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Cell gap optimization and alignment effects in reflective PDLC microdisplays

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In general this reduction of the cell gap improves the electro-optic properties of a polymer dispersed liquid crystal (PDLC) in reflective microdisplays. At the interface between the PDLC film and the silicon backplane or cover glass, the LC molecules have a different alignment from those in the droplets in the interior of the PDLC film. This is shown by microscopic observations and the temperature dependency of the brightness and capacitance of the displays. The influence of this alignment effect increases for smaller cell gaps and has an impact on the properties of the PDLC. During and after the filling of the displays, a compression and expansion of the cell gap takes place, respectively. If the curing of the PDLC takes place before the expansion of the cell gap has stopped, transparent areas in the PDLC film may occur some time after curing. This effect is caused by the expansion of the cell gap after curing resulting in the vertical alignment of LC molecules. This can be concluded from microscopic observations and from measurements of the refractive index and cell gap.

1. Introduction

Microdisplays are becoming an important new display technology. Typical dimensions for microdisplays are about 2.5 cm or smaller. The downscaling of the display size is made possible by CMOS technology, which offers the advantages of low power consumption, high addressing speed and high pixel resolution [1]. The microdisplays have to operate in a reflective mode because CMOS technology is integrated on a silicon wafer. A reflective pixel electrode is placed on top of the pixel transistor [2]; this allows the displays to have a higher aperture ratio compared with TFT displays in which the pixel electrode is next to the pixel transistors. The target applications for microdisplays are projectors and personal viewers for mobile applications [3]. The combination of PDLC and microdisplay technologies focuses on personal viewers for mobile applications [4].

To date, PDLCs have been mainly used in displays with an absorber as a backplane. By using a reflector the scattering effect of the display is drastically increased, because both the backscattering and frontscattering are reflected to the observer. This results in high brightness for a wide viewing angle and high contrast in a non-specular reflection direction. This behaviour is similar to other light scattering LCDs such as polymer network liquid crystal displays [5]. These characteristics favour the use of PDLCs for direct view or personal viewer applications. Other reflective LC technologies, for example, twisted nematic (TN) and super twisted nematic (STN) displays, have a high brightness for a small viewing angle only. They require special electrodes [6] or have diffusing layers to improve the low brightness in the non-specular reflection direction.

2. Influence of the cell gap on the electro-optic properties

The PDLC used in the experiments described in this paper was a mixture of 20% PN393 and 80 wt% TL213 (Merck). The PDLC was cured for 180 s using a UV intensity of 12.5 mW cm^{-2}. A d.c. voltage occurs in reflective displays [7, 8]; this is caused by the difference in the material used for the cover glass electrode, ITO, and the material used for the backplane electrode, in general aluminium or an aluminium alloy [2]. This d.c. voltage is compensated by applying an inverse d.c. voltage across the cell gap during the characterization of the PDLC. The experimental set-up used for the measurement of the electro-optical properties is described in figure 1. The cover glass of the displays used for the characterization of the PDLC has an ITO electrode on one side and an anti reflective coating on the other. The backplane is an aluminium electrode on glass. Figure 2 illustrates the influence of reducing the cell gap on the switching voltages.

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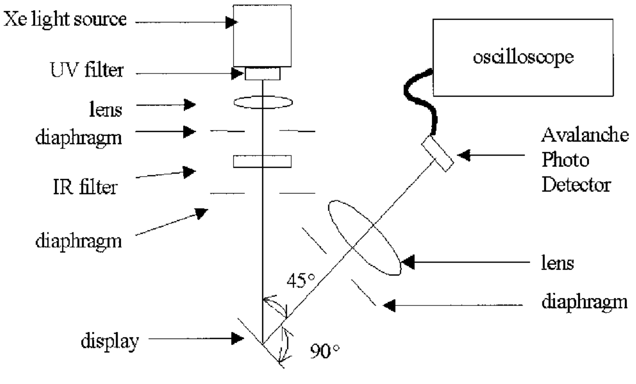

Figure 1. Experimental set-up used for the measurement of the electro-optic properties.

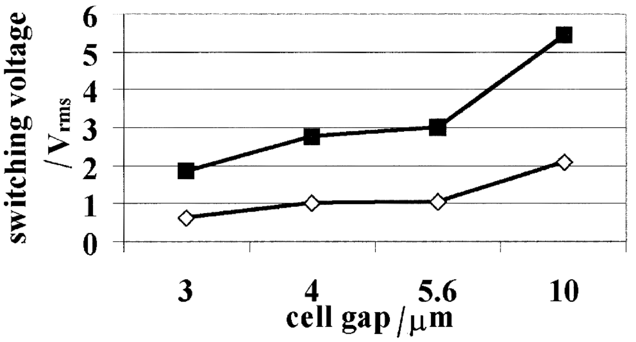

Figure 2. Influence of the cell gap on the switching voltage: ◇ = V_{th}, ■ = V_{90} (see text for definitions).

The maximum light intensity is measured when the PDLC is scattering because the electro-optic properties are measured in the off specular reflection direction (figure 1). This is different from measurements with the detector in the specular transmission direction in the case of transmissive displays, or with the detector in the specular reflection direction in the case of reflective displays. V_{90} is the voltage required to detect a light intensity of $I_{90} = I_{min} + 0.1\Delta I$ with $\Delta I = I_{max} - I_{min}$. I_{min} is the minimum detected light intensity (for a voltage of 13 V_{rms}) and I_{max} the maximum detected light intensity (for a voltage of 0 V). The threshold voltage, V_{th}, is the voltage required to detect a light intensity of $I_{th} = I_{max} - 0.1\Delta I$. For a display with 3 μm spacers $V_{th} = 0.6$ V_{rms} and $V_{90} = 1.9$ V_{rms}, while for a 10 μm display $V_{th} = 2.1$ V_{rms} and $V_{90} = 5.5$ V_{rms}. The linear relationship between the switching voltages, V_{th} and V_{90}, and the cell gap is in accord with the theory that the electric alignment fields in PDLC films are constant [9]. The electric field corresponding to V_{th} and V_{90} is $E_{th} \cong 0.22$ V μm^{-1} and $E_{90} \cong 0.55$ V μm^{-1}, respectively, for a cell gap $\geqslant 5.6$ μm. These values are smaller than for other PDLC displays [10] for which $E_{th} \cong 0.38$ V μm^{-1} and $E_{90} \cong 0.61$ V μm^{-1} for a cell gap $\geqslant 5$ μm. For a cell gap of 3 μm, E_{90} increases to a value of 0.62 V μm^{-1}; the reason for this increase will be explained later.

Other electro-optic properties are also influenced by the reduction of the cell gap. The contrast ratio increases as the cell gap decreases (figure 3). The contrast ratio is given by $(I_{max} - I_{noise})/(I_{min} - I_{noise})$ where I_{noise} is the default light intensity measured by the detector without a display in the measurement spot. For a display with a cell gap of 3 μm the contrast ratio is 33. This is a good result if we compare it with other reflective displays such as reflective TN or STN displays [11].

The hysteresis was measured by increasing the rms value of a 50 Hz square wave from 0 V to V_{90rms} (the rms value of V_{90}). The modulation frequency of the square wave is 0.4 Hz. The absolute value of the hysteresis ΔV_{hyst} in V_{rms} is the difference between the two voltages for which the detected light intensity is given by $I_{50} = (I_{min} + I_{max})/2$. The relative value of the hysteresis is $100 \times \Delta V_{hyst}/V_{90}$. The hysteresis determines the number of greyscales that the display is able to display [12]. A reduction of the cell gap reduces the hysteresis (figure 4).

The switching time, T_{rise}, is the time needed to switch from a scattering PDLC with intensity I_{max} to a transparent PDLC with an intensity I_{90}. T_{decay} is the time needed to switch from a non-scattering PDLC with an intensity I_{min} to a scattering PDLC with an intensity of

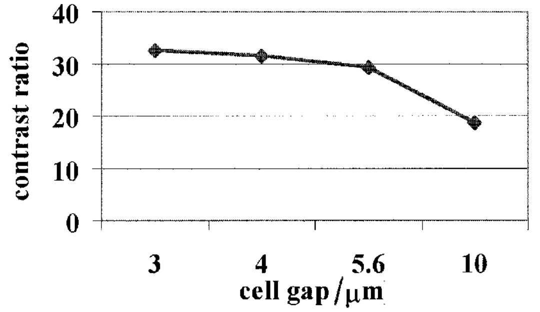

Figure 3. Contrast ratio as a function of the cell gap.

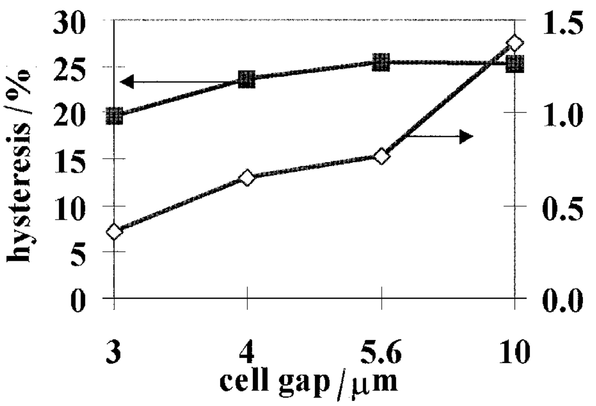

Figure 4. Hysteresis as a function of the cell gap.

I_{th}. According to theory [13],

$$T_{\mathrm{decay}} \cong \frac{2\gamma}{\varepsilon_0 \Delta\varepsilon E_{\mathrm{th}}^2} \qquad (1)$$

$$T_{\mathrm{rise}} \cong \frac{\gamma}{\varepsilon_0 \Delta\varepsilon (E_{\mathrm{appl}}^2 - E_{\mathrm{th}}^2)} \qquad (2)$$

where γ is the rotational viscosity coefficient, ε_0 the permittivity of free space, $\Delta\varepsilon$ the dielectric anisotropy and E_{appl} the applied electric field within the LC. For the measurement of T_{rise}, an electric field $E_{\mathrm{appl}} = 2E_{90}$ is applied for all values of the cell gap. T_{decay} depends on E_{th}, equation (1), and $E_{\mathrm{th}} \cong 0.38$ V μm^{-1} for all cell gaps (figure 2). So it is no surprise that T_{rise} and T_{decay} do not depend appreciably on the cell gap for cell gaps $\geqslant 4$ μm (figure 5). The switching times for a 3 μm cell gap are considerably larger than for the 4 μm cell gap. This will be discussed later.

The values of the brightness were measured relative to a white standard with the measurement set-up shown in figure 1. The white standard used in the measurements was a Spectralon® Reflectance Standard (Labsphere®). The brightness is defined as $100 \times (I_{\mathrm{max}} - I_{\mathrm{noise}})/(I_{\mathrm{white\ standard}} - I_{\mathrm{noise}})$ where $I_{\mathrm{white\ standard}}$ is light intensity of the white standard for the same illumination conditions as the display and I_{max} and I_{noise} have the same definitions as for the contrast ratio. The brightness of a 10 μm display, 57%, drops to 48% for a 4 μm display (figure 6). This linear dependency was also seen for displays with cell gaps between 5 and 20 μm [10]. The 25% drop in brightness of a 4 μm display to 23% for a 3 μm display is large compared with the drop in brightness for a 10 μm to a 4 μm display. This will be discussed later.

3. Vertical alignment of liquid crystal molecules

The scattering properties of a cured PDLC are not always stable with time. Sometimes a PDLC that was scattering immediately after UV curing turns transparent. In general, the transition from the scattering state to the transparent state starts within 24 h after the curing of the PDLC; this transition is irreversible at room temperature. The transparent PDLC cannot be switched to a scattering state and is therefore useless for displaying information. Some areas in the display are more sensitive than others to this effect, depending on the filling method.

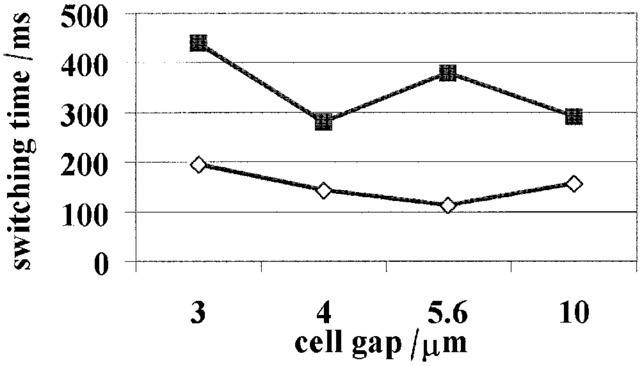

Figure 5. Switching times as a function of the cell gap: ◇ = T_{rise}, ■ = T_{decay}.

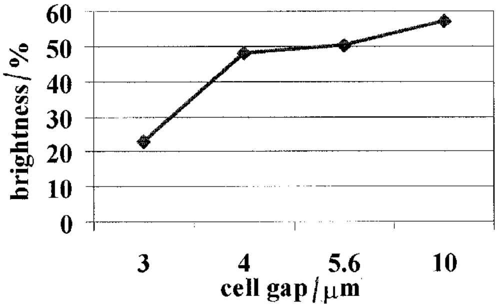

Figure 6. Brightness as a function of the cell gap.

One filling method is the droplet filling method (DFM). In this case, the transparent areas start in the middle of the short edges of the cover glass (figure 7) and in time expand towards the centre of the display. A droplet of PDLC is placed on the backplane of the display when using the DFM method. By pressing the cover glass onto the backplane, the PDLC spreads across the display and fills the cell gap. The curing of the PDLC takes place while the cover glass is pressed against the backplane. After curing, the display is sealed with glue.

When using a vacuum filling method (VFM), the transparent regions start at the filling opening and expand to the opposite side of the display (figure 8).

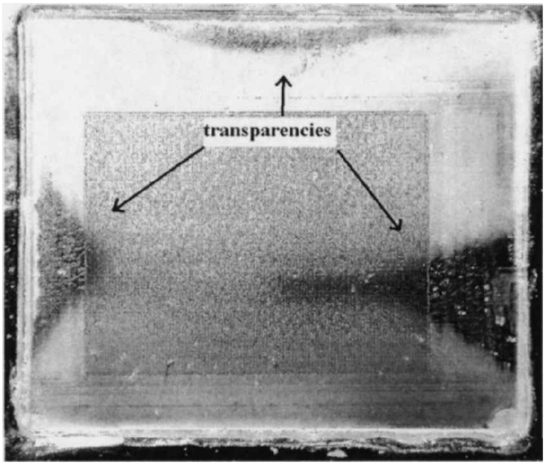

Figure 7. Typical growth of transparent regions in displays filled using the DFM method.

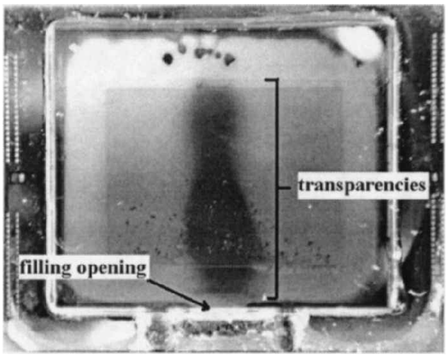

Figure 8. Typical growth of transparent regions in displays filled using the VFM method.

The monomers in the PDLC mixture are sensitive to evaporation when exposed to a vacuum. By putting the PDLC in a syringe, the contact surface with the vacuum and the time the PDLC is exposed to vacuum is small. The measurements indicate that the electro-optic properties of a PDLC filled using the VFM method are not influenced by the vacuum.

Figure 9 shows micrographs of the transparent areas at the edge, (*a*) and (*c*), and in the centre of the display, (*b*) and (*d*). The display is illuminated by light passing through a linear polarizer. The reflected light is observed using a CCD camera; an analyser is in front of the CCD camera. The micrographs were taken with the polarization direction of the analyser perpendicular, i.e. crossed, (*a*) and (*b*), or parallel, (*c*) and (*d*), to the polarization direction of the polarizer. The transparent PDLC regions are dark in the micrographs taken with crossed polarizers and white in the micrographs taken with parallel polarizers. The scattering regions have about the same brightness when viewed through both crossed and parallel polarizers. In figures 9(*a*) and 9(*c*) one clearly sees the transition from a scattering PDLC (left part of the picture) to a transparent PDLC (right part of the picture). In figures 9(*b*) and 9(*d*) the pixel electrodes and the via (the big black dot) connecting the pixel electrode to the underlying pixel transistors are visible. In the micrograph taken with crossed polarizers there are white dots on a black background; in the pictures taken with parallel polarizers, there are dark dots on a white background. The concentration of these dots decreases on moving from a scattering region to a transparent region.

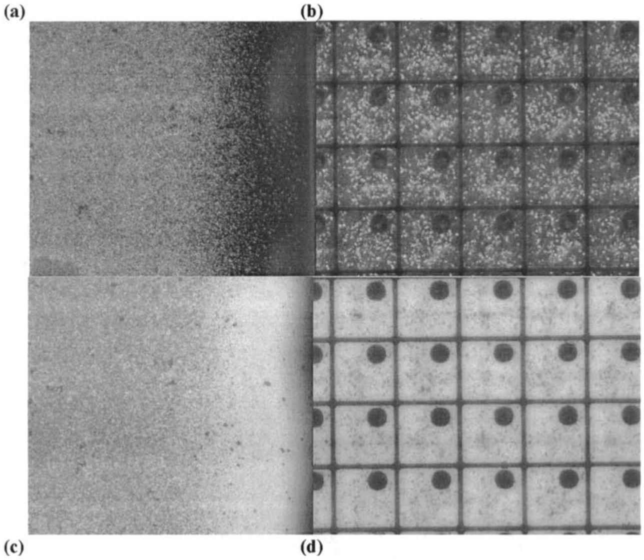

Figure 9. Micrographs of the transparent regions in a PDLC using crossed, (*a*) and (*b*), and parallel, (*c*) and (*d*), polarizers. The dimensions of the pixels in (*b*) and (*d*) are 80 μm × 80 μm.

These observations indicate that the transparent regions are caused by a vertical alignment of the LC, i.e. alignment perpendicular to the backplane. The vertical alignment of the LC molecules explains why the transparent regions above the Al pixel electrodes are dark when using crossed polarizers and bright when using parallel polarizers. The observed dots in the micrographs with crossed and parallel polarizers are LC droplets in the PDLC containing LC molecules that did not align vertically. These droplets still scatter the light and are therefore visible in the micrographs with crossed and parallel polarizers. The presence of the dots indicates that the polymer matrix and the LC are still intact. This is confirmed by the observation that the transparent regions in the display become scattering by heating the PDLC to 40°C or higher. In addition, incident light perpendicular to the backplane of the display reflects the light perpendicular to the backplane. This reflected light has an interference pattern determined by the optical path $n_{\mathrm{gap}}d_{\mathrm{gap}}$ [14] where d_{gap} is the cell gap of the display and n_{gap} the refractive index of the material in the cell gap. In the case in which the LC is vertically aligned $n_{\mathrm{gap}} = n_{\mathrm{o}}$ where n_{o} is the ordinary refractive index of the LC. The interference pattern is measured in a transparent region without a voltage being applied to the display and then with a voltage of 10 $\mathrm{V_{rms}}$. This voltage is sufficient to align the LC vertically. In both cases the same optical path, $n_{\mathrm{gap}}d_{\mathrm{gap}} = 6950$ nm, was measured (figure 10). For TL213, $n_{\mathrm{gap}} = n_{\mathrm{o}} = 1.527$ [10] so $d_{\mathrm{gap}} = 4552$ nm. This is an acceptable value of the cell gap for a display with 4 μm spacers. All these experiments indicate that the LC is vertically aligned.

The vertical alignment of the LC is caused by the instability of the cell gap after the curing of the PDLC. The cell gap was measured at different spots (figure 11) of several displays. These displays consisted of a cover glass with an ITO layer and a silicon backplane with an Al reflector electrode. Silicon was chosen as backplane material because, based on our experience, the change of transparent areas appearing in displays with a silicon

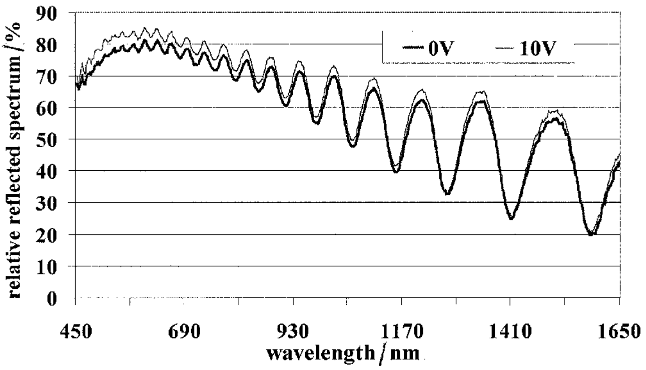

Figure 10. Measurement of the change in refractive index obtained by measuring the interference pattern without an applied voltage, i.e. 0 V, and with an applied voltage of 10 V_{rms}.

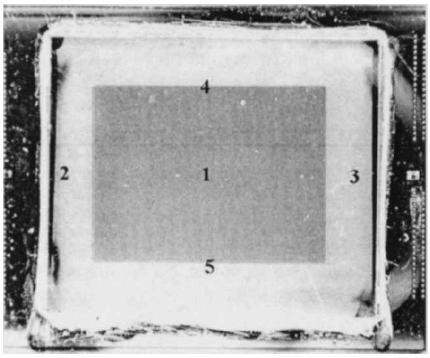

Figure 11. The five positions described in table 1 at which change in display cell gap with time was measured.

backplane is higher than for displays with a glass backplane. The displays were filled with the same PDLC material and cured with the same UV parameters as in §2. Some of the displays were filled using the DFM method others using the VFM method. Measurement of the cell gap [14] immediately after the curing of the PDLC indicated that the cell gap in some regions of the display (figure 11) to be considerably smaller than the diameter of the spacers. An example of a measurement on a display filled using the DFM method is given in the table.

The positions with the biggest cell gap compression (positions 2 and 3) correspond to the positions where the transparent regions originate. After 30 days, the PDLC in positions 1, 2 and 3 was transparent, while still scattering in positions 4 and 5. This pattern of transparent and scattering regions is similar to the one in figure 7. In another experiment, a mechanical pressure was applied to compress the cell gap. As a result the transparent areas became scattering. As soon as the mechanical pressure was removed the transparent regions returned.

4. Discussion

4.1. *Influence of the cell gap on the electro-optic properties*

The reduction of the cell gap has a desirable influence on the switching voltage, contrast ratio and hysteresis but not on the brightness. The cell gap has almost no influence on the switching time for cell gaps $\geqslant 4\,\mu m$. The switching voltage and the switching time for cell gaps $\geqslant 4\,\mu m$ seem to be in accord with theoretical models. The contrast ratio is higher for a smaller cell gap because the reduction of the light intensity of the PDLC in the scattering state is smaller than for the PDLC in the transparent state. The transparent state of the PDLC corresponds to the dark state of the display as measured with the set-up shown in figure 1. The main causes for the hysteresis are believed to be the anchoring energy of the LC molecules at the interface with the polymer matrix, defect structures in the droplets, internal electric fields, and so on [15]. The strong reduction of the hysteresis for a cell gap $\leqslant 4\,\mu m$ is caused by a change in the alignment of the LC at the interface with the polymer matrix. This can be concluded from the following observations. First, there is a large difference in brightness between 4 µm display and a 3 µm display, and this is much larger than the difference in brightness between a 10 µm and a 4 µm display. Observation of the PDLC shows a uniform brightness for 10 µm displays (figure 12) but this is not the case for 3 µm displays. Bright and dark regions appear all over the PDLC in a 3 µm display. Closer observation of the 3 µm PDLC

Table. Example of the change in cell gap with time, measured in a 4 µm display filled using the DFM method.

	cell gap/µm				
Time after curing	Position 1	Position 2	Position 3	Position 4	Position 5
1 hour	3.6	3.3	3.5	3.8	3.6
12 days	3.8	3.4	3.6	3.7	3.6
30 days	3.9	3.7	3.8	3.7	3.6

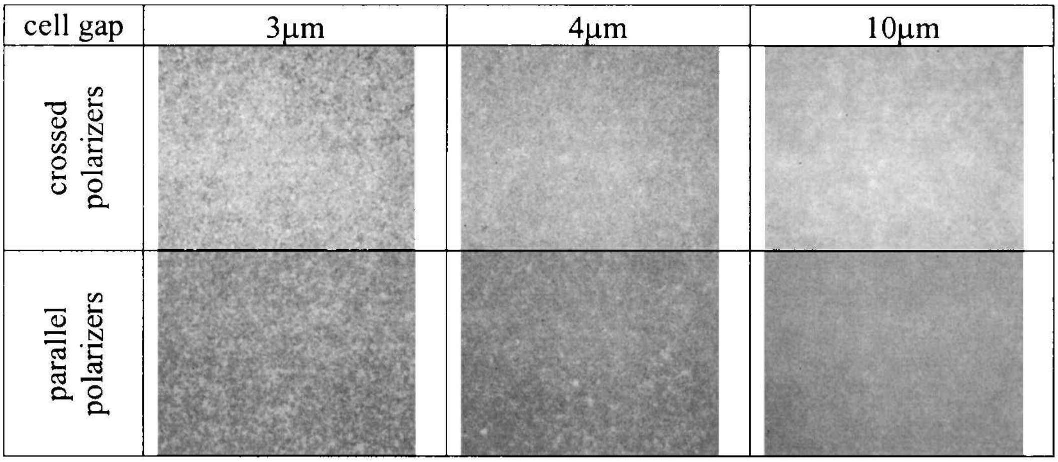

Figure 12. PDLC with different cell gaps viewed between crossed and parallel polarizers.

reveals areas that are dark when viewed between crossed polarizers and bright when viewed between parallel polarizers. This indicates that there are areas in the 3 µm PDLC display with little or no scattering of light.

The brightness (figure 13) and the capacitance (figure 14) of the PDLC displays depends on the temperature and the cell gap thickness. The brightness for all the cell gaps increases as the temperature increases. The brightness is more sensitive to temperature for displays with smaller cell gaps. For a 10 µm cell gap the brightness of the display increases by up to 7% compared with the brightness at 30°C. For a 3 µm cell gap the maximum increase is 25%. The temperature dependent behaviour of the capacitance of the PDLC display also differs considerably for the different cell gaps. The capacitance of a 10 µm display is slightly reduced at 35°C compared with the capacitance at 30°C, and increases slowly for temperatures higher than 35°C. However, a 3 µm display has an abrupt reduction of the capacitance between 35 and 45°C. For temperatures higher than 50°C the capacitance slowly increases. This is due to the temperature dependency of the dielectric constant of the PDLC film. Measurements of the cell gap [14] indicate that the changes in capacitance and brightness are not caused by a change in the cell gap.

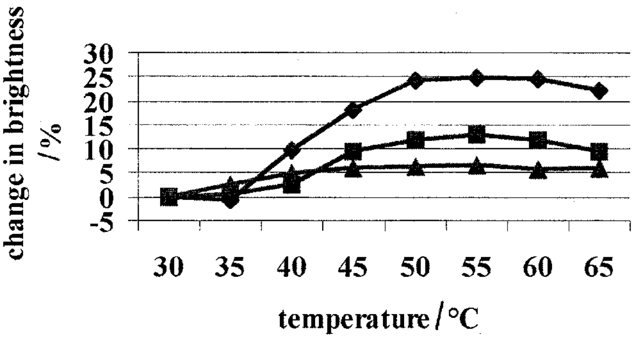

Figure 13. Influence of the temperature on the brightness of PDLC displays with different cell gaps relative to the brightness at 30°C: ◆ = 3 µm, ■ = 4 µm and ▲ = 10 µm cell gap.

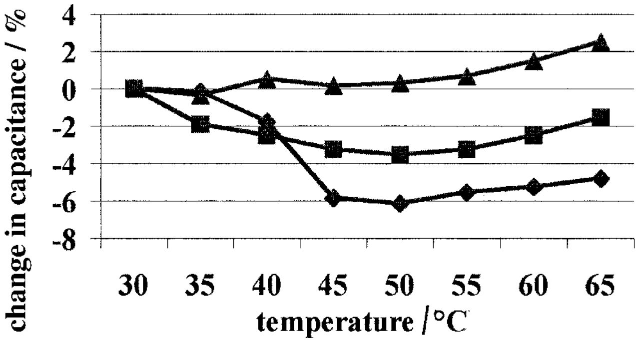

Figure 14. Influence of the temperature on the capacitance of PDLC displays with different cell gaps relative to the capacitance at 30°C: ◆ = 3 µm, ■ = 4 µm and ▲ = 10 µm cell gap.

The abrupt change in capacitance between 35 and 45°C for a 3 µm display can be explained by a change in the alignment of the LC molecules at the interface with the polymer matrix [16]. The LC molecules at the interface with the polymer matrix are aligned perpendicular to the polymer matrix at 30°C. These LC molecules align parallel to the polymer matrix for temperatures higher than 45°C. This transition only occurs in the LC droplets at the interface with the ITO and Al layer. In the LC droplets in the interior of the PDLC film the LC molecules at the interface with the polymer matrix are aligned parallel to the polymer matrix. The 3 μm display does not contain many LC droplets that are not in contact with either the ITO or Al layer as compared with either a 4 μm and even more so, with a 10 μm display. First, this explains why the drop in capacitance between 35 and 45°C is larger for a 3 μm display than for a 4 μm display or even insignificant in the case of a 10 μm display. Second, this also explains why the maximum increase in brightness is relatively larger for displays with smaller cell gaps.

This alignment effect explains the deviations from the theoretical model of the hysteresis, the switching times—equations (1) and (2)—and the reorientation field for cell gaps $\leqslant 4\,\mu m$. These PDLC characteristics depend on the alignment of the LC molecules at the interface with the polymer matrix [9, 13, 15]. An alignment of the LC perpendicular to the interface with the polymer matrix results in lower hysteresis, higher switching times and a higher reorientation field than for an alignment parallel to the interface with the polymer matrix.

4.2. *Vertical alignment of LC molecules*

The compression of the cell gap to a value smaller than the spacer diameter (see the table) is caused by capillary forces occurring during the filling of the displays. This can also be derived from the fact that the sealing glue penetrates the filled display before curing. The compressed spacers are forcing the cell gap to expand. When the cell gap expands after the curing of the PDLC, the LC droplets in the cured PDLC will change into ellipsoids with long axes parallel to the direction of the expanding cell gap. The change of the shape causes the LC to align vertically. The alignment of the LC molecules due to the change of the shape of the LC droplets also occurs in PDLCs based on a polyvinyl alcohol (PVA) system [17]. However, the alignment of the LC in the PDLC based on a PVA system is horizontal due to a shrinkage of the cell gap. This is different from the PDLC used in the experiments here which are based on a photo-initiated polymerization-induced phase separation system, and for which the alignment of the LC is vertical due to an expansion of the cell gap. The instability of the cell gap as a reason for the transparent regions also explains other aspects of the phenomenon. First, it accounts for where the first transparent areas occur. These are in the regions having the largest expansion of the cell gap after the curing of the PDLC. Displays with a silicon backplane, such as microdisplays, are more prone to having transparent areas, than are displays with a glass backplane. Silicon backplanes are less rigid and flat than glass backplanes making the display more sensitive to cell gap compression and expansion.

One solution to this problem is to prevent a strong cell gap compression during the filling process by increasing the number of spacers. Alternatively, one could wait until the cell gap is decompressed and stable before curing the PDLC. For the capillary filling method a period of 15 min separates the filling of the display and the curing of the PDLC. This period is sufficient to prevent the formation of transparent areas caused by the vertical alignment of LC molecules.

5. Conclusion

In general, the reduction of the cell gap improves the electro-optic properties of reflective PDLC displays. However, the smaller the cell gap of the display, the larger will be the influence of alignment effects in the LC droplets at the interface with the cover glass or the backplane on the performance of the PDLC. The cell gap has to be stable before the PDLC is cured. Otherwise unwanted transparent areas can appear in the display. Silicon based microdisplays are particularly prone to this problem.

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