Optimum design of liquid crystal display parameters in projection and direct view applications

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Abstract. Two kinds of liquid crystals are selected with the aid of computer simulation for the fabrication of high-contrast liquid crystal displays (LCDs). One is suitable for the first minimum operation of a twisted nematic LCD and the other is suitable for the second minimum operation. The contrast ratios in the normally white mode of the first minimum operation and the contrast ratio in the normally black mode of the second minimum operation are both higher than 100:1. These LCDs can be used in direct view and projection applications.

Subject terms: display technologies; liquid crystal displays.

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1 Introduction

Liquid crystal displays (LCDs) have been widely employed for high information content displays such as pocket TVs, portable personal computer monitors, and high-density projection TVs. High contrast ratio and high brightness are the main concerns in LCD design. To achieve these requirements, considerable investigation and critical decisions regarding the liquid crystal (LC) materials and cell process parameters are necessary. For example, there are more than 10 physical parameters of an LC device that may affect its optoelectronic phenomena. With the aid of a computer simulation tool, a number of experiments and resources can be saved during the optimization process.

In this work, numerical calculations based on the Berreman 4×4 matrix method[1] are carried out with a twisted nematic (TN) LCD. To simplify the computation, ideal polarizer films are assumed in the simulation. The optical properties of the display are obtained with the controllable LCD parameters, $\Delta nd/\lambda$, pitch of the LC (nematic LC with chiral dopant), and pretilt angle. Viewing angle, contrast ratio, coloration, LC cell process simplicity, and driver integrated circuit (IC) design are taken into consideration during the optimization process. The optimum process parameters are obtained for the LCDs applied in projection TV and direct view LC TV.

2 Simulation Design

High contrast, enough brightness, and a satisfactory viewing angle are the basic requirements for a LC display. By the arrangement of the direction of polarizers, an LCD can be in either the normally black (NB) or the normally white (NW) mode. In the NW mode, the light is transparent through the LC cell at V_{off} and is blocked at V_{on}. The NB mode is the reverse.

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A high-contrast display cannot be obtained without a satisfied dark state. In the NB mode, the light intensity transmittance for TN LC panels under zero applied voltage, or the dark state, is given by

$$T(d,\lambda)=\frac{1}{2}\frac{\sin^2[(1+u^2)^{1/2}\pi/2]}{1+u^2}\ , \qquad (1)$$

where

$u = 2\Delta nd/\lambda$
$\Delta n = (n_e - n_o)$, or birefringence
d = cell gap
λ = wavelength.

Thus, a satisfied dark state can be obtained only if the factor u or $\Delta nd/\lambda$ is a constant for all primary colors. Birefringence of LCs is a function of wavelength. An ideal approach is to find a LC material for which the birefringence decreases as the wavelength shortens. But the birefringence value usually varies inversely proportional to the wavelength. Thus, a rotary dispersion effect is observed, i.e., part of the full visible light spectrum is transparent through the off-state LC cell. For projection TV, the video is made by superposition of monochrome images from three individual LCDs. The rotary dispersion effect can be eliminated by choosing suitable cell gaps for the specific colors.

2.1 *NW-Mode Simulation*

For direct view LC TV, without special techniques, rotary dispersion cannot be eliminated. Multigap color filter design is one way to correct the rotary dispersion effect.[2] The process of multigap color filter design is complex, so NW-mode LCDs are a practical solution to solve the rotary dispersion effect. With the physical properties of a popularly used LC (LC-A in Table 1), the computation results show the relationship between the driving voltage and transmittance in different cell gap thicknesses (Fig. 1). The contrast ratio is the cell transmittance ratio at the applied voltages of 0 and

Table 1 Physical properties of LC-A and LC-B.

PROPERTIES		LC-A	LC-B
Viscosity	20 C	20	19
[mm^2/s]	0 C	64	57
Gamma 1	20 C	154	133
[MPAS]	0 C	546	432
Density [g/cc]		0.9644	0.9906
Delta Epsilon		+5.4	+7.9
Epsilon Parallel		9.6	11.8
Delta n		+0.0837	+0.1311
ne		1.5629	1.6319
K3/K1		1.16	1.26
K3/K2		2.23	3.10
V(10,0,20) [volt]		1.97	2.13
V(50,0,20) [volt]		2.35	2.44
V(90,0,20) [volt]		2.94	3.03

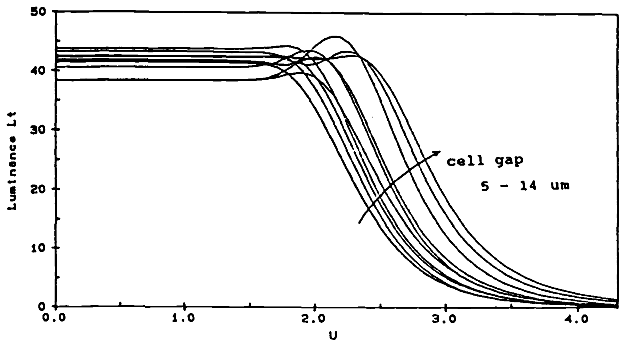


Fig. 1 Transmittance versus applied voltage for LC-A in the NW mode.

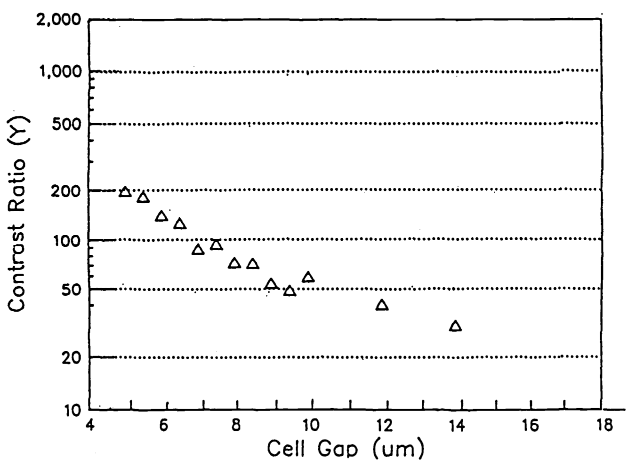


Fig. 2 Contrast ratio for LC-A at different cell gaps.

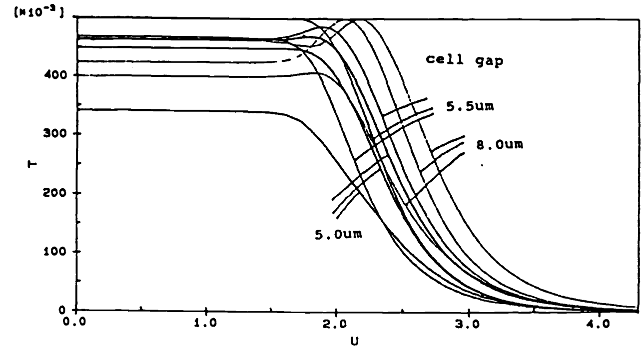


Fig. 3 Transmittance of blue (B), green (G), and red (R) light (top to bottom) versus applied voltage for LC-A in the NW mode.

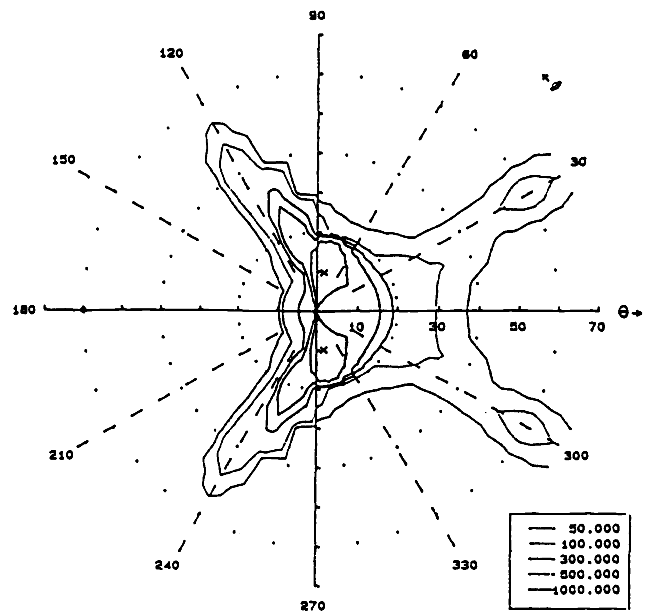


Fig. 4 Contrast ratio mapping for LC-A in the NW mode (cell gap = 5.5 μm).

5 V. As the cell gap varies from 5 to 14 μm, V_{10} and V_{90} both shift to higher voltages. But ΔV (the difference between V_{10} and V_{90}) remains constant. Since the voltage endurance for driver IC devices is limited, a higher cell gap is less preferable. Figure 2 represents the contrast ratio mapping at different cell gap thicknesses for normal incident light. The contrast ratio is much higher at the first minimum region. Figure 3 shows that the cell gap between 5.5 to 6.0 μm is suitable to obtain good color quality for the NW mode. For both 5.5- and 6.0-μm cell gaps, good viewing angles are possible in at least three quarters of the view (Figs. 4 and 5). The simulation shows that LC-A with a cell gap of 5.5 to 6.0 μm in the NW mode can be applied to direct view LCDs and projection LCDs. Gamma correction is necessary in driving IC designs to obtain a satisfactory gray scale and contrast ratio.

2.2 *NB-Mode Simulation*

NB-mode LCDs usually need lower driving voltages than NW-mode LCDs to reach the saturation state. The rotary dispersion effect is not a problem in projection systems where three separately designed LCDs are used for different colors, thus the NB mode is a better choice. Figure 6 is the simulation work with LC-A that shows the relationship between the cell gap and contrast ratio in the NB mode. In the NB mode, the contrast ratio is the cell transmittance ratio at the applied voltages at 5 V and at the first minimum state. Thus, a second minimum LC that is suitable for the second minimum operation of a TN LCD (LC-B in Table 1) is chosen for further calculation on the transmittance to applied voltage in different colors. The results are shown in Fig. 7. The optimum cell gap thickness is 9.5 μm. Compared to the NW mode, the cell gap allowance is bigger, thus the LCD cell process is

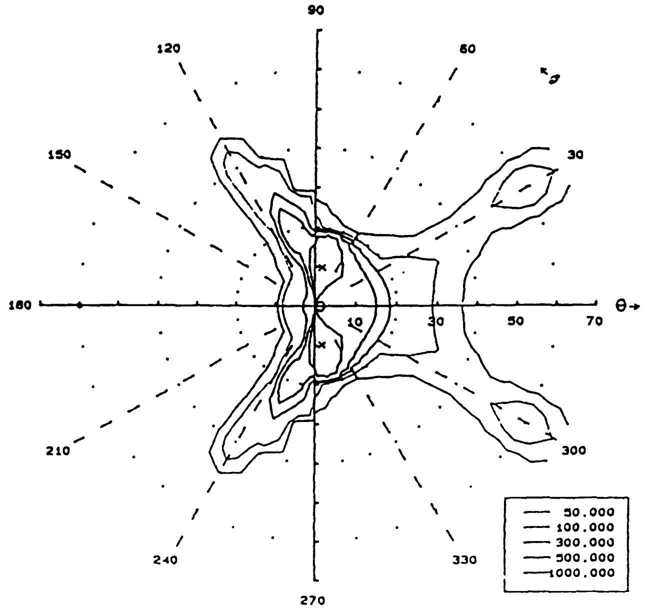


Fig. 5 Contrast ratio mapping for LC-A in the NW mode (cell gap = 6.0 μm).

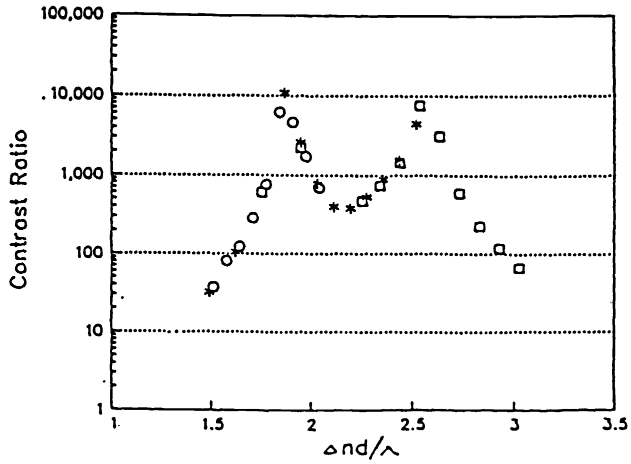


Fig. 6 Contrast ratio versus birefringence.

less difficult. The viewing angle mapping in Fig. 8 shows that the viewing angle of an NB-mode LCD is rather narrow. But it does not cause a problem for projection TV. The second minimum cell gap design has less cell gap sensitivity, as shown in Fig. 9, which gives the transmittance of three different thicknesses: 9.0, 9.5, and 10.0 μm. The transmittance curves show little differences, therefore, there are two benefits in the second minimum design: (1) a broader linear region in the voltage-transmittance curve and (2) excellent gray-scale controllability as a function of thickness nonuniformity. The first makes the driver IC design simpler and the second makes processing easier.

2.3 *Other Parameters in Simulation*

The pitch of the LC affects the viewing angle and threshold voltage. Figures 10 and 11 show the relationship between the voltage and transmittance in the NW mode and NB mode,

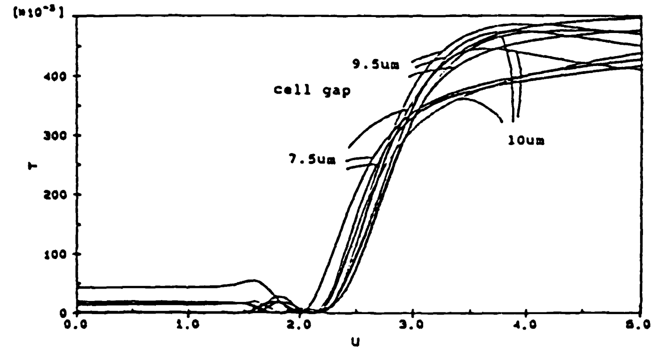


Fig. 7 Transmittance of different spectrum versus applied voltage for LC-B in the NB mode.

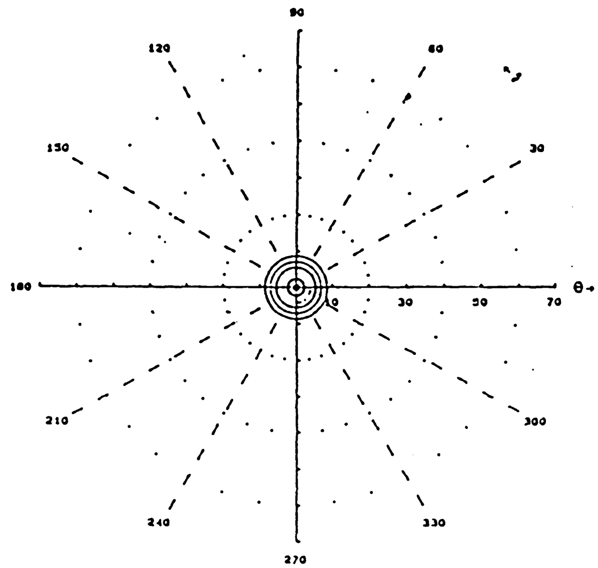


Fig. 8 Contrast ratio mapping for LC-B in the NB mode (cell gap = 9.5 μm).

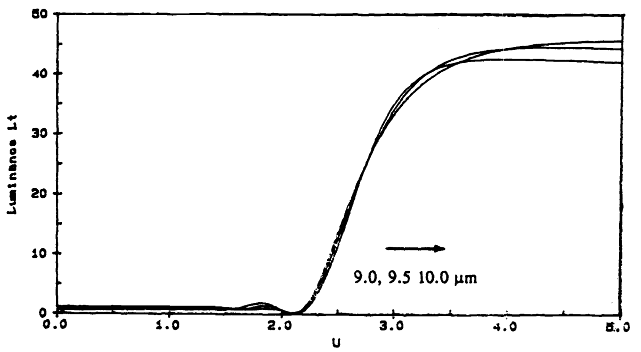


Fig. 9 Transmittance curves of LC-B with 9.0-, 9.5-, and 10.0-μm cell gaps.

respectively. The display with a smaller LC pitch has a lower voltage threshold, thus, smaller pitch is a better choice for both NW- and NB-mode LCDs. However, control of the LC cell gap becomes extraordinarily difficult when the cell gap is less than 4 μm. Practically, a pitch value of −0.12 is suggested.

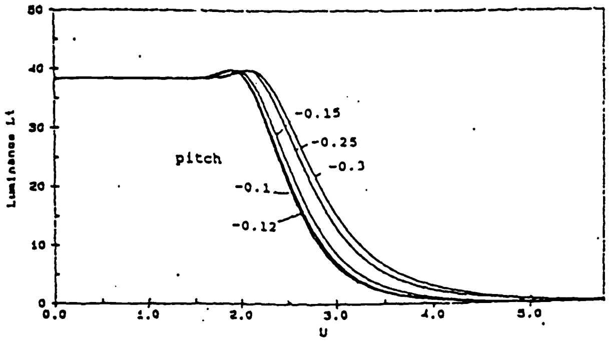


Fig. 10 Transmittance of different pitches versus applied voltage for LC-A.

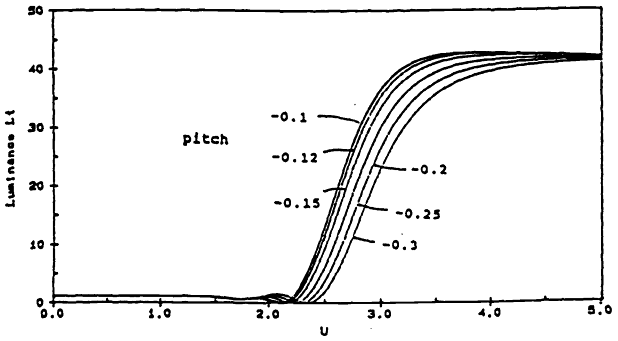


Fig. 11 Transmittance of different pitches versus applied voltage for LC-B.

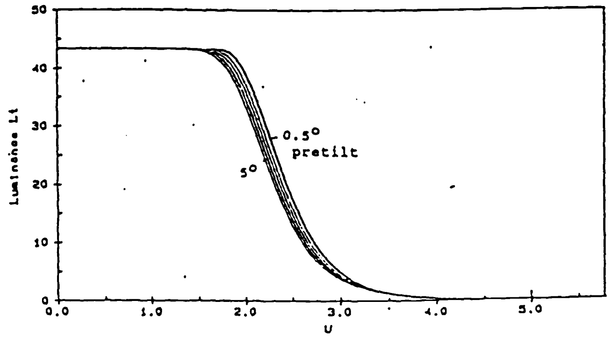


Fig. 12 Transmittance of different pretilts versus applied voltage for LC-A.

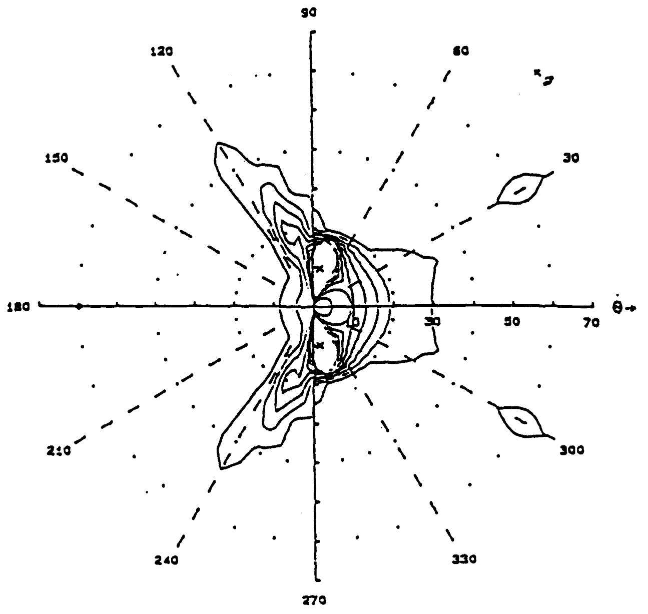


Fig. 13 Contrast ratio mapping for LC-A in the NW mode (cell gap = 5.5 μm, pretilt = 0.5 deg).

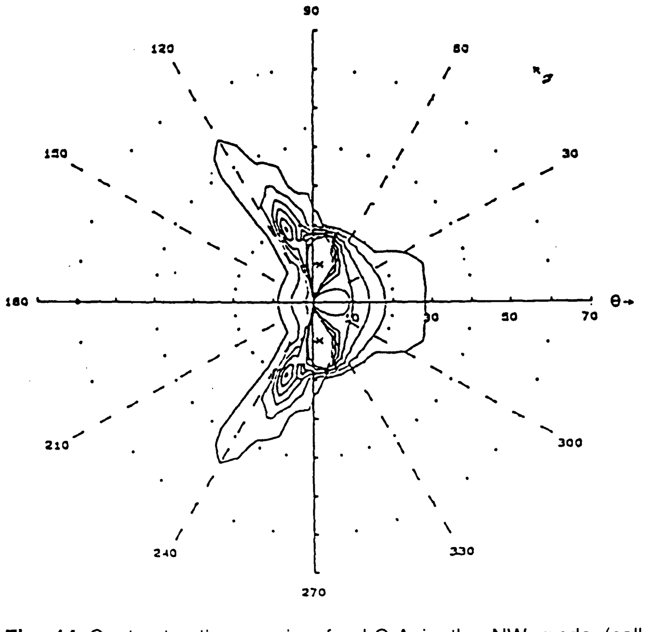


Fig. 14 Contrast ratio mapping for LC-A in the NW mode (cell gap = 5.5 μm, pretilt = 5.0 deg).

The pretilt angle is essentially a result of interactions between the LC, polyimide materials, and the alignment layer processes. The pretilt provides a tendency of the twist of the LC molecules in the electric field. For the TN LC, the pretilt angle is usually less than 5 deg. In the simulation work, we found that the threshold voltage decreases as the pretilt angle increases, but the saturation voltage remains independent to the pretilt angle (Fig. 12). In Figs. 13 and 14, we found that the pretilt angles cause only a very limited difference in viewing angle. The pretilt angle for the TN LC is not a sensitive parameter, but the reverse tilt effect was observed in a small pretilt angle case,[3,4] thus, a higher pretilt angle is preferred.

In addition to the device parameters, the temperature is another important factor that should be considered. It greatly affects Δn, viscosity, and the elastic constants. In the case of LC-B, Δn varies from 0.1311 to 0.11 as the temperature increases from room temperature to 75°C. From the relationship between the LC parameters and temperature[5]:

$$\Delta n \sim (1 - T/T_{NI})^{\beta} \ , \quad K \sim [(1 - T/T_{NI})^{\beta}]^2 \ .$$

This suggests that the elastic constants will be reduced by 30% when the temperature increases from room temperature to 75°C. If we substitute these values into the simulation program, we obtain the transmittance curves at 75°C , as shown in Fig. 15.

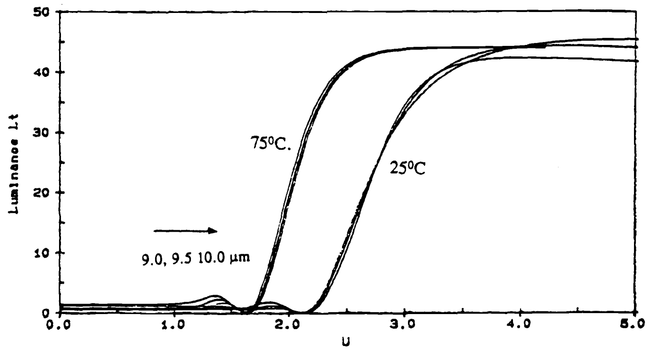


Fig. 15 Transmittance curves of LC-B at 25 and 75°C with 9.0-, 9.5-, and 10.0-μm cell gaps.

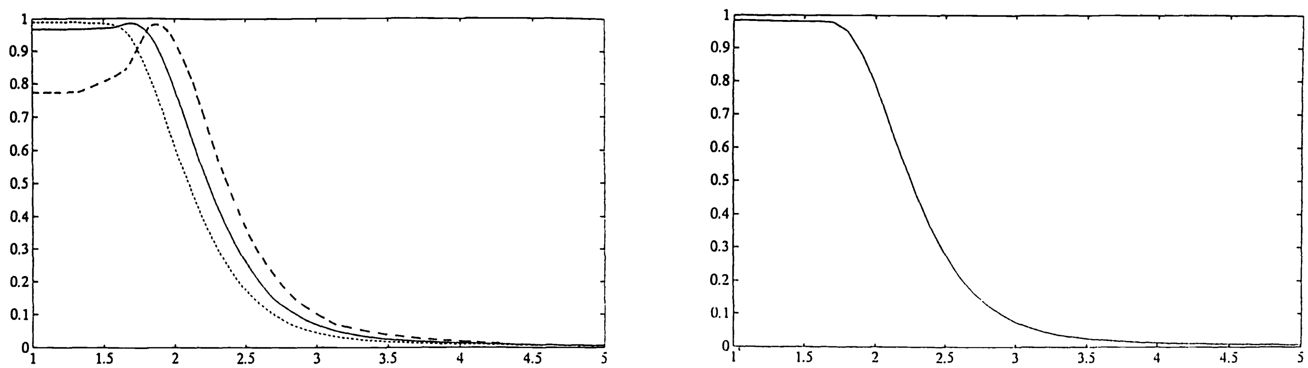
Table 2 Process parameters of testing LC cells.

Cell	LCD-B	LCD-A
LC	LC-B	LC-A
Cell Gap	9.5 um	6.0 um
Minimum	2nd	1st
Pitch	-0.12	-0.12

Figure 15 implies that (1) the threshold voltage shift due to the reduction of elastic constants is serious and (2) the cell gap plays a minor role in the temperature variation due to the reduction of Δn. Since the differences between the transmittance curves at 75°C are smaller compared with room temperature, the optimum LCD thickness is almost the same from 25 to 75°C.

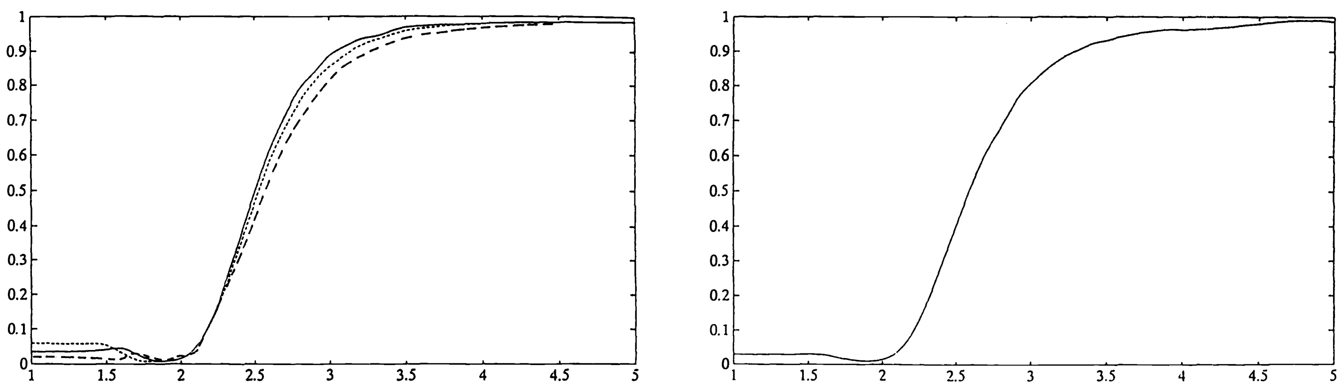
3 Experiments

LCD cells LCD-A and LCD-B were processed and filled with liquid crystals LC-A and LC-B, respectively. The other cell process parameters are listed in Table 2. The light transmittance at different applied voltages of the testing cells was measured at normal direction and room temperature (Figs. 16 and 17). The experimental results were fairly consistent with the simulation-calculated transmittance curves. The difference between the results of the simulation and testing cells may have been caused by the simplification of ideal polarizers in the simulations. In an ideal case, the light passing through cross polarizer film is cut off completely and the light passing through parallel polarizer film is allowed to pass completely. The small process-allowed errors in the cells, such as alignment layer arrangement and LC twisting, also result in different transmittance curves. Practically, the experimental



(a) (b)

Fig. 16 Transmittance curves of testing cell LCD-A: (a) for *R* (dotted line), *G* (continuous line), and *B* (dashed line) light and (b) for the overall visible spectrum.



(a) (b)

Fig. 17 Transmittance curves of testing cell LCD-B: (a) for *R* (dotted line), *G* (continuous line), and *B* (dashed line) light and (b) for the overall visible spectrum.

contrast ratio is somewhat less than that of an ideal case simulation.

4 Conclusions

With a Berreman 4×4 matrix simulation, two kinds of LC and process parameters were selected for the applications of direct view and projection LCDs. Both the NW mode and NB mode are able to achieve a contrast ratio greater than 100 for the displays. Testing cells were fabricated with the simulation recommended parameters and fairly consistent results were obtained. This computer simulation program is proven to be a useful tool in LCD design.

Acknowledgment

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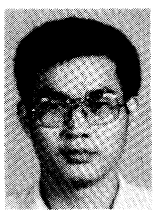

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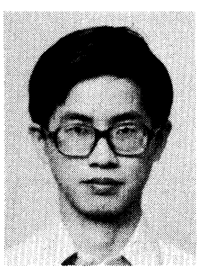

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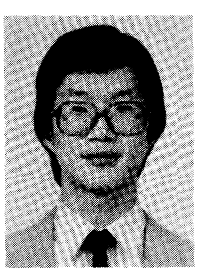

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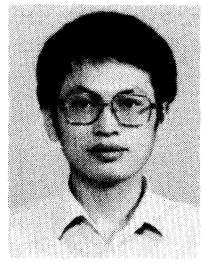

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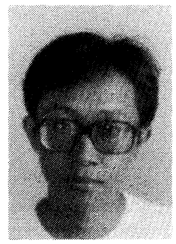

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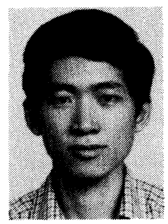

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