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Novel high light efficiency pancake optics for HMD named "double path"

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Abstract
The folded optics for HMD (head-mounted display), commonly referred to as pancake optics, is widely used to realize a compact HMD headset. The optics has the advantage of compactness, but also has a big drawback of lowering light efficiency. To overcome the issue, we proposed novel HMD pancake optics named "DP (double path) pancake optics" to achieve both compactness and high light efficiency simultaneously. In this paper, we introduce the principle of our "DP pancake optics" and review our prototype. We describe optical simulation results to find a highly balanced design among thickness, lens power, and magnification ratio. We also describe fabrication study of, such as polarization state and alignment accuracy. We successfully have fabricated two prototypes with 90° FOV (field of view), one of which is 20.6 mm optics thickness and the other is 25.5 mm optics thickness. The latter prototype especially shows high MTF with a 1200 ppi (pixel per inch) resolution LCD (liquid crystal display). Both prototypes have 1.8 times higher light efficiency than that of conventional one. In addition, to further expand the DP pancake optics, we also describe the improved design with wider FOV for future prototype fabrication. Therefore, we also show the optical simulation result of the improved design.

Keywords HMD · Compact HMD · Virtual reality · Polarized pancake optics · Folded optics · High-resolution LCD

1 Introduction

HMD is one of the remarkable categories and this market is expected to be grown rapidly [1]. Recently, compactness and light weight of HMD products have been strongly required to improve comfort for the user. Because it is said that discomfort and big outfit prevent HMD from spreading to be more popular. Since the optics greatly affects the size of HMD headset, there have been many proposals to achieve compact HMDs [2–4]. The folded optics for HMD, commonly referred to as pancake optics, was also proposed [5] and recently, the optics has been used in many products, such as Pico 4 by Pico [6], Quest 3 by Meta [7], and Apple vision pro by Apple [8]. This shows the optics has become the de facto standard in HMD products. However, the conventional pancake optics has a big drawback of lowering light efficiency because light goes through HM (half mirror) twice, then theoretical maximum light efficiency is 25%. Current HMD is usually battery-powered. Hence, the low light efficiency reduces use time without power supply and it affects attractiveness of products.

To improve light efficiency of pancake optics, we proposed "DP pancake optics" using two light paths [9]. At the same time, Z. Luo et al. also proposed DP pancake optics concept similar to ours [10]. They used CLC (cholesteric liquid crystal) instead of a combination of RP (reflective polarizer) and QWP (quarter wave plate). CLC can realize the function of a concave mirror with a flat shape but is likely to be low contrast due to imperfectness of the polarization state and is likely to have a large wavelength dependency depending on the incident angle. Recently, Y. Ding et al. proposed theoretically predicted 100% efficiency pancake optics using Faraday rotator [11]. However, even if the commercial Faraday rotator can be used, there are some hurdles to be applied into a commercial HMD product, such as larger effective diameter, thickness, and cost. Thus, we believe, at present, DP pancake optics is the most promising

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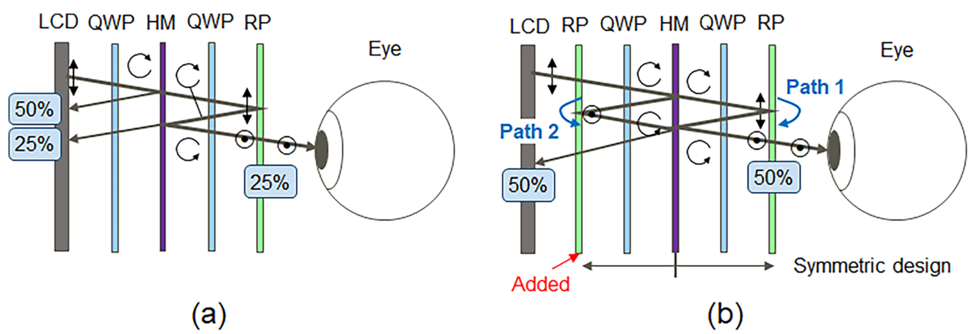


Fig. 1 Principle of pancake optics **a** SP, **b** DP

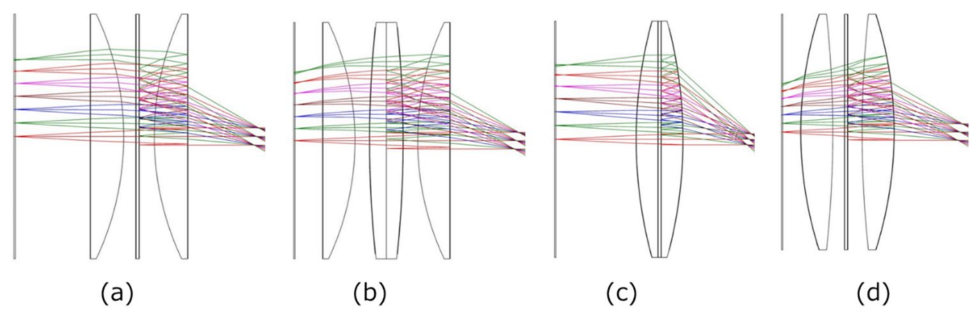


Fig. 2 Concrete models of optical simulation (only path 1 is shown) **a** flat RP surface with additional HM substrate, **b** flat RP surface with additional lens with HM, **c** curved RP surface with attached HM, **d** curved RP surface with additional HM substrate

technology to improve light efficiency of current pancake optics for HMD and we have improved optical designs, step by step, targeting mass production [12, 13].

In this paper, we review the concept of DP pancake optics and our prototype with 90° FOV to achieve compact HMD. In addition, 90° FOV is not enough to further expand the DP pancake optics. Therefore, we investigate targeting 105° FOV and show an improved optical design, to make a prototype as a next step.

2 Principle of DP pancake optics

Here, we refer conventional pancake as SP (single path). Figure 1 shows basic optical concept of (a) SP pancake optics and (b) DP pancake optics. These drawings only illustrate stacking order, and do not present bonding/non-bonding between layers.

In (a) SP pancake optics, in an ideal case (this means that there is no surface reflection, no absorption, and polarization states are ideal), the light from LCD goes to HM, then 50% of the light reflects, which becomes loss. The other 50% goes through HM and reaches RP, then all reflect and go back to HM. 25% of the light goes through HM and this becomes the other loss. Finally, light reflection at HM is 25% of the light from LCD, and this reaches to the eye of observer.

To minimize such light loss, we focused on the light reflected at HM at first time. As shown in Fig. 1b, if the RP layer is added between LCD and QWP, the reflected light can be used as second light path (path 2). In the ideal case, 50% of the light from LCD can be used as HMD images.

However, to overlay images through both paths, there is a restriction that the structure must be symmetry on the HM surface. This affects to achieve thinner design than conventional one, which is approximately 20 mm thickness.

Table 1 Optical design example of each structure

Structure	RP shape	FOV	Thickness	Focal length
Figure 2a	Flat	80°	30.5 mm	27.5 mm
Figure 2b	Flat	80°	28.5 mm	25.0 mm
Figure 2c	Curved	100°	23.5 mm	20.5 mm
Figure 2d	Curved	90°	20.5 mm	18.0 mm

3 Optical simulation

Considering symmetric structure, we mainly focused on four models of DP as shown in Fig. 2. Table 1 shows summary of roughly optimized results of Fig. 2a–d. With current mature technology, RP can be provided as a film. Thus, flat RP is better from a viewpoint of productivity. We assume 90° FOV is allowable minimum value. Thus, optical design targets of 90° FOV, around 20 mm thickness, and around 20 mm focal length realize our compact HMD concept. Also, eyesight correction by movable optical components is supposed to be installed to expand the freedom of optical design and

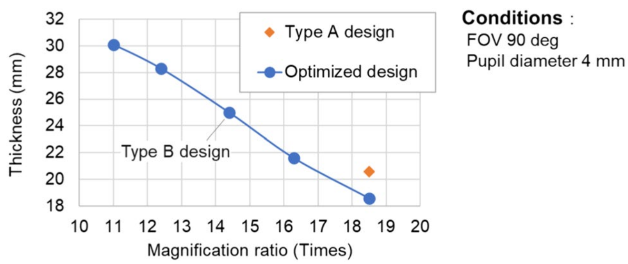


Fig. 3 Relationship between thickness and magnification ratio

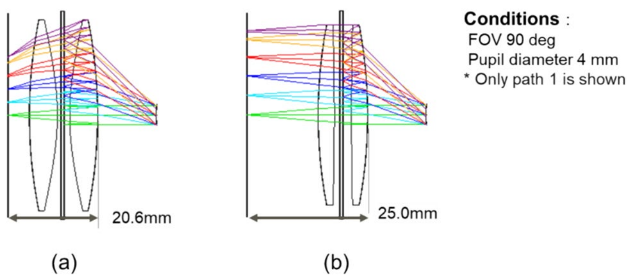


Fig. 4 Ray diagram of **a** Type A, **b** Type B

to achieve a compact design. Thus, assuming without eyeglasses, eye relief is fixed at 12 mm. Lens power (focal length) is an important factor, and a strong lens power (short focal length) is required for a thin design. In addition, after making the prototype, we realize magnification ratio is also an important factor for SDE (screen-door-effect) visibility. We introduce how to fix the design below.

Based on Table 1, we realize the curved RP is very effective to get a strong lens power, and Fig. 2d seems to have a possibility to achieve our targets. As a result of our precise optical simulation based on Fig. 2d, even though there is a steepness restriction to make RP film curved, we reach the optimized design. After we have fabricated the prototype, which is referred to as Type A (or prototype A) [9], we have found out SDE is visible easily owing to high magnification ratio. To manage the visibility, we calculate the relationship between thickness and magnification ratio as shown in Fig. 3. From the relationship, we have chosen the other design referred to as Type B (or prototype B) [12]. We explain this in detail later in chapter 6.

The simulation results of ray diagram and MTF of both prototypes are shown in Figs. 4 and 5, respectively. 24 LP/mm means 1 line in resolution chart is approximately 20.3 µm which is close to a pixel size of 1200 ppi LCD. We prioritize the sagittal performance in our design because the sagittal performance is easier to recognize and to be improved. When designing Type A, we also prioritize the thickness. Therefore, in the sagittal performance, MTF at the center region is not good especially around 20° region. On the other hand, when designing Type B, since the human eye is more sensitive in front of the pupil, we prioritize MTF at the center region and get better performance. When looking at over MTF 0.5 in 24 LP/mm, Type A achieves only around 35° region, on the other hand, Type B achieves from 0- to over 15° region.

4 Fabrication study

To make a prototype, there are three main concerns. The first concern is the polarization state through the resin lens. By putting the resin lens between polarizers with crossed Nicol arrangement, we have found polarization state is not disturbed at least visually as shown in Fig. 6, thanks to mild curvature and low retardation caused by resin. The second concern is how to bond RP film on a curved surface. At first, we tried to bond RP film without heat, but, as time passed, the edge of the film was peeling off little by little, and 3 days

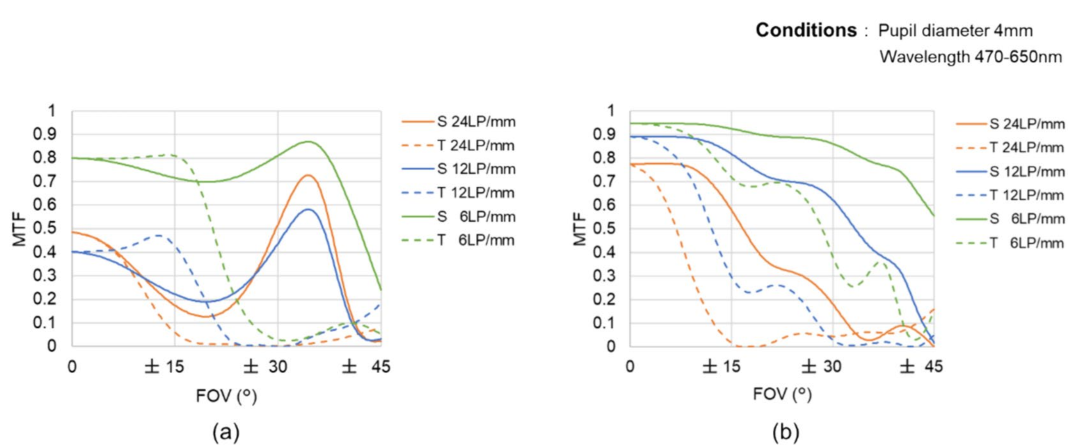


Fig. 5 MTF of **a** Type A, **b** Type B

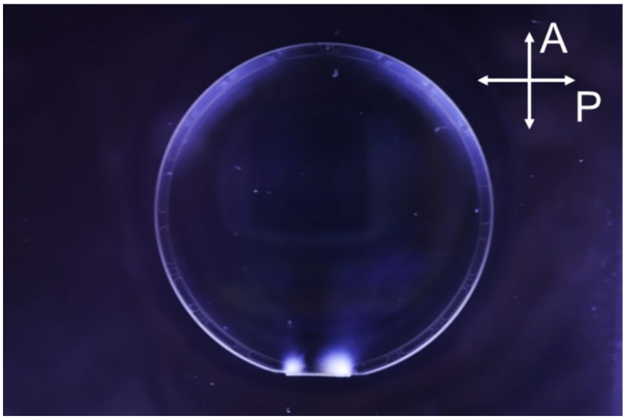


Fig. 6 Polarization state of the lens by crossed Nicol arrangement

later, it was confirmed the film was peeled off by around 5 mm width at the periphery. Thus, we use heat bonding, and have confirmed relatively steep curvature can be bonded. The third concern is alignment accuracy of two lenses. Symmetric structure is important in this design, but our structure is not strictly symmetry due to the glass substrate for HM. Therefore, beforehand, we simulated and confirmed the difference in the glass substrate could be compensated by air thickness. To align two lenses, we use the active alignment process as follows: the image of LCD displayed through two lenses becomes double images (path 1 and path 2), then the alignment is adjusted to overlay these double images as one display image. After the alignment, lenses are bonded in the mechanics and completed as an optical module. We have confirmed the alignment can be successfully achieved and difference of the glass substrate can be compensated.

5 Light efficiency measurement

To compare our prototype with best SP pancake optics, we chose some pancake lenses from commercially available products as samples. In the display industry, the measurement by luminance is the most popular to compare. But, in this case, optical design parameters, such as FOV and magnification ratio, of each product are so different that luminance is affected by the parameters. Thus, we consider the measurement by total light transmittance using parallel light is better to compare.

The measurement setup for total light transmittance is shown in Fig. 7. The parallel light emitted from the halogen lamp enters the DP or SP pancake optics, and the integrating sphere detects the light passing through the optics.

Figure 8 shows total light transmittance spectra and Table 2 shows exact values of each sample. DP pancake optics can get approximately 42% efficiency and SP pancake optics can get approximately 23% which is the best value

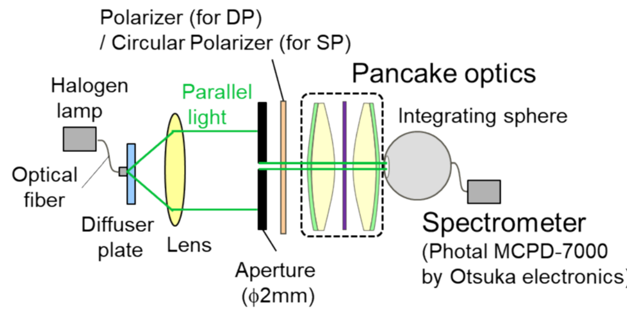


Fig. 7 Measurement setup

among three samples we measured. From the comparison, even though detail conditions are different, we can conclude that light efficiency of DP pancake optics is approximately 1.8 times higher than SP one.

Low light transmittance at blue resign remains an issue. It is presumably because of absorption by resin and / or anti-reflection coating property. We need further investigation and improvement.

6 Prototype properties

Figure 9 shows the appearance of both prototypes using our 1200 ppi high-resolution LCD. The main specifications of both prototypes are shown in Table 2. Prototype A achieves 20.6 mm thickness with 18.5 times magnification, which is slightly too high for current 1200 ppi LCD. Therefore, as described above, SDE is easily visible, as shown in the enlarged drawing in Table 2. But it is suitable for higher ppi displays, such as silicon-based micro-displays and future higher ppi LCDs. Based on our rough calculation, it is suitable for over 1700 ppi display. On the other hand, prototype B is 25.5 mm thickness with 14.4 times magnification, which is suitable for 1200 ppi display. Even though prototype B has

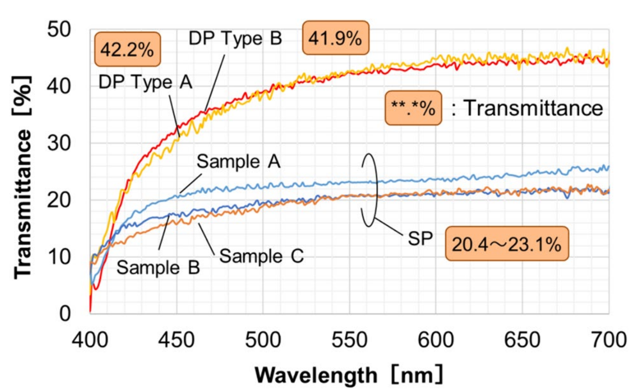
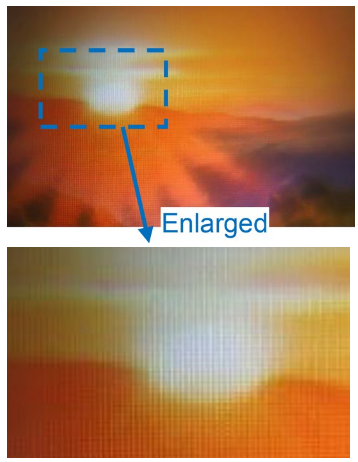
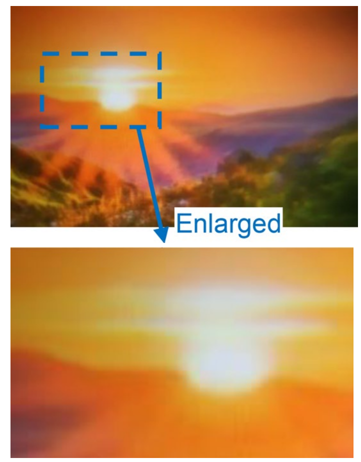


Fig. 8 Measurement result

Table 2 Specifications of double path pancake optics prototype

Items		Prototype A	Prototype B
LCD	Active area size	Approximately 2.5 inch	←
	Resolution	Approximately 1200 ppi	←
Optics	Thickness	20.6 mm	25.5 mm
	Weight	25.9 g	24.6 g
	FOV	90°	←
	Lens diameter	42 mm	41 mm
	Transmittance (efficiency)	42.2% (1.8 times)	41.9% (1.8 times)
	Magnification	18.5	14.4
	Eye relief	12 mm	←
	Focal length	15.3 mm	23.2 mm
Image quality	Image		

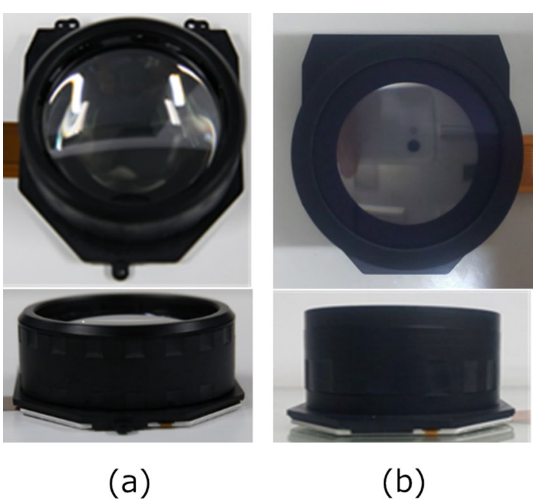


Fig. 9 Appearance of **a** prototype A, **b** prototype B

slightly lower light efficiency, light efficiency of both is still 1.8 times higher than that of SP sample.

7 Optical simulation for 105° FOV

Our prototypes have 90° FOV to achieve compact HMD concept as mentioned above. However, for this technology to become more popular, wider FOV should be achieved. Of course, various FOV targets can be considered, but we have thought 105° FOV is an appropriate target as a next step.

While doing optical simulation, we find out not only how to achieve 105° FOV but also how to achieve higher MTF. Optimizing the gap between the HM substrate and the lens is a very important factor to consider. As a result of this optimization, we find the 105° FOV optical design with 27.7 mm thickness and 51.8 mm diameter. The ray diagram is shown

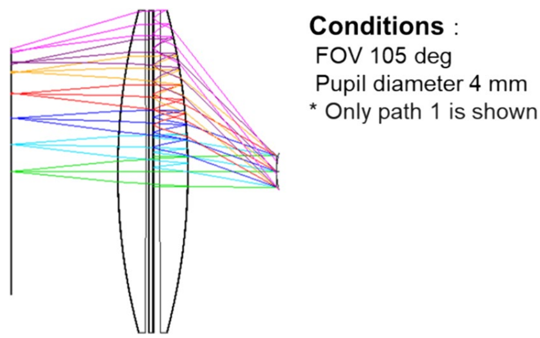


Fig. 10 Simulated ray diagram of 105° FOV model

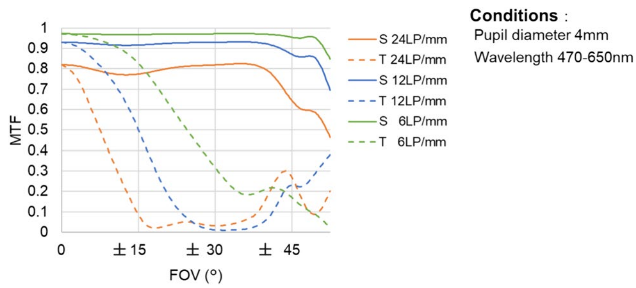


Fig. 11 MTF of 105° FOV model

in Fig. 10 and the MTF is shown in Fig. 11. When comparing between Figs. 5b and 11, the sagittal performance is dramatically improved in Fig. 11, despite FOV being wider than in Fig. 5b. When looking at over MTF 0.5 in 24 LP/mm, the design achieves from 0 to around 50° region. This optimized design also can be applied in a 90° FOV design as a next step.

8 Conclusion

We proposed the novel HMD pancake optics named "double path" to achieve both compactness and high light efficiency simultaneously. We make the prototype based on the results of optical simulation. Through this fabrication, it is confirmed that the alignment for a symmetric design can be achieved, and bonding RP film on curved surface is realized. Our prototype has 90° FOV and optics thickness of 20.6 mm (prototype A) and 25.5 mm (prototype B). We confirm 1.8 times higher light efficiency compared to that of SP sample, which provides a significant advantage of compact HMD headsets through reduced power consumption.

Additionally, we also have found the better optical design with 105° FOV. This will make DP pancake optics being more popular.

Author contributions N.U contributed for this paper as 1st author. N.U, T.Y, and K.M considered concept model of the design and how to make a prototype. Y.H designed optics and made the optical module of the prototype. N.U and T.Y evaluated the prototype.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest associated with this manuscript.

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