram of Curved RP structure is shown in Fig. 2(a) as a reference for later discussion. Only path 1 is shown in the ray diagrams, including subsequent drawings. 24 Line Pairs (LP) / mm is almost the same as 1200 ppi which is the resolution of our prototype’s display.

Additionally, we successfully fabricated prototypes and confirmed that both structures can achieve over 40% transmittance, which is approximately 1.8 times higher light efficiency than conventional one.



(a) Ray diagram



(b) MTF

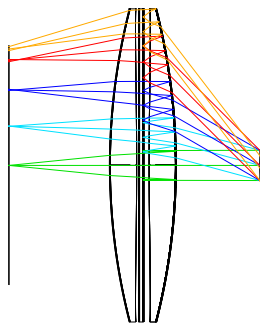
Figure 2. Optical design of Curved RP structure

3. Double path pancake optics with 105 deg FOV

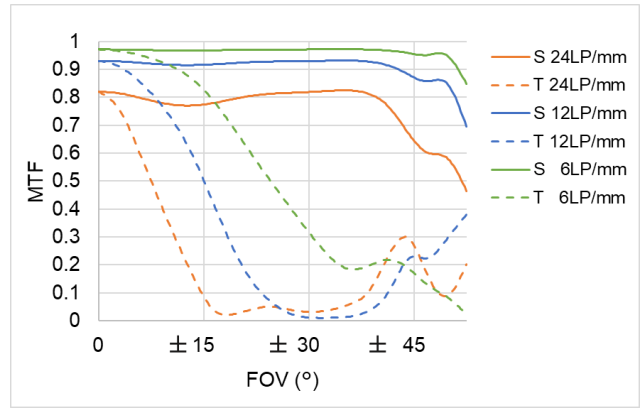
3.1. Basic optical concept to achieve wider FOV

To achieve a wider FOV DP design, we first considered what FOV should be targeted. We considered following key points: (1) Current products have FOVs ranging roughly from 90 deg to 115 deg; (2) From the view of Inter-pupillary distance (IPD), the lens diameter should be lower than approximately 55 mm; (3) There is a trade-off relationship between FOV and view area size (such as eye relief and eye box size).

From our previous optical simulations, we found that, using Flat RP structure, 90 deg FOV is almost maximum mainly due to the considerations in above key point (3). Thus, to achieve a wider FOV, we chose Curved RP structure design and determined that 105 deg FOV is a suitable target.



(a) Ray diagram



(b) MTF

Figure 3. Optical design of 105 deg FOV DP

We optimized Curved RP structure through optical simulation and found that optimizing the gap between the HM substrate and the lens is key to achieving a wider FOV and improving MTF especially in the sagittal direction. As a result of the optimization, we developed a 105 deg FOV optical design with 27.7 mm thickness and 51.8 mm diameter. The ray diagram and MTF are shown in Fig.3. Although the basic structure looks similar to the previous one shown in Fig. 2(a), the gap between the HM substrate and the lens is smaller, and the curvature is optimized. The sagittal performance is dramatically improved, as shown in Fig. 3(b), despite the wider FOV compared to Fig. 2 (b). The MTF in the sagittal direction is maintained at approximately 0.8 at 24 LP/mm within +/-40 deg region.

3.2. Prototype with 105 deg FOV

Based on our simulation results, we fabricated the optical module prototype shown in Fig. 4. The specifications for our demonstrator using 1,200ppi high resolution LCD are shown in Tab. 1. We measured light efficiency by using parallel light with a 2 mm diameter aperture as the light source and confirmed that the transmittance is 39.0%, which is slightly less efficiency than that of our previous 90 deg FOV prototypes. We have not yet optimized each optical component, particularly HM. Thus, the low efficiency is presumably due to insufficient HM property. However, we achieved approximately 1.7 times higher light efficiency than conventional one, as shown in Tab. 2. It's still strong advantage for HMD products.



Figure 4. Appearance of 105 deg FOV prototype

Table 1. Specifications of prototype.

	Items	Specifications
LCD	Active area size	Approx. 2.5 inch
	Resolution	Approx. 1,200 ppi
Optics	Thickness of optics	27.7 mm
	Weight	33.8 g
	FOV	105 deg
	Lens diameter	51.8 mm
	Efficiency	1.8 times
	Magnification	Approx. 10
	Eye relief	13.5 mm
	Focal length	24.6 mm

Table 2. Measurement result of total light transmittance

	Double path		Single path
	105 deg FOV	90 deg FOV	
Total light transmittance	39.0%	42.2%	23.1%
Transmittance ratio	1 (ref)	1 / 0.92 (= 1.08)	1 / 1.69 (= 0.59)

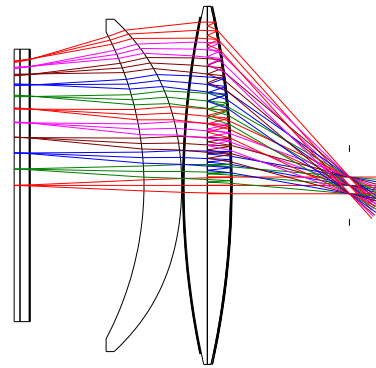
3.3. Better MTF in the tangential direction with 105 deg FOV

The MTF in the sagittal direction is greatly improved, as shown in Fig.3. But the MTF in the tangential direction is not enough, thus, we considered additional lens design to improve.

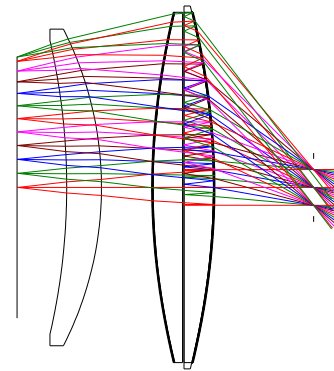
We considered mainly 2 designs shown in Fig. 5. Owing to additional lens, plano-convex lens can be chosen for symmetric lenses and bonded to each other at the flat surfaces. A HM was coated on one of two flat surfaces of the plano-convex lenses. This structure doesn't require the HM glass substrate, thus contributing lower cost. An additional lens is configured in the air gap between the display and the symmetric lens to adjust aberrations, especially field curvature, which also contributes to improve the tangential MTF property.

Initially, we designed a spherical symmetric lenses design, as shown in Fig. 5(a). But we could only find a 100 deg FOV design and the MTF in the sagittal direction did not improve significantly, as shown in Fig. 6. Consequently, we considered an aspherical symmetric lenses design, as depicted in Fig. 5(b). By increasing the freedom of lens parameters, we observed a dramatically improvement in the MTF in the sagittal direction. After optimizing the structure based on Fig. 5(b), we finally achieved a high MTF design, as shown in Fig 7. The aspherical surface significantly enhances the tangential MTF in the wide FOV region (Over 15 degrees), realizing the MTF to exceed 0.6 at 24 LP/mm across the entire FOV. The specifications of the optics are shown in Tab. 3.

We also considered an aspherical design for the additional lens, but we found that virtual image is likely to be distorted irregularly. Thus, we concluded design of aspherical symmetric lenses with additional spherical lens is best for wider FOV DP pancake optics design.



(a) Spherical symmetric lenses with additional lens



(b) Aspherical symmetric lenses with additional lens

Figure 5. Concept structures for additional lens design

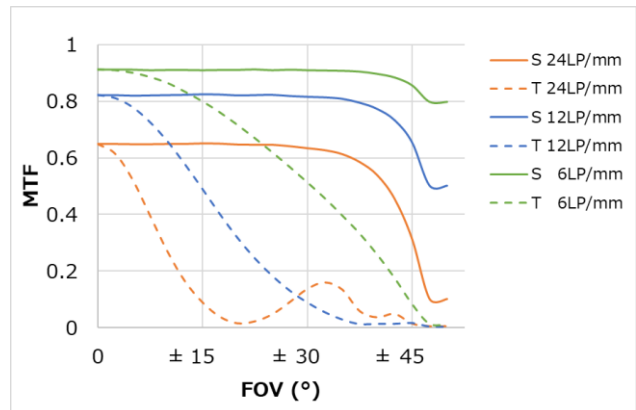
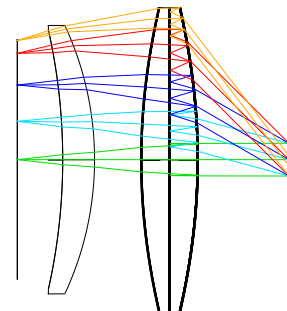
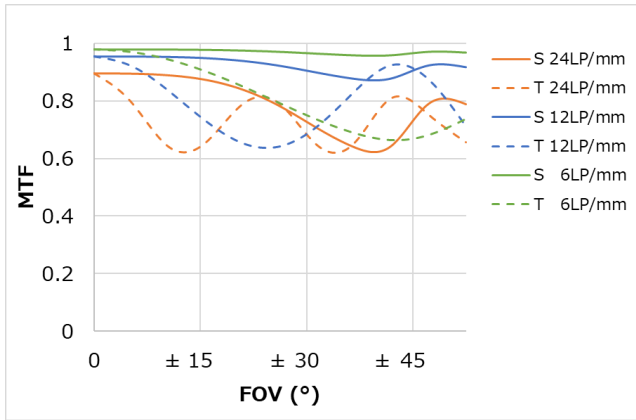


Figure 6. MTF of additional spherical lens design



(a) Ray diagram



(b) MTF

Figure 7. Optimized design of additional aspherical lens design

Table 3. Specifications of additional aspherical lens design

	Items	Specifications
Optics	Thickness of optics	27.6 mm
	FOV	105 deg
	Lens diameter	51.8 mm
	Magnification	Approx. 15.5
	Eye relief	13.5 mm
	Focal length	22.5 mm

4. Conclusion

This paper proposes 105 deg FOV DP pancake optics for HMD. 105 deg FOV design achieves superior MTF compared to the previous 90 deg FOV design, even within 90 deg FOV region. We fabricated the prototype based on the result of optical simulations and confirmed high light efficiency are almost the same as our previous 90 deg FOV design.

Additionally, the MTF in the tangential direction has also improved by using aspherical symmetric lenses with an additional spherical lens design. This configuration achieves an MTF of over 0.6 at 24 LP/mm across the entire FOV region, demonstrating DP pancake optics design with 105 deg FOV can be realized with high MTF performance.

5. Impact of the technology

Our DP pancake optics design itself contributes to a higher light efficiency for HMDs compared to conventional one, although size of optics is almost as compact as traditional (single path) pancake

optics. Increasing brightness (1.7-1.8 times) brings power consumption reduction (approximately 41-44 %) of LCD backlight. This concept can also be applied to higher ppi displays such as micro OLEDs. This offers strong advantages for compact HMD products, such as longer usage time without a power supply and / or light weight (comfortableness of wearing HMD) by using small battery. Realizing 105 deg FOV DP pancake optics contributes to be more immersive experience and allows for broader application of the DP design in HMD products widely. We believe that the technology will further expand the market for HMDs.

6. References

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