Multidomain LCDs and Complex Optical Retarders Generated by Photo-Alignment

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Abstract

Photo-alignment of liquid crystal displays (LCDs) with our linear photo-polymerisation (LPP)-technology enables well defined boundary conditions such as high anchoring strength and stable, pretilt angles [1,2]. We report a photo-aligned four-domain vertical aligned nematic (VAN)-LCD. The display is compensated by a new VAN-compensator which is based on our LPP- and liquid crystal polymer (LCP)-technology. The four-domain VAN-LCD exhibits an excellent off-state angular brightness performance which exceeds crossed polarizers.

To further simplify photo-patterning of LPP-alignment, an alignment master is proposed which generates complex alignment patterns in a single exposure step. An example of a dual-domain 80° TN-LCD is presented which is LPP-photopatterned via the new master.

1. Introduction

Apart from the well known drawbacks of conventional rubbing alignment, such as the generation of dust and electrostatic charges, new limitations become obvious as the LCD technology progresses. Problems arise for instance from the increasing size of the motherglass used for desktop LCDs where uniform alignment and well defined pretilt angles over the entire substrate area are more and more difficult to achieve. On the other hand, the limitations of rubbing become also evident when aligning small substrate sizes of LCDs designed for high resolution microdisplays in projectors and small portable electronic instruments. For instance, scratches generated during rubbing become visible due to the strong optical magnification and reduce contrast. Because there is no mechanical contact with the substrate surface, photo-alignment solves all of the above problems. In addition, photo-alignment allows to generate alignment patterns rendering multidomain twisted nematic (TN-) [1,3], supertwisted nematic (STN-) [2] and vertically aligned nematic (VAN-) [4] LCDs with improved viewing angle feasible.

Large sized liquid crystal displays become more and more dominant for desktop applications. However, for LCDs to successfully compete with CRTs, different requirements have to be met. Among these are low costs, high brightness and high contrast over large angles of view. To increase contrast, strong activities to develop multidomain VAN-LCDs have recently been started. However, most of the techniques used to control the demanding liquid crystal alignment in the different domains require additional photolithographic process steps, which lower production yield, reduce brightness and increase costs.

On the other hand, most of today’s high resolution LCDs make use of external compensation films to improve contrast, to get rid of intrinsic coloration and/or to enhance the viewing angle. Much progress has been made in the past few years to design optical films such as biaxial retarders, negative birefringent retarders and retarders exhibiting tilted optical axes to improve LCD performance. The classical technique of stretching plastic films to produce uniaxial retarder films with in-plane optical axis can hardly be applied to modern compensation films which require complex optical axes configurations. We have shown that stacks of retarder layers with various configurations can be generated with liquid crystal polymers (LCP) which are photoaligned by LPP layers [5]. For example, retarders with off-plane optical axes can easily be realized with our LPP/LCP technology by generating a pretilt angle during the LPP exposure process [1]. Hence, any tilt angle between 0° and 90° as well as complex tilt angle distributions can be achieved in LCP-layers. Because LCP retarders are based on liquid crystalline materials, their dispersion is similar to the dispersion of the liquid crystal in the LCD. Therefore, the use of optical compensators based on nematic LCP-materials enables to realize wavelength independent compensation.

In this paper we show that a four-domain VAN-LCD can be realized by photo-alignment using novel vertical photo-aligning LPP-materials developed in our labs. The angular contrast dependence of the four-domain VAN-LCD will be shown to further strongly improve when compensated by a new type of VAN-compensator which is also based on our LPP/LCP technology.

To reduce the number of steps required for photo-patterning LPP-layers we developed an alignment master which enables to generate complex alignment patterns in a single exposure step. Results of a dual-domain 80° TN-LCD which was photo-patterned via the new alignment master demonstrate the remarkable angular contrast improvement achieved by this technique.
2. Optical Compensation of Multidomain, Photo-Aligned VAN-LCDs by LPP/LCP Films

2.1 Photo-Aligned Four-Domain VAN LCD

Although VAN-LCDs offer extremely large contrast as long as light propagates vertically through the cell, the strong angular dependency of gray levels prohibits the use of mono-domain VAN-LCDs in direct view applications. However, self-compensating multidomain VAN-configurations were shown to greatly enhance the viewing angle. Fringe field effects [6] and surface topologies [7, 8] which were so far mainly used to control the liquid crystal tilting directions of the different domains, require both additional photolithographic steps which decrease production yield, add costs and reduce brightness.

Recently, we have presented the first photo-aligned dual-domain VAN-LCD incorporating novel LPP-materials designed for slightly off-axis vertical alignment [4]. To generate the two domains, only one substrate had to be photo-patterned using a double exposure process which required a photomask only for the first exposure step.

![Fig. 1](image1.png) Geometry of an LPP-photo-aligned four-domain VAN-LCD, comprising our new external BC-compensator for optimal off-state compensation.

To further improve the viewing angle, we have realized a LPP-photo-aligned four-domain VAN-LCD with a domain size of 100 x 100µm. The configuration which we used (fig. 1) requires only one of the substrates to be photo-patterned to define the domain tilt direction, whereas homeotropic alignment without any pretilt angle is sufficient on the second substrate. Because the photomask was designed such that it could be shifted to each of the four subpixel positions, the same mask could be used for each of the four exposure steps which are required to control the different subpixel alignment directions on the lower substrate.

![Fig. 2](image2.png) Micrograph of the four differently photo-aligned VAN-domains.

The optical appearance of the four subpixels at 50% vertical transmission is shown in the micrograph of fig. 2. Because adjacent domains are aligned perpendicular to each other, as indicated by the arrows in fig. 2, twist deformations are induced at the domain boundaries which appear black between crossed polarizers which are arranged 45° with respect to the domain alignment directions. Of course any other alignment configuration can be realized by the LPP-photo-alignment technology. For example, in a configuration exhibiting parallel alignment of neighboring domains, disclination lines at the domain boundaries are formed upon applying a voltage which appear bright, thus increasing the overall brightness of the display.

2.2 New LPP/LCP Compensation Films for VAN-LCDs

Multidomain configurations strongly improve the azimuthal viewing angle dependence of VAN-LCDs, however, the strong polar viewing angle dependence of the dark state has to be compensated by external optical retarders. Negative birefringent retarders are known to compensate the off-axis birefringence of the homeotropic liquid crystal configuration of a VAN-LCD [9], whereas the introduction of an additional positive birefringent planar retarder further improves the viewing angle of a VAN-LCD [10]. As an alternative to stretched plastic films, a cholesteric liquid crystal display comprising an ultra-short pitch helical twist which shifts the selective reflection band to wavelengths shorter than the range of visible light was proposed as a negative birefringent compensator [11]. However, because of the additional weight and costs, LCDs are not acceptable as compensators.

Fig. 3 Configuration and geometry for optimal VAN-LCD compensation with our new LPP/LCP BC-compensator.

We have realized a new biaxial compensator based on our LPP/LCP technology which comprises an LPP-photoaligned planar retarder and a solid state negative birefringent cholesteric filter (NBCF). Because the planar LCP-retarder induces alignment in the NBCF, the new Biaxial Cholesteric based Compensator (BCC) consists of only three layers on a single substrate (fig. 3). Since neither mechanical stretching nor rubbing are involved, the new compensator is ideally suited for roll to roll plastic film manufacturing [12]. Both the planar retarder and the cholesteric filter are based on positive birefringent LCP-materials with ordinary and extraordinary refractive indices $n_o$ and $n_e$, respectively. Due to the exceptional high helical twisting power designed into the cholesteric material, we managed to shift the selective reflection band well below the visible wavelength range. As a consequence, the effective refractive index for visible light in the plane perpendicular to the helical axis averages to

$$n_p = \sqrt{\frac{n_o^2 + n_e^2}{2}} \quad [13]$$

whereas the refractive index along the helical axis $n_p'$ equals the ordinary index of refraction $n_o$ of the LCP-material, thus:

To test the BCC performance, we have compensated the above four-domain VAN-LCD using the configuration depicted in fig. 3. The optical retardations of the planar retarder and of the NBCF were 140nm and $-340\text{nm}$ respectively, whereas the pitch of the cholesteric NBCF layer was set to 250nm. In the measurement set-up the alignment directions of the VAN-LCD were arranged parallel and perpendicular to the horizontal direction whereas the crossed polarizers were at $45^\circ$ and $135^\circ$, respectively. The measurements of the transmission versus horizontal viewing angle in fig. 4 demonstrate the excellent compensation performance of our new BC-compensator: The off-state viewing angle dependence of the BCC-compensated four-domain VAN-LCD is even much better than that of a reference LCD comprising only an isotropic index matching fluid. The measurement of the angular contrast dependency in fig. 5 shows high symmetry and a very high contrast over an extremely large viewing angle range. The result confirms the excellent performance of both, the LPP-photoaligned four-domain VAN-LCD as well as the new LPP/LCP based BC-compensator.

Fig. 5 Angular dependence of the contrast of an LPP-photoaligned four-domain VAN-LCD compensated by a BC-compensator.

3. LPP-alignment master

While four exposure steps were required to achieve the domain divided alignment of the above four-domain VAN LCD, alignment patterns of even much higher complexity can be generated in a single exposure step by using an alignment master. The principle of an alignment master is to spatially generate or modify the polarization of incident light. Therefore, the light transmitted through the alignment master forms a spatial polarization pattern, which when projected onto an LPP-layer, generates the desired alignment pattern. The pattern of the alignment master - which may comprise a very high number of different directions, including continuous variations - can be produced very elegantly with our
LPP/LCP-photo-aligning technology. There are different approaches on how to realize an alignment master [14]. Examples are:

- A patterned half wave retarder exhibiting locally varying optical axes which cause the polarization plane of incident light to rotate according to the pattern.
- A microstructured polarizer which generates polarized light from non-polarized incident light with locally different polarization directions.

Our approach presented in the following uses a passive multidomain liquid crystal cell which locally rotates the plane of incident uv-polarization (fig. 6). Only one of the cell substrates exhibits an LPP-photoalignment pattern, whereas the other substrate is uniaxially aligned. The polarization of light which is polarized parallel to the liquid crystal alignment at the cell input (fig. 6) is rotated according to the local liquid crystal twist angle while propagating through the cell. Therefore, the polarization direction of the transmitted light parallels the desired local liquid crystal alignment direction at the lower substrate; i.e. at the output of the cell (fig. 6). The polarization pattern is then projected onto an LPP-coated substrate which is photopatterned in a single step. To warrant perfect linear polarization of the transmitted light, the master cell must be operated in a wave-guiding condition for uv-light (\(\lambda = 310 \text{nm}\)) was satisfied. To visualize the left and right handed twisted domains of the LCD-master in fig. 7 (left), the analyzer direction was set asymmetrically to the respective alignment directions. Therefore, the stripes appear bright and dark.

As an example, we have realized a dual-domain alignment master which can be used to generate the alignment pattern of a dual-domain 80° TN-LCD in a single exposure step. The two domains of the master are stripes of 100μm width exhibiting alternating left and right handed twist of -80° and +80°, respectively. To minimize parallax in a direct contact exposure, we used a 0.2mm thin glass for the lower master substrate, whereas a 1.7mm thick uv-transmissive glass was used for the upper substrate. Because a cell gap of \(d=20\mu\text{m}\) was chosen for the master the wave-guiding condition for uv-light (\(\lambda = 310\text{nm}\)) was satisfied. To visualize the left and right handed twisted domains of the LCD-master in fig. 7 (left), the analyzer direction was set asymmetrically to the respective alignment directions. Therefore, the stripes appear bright and dark.

We used the above master to generate the alignment pattern for a dual-domain 80° TN-LCD. The first of the two LPP-coated LCD substrates was uniaxially photoaligned by obliquely incident polarized uv-light to induce a pretilt angle of 5°. The LCD-master was in direct contact with the second LPP-coated substrate which was exposed to vertically incident linearly polarized uv-light. Therefore, no pretilt angle was induced in the patterned alignment of the second substrate. The micrograph of the dual-domain 80° TN-LCD which was built from the two substrates (fig. 7, right) shows that the aligning
information of the master was successfully transferred within a single exposure step.

![Image](https://via.placeholder.com/150)

**Fig. 8** Angular dependence of a ±80° twisted dual-domain TN-LCD (top) and of a single-domain 90° TN-LCD (bottom).

The measurements of the angular contrast dependencies in fig. 8 demonstrate the increased horizontal viewing angle of the ±80° dual-domain TN-LCD compared with a conventional single-domain 90° TN-LCD. However, a variety of other multidomain configurations with and without simple uniaxial retarders for further viewing angle improvement can be realized with an LPP-alignment master without increasing the number of process steps. This enables to manufacture multidomain LCDs using a single LPP-photo-aligning exposure step.

Apart from multidomain LCDs, complex LPP-aligning patterns for LCP layers can also be realized in a single exposure step using an alignment master. This considerably simplifies the production of patterned retarders, polarizers and color interference filters.

4. Summary

A photoaligned four-domain vertical aligned LCD was realized using novel LPP-photo-aligning materials for vertical alignment. Using a new biaxial compensator based on our LPP/LCP technology, excellent off-state compensation of the VAN-LCD is achieved which results in an angular dark state dependency of the display which is better than that of crossed polarizers.

We have developed an alignment master concept which allows to generate complex alignment patterns in LPP-layers in a single exposure step. This enables to photo-pattern LPP-alignment layers in mass production. Multidomain LCDs, complex patterned optical retarders and polarizers can therefore be made in a single exposure step.

References