Lightweight, Thin and High-Performance Polarization Modulator for Varifocal Liquid-Crystal Lens System

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Abstract
To realize a varifocal lens for head mounted displays (HMDs), we have fabricated a single liquid crystal switchable half wave retarder using dual frequency liquid crystals. This switchable half wave retarder has shown high modulation efficiency comparable to that of conventional switchable half wave retarders. In addition, our switchable half wave retarder exhibits very high transmittance with a broad wavelength range.

Author Keywords
Switchable Half Wave Retarder, Varifocal Lens System, Pancharatnam Berry Lens, Dual Frequency Liquid Crystal

1. Introduction
The realization of a more immersive virtual reality (VR) world has been required with expansion of the VR market. One of the key requirements is a solution of vergence-accommodation conflict (VAC) for the realization of this VR world [1]. VAC is a phenomenon of feeling discomfort caused by mismatching a vergence and a focal length. Because lenses with a fixed focal length are used in current HMDs. Therefore, VAC can be solved by using varifocal lenses. Several approaches have been proposed, such as the use of holographic displays [2], multifocal displays [3], light field displays [4], and variable focus lenses based on liquid crystal (LC) technology. The display system that uses variable focus lenses based on LC technology does not have drawbacks such as reduced resolution or increased bandwidth. Therefore, the discussion below focuses on LC lenses.

There are mainly three types of LC lenses. The first is the Fresnel type [5], the second is GRIN type [6], and the third is a type combining the Pancharatnam Berry Lens (PBL) and the switchable half wave retarder (SHWR) [7]. The Fresnel and the GRIN types have slow response times (>100ms) because the LC layer is thick. This means that it is difficult to consistently match the vergence with the focal length. Therefore, use of the Fresnel and the GRIN types can reduce discomfort caused by the VAC, but it will not completely remove discomfort. On the other hand, the combination of the PBL and the SHWR has a fast response time due to a thin cell thickness compatible with that of regular LCDs. However, multi-stacking of PBL and SHWR set is needed for varifocal lenses, as a binary focal length is obtained with each PBL and SHWR set. Therefore, the weight and the thickness of this type are important factors to consider when incorporating it into HMDs.

A PBL is an optical element that focuses light with a focal length of ±f on an incident circular polarization state. An SHWR is a switching device for the circular polarization state. It has two states, the unmodulated state and the modulated state. In the unmodulated state, the SHWR outputs the same circular polarization state as the incident circular polarization state. Conversely, in the modulated state, the SHWR outputs the orthogonal circular polarization state compared with the incident circular polarization state. Therefore, the entire lens system works as both a convex and concave lens by switching the SHWR between the unmodulated and the modulated states as shown in figure 1.

Therefore, the focus of the PBL changes by switching the SHWR between the unmodulated and modulated states. Since this lens system is incorporated into an HMD, high lens performance is desirable not only for on-axis incident light but also for off-axis incident light. Consequently, the SHWR is required to achieve high modulation efficiency over a wide wavelength range in the visible spectrum, along with a wide viewing angle.

We have studied a dual LC layer SHWR that exhibits high modulation efficiency and a wide viewing angle, and we reported our findings in 2023 [8]. However, adaptation of this design for HMDs seems difficult because its weight and thickness increase with the use of two LC layers. Additionally, transmittance decreases due to increased absorption and reflection in each layer. In this paper, we propose a single LC layer SHWR that has optical performance equivalent to that of a dual LC layer SHWR. We believe this approach will help to solve the VAC.

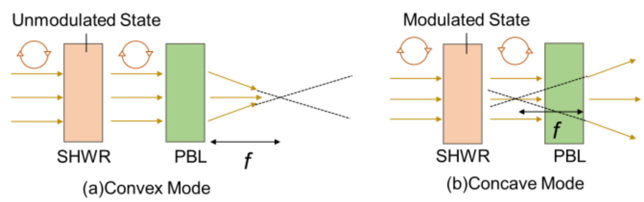


Figure 1. Operating Principle of SHWR and PBL

2. Device Structure and Polarization Modulation Principle
Here, we explain the LC alignment principles of the SHWR to realize achromatic and wide viewing angle performance. First, figure 2 shows the device structures of the conventional dual LC layer SHWR and our single LC layer SHWR. As shown in figure 2, compensation films are used to achieve achromatic and wide viewing angle performance. The LC alignment is twisted by approximately 70 degrees to realize high-efficiency modulation [9]. Additionally, the total LC alignment is rotated by 90 degrees between the unmodulated state and the modulated state, as shown in figure 3. In the conventional dual LC layer SHWR, the two LC layers are aligned in the first and second alignment states, respectively. When voltage is applied to the LC layer with the first alignment state, LC molecules are aligned vertically in the bottom LC cell. The SHWR thus shows the modulated state to contribute to polarization modulation in the top LC cell only. Conversely, when voltage is applied to the LC layer with the second alignment state, the LC molecules are aligned vertically in the top LC cell. The SHWR thus becomes the unmodulated state to contribute to polarization modulation in the bottom LC cell only.

To achieve the same LC alignment in a single LC layer, we use dual frequency LC (DF-LC) provided by Merck Electronics KGaA. DF-

LC behaves as a positive LC when a low-frequency voltage is applied and behaves as a negative LC when the frequency of the applied voltage increases. This means that the total LC alignment can be switched by changing the frequency of the applied voltage. Focusing on the polarization state, the circular polarization state is modulated to a linear polarization state by 70 degrees twisted LC alignment. The linear polarization state output from the LC layer is rotated by 90 degrees between the unmodulated and modulated states because the LC alignment is rotated a total of 90 degrees. After that, the linear polarization state is modulated back to a circular polarization state by compensation films. During this modulation, the linear polarization states that differ by 90 degrees are modulated into orthogonal circular polarization states. The above sequence describes the driving principles of the LC layer and the modulation mechanism.

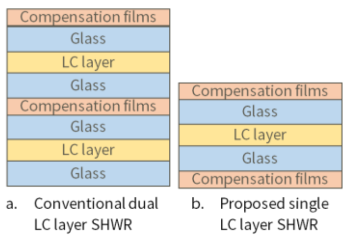


Figure 2. Device Structure

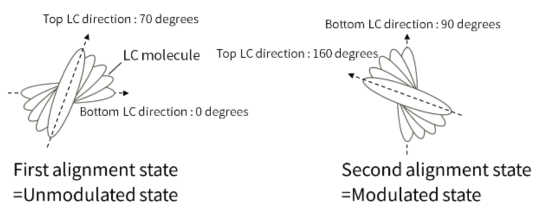


Figure 3. LC Alignment Illustration Viewed from Above

3. Characteristics of SHWR

3.1. Modulate Characteristics in simulation

First, we discuss the modulation characteristics based on the calculation results. In this paper, the S3/S0 ratio is used as the indicator of modulation efficiency. An output of S3/S0 being +1 means that the emitted polarization state is the ideal right-handed circular polarization, while an output of S3/S0 being -1 means that the emitted polarization state is the ideal left-handed circular polarization. In other words, high modulation efficiency is achieved when an output S3/S0 is close to ±1.

In this section, the S3/S0 values of the output light is evaluated in response to incident light with S3 = +1. Figure 4 shows the calculation results for the on-axis modulated and unmodulated characteristics of the conventional single twisted-nematic liquid crystal (TN-LC) layer, dual LC layers, and the proposed single LC layer structure. The conventional single TN-LC layer structure exhibits poor on-axis modulation characteristics. In contrast, both the conventional dual LC layer structure and the proposed structure demonstrate high modulation efficiency (≥95%) across a wide wavelength range from 450 nm to 650 nm for both the modulated and unmodulated states.

Figure 5 shows the off-axis modulated and unmodulated characteristics in contour diagrams. In the unmodulated state, a larger red area indicates better performance, while in the modulated state, a larger blue area indicates better performance. The conventional single TN-LC layer structure exhibits poor viewing angles in both the unmodulated and modulated states, as shown in figure 5(a-1) and 5(a-2). The conventional dual structure achieves very high modulation ratios in both modulated and unmodulated states at wavelengths of 450 nm, 550 nm, and 650 nm, as shown in figure 5(b-1) and 5(b-2). Our proposed single LC layer SHWR maintains the same high level of modulation ratio as that of the conventional dual LC layer SHWR, as shown in figure 5(c-1) and 5(c-2).

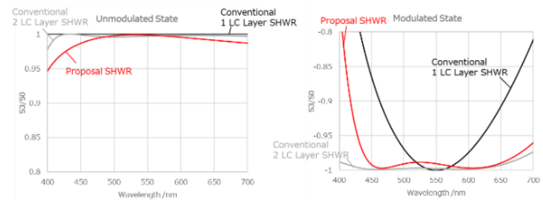
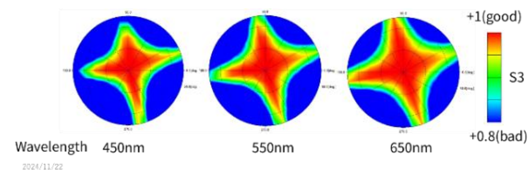
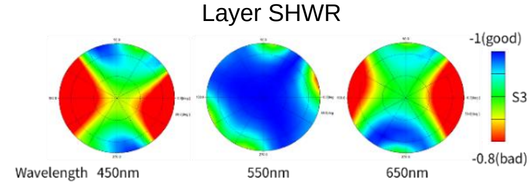


Figure 4. On-axis Modulated and Unmodulated Characteristics

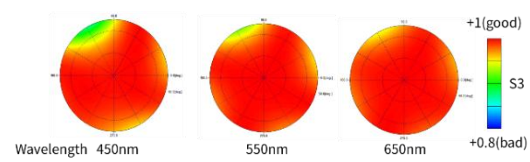


(a-1) Unmodulated State of Conventional single TN-LC Layer SHWR

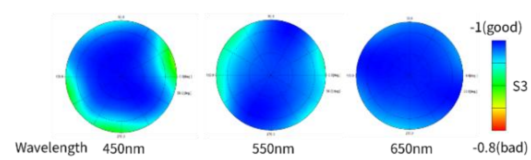


(a-2) Modulated State of Conventional single TN-LC Layer SHWR

(a) Conventional 1 LC Layer Structure SHWR

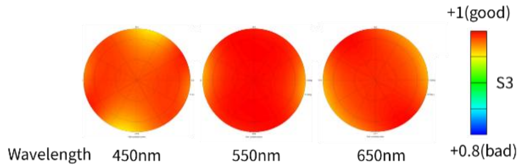


(b-1) Unmodulated State of Conventional Dual LC Layer SHWR

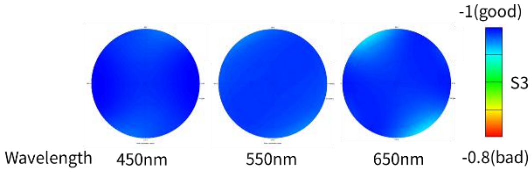


(b-2) Modulated State of Conventional Dual LC Layer SHWR

(b) Conventional Dual LC Layer Structure SHWR



(c-1) Unmodulated State of Our Single LC Layer SHWR



(c-2) Modulated State of Our Single LC Layer SHWR

(c) Our Single LC Layer Structure SHWR

Figure 5. Modulation Characteristics by Contour Plot

3.2. S3/S0 Measurement

We evaluated the S3/S0 values of the SHWR fabricated in our laboratory. In the previous section, it was clarified that the conventional single TN-LC SHWR exhibits poor S3 characteristics. Here, the evaluation is focused on comparing the characteristics of the conventional dual LC SHWR and the proposed single LC SHWR.

First, we evaluated the voltage dependency of the on-axis |S3/S0| spectrum to determine the optimal applied voltage in the modulated state and unmodulated state. The frequency-Δε characteristics of the DF-LC are shown in figure 6. In figure 6, the crossover frequency, which is the switching frequency between positive and negative polarities, is 14kHz. In this evaluation, 30 Hz and 50 kHz were adopted for the modulated state and unmodulated state respectively. We defined the worst S3/S0 value from wavelengths of 450 nm to 650 nm in both unmodulated and modulated states as the worst |S3/S0|. The results are shown in figure 7. In figure 7, 8 V is optimal at 30 Hz in the modulated state, and 13.5 V is optimal at 50 kHz in the unmodulated state. We expect that the variation in the worst |S3/S0| value with voltage is due to changes in the twist angle resulting from the applied voltage.

Figure 8 shows the on-axis |S3/S0| spectrum of our single LC layer SHWR compared to the conventional dual SHWR. Although our single LC layer SHWR shows slightly poorer characteristics than that of conventional dual SHWR, the S3/S0 value of our single LC layer SHWR is 0.96 or more at wavelengths from 450nm to 650nm. This means that equivalent modulation performance is achieved in both states. To confirm the wide viewing angle, S3/S0 values were measured at all azimuthal angles at a polar angle of 30 degrees. To assess achromatic performance, S3/S0 values were evaluated at three wavelengths: 450 nm, 550 nm, and 650 nm. The results are shown in figure 9

In figure 9, the proposed single LC layer SHWR demonstrates good performance comparable to that of the dual LC layer SHWR, even at a polar angle of 30-degree.

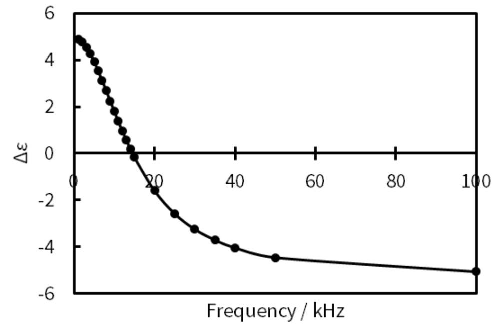


Figure 6. Δε Characteristics Versus Frequency

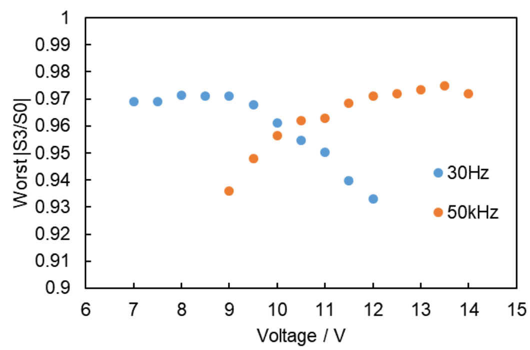
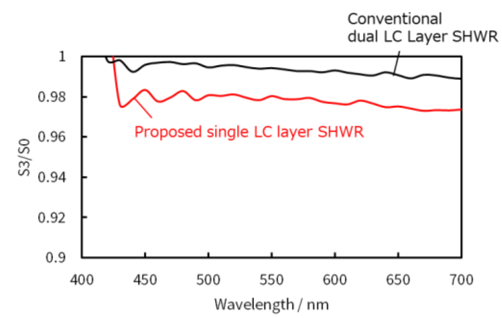
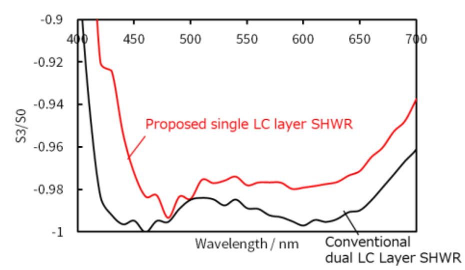


Figure 7. Worst |S3/S0| Versus Voltage at Low and High Frequency at On-axis

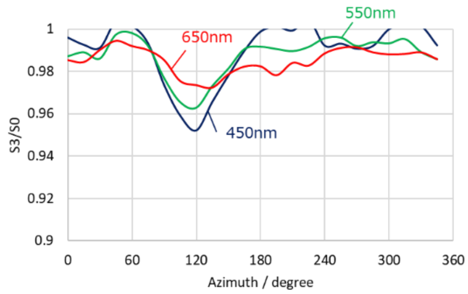


(a) Unmodulated State

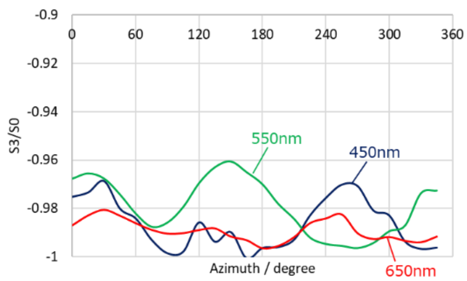


(b) Modulated State

Figure 8. S3/S0 Value Versus Wavelength at On-axis

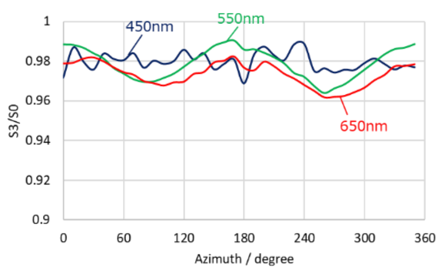


(a-1) Unmodulated State of Conventional Dual LC Layer SHWR

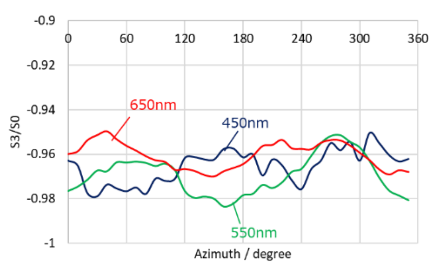


(a-2) Modulated State of Conventional Dual LC Layer SHWR

(a) Conventional Dual LC Layer Structure SHWR



(b-1) Unmodulated State of Our Single LC Layer SHWR



(b-2) Unmodulated State of Our Single LC Layer SHWR

(b) Our Single LC Layer Structure SHWR

Figure 9. Off-axis S3/S0 Value in all azimuth angle at 30 degrees polar angle

3.3. Transmittance

Since the SHWR is part of the optical components in the lens system, high transmittance is required. Therefore, we measured the transmittance, and the results are shown in figure 10. The findings indicate that our single LC layer SHWR exhibits high overall transmittance, with the transmittance at 450 nm increasing by 6%. We attribute this improvement to the suppression of absorption by the ITO and compensation film in our SHWR.

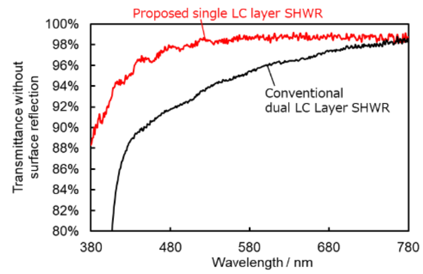


Figure 10. Transmittance in visible wavelength

4. Conclusions

In this paper, we have proposed a novel single LC layer SHWR utilizing DF-LC. We also have demonstrated that the proposed SHWR achieves modulation characteristics comparable to those of the conventional SHWR even when the number of LC layers is reduced from two to one, as evidenced by both calculations and experimental measurements. These findings are expected to facilitate the development of varifocal lenses that are thinner, lighter, and exhibit enhanced optical properties.

5. Acknowledgements

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6. References

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