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The alignment of nematic liquid crystals on photolithographic micro-groove patterns

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The alignment of nematic liquid crystals on micro-groove patterns was studied. It has been found that the order of the alignments is determined by the edge shape, spacing, and line pitch of the micro-groove patterns. On coarse patterns, with pitches greater than 2 μm, striped patterns of the liquid crystal alignment were observed using polarized light which manifested different orientations of the liquid crystals on the top, edge, and bottom of the grooves, respectively. On fine patterns, with pitches less than 2 μm, a uniform device-quality alignment has been realized, with which twisted nematic cells were constructed in combination with the rubbed alignment layer on the opposite substrate. Their viewing angle characteristics and tilt orientations of the director were also investigated.

1. Introduction

It was shown by Kanel and Litster that micro grooves, for example, an optical grating, and micro-groove patterns fabricated by the photolithographic technique effectively aligned liquid crystals [1, 2, 3].

Generally, the alignment of liquid crystals on microgroove patterns is dominated by the elastic energy of the liquid crystal material on the grooved surface [4, 5, 6].

A device-quality alignment due to surface roughness is realized only through the oblique evaporation of SiO [7, 8]. The evaporated surface is covered by obliquely grown rod-like crystallites which are much smaller than photolithographic groove patterns. Photolithographic grooves are more convenient to use than the oblique evaporation method in order to study the surface elastic energy effect on liquid crystal alignment, because photolithographic patterns are fabricated into a specified dimension and simple geometry. It seems that the liquid crystal alignment technique through micro-grooves has not yet been fully investigated for actual display device fabrication other than for pure scientific interest. The authors fabricated the alignment layer with simple line and space patterns (micro-grooves) and analysed the alignment of nematic liquid crystals 5CB (*n*-pentylcyanobiphenyl, and ZLI-3276-100 (E. Merck, Darmstadt; a nematic liquid crystal mixture containing chiral materials) on the grooved surface with various spacings and pitches.

It has been found that a uniform device-quality alignment is realized by reducing the pitch of the line and space to less than 2 μm. A twisted nematic device was constructed in combination with the conventional rubbed surface. This device, with

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the combined alignment layer (hybrid alignment), was analysed with regard to the electro-optical characteristics—the viewing angle and the tilt direction under an electric field.

2. Experiment

2.1. *Fabrication of the alignment layer with micro-grooves*

Micro-grooves were fabricated by using photo-curable polyimide resin (Probimide: Ciba-Geigy Ltd.) through a photolithographic process. The photo-curable polyimide resin was spin-coated 300–1000 nm thick onto a glass substrate. The coated film was prebaked at 110°C for 15 minutes prior to exposure. A UV exposure with a 356 nm mercury lamp was carried out with the Nikon PLA-105 contact exposing machine. The dimension of the pattern is determined by the width of the line and space, as shown in figure 1, which illustrates the structure of the surface with the micro-groove pattern. The shape of the pattern was varied by the process conditions. Thus it was possible to control the edge sharpness of the pattern by adjusting the exposure time and development condition.

2.2. *LCD-cell fabrication*

Three types of liquid crystal cell were fabricated to investigate the liquid crystal alignment, including in-plane orientation and tilt direction of the nematic director on the grooved surface. The combinations of the alignment layer of the cells are listed in the table. The rubbed surface was coated with polyimide resin (Optomer AL-1051, Japan Synthetic Rubber Co.) 100 nm thick. The surface treated glass substrate was obtained through immersion into a water solution of octadecylethoxysilane, followed by drying and heat-curing at 90°C for 1 hour.

2.3. *Liquid crystals*

5CB and ZLI 3276-100 were used to observe the alignment on the micro-grooved surfaces. ZLI 3261 (Merck, Darmstadt, guest–host type nematic liquid crystal mixture) was used to indicate the orientation of the liquid crystal director and tilt direction on the micro-grooved surfaces [9].

2.4. *Microscopic observations of liquid crystalline alignment*

The alignment of the liquid crystals on the micro-grooved surfaces was observed by polarizing light microscopy. The tilt directions, in which the director on the surface rose up with the tilt angle, were determined from the observation of the conoscopic figure, where the shift of the isogyre reflected the tilting [10].

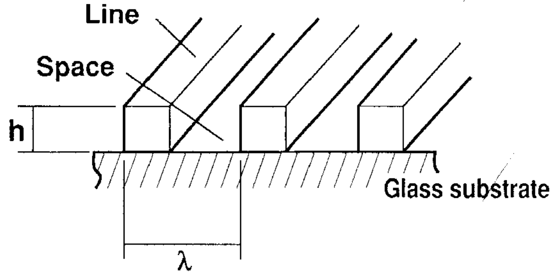


Figure 1. Schematic drawing of the micro-groove pattern; h and λ are the height and pitch of the lines, respectively.

Structures of the three types of cells.

Alignment layer	LC material	Type No.
Micro-groove Polyimide rubbing	5CB† ZLI 3276-100‡	1 (TN: Left-handed twist)
Micro-groove Micro-groove	5CB ZLI 3276-100	2 (TN: Left-handed twist)
Micro-groove Active agent (ODSE§)	ZLI 3261 (guest-host)	3 (Hybrid)

† 5CB: *n*-pentylcyanobiphenyl.

‡ ZLI-3276-100: E Merck, nematic liquid crystal mixture containing chiral materials.

§ ODSE: octadecylethoxysilane.

Optical transmission measurement with a rotating sample cell, sandwiched between parallel polarizers, was carried out to measure the uniformity of the twisted nematic liquid crystal alignment. Transmission was obtained as a function of the in-plane rotation angle. The experimental set-up is shown in figure 2.

3. Results

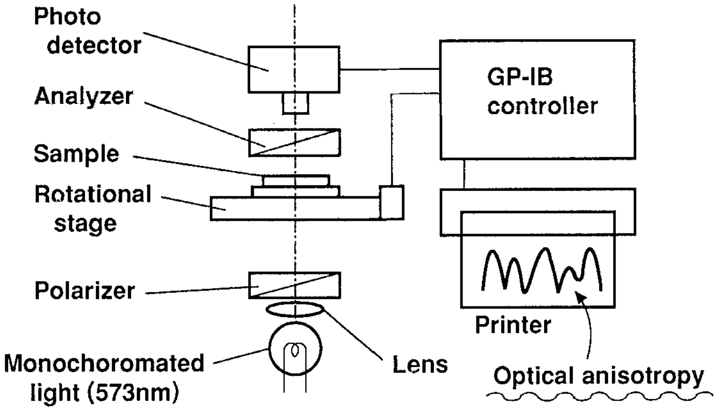
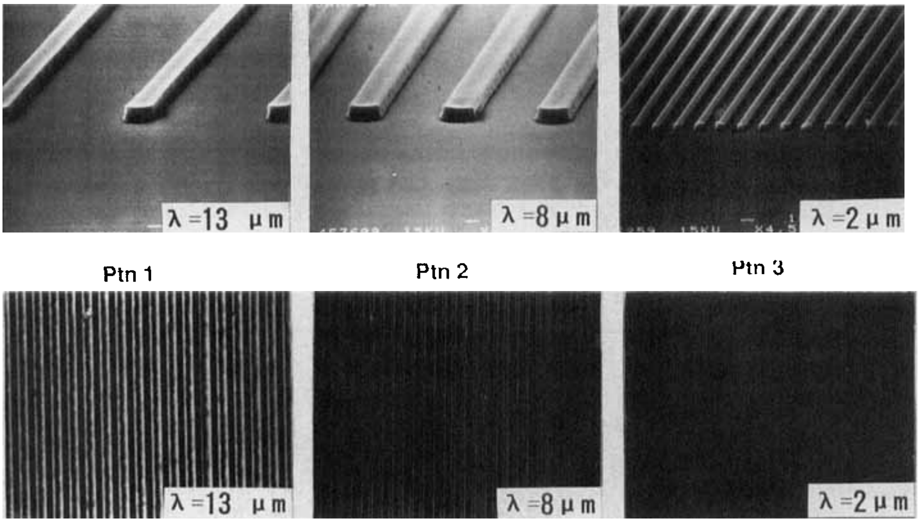


Figure 2. The optical anisotropy measurement system between parallel polarizers.

3.1. *Molecular alignment on micro-grooved patterns*

Figure 3 shows three types of micro-grooved pattern and the liquid crystal alignment on them. In figure 3 (*a*), the line pitch and spacing were 13 μm and 10 μm, respectively. The liquid crystal alignment showed two different domains in the striped pattern using parallel polarizers. In one domain, the director aligned along the line. In another domain, the liquid crystals aligned with some tilt angle.

In figure 3 (*b*), the line pitch and spacing were 8 μm and 5 μm, respectively. The alignment was quite uniform, as shown in figure 3 (*b*), except for a shiny lines, which could be observed by disclination lines, in the middle of the space between the lines.



(*a*) (*b*) (*c*)

Figure 3. Three types of micro-groove pattern and liquid crystalline molecular alignment using parallel polarizers. (*a*) Pattern 1, $\lambda = 13\,\mu$m; (*b*) Pattern 2, $\lambda = 8\,\mu$m, (*c*) Pattern 3, $\lambda = 2\,\mu$m. Hybrid TN-LCD cells fabricated with micro-grooved and rubbed substrate (type 1).

In figure 3 (*c*), the line pitch and spacing were 2 μm and 1 μm, respectively. In this case, the alignment was almost completely uniform and only fine lines of disclination on the edge of the pattern were observed. Accordingly as the pattern pitch λ decreased, the molecular alignment became uniform.

Figure 4 shows the effect of pattern sharpness on the liquid crystal alignment. The dull pattern and semi-cylindrical lines were fabricated through the multiple

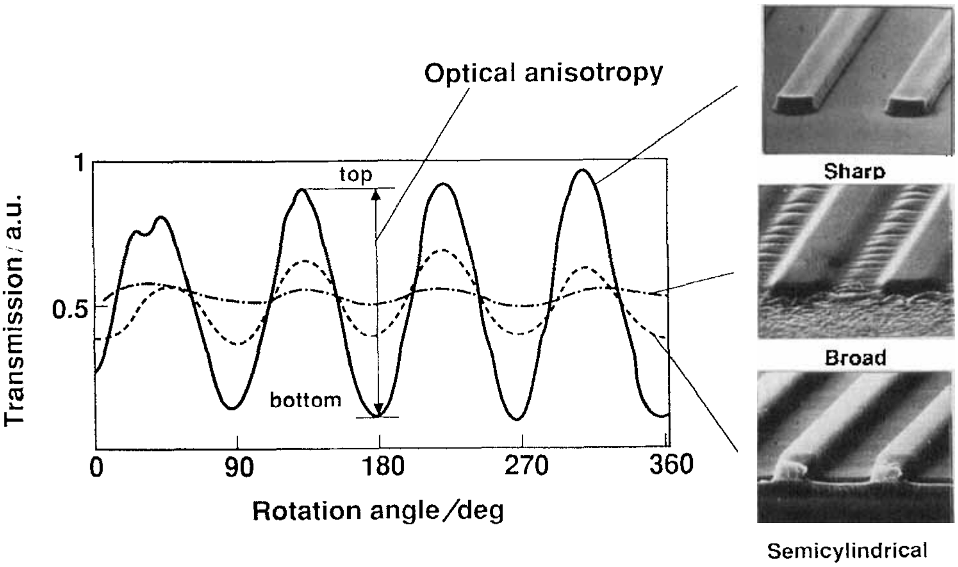


Figure 4. The effect of pattern sharpness on optical anisotropy. Rotating sample cells were sandwiched between parallel polarizers ($\lambda = 8\,\mu$m, $h = 1\,\mu$m: (*a*), (*b*), (*c*)).

exposure technique. The transmittance of the monochromated light (573 nm) using parallel polarizers is also indicated in figure 4 as a function of the in-plane rotational angle. As the uniformity of the alignment increased, the difference between the top and bottom of the curve increased, reflecting the decreasing contribution of the depolarizing light scattering from the disclination lines and defects. Accordingly, as the pattern sharpness increased, the optical anisotropy increased. This tendency indicates a significant contribution of the elastic energy of the liquid crystals on the edge of the line.

3.2. *Pre-tilt angle and tilt direction*

The pre-tilt angle plays a significant role in constructing a twisted nematic (TN) cell to prevent the occurrence of a reverse-tilt disclination. If the alignment layer has neither pre-tilt angle nor a preferential tilt-up direction of the nematic director on the surface, a reverse-twist and reverse-tilt disclination may appear with the orientation of the director under an electric field.

Figure 5 shows the alignment of the twisted nematic liquid crystal in an area of $1{\cdot}5 \times 1{\cdot}8\,\mathrm{mm}^2$. A fairly uniform alignment was realized both in type 1 and 2 TN cells without an electric field (normally white condition). Under an electric field, however, several reverse-tilt disclination lines appeared in the type 2 cell, as indicated in figure 5 (*d*). The bright striped grids show the electrode pattern. On the other hand, in the type 1 cell, no disclination lines appeared even under an electric field. This implies that the pre-tilt angle and tilt-up direction on the grooved surface were dominated by the rubbed surface on the opposite side.

A type 3 cell was fabricated to analyse the pre-tilt angle and tilt-up direction on the surface of micro-grooves. In this type 3 cell, which had a homeotropically

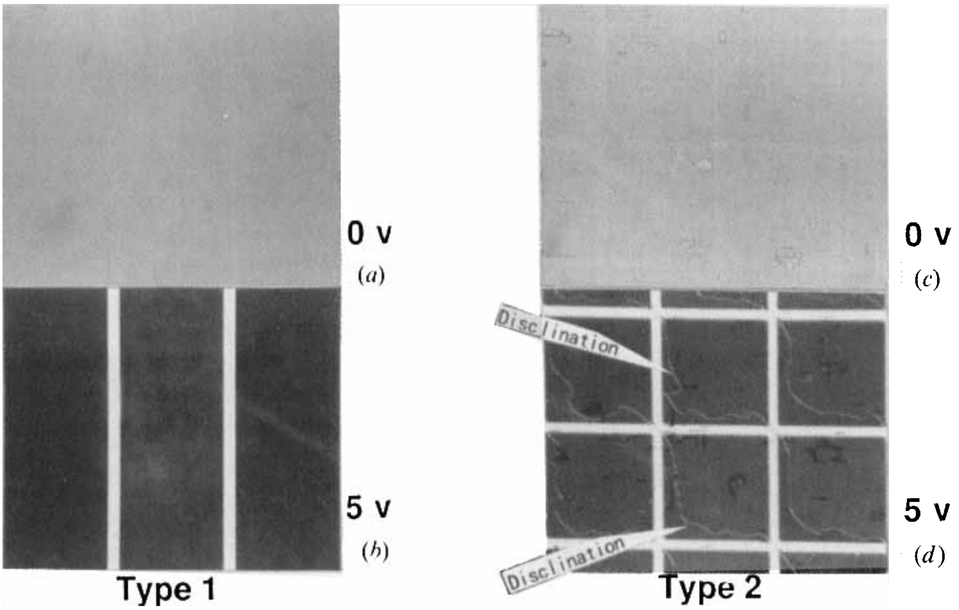


Figure 5. Microphotographs showing the conditions of the liquid crystal alignment under an electric field. The sample cells were sandwiched between parallel polarizers. Type 1 cell showed a uniform change (*a*)→(*b*) without any disclination line. Type 2 cell showed dual conditions (*c*)→(*d*) with disclination lines (arrows).

aligned surface on one substrate, the director alignment on the grooved surface was directly indicated through the absorption axis of the dichroic guest dye. Figure 6 shows a photograph of the type 3 cell on a fluorescent light box, through a polarizer at an oblique viewing angle. The directional vector of the viewing angle lies in a plane spanned by the normal to the grooved surface and the groove direction.

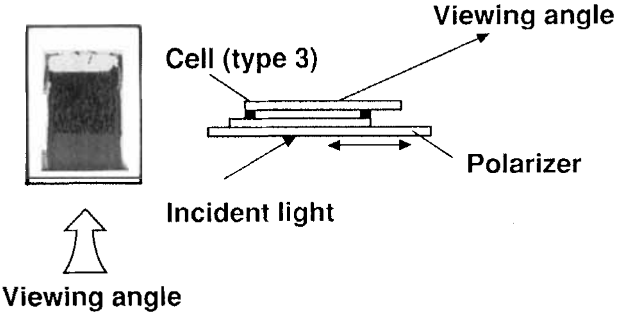


Figure 6. Photograph of the hybrid cell (type 3) taken at an oblique angle (left), and a schematic drawing of the cell and the illumination conditions. ZLI 3261 (E Merck: guest-host type nematic liquid crystal mixture) was used.

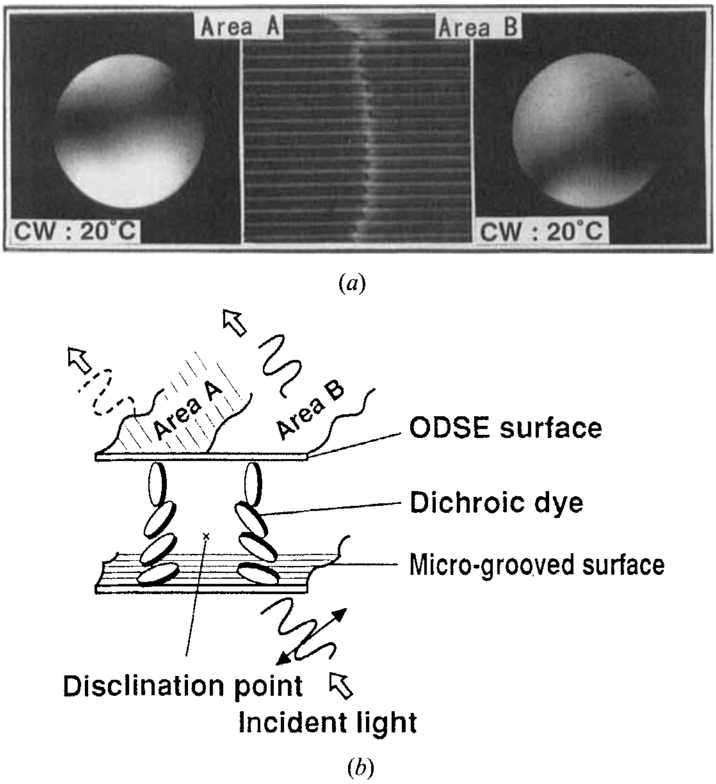
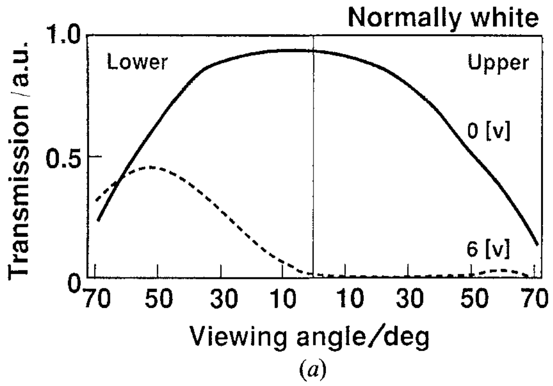


Figure 7. (*a*) Tilt reverse domains (area *A*, *B*) near the disclination line and their conoscopic images. (*b*) The molecular conformation model of tilt reverse domains in the hybrid cell (type 3).



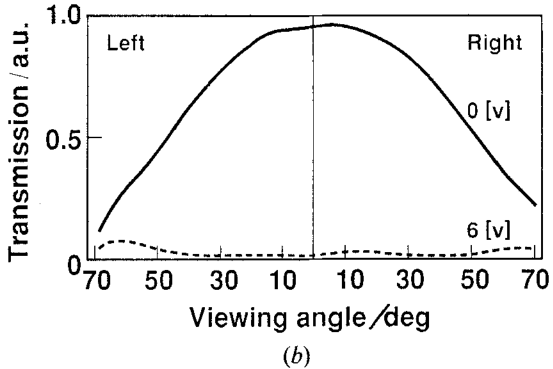


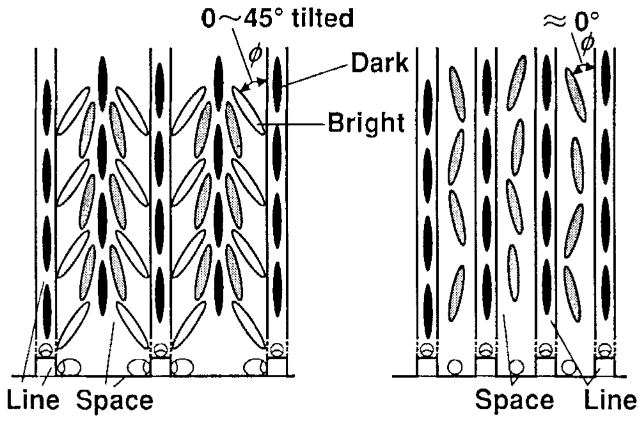
Figure 8. Viewing angle dependence of the optical transmission for the hybrid cell fabricated with micro-grooved and rubbed substrates. (*a*) Upper–lower direction; (*b*) left–right direction.

Conoscopic images of the domains *A* and *B* which were separated by a reverse-tilt disclination line are shown in figure 7 (*a*). The isogyres in both interference images were diffuse, indicating that the azimuthal angle of the liquid crystal director in the type 3 cell was not uniform due to the hybrid alignment [11]. The isogyres of both images shifted in an opposite direction with respect to each other. The mosaic-like domains showed the dispersion of the tilt-up direction domain by domain. In a dark domain, the nematic director tilted up in a direction to increase the absorption of the dye, whereas in a bright domain, the nematic director tilted up in an opposite direction to reduce the dye absorption. The director configuration can be described schematically as in figure 7 (*b*).

As shown in this analysis, a uniform pre-tilt and tilt-up direction were not realized on the micro-grooved surface. On the other hand, combination with a rubbed polyimide layer for the opposite substrate surface could afford an alignment in which the pre-tilt direction was determined subsidiarily, even on micro-grooves.

3.3. *Viewing angle of the hybrid cell*

For the device application of micro-grooves, the authors studied a cell fabricated with a micro-grooved surface and rubbed polyimide, i.e. a hybrid cell, type 1. The viewing angle dependences of optical transmittance with and without an electric field were measured, as indicated in figures 8 (*a*) and (*b*). They are similar to those of



(*a*) λ≧10μm (*b*) λ≦2μm

Figure 9. A model for molecular alignment on micro-grooved patterns and conditions of optical transmission with parallel polarizers.

normal cells with a polyimide alignment layer treated by the rubbing process on both sides [12–14].

This implies that the tilt-up direction on a micro-grooved surface is subsidiarily determined by the opposite alignment layer. The determination of the tilt-up direction by the surface on the opposite substrate has been confirmed in all other hybrid-type cells.

4. Discussion

The authors obtained a uniform alignment of the nematic liquid crystal on micro-grooved patterns fabricated by the photolithographic process. The detailed mechanism for the alignment of a nematic liquid crystal along the micro-grooved pattern has not yet been fully clarified. Regarding the alignment of nematic liquid crystals, only a micro-grooved surface can be described using the elastic theory of liquid crystals, as shown schematically in figure 9 (*b*) where the pitch λ of the pattern is smaller than $2\,\mu$m, in the experiment. However, for patterns with a large pitch, there appears a striped alignment structure in the space between the lines, as described in figure 9 (*a*), in which the nematic director is attached to the side wall of the line at an angle ϕ. This angle ϕ was in the range $0\sim45°$, and was confirmed by the absorption directions of dichroic dye in the type 3 cell. The director bends to an orientation parallel with lines in the middle of the space to avoid a disclination line. This can be considered to be the explanation of the striped figure in figure 3 (*a*). This side wall effect is thought to be a similar phenomenon to the normal alignment of a nematic liquid crystal in a capillary tube [15–17].

On the other hand, when the pattern pitch λ was smaller than $2\,\mu$m, the liquid crystal aligned uniformly without the side wall effect. In this case, the configuration was unstable; the liquid crystal molecules aligned with some tilt angle near the surface of both side walls in the groove, because the width was no sufficient for the liquid crystals to avoid disclination lines by director bending. Thus, a nematic liquid crystal is considered to prefer distortion on the side walls with a parallel alignment, and uniform alignment on a micro-grooved surface can be realized.

Furthermore, a hybrid cell fabricated with a micro-grooved surface and rubbed surface exhibited a uniform tilt-up direction even on the micro-grooved surface. This suggests that these uniform tilt-up directions on the micro-grooved surface were formed by opposite alignment layers. Figure 10 shows a molecular conformation model of the type 1 cell under an electric field. A rubbed surface shows a uniform tilt-up direction, but a micro-grooved surface has no preferential tilt-up direction because of the two-fold in-plane symmetry of the pattern. Thus, a hybrid cell has the possibility of two choices of director configuration: one is a splayed configuration with left-handed twist and the other is non-splayed. Generally, the elastic free energy is higher in a splayed than a non-splayed configuration. Therefore, non-splayed configurations were selected.

5. Summary

A method for the molecular alignment of nematic liquid crystals on micro-grooves was investigated. Surfaces with micro-grooves, fabricated by the photolithographic technique, were used as the alignment layer of the liquid crystal cell. Uniform alignment, on micro-grooved patterns, of which the pitch was less than 2 μm, was obtained, but a uniform tilt-up direction was not realized. On the other hand, a combination with a rubbing alignment layer on the opposite substrate surface was able to afford an alignment in which the pre-tilt direction was determined to be uniform even on micro grooved patterns.

This hybrid-type cell showed viewing angles like those of cells with an alignment layer with both sides treated by the rubbing process. This means that the pre-tilt direction on the micro-grooved surface is determined subsidiarily by the rubbing direction of the opposite alignment layer.

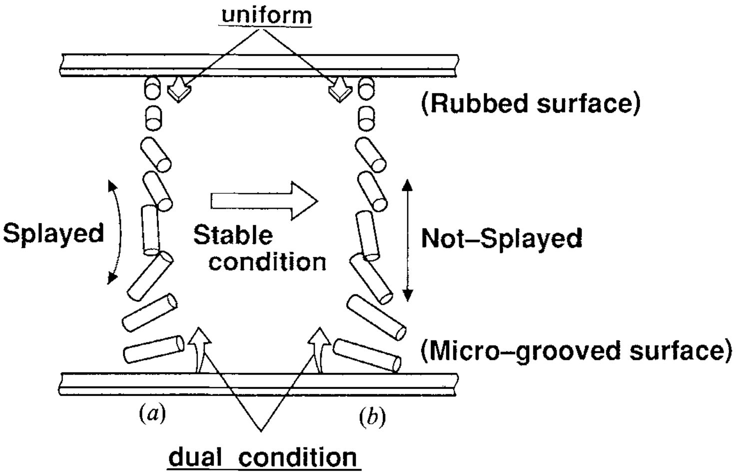


Figure 10. The molecular conformation of the hybrid cell. The rubbed surface shows uniform tilt-up direction. The micro-grooved surface cannot be used to determine tilt-up direction. (*a*) Splayed conformation with left-handed twist: (*b*) not-splayed.

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