Development of an Ultra-Thin, Lightweight Pancake Optics with a High-Curvature Single-Resin-Lens

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ABSTRACT

We developed an ultra-thin and lightweight pancake optics with a single resin lens. To realize this, a new liquid crystal QWP technique and a RP high-curvature vacuum lamination technique for a reflective polarizer were developed. A prototype lens, 12 mm thick and weighing 10g, demonstrated high image quality.

1 Introduction

VR-HMDs enable immersive experiences that are not possible in the real world. The advent of MR-HMDs, which seamlessly merge real and digital worlds, has expanded user utility and driven rapid market growth. [1]

However, for daily use, the weight of head-mounted displays directly contributes to user discomfort and fatigue, especially when the optical system is front-heavy due to its thickness or weight, causing significant discomfort to the head and neck. Thus, more compact, thinner optics are strongly demanded. [2]

Within this trend, pancake optics based on polarization control have attracted attention. As shown in Fig. 1, they use a quarter-wave plate (QWP) and a reflective polarizer (RP) to convert between right- and left-handed circular polarization (RCP/LCP), allowing light to fold back and shorten the optical path. With micro-displays such as Si-OLEDs, smaller pancake optics have also emerged. [3]

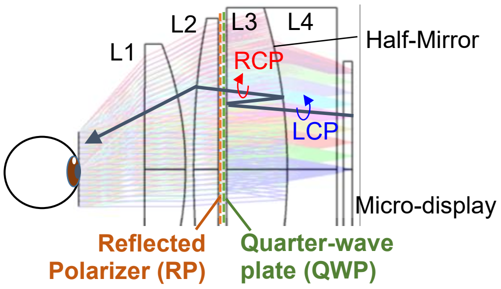


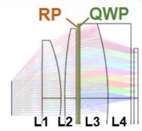
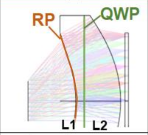
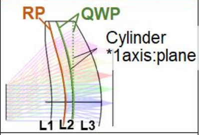
Fig.1 Conventional pancake optics
(Only the upper half is shown for clarity)

In conventional pancake optics, polarization elements such as QWP and RP are applied to the flat portion of the lens (Fig. 1), where their film form simplifies integration.

In contrast, from an optical design perspective, configuring RP on a curved surface imparts lensing power to the reflective surface, thereby increasing optical design flexibility. For example, by using RP films, such as 3M's multilayer reflective polarizer, implementation on curved lens surfaces can be feasible. Using the configuration in Fig. 1 as a reference, Table 1(a) and (b) show examples where RP is applied to curved surface.

In (a), the RP is placed on a concave surface facing the eye, whereas in (b), it is sandwiched between the concave and convex surfaces of the lens. The RP is configured on a concave reflective surface to correct the field curvature caused by the convex surface on the opposite side, thereby minimizing the Petzval sum.

Table1 Optical configuration with curved RP

	Reference	(a)	(b)
Layout			
Optics	Four Lenses	Two lenses	Three lenses
RP	Plane	Curved	Curved
QWP	Plane	Plane	Cylinder Surface

QWP placement, meanwhile, is also limited to flat or cylindrical surfaces with curvature along only one axis, as conventional QWP films cannot maintain their optical characteristics when laminated onto curved surfaces.[4]

Accordingly, in conventional designs involving curved RP surfaces, the optical layout and component design had to be adjusted to avoid interference with the QWP's flat portion. As a result, the RP curvature was limited, which limited its refractive contribution. Therefore, additional lenses were required to achieve the necessary optical power, resulting in a multi-lens configuration.

In addition, Table 1(a) shows a configuration where the QWP is placed on the flat portion of the resin lens (L1), which has a non-uniform thickness across the lens. Such a shape causes birefringence during molding, which disturbs the polarization state and may degrade image quality. Therefore, constraints on lens curvature and thickness are required. In this way, the placement of the QWP limits the design flexibility of lens thickness and shape, hindering further thinning of the pancake optics.

In this work, to maximize the lensing effect of the RP, we implemented both the QWP and the RP on the same concave surface and proposed an ultra-thin and lightweight pancake optics with a single-resin-lens.

2 Design of proposed optics

Table 2 shows the specs of the proposed single-resin-lens pancake optics design, and Fig. 2.1 shows the shape of the proposed optics and its ray tracing.

The resin-lens was fabricated from a low-birefringence injection-molded-resin. The concave surface is spherical (R = 40 mm), and the convex surface is aspheric. High curvature on both sides enabled a compact 12 mm-thick, 40.0 mm-diameter lens.

Table2 Pancake optics design specification

Item	Spec
FOV	Horizon : 92deg, Vertical : 100deg
EyeBox	φ9.4mm
EyeRelief	8mm
Panel Size	1.35in
Panel Resolution	3552×3840

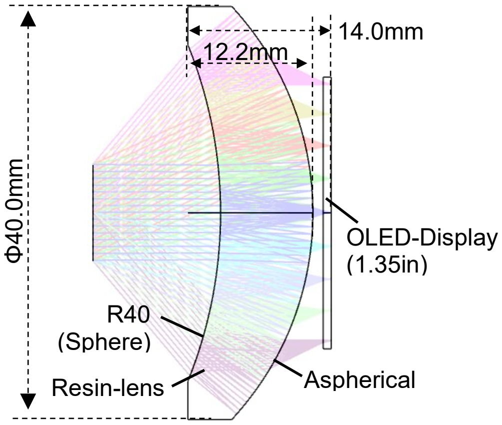


Fig.2.1 Proposed optics design

Table 3 compares the proposed design with conventional optics. The proposed optics is more than 20% thinner and 30% lighter than conventional optics.

Compared to conventional optics with multi-lenses, the proposed optics does not require assembly, which simplifies manufacturing, reduces cost, and improves alignment robustness, thus ensuring stable image quality.

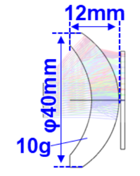
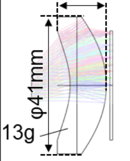
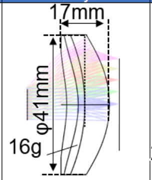
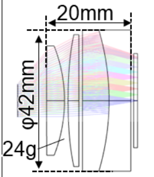
However, applying both QWP and RP to a highly curved concave surface presents significant technical problems.

First, QWP films, which are made from birefringent materials, lose their phase retardation properties when expanded, resulting in degraded polarization control and thus impaired image quality. Therefore, QWP films are fundamentally infeasible for application to curved surfaces.

Second, when laminated onto highly curved surfaces, RP films are prone to wrinkles or air pockets, making uniform adhesion across the optical surface difficult [5]. This configuration requires lamination onto a concave, which is more difficult than convex lamination, where the film can be stretched and pressed into shape. For optical lens, defects degrade HMD image quality, especially resolution, requiring higher precision than in decorative applications.

To realize proposed optics, we developed two new techniques: a Liquid Crystal QWP process and a vacuum lamination method for RP.

Table3 Comparison of optics in size and weight

Proposed design	RP: Curved QWP: Plane	RP: Curved QWP: Cylinder	RP: Plane QWP: Plane
			

3 Construction of a prototype

3.1 Deposition technology of Liquid Crystal QWP

Fig. 3.1 shows the Liquid Crystal QWP(LCQWP) developed by Hayashi Telempu Co., Ltd. A photo-orientable liquid crystalline polymer material〔Photo-Orientation Material (POM)〕forms a retardation film through polarized UV exposure and thermal treatment [6]. POM initially forms an isotropic film when coated onto a substrate. Polarized UV exposure induces axis-selective photoreactions. Although the film remains optically isotropic at this point, subsequent thermal treatment induces molecular alignment, resulting in strong optical anisotropy. By depositing POM directly onto the lens surface, QWP functionality can be implemented even on highly curved concave surface.

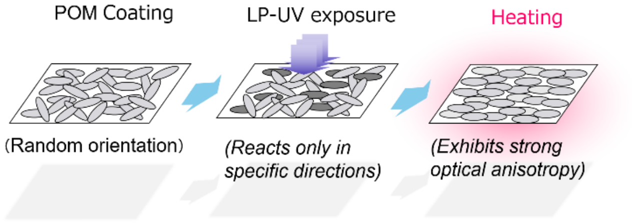


Fig.3.1 Liquid Crystal QWP technology

3.2 RP vacuum lamination technology

As shown in Fig. 3.2, the vacuum lamination technology forms a vacuum at a high temperature that facilitates film stretching, then rapidly releases atmospheric pressure to laminate the film via pressure differential. This process enables more uniform film stretching and prevents scratches from direct contact with metal molds or lens. Thus, it offers higher precision and quality, making it suitable for curved optical surfaces.

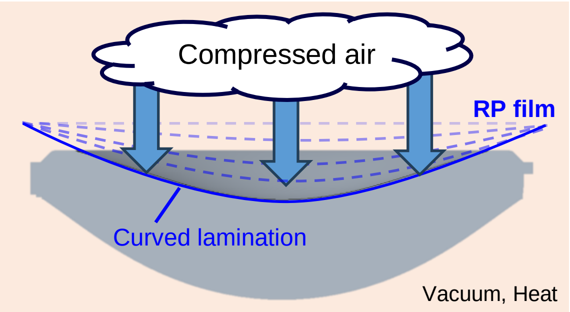


Fig.3.2 Film behavior during vacuum lamination

3.3 Manufacturing process of prototype lens

As shown in Fig. 3.3, this pancake optics requires three optical functions, namely LCQWP, half-mirror, and reflective polarizer, to be formed on the resin lens.

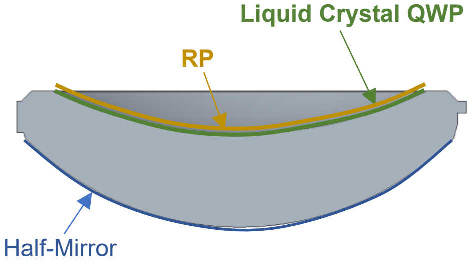


Fig.3.3 Optical functions implemented in resin-lens

After lens injection molding, birefringence was eliminated by annealing. The POM was then coated onto concave surface using the process shown in Fig.3.4

To enable low-temperature processing below the resin's Tg and suppress chemical attack, the liquid crystal and solvent conditions were optimized. The optimized POM solution was coated and dried on the concave surface. After polarized UV exposure and thermal treatment below Tg, a retardation layer (LCQWP) was formed. As shown in Fig. 3.5, Cross-Nicol observation confirmed uniform QWP retardation characteristics across the lens.

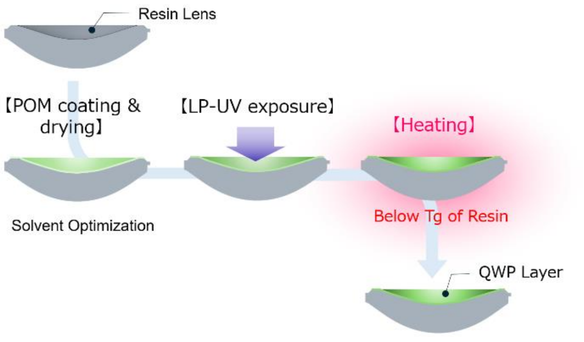


Fig.3.4 Liquid Crystal QWP coating process

Fig.3.5 Uniform retardation on the resin-lens

Next, an Ag half-mirror coating with equal transmittance and reflectance was deposited on the convex side.

After that, vacuum lamination was used to apply the RP film onto the LCQWP-coated concave. In this process, uniform pressure deforms the film spherically, allowing it to conform to the lens. Based on this mechanism, using an R40-curved surface enables high-quality lamination without wrinkles or air pockets, even on highly curved concave. Applying this method to the present lens resulted in uniform lamination across the entire surface.

Finally, by assembling the pancake lens, barrel, and an OLED panel, we fabricated a prototype pancake optical system weighing 17 g (lens: 10 g,lens barrel: 4 g, panel: 3 g), as shown in Fig. 3.6.

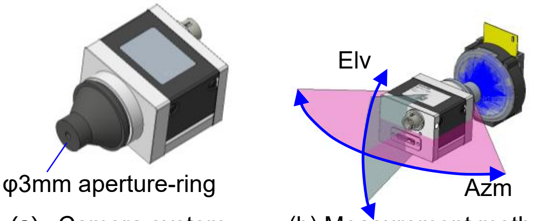
Fig3.6 Prototype fabrication

4 Imaging test of prototype

4.1 Measurement method

Using our developed camera system (Fig. 4.1(a)), we evaluated the prototype's projected image quality, capable of measuring resolution, brightness, and chromaticity. The camera lens was designed to assess eyepiece optics, such as those in HMDs, by positioning the exit pupil outside the front lens. A φ3 mm aperture ring simulates the human pupil. The system has a 50° FOV and can resolve each pixel on the prototype display.

Using this camera system, we evaluated image quality of the prototype projected image by varying elevation and azimuth angles, as shown in Fig. 4.1(b). We focused on resolution and luminance/chromaticity uniformity, affected by polarization elements (QWP and RP), to verify the feasibility of the proposed configuration.

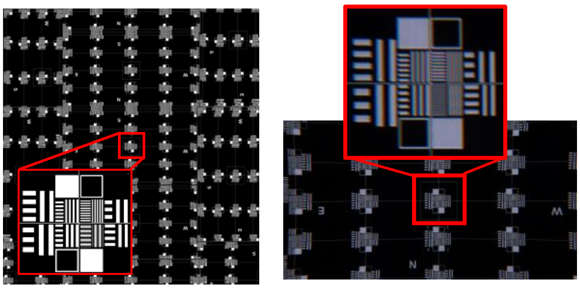


(a) Camera system (b) Measurement method

Fig4.1 Measurement System

4.2 Resolution test

Using a resolution chart displayed on the OLED (Fig. 4.2(a)), we aligned the camera to predetermined field positions within the projected image area of the prototype. Fig. 4.2(b) shows the captured image when the camera was aimed at the center of the display. From chart images up to a maximum of 20 [lp/deg] resolution, we calculated MTF contrast values. The proposed optics is axisymmetric, so images were captured at 10° intervals from 0° to 50° in the horizontal field on one side. The MTF contrast was then calculated at each angle (Fig. 4.3). As a result, no significant degradation in MTF performance was observed compared to the optical design. It is inferred that the LCQWP and RP film formed highly uniformly on the concave surface.



(a) Chart-image (b) Captured image

Fig4.2 Resolution measurement

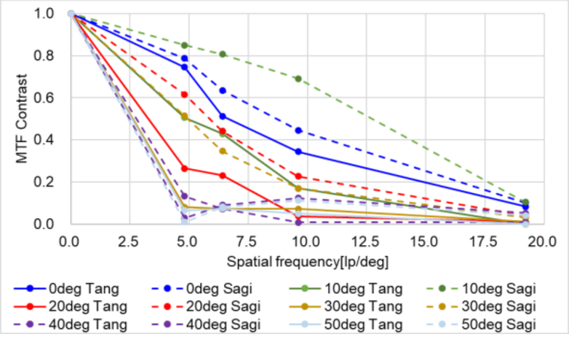


Fig4.3 Measurement MTF Contrast of prototype

4.3 White uniformity test – Luminance/Color

Using the same measurement setup, we conducted a white uniformity test by measuring luminance and chromaticity at set angles. Fig. 4.4 shows the luminance uniformity and Fig. 4.5 shows the color difference, both defined as the deviation from the image center.

In the horizontal and vertical crossline directions, luminance difference exceeded 65% and color difference remained below 0.005 (ISO 9241-303 thresholds: 58.8% and Δu′v′ < 0.02, used here as reference values).

Fig. 4.6 shows overall images by the prototype captured with fisheye camera. Visual inspection confirmed good resolution and minimal luminance and color difference.

5 Conclusions

To achieve an ultra-thin and lightweight design, a single-resin lens pancake optical configuration was developed. By integrating liquid crystal QWP technology and RP curved vacuum lamination technology, these components were successfully implemented onto a highly curved concave surface. A prototype was fabricated and evaluated, demonstrating good resolution and minimal luminance and color difference in both quantitative and visual assessments, thereby confirming the feasibility of the proposed optical system. This optical technology is not limited to VR applications and is expected to be extended to other optical fields.

Acknowledgements

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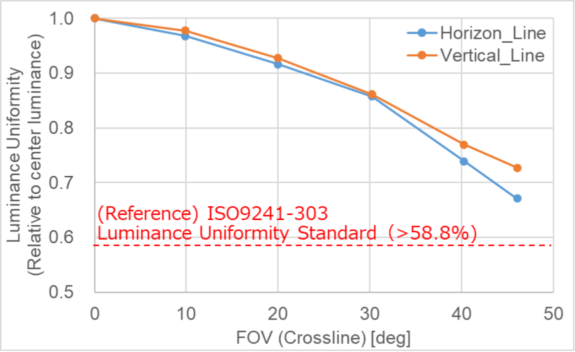

Fig4.4 Luminance difference from image center

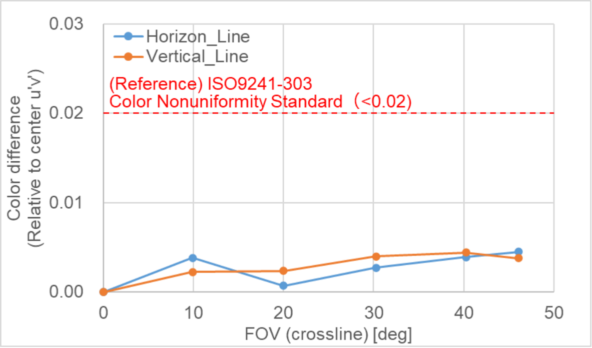

Fig4.5 Color difference from image center

Fig4.6 Prototype display image

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