Broadband In-Cell Quarter Wave Plate using a Combination of Solution-processed Self-aligning Liquid Crystal Polymer by Coating Technique and Photoalignment

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Keywords: quarter wave plate, ambient contrast ratio, liquid crystal polymer, broadband, photoalignment

ABSTRACT

A new kind of in-cell solution-processed broadband quarter wave plate for the circular polarizer made of liquid crystal polymer using coating technique has been proposed and manufactured in this work. The transmittance and reflectance spectrum can show high ambient contrast ratio (ACR) improvement for the light emitting display system.

1 INTRODUCTION

Retardation film are widely used in optical system because they can easily change the polarization state of the output light by changing the phase difference between two eigen polarization state of the incident light. That phase difference is defined by retardation which is given by

$$\delta = \frac{\pi \Delta n d}{\lambda}$$

where δ is retardation, d is the physical thickness and Δn is the birefringence of the retardation film, respectively. And λ is the wavelength of the incident light. Some may define retardation as two times over here. To avoid confusion, here we illustrate the retardation Δnd as $\lambda/2$ and $\lambda/4$ for half wave plate (HWP) and quarter wave plate (QWP), respectively.

Retardation films such as QWP and HWP have many applications such as in polarization manipulation, phase compensation, viewing angle enhancement and dispersion compensation. In projection system, QWP and HWP are used in polarization conversion optics and in skew ray compensation [1]. As well in OLED display system, the ambient contrast ratio, which is the transmittance ratio of bright state and dark state under ambient light illumination, is strongly depends on how much the reflection of the light from the panel is, instead of infinity [9]. But in order to improve the efficiency and make full use of the light emitted from the OLED material, people introduce strong reflection material as negative electrode to collect the backward propagation light. Because of that, the ambient light will also be reflected and play an important but undesired part in the dark state of the display system. For the elimination of the ambient light in OLED display system, A circular polarizer is needed to block the ambient light from being reflected. Usually, the QWP has strong wavelength dependent which is dispersion relation of an anisotropic material.

Above all, for all display applications, the QWP and polarizer should be achromatic in the wavelength range for display which is the whole visible spectrum from 400nm to 700nm wavelength. However, commercial circular polarizer usually has strong wavelength dependence and bad reflectance spectrum performance. And usually, the commercial circular polarizer has to be combined with the panel using the adhesive which improves the thickness and surface roughness sensitivity of the display system. And the thickness and surface roughness will play an important part in the viewing angle, light recycling efficiency and diffuse reflection of the panel [8-9]. Recently, the broadband in-cell circular polarizer fabricated by direct coating the circular polarizer on the top of the display unit become the best solutions for this problem.

In order to make a good broadband QWP who can block the light perfectly and have good viewing angle, many approaches have been developed [2]. There are two kinds of major approaches. One is using positive dispersion and negative dispersion uniaxial material to compensate each other to get nondispersive material. Another one is using multi-layer retardation films to get broadband QWP [3-7]. In Shin-Tson Wu's patents [4-5], they showed very good spectrum and good angle arrangement, but they used very thick layers of retardation film and didn't mention how to manage the difference of alignment direction for the two adjacent layers of retardation film. Ravi K. Komanduri and Michael J. Escuti introduce the self-aligning multi twist retarders to solve the alignment problem, but they did not show good reflection spectrum using their broadband QWP as a circular polarizer [6]. And they show lots of combination of layers of liquid crystal polymer, but they just talk about how to design the broadband QWP without the discussion of the linear polarizer on the top also. In our work, we use the same self-aligning technique to design and fabricate two kinds of QWP. One is aimed for thin retardation film and another is aimed for optimizing the direction relation between the polarizer and outmost retardation film to minimize the interaction between the polarizer and QWP. And we also compare the results using commercial linear polarizer.

In this paper, we search the whole parameter space for the combination of two twist retarders. And we use coating technique to fabricate the structure according to the simulation and get very good reflectance spectrum using commercial polarizer. The retardation films are made by liquid crystal polymer (LCP) (UCL017 from DIC) mixed with the proper chiral dopant using spin-coating on the top of the photoalignment layer. After polymerization, the lower layer will not be dissolved by the upper layer solutions. And the output director of the lower layer will help to align the upper layer. We optimized the broadband QWP to make the output director have same direction as the polarizer.

2 EXPERIMENT

2.1 Simulation

With the help of MATLAB, we use Jones Matrix to follow the optical path procedure. The measurement setup is like below which is also the setup for the optical isolator.

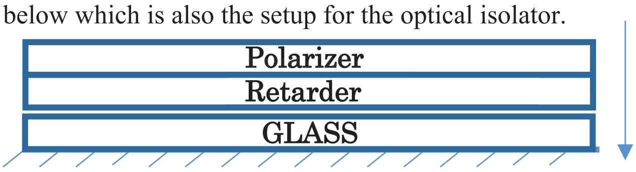


Figure 1 Schematic setup, light comes from top to bottom

$$M = \prod_i \begin{bmatrix} cos\theta_i & sin\theta_i \\ -sin\theta_i & cos\theta_i \end{bmatrix} \begin{bmatrix} e^{-j\delta_i(\lambda)} & 0 \\ 0 & e^{j\delta_i(\lambda)} \end{bmatrix} \begin{bmatrix} cos\theta_i & -sin\theta_i \\ sin\theta_i & cos\theta_i \end{bmatrix}$$

Equation 1 M is the Jones Matrix of the combination of the retarders, $\boldsymbol{\delta_i(\lambda)}$ is the retardation, $\boldsymbol{\theta_i}$ is the optical axis direction relative to the polarizer

$$Reflectance = \left| \begin{bmatrix} 1 & 0 \end{bmatrix} \cdot M^T \cdot M \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right|^2$$

Equation 2 The calculation of the reflection spectrum, M is the Jones Matrix of the combination of all the retarders, $\boldsymbol{M^T}$ means the transposition of the Matrix M

For the two a-plate combination structure, the reflectance when light reflects from the mirror depends on the optical axis direction and the retardation of the two waveplates. The simulation result shows that when the optical axes of the two waveplates deviate from each other by 55 degree and the HWP deviates from the polarizer by 22 degree has the smallest reflectance and has large retardation tolerance which means weakly dependent on the viewing angle as well.

For the twist retarder and a-plate retarder combination structure, we search the retardations, twist angle and the input director angle deviated from the polarizer. These four parameters form the whole parameter space. After search the whole space, we get the optimal result when the twist retarder has 81.6 degree twist angle, the input director is 76 degree deviated from the polarizer and the twist retarder and the a-plate has the same retardation whose thickness are 950nm for UCL017.

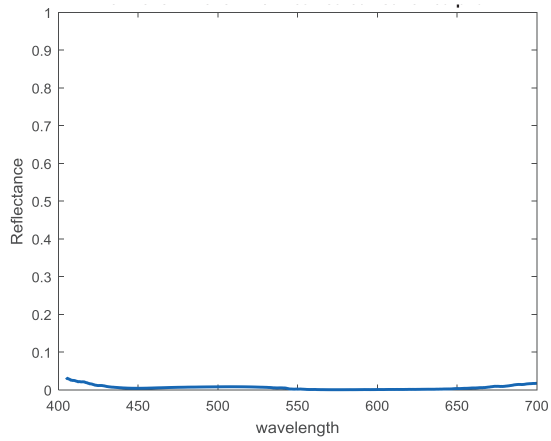


Figure 2 optimal simulation result for UCL017 twist and a-plate retarder combination structure

2.2 Experiment

The LCP that we used is UCL017 whose birefringence Δn is around 0.17. UCL017 has advantages because UCL017 can be easily coated by spin-coating and cured by UV light with good mechanical properties as well. By trying different kinds of spin coating speed (revolutions per second) and concentration of UCL017 (dissolved in PGMEA) which can influence the viscosity of the solutions, we got the table below to show the thickness for different conditions. For the twist retarder, in order to get a twist LCP film, we add some chiral dopants into the solutions which is S811 for left-hand twist whose helix twist power is 11 /um so that we can get the 81.6 degree twist angle when the thickness is 950nm.

LCP c %	S811 cS811	spin coating r/s	thickness /nm
30%	0.65%	3500	1000
30%	0.65%	2000	948
combination			1989

Table 1 Thickness measure by step profiler for optimal condition of the a-plate and twist retarder combination. S811 refers to the chiral dopant concentration in the PGMEA solutions. The concentration of S811 in LCP is 2.17%

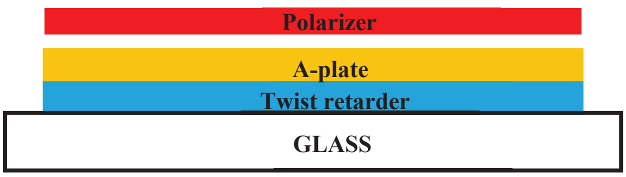


Figure 3 Schematic structure of the twist and a-plate combination structure. The a-plate has the same direction as the input director of the twist retarder

In order to fit the command of the alignment of the linear polarizer on the top to make the system even thinner, we propose a second design of the broadband quarter wave plate that the out director of the top retarder has the same direction as the direction of the linear polarizer. The linear polarizer can be thin-film polarizer or LCP dyes.

I	thickness	Direction change
LCP_layer1	950nm	81°
LCP_layer2	950nm	0°
Polarizer	NA	-5 °
II	thickness	Direction change
LCP_layer1	807nm	78°
LCP_layer2	1614nm	18°
Polarizer	NA	0°

Table 2 Design of the broadband retardation film

3 RESULTS

The reflection spectrum was measured under microscope. In order to see the performance of the film, intensity "1" represents the reflection of the mirror after adjusting the focal plane to the front surface of the film and intensity "0" represents the front surface reflection of the glass which is very close to the front surface reflection of the film (around 5% of the reflection of the mirror). We also show the prototype in the figure below.

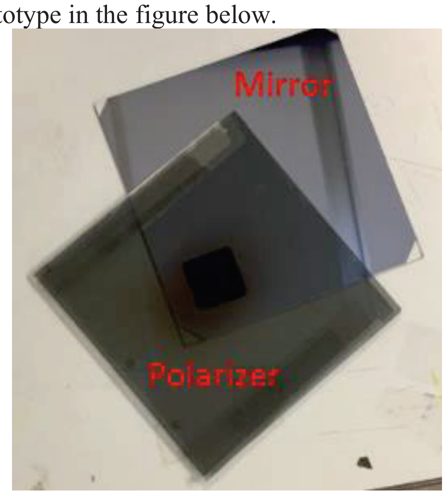


Figure 4 The prototype of the broadband QWP with commercial linear polarizer

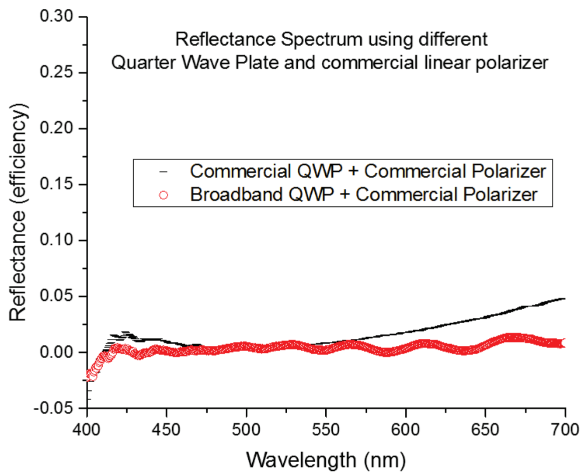


Figure 5 The reflection spectrum of the solution-processed broadband quarter wave plate compared with commercial quarter wave plate.

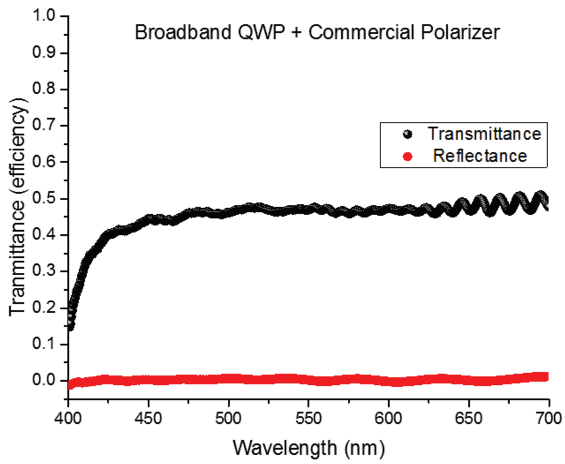
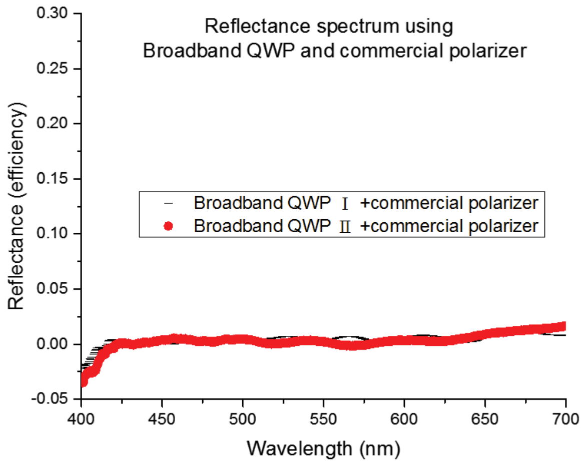


Figure 6 Spectrum for combination of solution-processed quarter-wave plate and commercial linear polarizer

The intensity of the light source is not stable for wavelength from 400nm to 430nm. We can also get the same conclusion based on the transmittance spectrum of the polarizer. For the a-plate structure, there is some interference pattern in the spectrum, that is because the buffer layer is around 1um resulting in interference. Even before we coat the second a-plate on the buffer layer, there is vibration in the spectrum of the first QWP. And the period is around 20nm which corresponds to the thickness of the buffer layer.

For the twist and a-plate retarder combination structure, there is still some interference pattern in the spectrum which also makes the reflectance below 0 intensity (the reflectance of the front surface of the glass). The interference pattern disappears when we measure the transmittance of the retarder under cross polarizer which means this interference is not due to the reflection between any two layers in the retarder. It is also not due to the air gap between glass and the mirror as we have checked. The period is around 50nm which is quite different from the former structure, as they have similar thickness, it is easy to predict that it is because the interference at the front surface of the retarder. Although in **principle**, the reflected light be orthogonal to each other. Further work should be done for improvement.

For the both design of the broadband quarter wave plate, we got the reflectance spectrum comparison in the figure below.



4 CONCLUSION

In a word, the combination of two retardation films is a promising way to realize broadband quarter wave plate as this method can be realized by coating technique which is still effective for large size manufacturing. And the simulation procedure can be repeated for any other anisotropic material. Furthermore, the above experiment results can still be improved a little bit if we go over every detail. The angle mentioned above can be regarded as a general approximate solution for retardation film made by UCL017 LCP. In the future, we may continue to optimize the dark state by precisely calculation or other retardation film combination and figure out the reason for the interference existing and eliminate it. So far, we have decreased the reflection from 100% to around 4% which is the reflection of the front surface of the film, similar to the glass which can be eliminated by the anti-reflection coating.

As the in-cell circular polarizer is urgently required in the light emitting display system and other display system which needs high ambient contrast ratio under strong ambient light [9], our recent results about the in-cell QWP can play an important part in both research and market. And we didn't see severe problem to transfer this technique to the production. Because our fabrication system only needs normal coating technique and exposure of UV light (365nm) to give polymerization and photoalignment without any mechanical contact.

5 ACKNOWLEDGEMENTS

This research is supported by The State Key Laboratory of Advanced Displays and Optoelectronics through the Innovations and Technology Commission of Hong Kong.

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