Compact Augmented Reality Combiner Using Pancharatnam-Berry Phase Lens

Seokil Moon, Seung-Woo Nam, Youngmo Jeong, Chang-Kun Lee, Hong-Seok Lee, and Byoungho Lee, *Fellow, IEEE*

***Abstract*— A compact augmented reality (AR) combiner using Pancharatnam-Berry phase (PBP) lens and holographic optical element (HOE) is proposed. PBP lens is activated as a convex lens or a concave lens according to the polarization state of the input light wave. By using this characteristic, a thin AR eyepiece with a large numerical aperture (NA) is constructed. The AR eyepiece operates as a convex lens for the input light with a right-handed circular polarization state and operates as a transparent plate for the left-handed circularly polarized light. In order to adopt this AR eyepiece to the AR combiner, a chromatic aberration should be compensated. To resolve the chromatic aberration, HOE which diffracts the light rays with different profiles according to the input wavelength is designed. By combining this HOE with the AR eyepiece and a light guide, a compact AR combiner providing a wide field of view (FOV) is designed. A prototype of the proposed AR combiner is presented along with experimental results and analysis.**

***Index Terms*— Pancharatnam-Berry phase lens, holographic optical components, augmented reality, displays.**

I. Introduction

TODAY many research groups in companies and academia are interested in developing wearable AR devices. The most important component of these devices is an AR combiner. To represent a realistic, immersive, and visually comfortable AR environment, the combiner should meet several conditions. First, the AR combiner should deliver the clear outdoor scene as well as the virtual images. Second, the AR combiner should provide virtual images with a wide FOV and a high resolution. Theoretically, a human binocular vision covers up to 110 degrees of the horizontal visual field and a visual acuity of the human eye is known as ∼30 cycles per degree (cpd) [1]. Thus, it is essential to enhance the FOV and the resolution of virtual images to represent the realistic AR. Lastly, the AR combiner should be compact and light enough so that the user can observe visually comfortable AR during the long-term use.

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To fulfil these conditions, many different approaches have been proposed including the usage of HOEs or diffractive optical elements (DOEs). HOEs and DOEs are passive volume gratings which only react to the light with specific incident angle and wavelength [2]. By exploiting this characteristic, various types of AR combiners such as a lens-HOE/DOE or a mirror-HOE/DOE are proposed for the past few years [3]–[5]. The use of HOEs and diffractive optical elements (DOEs) can achieve various optical performances without increasing system form factor. Despite the durability, efficiency, and color uniformity issues, HOEs and DOEs still have enough potential to be adopted in future AR combiners.

Another approach to construct the AR combiner is an implementation of PBP optical elements. PBP optical elements operate by locally modifying the polarization state of light waves passing through them. The properties of PBP optical elements have been used in AR systems to achieve wide FOV and non-mechanical beam steering [6], [7]. One of the most representative applications for PBP optical elements is a PBP lens. PBP lens modulates the phase using anisotropic molecules to provide a special profile according to the polarization state of the input light. Recently, we proposed a novel type of AR near-eye display using an AR eyepiece consisting of stacked PBP lenses [8]. The system presents virtual images with relatively wide FOV and deals with severe chromatic aberration from PBP lenses by adopting layered diffuser-HOEs (DHOEs). However, the system is too bulky to become a wearable device and the transparency is low. Also the image quality is degraded due to the gratings in HOE layers.

In this letter, a compact AR combiner is proposed by combining HOE and PBP lens. As a follow-up research of our previous work, this research is focused on reducing the system form factor, enhancing the transparency and image resolution. The proposed combiner delivers a clear real-world scene and high contrast virtual images simultaneously. By adopting a light guide and an HOE, the combiner presents virtual images with wide FOV without chromatic aberration while maintaining the compactness.

II. Principle and Previous Work

A. AR Eyepiece Using PBP Lens

Fig. 1(a) represents the operation principle of a general PBP lens. If the right-handed circularly polarized (RCP) light is illuminated, the PBP lens is activated as a convex lens. In this case, the output light is modulated to have a left-handed circularly polarized (LCP) state. On the other hand, the PBP

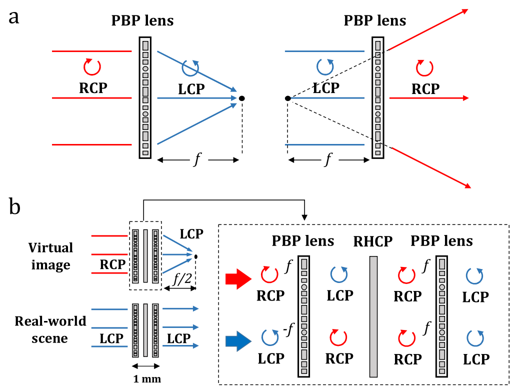


Fig. 1. Operation principle of (a) general PBP lens and (b) PBPE.

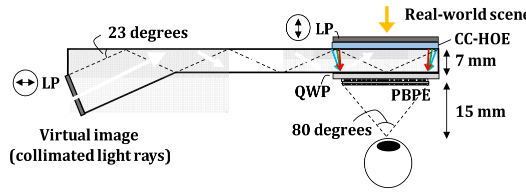
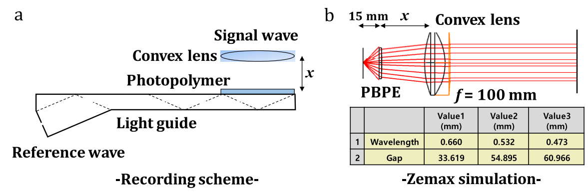


Fig. 2. Schematic diagram of the proposed compact AR combiner.



		Value1 (mm)	Value2 (mm)	Value3 (mm)
1	Wavelength	0.660	0.532	0.473
2	Gap	33.619	54.895	60.966

Fig. 3. (a) Recording process of CC-HOE and (b) a Zemax simulation to determine the recording conditions.

lens is activated as a concave lens for the LCP light and the output light becomes RCP state. In the previous work, we have suggested an AR eyepiece consisting of stacked PBP lenses as presented in Fig. 1(b) [8]. The AR eyepiece consists of three layers; two PBP lenses and one right-handed circular polarizer (RHCP) between them. As presented in Fig. 1(b), if the RCP light passes through the eyepiece, it undergoes two identical convex lenses with focal length f due to the RHCP where f is the focal length of the PBP lens. Since the gap between two PBP lenses is infinitesimally small, the focal length of the AR eyepiece for the input RCP light becomes $f/2$. On the contrary, if the LCP light goes through the AR eyepiece, it undergoes two conjugate lenses. Thus, the AR eyepiece is activated as a transparent plate for the LCP light. We named this AR eyepiece PBPE (PBP lens-eyepiece) for convenience. Two identical commercialized LC-based PBP lenses with a focal length of 45 mm and a diameter of 25 mm are adopted to construct PBPE. The measured focal lengths of PBPE are 18.17 mm, 22.54 mm, and 25.35 mm for the wavelength of 660 nm, 532 nm, and 473 nm, respectively. By using the polarization characteristic of PBPE, it is possible to achieve AR. If the external light is modulated to have the LCP state, the real-world scene will be delivered to the observer through PBPE without any distortion. Meanwhile, if the light from the display device is modulated to have RCP state, the virtual image will be floated in the real-world.

B. Previous Work

To employ PBPE to the AR combiner, a chromatic aberration should be resolved. The chromatic aberration of PBPE comes from the characteristic of PBP lens. From the phase modulation relationship between two different lights passing through PBP lens, it is possible to derive the relationship between the focal length of the PBP lens and the input wavelength [9]. Under the paraxial approximation, the focal length of the PBP lens is inversely proportional to the wavelength of input light. As shown in Fig. 1(b), the input LCP light passing through PBPE undergoes two conjugate phase modulations sequentially, and therefore the real-world scene is conveyed without the chromatic aberration. However, the input RCP light undergoes two identical modulations in sequence so that the chromatic aberration of virtual images would be twice aggravated. In the previous work, we settled the chromatic aberration by adopting three layered DHOEs [8]. Even though the chromatic aberration is effectively compensated, the overall form factor of the system becomes too large to be wearable. Furthermore, the transparency is too low and the quality of the virtual image is degraded due to the gratings in DHOEs.

III. Compact AR Combiner Using PBP Lens and HOE

A. Compact AR Combiner Using PBPE and HOE

Fig. 2 represents the schematic diagram of the proposed AR combiner. As shown in Fig. 2, collimated light rays from the display device are projected through the light guide with an incident angle of 23 degrees. After total internal reflections, these light rays are reached to a chromatic aberration-compensating-HOE (CC-HOE). CC-HOE is activated as an off-axis concave mirror which makes light rays converge with different convergence angle according to the wavelength of the input light. The red light converges with the smallest angle, and the convergence angle increases in order of green and blue light. After light rays with three different wavelengths are diffracted from CC-HOE, they converge into a single spot as they pass through PBPE. Ultimately, the observer can perceive an all-in-focus virtual image without chromatic aberration. In the proposed AR combiner, two orthogonal linear polarizers (LPs) and a quarter wave plate (QWP) are adopted to deliver the virtual image and real-world scene with appropriate polarization states.

B. Chromatic Aberration-Compensating-HOE (CC-COE)

Fig. 3 represents the recording process of CC-HOE. The reference wave is delivered to the photopolymer through the same light guide which is adopted in the proposed AR combiner. The signal wave is reached to the photopolymer after passing through a convex lens. To compensate the chromatic aberration from PBPE, the recording conditions of CC-HOE for each wavelength should be slightly different. To figure out the appropriate recording conditions, Zemax simulation is conducted as shown in Fig. 3. First, a grating pattern which

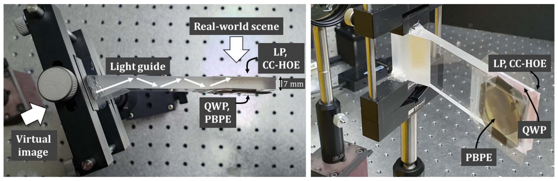


Fig. 4. Prototype of the proposed AR combiner. It consists of a light guide, CC-HOE, and PBPE.

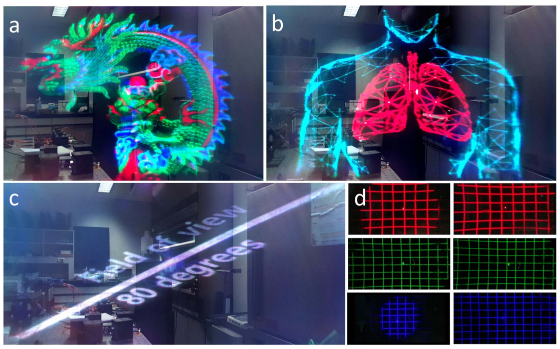


Fig. 5. Experimental results. (a) Dragon image, (b) human model, (c) maximum field of view, and (d) captured grid images before and after the compensation of chromatic aberration.

has the same wavelength-dependent focal lengths with PBPE is fabricated. Then, a convex lens with a focal length of 100 mm is placed behind PBPE. For each wavelength, a gap x between PBPE and the convex lens is calculated which generates a focal spot at 15 mm away from PBPE. The achieved values of x are 34 mm, 55 mm, 61 mm for wavelengths of 660 nm, 532 nm and 473 nm, respectively. By using the simulation results, CC-HOE is recorded in three steps by adjusting the gap between PBPE and the convex lens appropriately for each wavelength.

IV. Experiments and Analysis

A. Prototype of the Proposed AR Combiner

Fig. 4 represents a prototype of the proposed AR combiner. Collimated light rays are projected from a laser projector (Celluon, Picobit) with the incidence angle of 23 degrees to deliver the virtual image. The light guide is made of glass and the thickness of it is 7 mm.

Fig. 5 shows the experimental results. It is assumed that the light from the real-world is unpolarized. As shown in Figs. 5(a) and 5(b), both the virtual image and the real-world scene are delivered clearly without the chromatic aberration. The brightness of outer part of the real-world scene is slightly lower than the center part because the highest efficiency of PBP lens is obtained for the light rays that are parallel to the optical axis. The maximum FOV is measured as 80 degrees as presented in Fig. 5(c). Fig. 5(d) represents the captured grid images for each color channel before and after compensating the chromatic aberration. Three images in the left column of Fig. 5(d) are captured without CC-HOE. A CCD camera is placed on the green focal spot. Since the red and the blue focal spots are generated back and forth against the green focal spot, light rays outside of the certain angle cannot enter the CCD lens aperture. This vignetting problem can be resolved by compensating the chromatic aberration using CC-HOE as shown in the right three figures of Fig. 5(d).

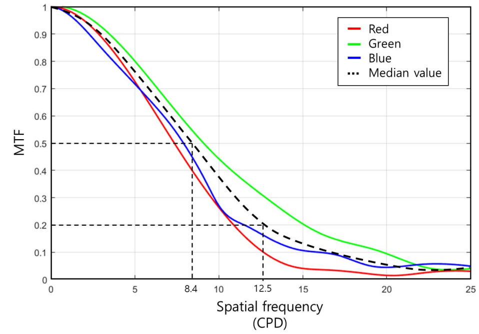


Fig. 6. Resolution of the virtual image provided by the proposed AR combiner as measured using the slanted edge MTF algorithm.

To measure the resolution of the virtual images provided by the proposed AR combiner, a slanted edge modulation transfer function (MTF) measurement algorithm is used [10]. Fig. 6 plots the MTF curves of each color channel within the FOV of 50 degrees. The MTF shows 0.5-relative intensity for 8.4 cycles per degree (cpd) and 0.2-relative intensity for 12.5 cpd.

B. Radial Aberration of PBPE

As shown in Fig. 5(c), the outermost part of the virtual image is slightly hazy compared to the center part. This phenomenon happens due to the physical characteristic of the phase modulation occurring in PBP lens. The phase modulation relationship can be written as below without a paraxial approximation [11]:

$$\frac{2\pi}{\lambda_d}\left(f_d-\sqrt{r^2+f_d^2}\right)=\frac{2\pi}{\lambda_i}\left(f_i-\sqrt{r^2+f_i^2}\right), \qquad (1)$$

where λ_d is the wavelength of the light source used in the design process of PBP lens and f_d is the designed focal length. r is the radial distance between a specific point on PBP lens and the center of the lens. As expressed in Eq. (1), the focal length of PBP lens f_i is not only a function of the wavelength of the input light source λ_i, but also a function of the radial distance r. From Eq. (1), the focal length of PBPE can be derived as follows:

$$f_i(\lambda_i, r)=\frac{1}{2}\cdot\frac{\lambda_d}{2\lambda_i\left(f_d-\sqrt{r^2+f_d^2}\right)} \cdot\left\{\frac{\lambda_i^2}{\lambda_d^2}\cdot\left(2f_d^2+r^2-2f_d\sqrt{r^2+f_d^2}\right)-r^2\right\}. \qquad (2)$$

A simulation is conducted to present how the light rays passing through PBPE are reached on the retinal plane according to the radial distance from the center of PBPE. Fig. 7 is a schematic diagram of the simulation. In the actual situation, a single light ray can be modeled as a Gaussian beam with a physical beam width and a diverging angle. As shown in Fig. 7, it is assumed that the beam-shaping optic makes the ray passing through the center of the PBPE form the sharpest spot

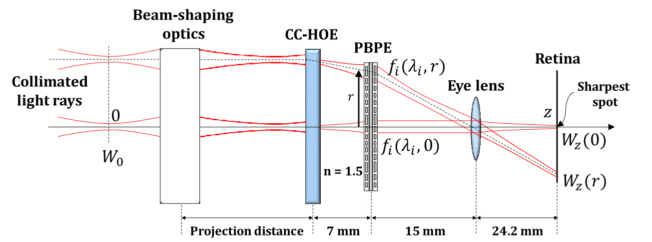


Fig. 7. Schematic diagram of the simulation environment. Projection distance was set to 500 mm.

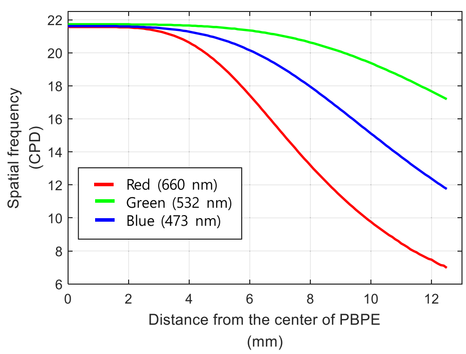


Fig. 8. The upper bound-spatial frequency corresponding to the 0.6-MTF on the retinal plane with varying the radial distance between the ray and the center of PBPE.

on the retina. Under this condition, $W_z(r)$ can be calculated, which is the size of the spot generated by the arbitrary light ray. Ultimately, point-spread-functions (PSFs) on the retinal plane for incident light rays can be achieved and by adopting Fourier transform to these PSFs, it is possible to plot MTF curves at every point on the retinal plane. Fig. 8 plots the upper bound-spatial frequency values corresponding to the 0.6-MTF at each point on the retinal plane. As the radial distance between the ray and the center of PBPE increases, the ray reaches the point farther from the center of the retina. Since the simulation condition is set to make the sharpest spot on the center of the retina, the spot becomes blurry in the periphery. Thus, the upper bound-spatial frequency values for 0.6-MTF decreases as the radial distance between the ray and the center of PBPE increases. For this reason, the resolution of the outer part of virtual images is degraded compared to the center part of them. As presented in Fig. 8, the simulation results indicate that the green light source provides relatively higher quality of images compared to other two sources. This is because the designed wavelength λ_d is 566 nm which is close to the wavelength of the green light source used in the experiments. The designed focal length f_d of the PBP lens is set to 22.5 mm in the simulation.

We are planning to resolve this aberration by adopting holographic display concept. We expect that both the chromatic aberration and the radial distortion can be resolved simultaneously by modulating the wavefront profile.

C. Limited Eye Box

The major limitation of the proposed AR combiner is the small eye box. For the practical situation, the combiner should be combined with eye box expansion methods. There are two representative methods which can be applied. The first method is to shift the focal spot by switching the incidence angle of the input beam. Due to the Bragg mismatch condition, a focal spot will be weakly generated at another position as the beam is projected with a different angle from the recording condition [12]. To adopt this method, the design of the entrance of the light guide should be modified. The simulation of a dynamic eye box using Bragg mismatch condition is attached in the supporting document. The second method is the use of HOE-multiplexing. By overlapping CC-HOEs that diffract light in different directions for a single reference wave, it is possible to generate multiple focal spots [5]. Besides these two methods, there can be other ways to expand the eye box. We are considering the eye box expansion as a future work.

V. Conclusion

A compact AR combiner using PBP lens and HOE is proposed. By exploiting the polarization characteristic of PBP lens, a thin AR eyepiece is constructed. The eyepiece has advantages of a compact size and a large NA value, but it has a severe chromatic aberration. To compensate the chromatic aberration, HOE which diffracts the light rays with different convergence profile according to the input wavelength is designed. By combining this HOE with the AR eyepiece and a light guide, a novel AR combiner is proposed. The proposed combiner provides high-resolution-virtual images with wide FOV while maintaining the compact size and transparency.

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