Liquid Crystal Displays with Variable Viewing Angles Using Electric-Field-Driven Liquid Crystal Lenses as Diffusers

Seung-Chul Lee, Taehyeon Kim and Woo-Sang Park *

Department of Electronic Engineering, Inha University, Incheon 22212, Korea; ilove8790@inha.edu (S.-C.L.); nvddm@inha.edu (T.K.)
* Correspondence: wspark@inha.ac.kr

Received: 28 November 2019; Accepted: 15 January 2020; Published: 17 January 2020

Abstract: We propose a novel method for appropriately controlling the luminance distribution of liquid crystal displays (LCDs) for different usage environments by using electric-field-driven liquid crystal (ELC) lenses. The LCD systems are composed of quasi-collimated backlights (QCBLs), LC panels, and ELC lenses that are used as diffusers. To achieve a wide viewing angle, light is diffused with the ELC lenses by controlling its retardation with the voltage applied to the electrodes. For private use, a narrow viewing angle is achieved by turning the ELC lenses off so that the collimated light from the QCBLs passes directly through the liquid-crystal layer of the ELC lens and travels without diffusion. To validate the proposed method, we simulated the luminance distributions of the wide-view and narrow-view modes by using a finite difference method (FDM) and Taguchi’s design of experiments method. The simulation results show that the light distribution of the wide-view mode was 84.3% similar to the ideal Lambertian distribution and was wider than that of IPS-LCDs with wide viewing angle characteristics. In addition, the light distribution of the narrow-view mode had a full width at half maximum of 7°. The luminance of the exiting light at viewing angles of 20° and above was calculated to be close to 0.

Keywords: liquid crystal display; liquid crystal lens; diffuser; viewing angle controllable

1. Introduction

Liquid crystal displays (LCDs) have played a leading role in the display market by virtue of their long service life, low power consumption, and low price. However, the viewing angles are restricted because of refractive index anisotropy. To improve the viewing angles in LCDs, in-plane switching (IPS) and fringe-field switching (FFS) have been used to control the liquid-crystal (LC) molecular behavior in the plane [1,2]. Furthermore, multiple domains have been used to symmetrically arrange LC molecules to reduce the difference in phase retardation according to the direction [3,4].

Another method that ensures a wide viewing angle involves adding a phase retardation film to the outer part of the LC panel, which can compensate for the difference of phase retardation between the normal direction and oblique directions. A lens array has also been used as a diffuser for LCDs with quasi-collimated backlights (QCBLs) [5,6]. However, a wide viewing angle may be a drawback for personal devices. Therefore, a technique is required to switch the viewing angles of an LCD in different usage environments. Several types of the LCDs for controllable viewing angles have been reported: Dividing the pixels according to the viewing angles [7–9], additional viewing angle control systems [10,11], switchable viewing angle backlight systems [12,13]. However, these methods reduce the resolution and brightness compared to the conventional LCDs, or use unique liquid crystals such as the blue phase and discotic phase, thereby causing problems in temperature reliability and fabrication.
process. Some of the methods with the viewing angle control system increase the weight and volume of the display due to the additional complex systems. As another method for adjusting the viewing angle, a technique of controlling the focal length or diffusing the light by electrically controlling the wavefront using the LC-polymer composite has been proposed [14–16]. However, the LC-polymer composite has a vulnerability to the light, low thermal stability, and electro-optical hysteresis due to the characteristics of a polymer compared to the nematic liquid crystal. In particular, the hysteresis of the LC-polymer composite, caused by the differences in LC molecular behavior with an applied voltage, results in image distortion or change in transmittance [17].

In this paper, a new method is proposed to electrically control the viewing angle of LCDs in various usage environments by using an electric-field-driven liquid crystal (ELC) lens [18] as a diffuser in front of the LCD. The ELC diffuser disperses or transmits light depending on whether a voltage is applied, so light distribution can be realized with a wide or narrow viewing angle. The retardation distribution affects the optical characteristics of the ELC diffuser and is obtained by numerically calculating the behavior of the liquid crystal through de Gennes’ order tensor theory and Ericksen–Leslie equation [19]. Taguchi’s design of experiments method was used to optimize the design factors of the ELC diffuser [20]. Finally, an LCD system was equipped with the ELC diffuser, and the light distribution was calculated by ray tracing, and the viewing angles could be switched by the voltages applied to the diffuser.

2. Optimal Design and Numerical Simulation

Figure 1 shows diagrams of the wide- and narrow-view modes of the proposed LCD system and structure of ELC diffusing unit. Each diffusing unit of the ELC diffuser is an ELC lens that can electrically control the direction of light. The LC molecules of the ELC diffusing unit are homogeneously aligned parallel to the polarizer direction of the LCD panel so that maximum retardation occurs in the field-off state. If no voltage is applied to the diffusing unit, the diffusing unit transmits collimated light from the QCBL without a wavefront change, as illustrated in Figure 1a. Thus, a light distribution appears with a narrow viewing angle. However, if an appropriate voltage is applied to the diffusing unit, the polarized light that passes through the LC panel undergoes different retardations because of the different spatial refractive indexes of the liquid crystals, as shown in Figure 1b. Accordingly, the wavefront of the light becomes spherical. This spherical wave forms a focus and then generates a wide light distribution in the viewing zone.

To form a spherical wave with a wide light distribution, the retardation needs to monotonically decrease from the center of the diffusing unit to both ends. In the case of liquid crystal with positive birefringence, the effective refractive index decreases if the tilt angle of the optic axis increases, which decreases the retardation at the corresponding position. Therefore, driving electrodes are installed at both ends of the diffusing unit as shown in Figure 1c, and an appropriate voltage is applied. As a result, LC molecules can be arranged in the vertical direction from the glass surface or in the direction where the tilt angle increases. The retardation distribution can be precisely controlled when the retardation distribution of the ELC diffusing unit is controlled and the unit has multiple driving electrodes. However, in this study, a single driving electrode was arranged at each end to reduce the thickness of the diffusing unit, as well as to ensure structural simplicity and convenience of the production process. Since the length of the lenticular-like ELC diffusing unit coincides with the vertical length of the LC panel, it does not affect the vertical viewing angle of the display and only changes the horizontal viewing angle.
Before the ELC diffusing unit was designed, the ideal retardation distribution of the diffusing unit (the Lambertian distribution) was calculated. This distribution is defined as a criterion for the retardation distribution of the ELC diffusing unit. The ideal shape of a diffusing unit with a Lambertian distribution was designed using the following equation, which is based on ray tracing and energy conservative mapping [21,22]:

\[ \iint T(r, z)E(r, z) \, ds = \iint I(\theta, \varphi) \, d\Omega, \]  

(1)

where \( r \) is the distance from the center of the diffusing unit (the position in the horizontal direction), and \( z \) is the height from the bottom of the unit (the position in the vertical direction). \( T(r, z) \) and \( E(r, z) \) are the transmittance and the illuminance of the incident light at \( (r, z) \) of the diffusing unit, respectively, and \( I(\theta, \varphi) \) is the intensity of the emitted light at tilt angle \( \theta \) and azimuth angle \( \varphi \). In the case of Lambertian emission, \( I(\theta, \varphi) \) can be expressed as follows:

\[ I(\theta, \varphi) = I_0 \cos \theta, \]

(2)

where \( I_0 \) is the peak intensity. The height \( z \) for any position \( r \) in the ideal diffusing unit can be obtained from Equation (1). Accordingly, the retardation distribution of the ideal unit is obtained by:

\[ \Gamma_{\text{ideal}}(r) = (n_{\text{diffuser}} - n_i)z(r), \]

(3)

where \( \Gamma_{\text{ideal}}(r) \) is the retardation according to the position \( r \) of the ideal diffusing unit, \( n_{\text{diffuser}} \) and \( n_i \) are the refractive indexes of the diffusing unit material and the incident area, respectively, and \( z(r) \) is the thickness of the diffusing unit according to the position \( r \).

For the ELC diffusing unit, the retardation according to the position is:

\[ \Gamma_{\text{ELC}}(r) = [n_{\text{eff}} - n_0]d_{\text{LC}}, \]

(4)

with

\[ n_{\text{eff}} = \sqrt{\frac{n_e^2 n_c^2}{n_c^2 \cos^2 \theta_{\text{LC}} + n_e^2 \sin^2 \theta_{\text{LC}}}}, \]

(5)

where \( \Gamma_{\text{ELC}}(r) \) is the retardation according to the position \( r \) of the ELC diffusing unit, \( n_{\text{eff}}, n_0, \) and \( n_e \) are the effective, the ordinary, and the extraordinary refractive indices of liquid crystal, respectively.
As a result, the retardation at the center of the unit is increased. However, the driving voltage and the pitch of the LC panel minimize the crosstalk which leads to the overlap of the images between adjacent pixels. The diodes of retardation and rates of change between the ideal diodes can be optimized if the electrode structure and voltage are determined so that the retardation distribution $\Gamma_{\text{ELC}}(r)$ according to the position of the ELC diffusing unit in Equation (4) can be equivalent to the ideal retardation distribution $\Gamma_{\text{ideal}}(r)$ of Equation (3). A wide viewing angle of the Lambertian distribution can be obtained if the optimized ELC diffusing is subject to an appropriate voltage.

The LC panel of the proposed LCD system uses IPS mode. Its resolution is $2960 \times 1440$, and its pixel size is $37 \times 37 \, \mu m$. The diffusing unit pitch of the ELC diffuser was set to be equal to the pixel. The pitch of the LC panel minimizes the crosstalk which leads to the overlap of the images between the adjacent pixels. The diffusing unit uses a nematic liquid crystal, which has a birefringence of 0.42 at a wavelength of 550 nm, elastic constants of $K_{11} = 12.5$ and $K_{33} = 32.1$, and dielectric anisotropy of 7.6 [23].

A maximum thickness for the maximum retardation of 15,500 nm was determined at the center of the ideal diffusing unit by applying a diffusing unit size of $37 \, \mu m$ and a refractive index of 1.5 to Equations (1)–(3). Accordingly, the cell gap needs to be at least 36.91 $\mu m$ for the birefringence of liquid crystal of 0.42 from Equation (4) to obtain the retardation of 15,500 nm in the ELC diffusing unit. In addition, the optical axis of the LC molecules needs to align in the vertical direction from the glass surface at both ends so that the retardation can become 0 to enable a 15,500 nm difference in the retardation at the center and both ends of the unit. Therefore, it is necessary to infinitely increase the applied voltage, which generates a strong vertical electric field at the electrodes and across the entire ELC diffusing unit. Consequently, the optical axes of the LC molecules are excessively arranged in the vertical direction from the glass surface such that the retardation distribution of the diffusing unit deviates from the ideal retardation distribution.

The vertical component of the electric field across the entire diffusing unit can be reduced if the applied voltage is decreased. However, in this case, the optical axes of the liquid crystals at the driving electrodes are not sufficiently arranged in the vertical direction, which increases the retardation to more than 0. Accordingly, the cell gap needs to be increased as much as the increase of the retardation at the electrodes to make the overall retardation distribution equivalent to the ideal retardation distribution. As a result, the retardation at the center of the unit is increased. However, the driving voltage and the response time of ELC diffusing unit increase if the cell gap becomes excessively large. To solve this problem, the optimal design of the ELC diffuser should consider both the driving voltage and the cell gap of the ELC diffuser.

Taguchi’s design of experiments method was used for the optimal design of factors that are influential on the optical characteristics of the ELC diffusing unit. This allows the number of simulations to be reduced effectively, and the correlation between the design factors of the ELC diffuser and retardation distribution can be obtained. Before applying the Taguchi method, the performance characteristics of the target diffuser need to be defined. The performance characteristics can be obtained by quantifying the proximity between the retardation distribution and the ideal retardation distribution.

The retardation distribution can be expressed based on retardation values at each position and their rates of change. The performance characteristics are determined by applying appropriate weights to the differences of retardation and rates of change between the ideal diffuser and the designed diffuser at each position. As the performance characteristic becomes closer to 0, the design becomes more ideal,
which is a smaller-the-better (STB) situation. Taguchi’s signal-to-noise ratio (SNR) for the performance characteristics can be calculated as follows:

\[
\text{SNR} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)
\]

where

\[
y_i = w_A \Delta \Gamma_i + w_B \frac{\Delta \Gamma_i}{dr},
\]

The ELC diffusing unit, respectively and \(w_A\) and \(w_B\) are weighting factors, which have values of 1 because they are equally important. Moreover, the selected control factors were the width of the electrode, the voltage applied to the electrode, and the cell gap. These were selected because they influence the behavior and light transmittance of liquid crystal molecules. As presented in Table 1, three levels were set for each factor by considering the physical properties of materials, the response time of liquid crystal, and the convenience of the production process.

| Factor | Description | Levels |
|--------|-------------|--------|
| A      | Applied voltage | 15 V, 20 V, 25 V |
| B      | Width of driving | 1 µm, 2 µm, 4 µm |
| C      | Cell gap | 38 µm, 40 µm, 42 µm |

Figure 2 shows the modeling results for analyzing the light transmittance of the ELC diffuser. The LC layer of the ELC diffusing unit was divided into grids. Each grid was 1 µm in the r direction and 0.1 µm in the z direction. The directions of each incident ray in the grid and the corresponding retardation can be obtained by using Snell’s law and the effective refractive indices in the grids. The direction of light transmitted through the ELC diffusing unit was identified by using the wavefront obtained from the directions of light in each grid and the corresponding retardation. The effective refractive index of liquid crystal in each grid was calculated using Equation (5). The angle \((\theta_{LC})\) was numerically obtained by using a finite difference method (FDM), which is suitable for highly nonlinear equations with de Gennes’ order tensor and the Ericksen–Leslie equation [19].

![Figure 2](image.png)

Figure 2. Modeling for ELC diffuser analysis. The LC layer is divided into grids. The behavior of LC molecules and the corresponding refractive index are calculated in each grid.

3. Results and Discussion

Table 2 presents the resulting signal-to-noise ratios (SNRs) from the simulation results for each scenario. The results were obtained from an L9 orthogonal array, which was constructed by using Taguchi’s design of experiments method. Figure 3 shows the average calculated SNRs according to the levels of each factor in Table 2. Figure 3 illustrates the relative influence of the levels of each factor on the performance characteristics. The slopes connecting the average values indicate the sensitivity of
each level to the performance characteristic. As the slope increases, the correlation to the performance characteristic also increases.

Table 2. Performance characteristics and signal-to-noise ratios (SNRs) in each simulation.

| Scenario | L9 Performance Characteristic | SNR (dB) |
|----------|------------------------------|----------|
| 1        | A=1, B=1, C=1               | 51.18335 | -34.1826 |
| 2        | A=1, B=2, C=2               | 27.07782 | -28.6523 |
| 3        | A=1, B=3, C=3               | 54.52134 | -34.7313 |
| 4        | A=2, B=1, C=2               | 33.20978 | -30.4253 |
| 5        | A=2, B=2, C=3               | 33.11352 | -30.4001 |
| 6        | A=2, B=3, C=1               | 98.72268 | -39.8883 |
| 7        | A=3, B=1, C=3               | 42.44344 | -32.5562 |
| 8        | A=3, B=2, C=1               | 68.32977 | -36.6922 |
| 9        | A=3, B=3, C=2               | 118.7621 | -41.4936 |

Figure 3. Average SNR according to the levels of each factor.

The factor levels of A1, B2, and C3 had the highest average Taguchi SNR. The corresponding applied voltage, driving electrode width, and liquid crystal thickness were 15 V, 2 and 42 µm, respectively. However, the SNR may increase if the control factor A is set to 15 V or below (level 1) and factor C is 42 µm or above (level 3). As a result, the performance is improved. Hence, it is necessary to conduct additional simulations for factors A and C.

In the case of factor C, the response time of the liquid crystal is seriously delayed if the thickness of the LC layer is excessively larger than the width of the diffusing unit, and the applied voltage becomes higher. Therefore, factor C was restricted to level 3. After factors B and C were fixed to levels 2 and 3, respectively, factor A was set to 15, 14, and 13 V, which correspond to level 1 and below. Each performance characteristic and SNR were calculated to identify the optimal values of factor A. The SNRs for 15, 14, and 13 V were −28.32, −31.23, and −33.31 dB, respectively. The SNR was highest when factor A was 15 V. Accordingly, the optimal design conditions for the applied voltage, electrode width, and cell gap of the ELC diffusing unit were 15 V, 2 and 42 µm, respectively. Under these conditions, the SNR of the performance characteristic for the retardation distribution was calculated as −28.32 dB.

Figure 4 shows the simulation results for the director distribution of the LC molecules on the cross-section of the ELC diffusing unit. The LC molecules homogeneously aligned with the same pre-tilt angle by rubbing process change to the vertical direction by applying a voltage above the threshold. In this case, the LC directors near one of the electrodes of the ELC unit are aligned in the opposite direction to the pre-tilt angle due to the mirror symmetry of the electric field distribution. As a result, the alignment of the LC molecules at the corresponding position becomes unstable, thereby leading to the disclination of the LC directors, as shown in Figure 4. Since the electrodes of the ELC unit
are located just above the black matrix, however, the optical distortion caused by the unstable behavior of the LC molecules near the edge of the unit is blocked by the black matrix and can be ignored.

Figure 4. LC directors in a cross section of the ELC diffusing unit under the optimum conditions obtained by Taguchi's method.

Figure 5 illustrates the retardation distributions of the ideal diffusing unit and the optimally designed ELC diffusing unit according to the positions. The retardation between both driving electrodes and the center of the ELC diffusing unit is lower than the ideal retardation. This occurs because the strong vertical component of the electric field heading from the driving electrodes at both ends to the common electrode makes the LC molecules excessively arranged in the vertical direction with respect to the surface. There is an inflection of the retardation distribution near the edge of a driving electrode, which is about 18 µm from the center of the unit. The inflection is caused by the distorted behaviors of LC molecules, which is attributable to the generation of the horizontal component in the electric field heading from the edge of the driving electrode to the common electrode.

Figure 5. Retardation distributions of the ELC diffusing unit and the ideal diffusing unit.

Figure 6 shows the normalized intensity of the exiting light at different viewing angles in wide-view mode. The results were calculated by ray tracing for an LCD system with the optimally designed ELC diffuser. The intensity of the exiting light was calculated by counting the number of rays that passed through the LC panel and the ELC diffuser according to the exit angles. The resulting intensity distribution was similar to the Lambertian distribution. However, the intensity of the exiting light was higher than the ideal one at a viewing angle of 50° or less but was lower at higher viewing angles.
This occurred because the discrepancy in the retardation distributions (Figure 4) results in deviation of the wavefront and direction of the exiting light from the ideal case. As shown in Figure 6, the intensity is higher than the ideal one at some viewing angles because the rays that are expected to exit at a viewing angle of at least 50° actually exit at lower angles.

![Normalized intensities of ELC diffuser and the ideal diffuser according to viewing angle.](image1)

**Figure 6.** Normalized intensities of ELC diffuser and the ideal diffuser according to viewing angle.

Figure 7 presents the normalized luminance of the exiting light according to the viewing angles, including the Lambertian distribution, wide-view mode of the LCD system with the ELC diffuser, the conventional IPS-LCD, and the calculation of the narrow-view mode with the ELC diffuser turned off. Similar to Figure 6, the luminance of the wide-view mode in Figure 7 “(b)” is generally lower than the ideal case in Figure 7 “(a)” at a viewing angle of 50° and above. However, in comparison with the IPS-LCD, a very high luminance is shown at almost all the viewing angles except in a few sections near 70°. The IPS-LCD is known to have the best wide-viewing characteristics among LCD modes. Even in comparison with the ideal Lambertian distribution, the similarity was 84.3%.

![Normalized luminance according to the viewing angle.](image2)

**Figure 7.** Normalized luminance according to the viewing angle. (a) Lambertian distribution, (b) wide-view mode of LCD system, (c) conventional IPS-LCD, and (d) narrow-view model of LCD.

To improve the similarity between the luminance distribution of the wide-view mode and the ideal Lambertian distribution, a liquid crystal with high birefringence needs to be employed to decrease the cell gap. Thus, the diffuser can be driven at a lower voltage, and the vertical component of the electric field near the electrodes can be appropriately controlled. In Figure 7 “(d)”, the collimated beam of the QCBL travels without changes of the wavefront, resulting in a narrow viewing angle. The FWHM was calculated to be 7° in the luminance distribution of the exiting light. In this case, most output light from the backlight is distributed in the front of the user. In the proposed LCD, considering that the QCBL has the FWHM of around 7°, and very few light is observed over 20° as shown in Figure 7, the
image distortion by the crosstalk between the adjacent pixels can be ignored. Consequently, bright and clear images are provided at low energy consumption.

4. Conclusions

This study proposed a novel method of controlling the viewing angle of LCDs for different usage environments by means of an ELC diffuser. The proposed LCD system was configured by attaching the ELC diffuser to the LC panel using QCBL. As the retardation of the ELC diffuser was electrically controlled, both wide and narrow viewing angles could be realized. First, to allow the ELC diffuser to have the ideal Lambertian distribution in the wide-view mode, the ideal retardation distribution was determined by using ray tracing and energy conservative mapping. Then, Taguchi’s design of the experiment method was employed to optimize the design factors of ELC diffuser (the electrode structure, the cell gap, and the applied voltage). De Gennes’ order tensor and the Ericksen–Leslie equation were used to numerically calculate the behavior of LC molecules that determine the retardation distribution of ELC diffuser. The light distribution of the LCD system was calculated through the ray tracing method.

The simulation results revealed that the light distribution of the LCD system with the ELC diffuser in the wide-view mode was 84.3% similar to the ideal Lambertian distribution and showed wide viewing angles that exceeded those of the IPS-LCD. In addition, the FWHM of the light distribution in narrow-view mode was $7^\circ$. The calculated luminance of the exiting light at a viewing angle of $20^\circ$ and above was close to 0. Consequently, the proposed LCD system shows a narrow viewing angle as the exiting light of the QCBL passes through the ELC diffuser without changing.

Author Contributions: Conceptualization, S.-C.L. and T.K.; Methodology, S.-C.L. and T.K.; Software, S.-C.L. and T.K.; Validation, S.-C.L., T.K., and W.-S.P.; Formal analysis, S.-C.L. and T.K.; Investigation, S.-C.L. and T.K.; Resources, W.-S.P.; Data curation, S.-C.L. and T.K.; Writing—original draft preparation, S.-C.L. and T.K.; Writing—review and editing, S.-C.L. and W.-S.P.; Visualization, S.-C.L. and T.K.; Supervision, W.-S.P.; Project administration, W.-S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This study was supported by the Inha University research grant.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Oh-e, M.; Kondo, K. Electro-optical characteristics and switching behavior of the in-plane switching mode. Appl. Phys. Lett. 1995, 67, 3895–3897. [CrossRef]
2. Lee, S.H.; Lee, S.L.; Kim, H.Y. Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching. Appl. Phys. Lett. 1998, 73, 2881–2883. [CrossRef]
3. Schadt, M.; Seiberle, H.; Schuster, A. Optical patterning of multidomain liquid-crystal. Nature 1996, 381, 212–215. [CrossRef]
4. Kim, K.H.; Jeon, E.Y.; Park, B.W.; Choi, S.W.; Song, D.H.; Kim, H.; Shin, K.C.; Kim, H.S.; Yoon, T.H. High-transmittance multi-domain vertical alignment liquid crystal device with protrusion structure. J. Opt. Soc. Korea 2012, 16, 166–169. [CrossRef]
5. Zhu, X.; Ge, Z.; Wu, S.T. Analytical solutions for uniaxial-film compensated wide-view liquid crystal displays. J. Display Technol. 2006, 2, 2–20. [CrossRef]
6. Zhu, R.; Hong, Q.; Gao, Y.; Luo, Z.; Wu, S.T.; Li, M.C.; Lee, S.L.; Tsai, W.C. Tailoring the light distribution of liquid crystal display with freeform engineered diffuser. Opt. Express 2015, 23, 14070–14084. [CrossRef]
7. Lim, Y.J.; Jeong, E.; Kim, Y.S.; Jeong, Y.H.; Jang, W.G.; Lee, S.H. Viewing Angle Switching in Fringe-Field Switching Liquid Crystal Display. Mol. Cryst. Liq. Cryst. 2008, 495, 186–193. [CrossRef]
8. Kim, M.S.; Lim, Y.J.; Yoon, S.; Kang, S.W.; Lee, S.H.; Kim, M.; Wu, S.T. A controllable viewing angle LCD with an optically isotropic liquid crystal. J. Phys. D Appl. Phys. 2010, 43, 145502–145507. [CrossRef]
9. Lim, Y.J.; Kim, J.H.; Her, J.H.; Bhattacharyya, S.S.; Park, K.H.; Lee, J.H.; Kim, B.K.; Lee, S.H. Viewing angle controllable liquid crystal display with high transmittance. Opt. Express 2010, 18, 6824–6830. [CrossRef]
10. Jeong, E.J.; Chin, M.H.; Lim, Y.J.; Srivastava, A.K.; Lee, S.H.; Park, K.H.; Choi, H.C. Switching of off-axis viewing quality in twisted nematic liquid crystal display by controlling phase retardation of additional liquid crystal layers. *J. Phys. D Appl. Phys.* **2008**, *104*, 033108. [CrossRef]

11. Kim, M.S.; Lim, Y.J.; Yoon, S.; Kim, M.K.; Kumar, P.; Kang, S.W.; Kang, W.S.; Lee, G.D.; Lee, S.H. Luminance-controlled viewing angle-switchable liquid crystal display using optically isotropic liquid crystal layer. *Liq. Cryst.* **2011**, *38*, 371–376. [CrossRef]

12. Chen, B.T.; Pan, J.W.; Hu, Y.W.; Tu, S.H. Design of a novel hybrid light guide plate for viewing angle switchable backlight module. *SID Symp. Digest* **2013**, *44*, 1181–1184. [CrossRef]

13. Wang, Y.J.; Lu, J.G.; Chao, W.C.; Shieh, H.D. Switchable viewing angle display with a compact directional backlight and striped diffuser. *Opt. Express* **2015**, *23*, 21443–21454. [CrossRef]

14. Patel, J.S.; Rastani, K. Electrically controlled polarization-independent liquid-crystal Fresnel lens arrays. *Opt. Lett.* **1991**, *16*, 532–534. [CrossRef]

15. Presnyakov, V.V.; Galstian, T.V. Electrically tunable polymer stabilized liquid-crystal lens. *J. Appl. Phys.* **2004**, *97*, 103101. [CrossRef]

16. Ren, H.; Fan, Y.H.; Wu, S.T. Polymer network liquid crystals for tunable microlens arrays. *J. Phys. D Appl. Phys.* **2004**, *37*, 400–403. [CrossRef]

17. Seo, D.S.; Lee, S.H.; Fung, Y.K.; West, J.L.; Gelerinter, E. A Study of Hysteresis and Bistability in a Polymer Stabilised Nematic Liquid Crystal Using Paramagnetic Resonance and Electro-Optical Studies. *Mol. Cryst. Liq. Cryst.* **1996**, *287*, 101–107. [CrossRef]

18. Hong, H. Analysis of the performance of the electric-field-driven liquid crystal lens (ELC Lens) for light of various incident angles. *Liq. Cryst.* **2012**, *39*, 1055–1061. [CrossRef]

19. Jung, S.M.; Jang, S.H.; Park, H.D.; Park, W.S. Determination of all the resistances within a pixel of a TFT-LCD by using a three-dimensional simulation. *J. Korean Phys. Soc.* **2004**, *44*, 190–194.

20. Taguchi, G.; El Sayed, M.; Hsaiing, C. *Quality Engineering and Quality System*; Mcgraw-Hill: New York, NY, USA, 1989.

21. Fournier, F.R.; Cassarly, W.J.; Rolland, J.P. Fast freeform reflector generation using source-target maps. *Opt. Express* **2010**, *18*, 5295–5304. [CrossRef]

22. Chen, E.; Wu, R.; Guo, T. Design a freeform microlens array module for any arbitrary-shape collimated beam shaping and color mixing. *Opt. Commun.* **2014**, *321*, 78–85. [CrossRef]

23. Nowinowski-Kruszelnicki, E.; Kędzierski, J.; Raszewski, Z.; Jaroszewicz, L.; Kojdecki, M.; Piecek, W.; Perkowski, P.; Garbat, K.; Oliferczuk, M.; Sutkowski, M.; et al. High birefringence liquid crystal mixtures for electro-optical devices. *Opt. Appl.* **2012**, *42*, 167–180.