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Fast response film-compensated liquid crystal on silicon display

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We have designed and constructed a fast response liquid crystal on silicon display. The stable alignment of this liquid crystal cell at zero-bias voltage is in the bend deformation. The measured total response time is 0.8 ms for the worst case and averages 0.3 ms for all gray levels. The optical reflectivity has been optimized to nearly 85% by using a compensation film. The white light contrast ratio is >500 at 6 V. This fast mode can be used in field sequential color systems. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2222338]

Liquid crystal on silicon (LCOS) light valve is potentially useful for projection displays. In particular, the field sequential color (FSC) scheme is attractive because only one LCOS panel is required, thus reducing overall optical system complexity and cost.[1] FSC is particularly attractive in light of the rapid development of high brightness light emitting diodes (LEDs). Such LED based microprojectors are expected to play an important role in future mobile display technologies.[2] FSC requires the response time of the light valve to be fast. For a 90 Hz frame rate, for example, the subframe time is only 3.7 ms. Thus the response time of the LCOS light valve needs to be 1 ms or less. Traditionally, FSC LCOS projectors employ fast ferroelectric liquid crystals (FLCs).[1] But FLCs are quite difficult to handle and cannot provide many gray levels. An alternative is a nematic LC mode based on the π cell or the optically compensated bend (OCB) mode.[3–5]

The π cell basically operates between the bend deformation and the homeotropic state of the nematic liquid crystal. The application of a voltage changes the degree of bending of the LC director and hence its overall effective birefringence. Thus the optical property of the π cell is basically that of an electrically controlled birefringent (ECB) cell. As such, it can be compensated readily using various optical films to obtain a wide viewing angle and large contrast ratios.[5]

A conventional π cell is formed with parallel rubbing on both sides of the LC cell. The possible director alignments that satisfy these boundary conditions are the splay deformation (S state), the bend deformation (B state), and the π-twist deformation (T state). At high voltage, the vertical homeotropic alignment (V state) is obtained. The difficulty of the conventional π cell is the need for transforming the stable S state to the B state. The S state can be eliminated if the pretilt angle of the LC cell is large enough.[6] The resulting B state display can be called the no-bias bend (NBB) mode.[7,8] In this letter, we apply this NBB to the case of LCOS. The important issue is the optimization of the design of the NBB LCOS so that a fast response time and good optical reflectivity can be achieved at reasonably low voltages. Our results show that a turn-on time of less than 0.04 ms and a total switching time of less than 0.8 ms can be achieved for a LCOS operating at 6 V.

The important step in the fabrication of the NBB cell is the preparation of the high pretilt angle. Many techniques have been introduced in the past for achieving a high pretilt angle in a LC cell. This includes SiO_2 evaporation,[9] ion beam or photoalignment,[10] side-chain polymers, and reverse mechanical rubbing.[11] We recently introduced a special alignment layer consisting of nanodomains of vertical and horizontal polyimides.[7,8] However, for projection applications, it has been shown that polyimides deteriorate at high light intensities. In this letter, we shall present data with the SiO_2 evaporation technique. Although the mass production capability of this technique is limited for large panel liquid crystals displays (LCDs), it is quite suitable for wafer scale LCOS production.

SiO_2 evaporation has been investigated extensively as a means of aligning liquid crystals. Its advantage is that the pretilt angle can be controlled precisely and the process is robust. The pretilt angles obtained also depend on the liquid crystal used to some degree. Recently Lu *et al.* showed that the pretilt angle is also dependent on the anisotropy of the liquid crystal molecules.[12] Positive and negative anisotropic liquid crystals behave quite differently. In this study we are concerned mainly with the achievement of a pretilt angle of 52°. This was achieved by optimizing the thickness of the SiO_2 layer and the evaporation angle.

The optical reflectivity of the fast response LCOS cell can be optimized readily. In a LCOS display, the π cell works in the reflective mode. The reflectivity is given by

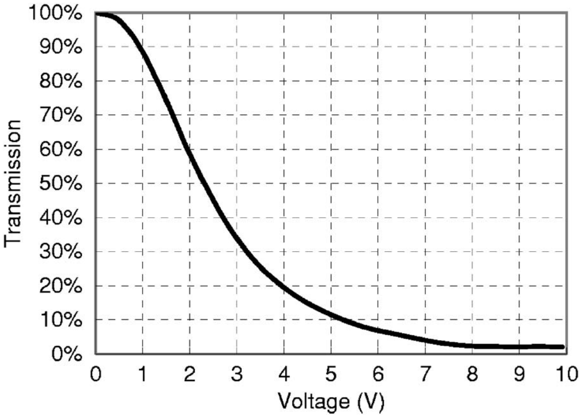

FIG. 1. The reflectivity-voltage behavior of an experimental NBB cell.

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TABLE I. Optimized film-compensated NBB cell with a cell gap of 3.5 μm.

	Orientation of film	Retardation of film (μm)	Orientation of cell
Mode 1	−45°	0.019	45°
Mode 2	−8.7°	0.368	−56.7°

$$R = \sin^2 \frac{2\pi}{\lambda} \int_0^d \Delta n(z) dz, \tag{1}$$

if a polarizing beam splitter (PBS) is placed at 45° to the alignment axis of the LC molecules in the cell. In Eq. (1) λ is the wavelength, d is the thickness of the LC layer, and $\Delta n(z)$ is the birefringence of the liquid crystal layer given by

$$\Delta n(z) = n_e[\theta(z)] - n_o, \tag{2}$$

where n_o and n_e are the ordinary and extraordinary refractive indices of the LC. In order to achieve the highest optical reflectivity R, large cell gap (d) and/or large Δn LC material are needed. One very important observation is that for field sequential color applications, the subframe rate is very fast. Thus the voltage holding ration (VHR) does not need to be very large as in the case of conventional active matrix LCD. Thus even lower grade LC materials can be used. So there is a wide range of LC with large Δn and reasonably small viscosity that can be chosen for this LCOS NBB cell.

An important issue for the π cell is the driving voltage. Figure 1 shows the experimental reflectivity-voltage behavior of an experimental π cell that was fabricated using MLC6080 with a cell gap of 3 μm. It can be seen that the *CR* is quite low even at 10 V, although the reflectance can be larger than 90% at the same conditions. For a white light *CR* of 500, 15 V is needed. This is too high for LCOS operation.

Thus in order to achieve large *CR* at reasonable voltages, a compensation film is needed. It is well known that the OCB mode is self-compensated and has an intrinsically large viewing angle.[13] Here, we are not too concerned with the viewing angle, since for LCOS projectors, $F/2$ optics is good enough. This corresponds to an external viewing angle of only ±15°. The function of the film is to achieve a large *CR* as well as the optical reflectivity at a low voltage without affecting a large response time. In our optimization, the maximum operating voltage is set to be 6 V. The minimum required white light *CR* is set to be 500. Generally, the cell gap should be less than 3.5 μm for fast switching. If the cell gap is larger, the response time will be longer. For example, a 5 μm cell will have a response time of around 4–5 ms, a reflectivity of 100% and a *CR* of >300. It is not acceptable for FSC operation.

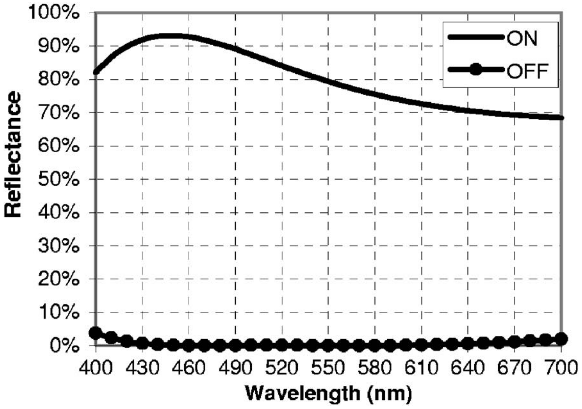


FIG. 2. The reflectivity of on and off states for mode 2 at 6 V.

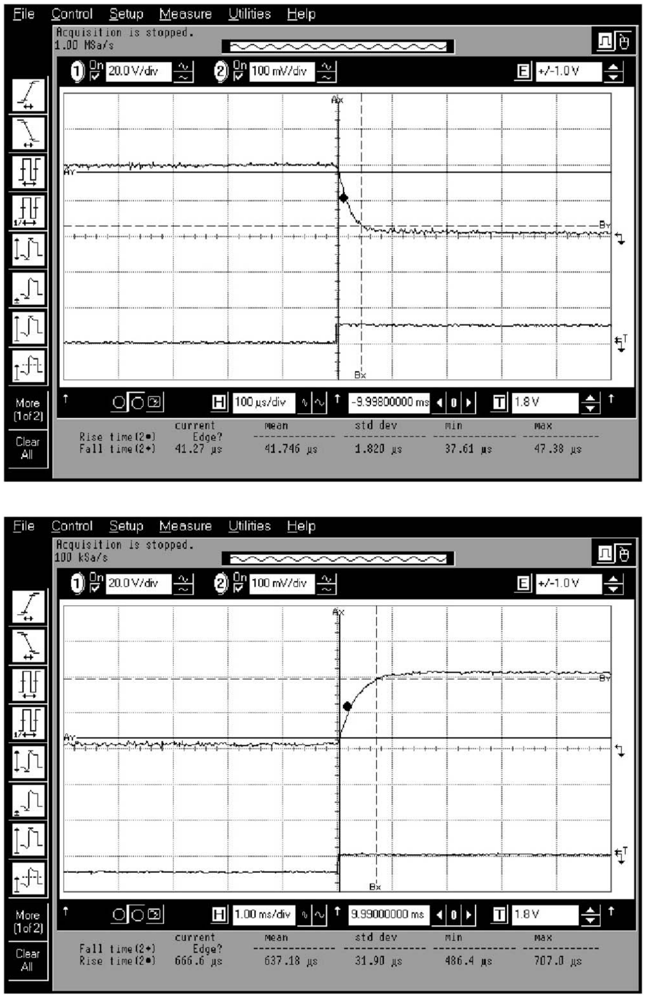
The free parameters in the optimization are the retardation and orientations of the compensation film and the LC cell. After much computer simulations, two modes with a cell gap of 3.5 μm are found to satisfy the requirements. Table I shows the simulation results. While mode 1 is obvious, mode 2 is interesting and unexpected. It comes about by including the orientation of the LC cell as a free parameter. Figure 2 shows the calculated reflectivity of the on and off states for mode 2. The LC material used in this calculation is MAD-01-4979 (MERCK), with $\Delta n = 0.2$. For both modes, the optical reflectivity is 70%–85% over the visible spectrum.

The ultimate issue is of course the response time of this fast response LCOS display. We have fabricated several reflective cells with different LC materials. The physical properties of these materials are listed in Table II. MLC6080 and MDA-0104679 are from Merck, and RDP-93421 is from Dainippon Ink & Chemicals, Inc. The cell gap is 3 μm. Figure 3 shows the temporal switching behavior of the fast response LCOS display for the worst situation of fully on and fully off. In each frame, the upper curves are the detector response, while the lower curves are the voltage pulse. All measurements were done at room temperature. It can be seen that the turn-on time is 40 μs, while the maximum relaxation time is 0.7 ms. As usual, the turn-on time is very fast since a voltage is applied. The relaxation time depends on the elastic behavior of the LC molecules and is considerably slower. Even so, it can be seen that the relaxation time is very fast since there is no backflow effect inside the LC cell. The twist deformation is not involved.

Figure 4 summarizes the switching times of the reflective NBB display between various gray levels. Eight equally spaced gray levels are used in this measurement. This LCOS mode operates in the normally white mode. Level 1 indicates the black state, and level 8 indicates the white state. Switching from a high reflectivity state to a low reflectivity state is always faster than the other way round, as is expected. The largest response time is 0.8 ms, while the average response time is 0.3 ms. Thus this NBB LCOS is suitable for FSC operation.

TABLE II. LC materials used for the fast response LCOS display.

LC material	LC type	Δn	$\Delta\varepsilon$	Rotational viscosity (m Pa s)	Viscosity	K_{33}/K_{11}
MLC6080	STN	0.2024	7.2	157	18	1.33
MDA-01-4679	TFT	0.2001	12.7	327	NA	1.06
RDP-93421	TFT	0.2388	6.57	136	38.9	NA



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Acquisition is stopped.
1.00 MSa/s

                 current        mean           std dev        min            max
Rise time(2●)     Edge?         -------------- -------------- -------------- -------------
Fall time(2♦)    41.27 µs       41.746 µs      1.820 µs       37.61 µs       47.38 µs
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Acquisition is stopped.
100 kSa/s

                 current        mean           std dev        min            max
Fall time(2♦)     Edge?         -------------- -------------- -------------- -------------
Rise time(2●)    666.6 µs       637.18 µs      31.90 µs       486.4 µs       707.0 µs
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FIG. 3. The temporal switching behavior of the fast response LCOS display. Horizontal scales for the upper and lower frames are 0.1 and 1 ms/div, respectively.

In summary, we have demonstrated a π cell or NBB cell under zero voltage bias conditions. The advantage of this NBB LCOS mode of course is the elimination of the splay state. With the use of SiO_2 as the alignment layer, this LCOS is robust against strong light operation. This NBB mode is fast enough for FSC operation. Switching times for all gray levels are below 0.8 ms. For average gray levels the switching time is 0.3 ms. The white light contrast ratio is 500:1. The optical reflectivity is also quite good. Depending on the birefringence of the liquid crystal used, the optical reflectivity can be as large as 85%. It is expected that the reflectivity can be increased further with better LC materials. This fast LCOS mode should be useful for FSC projectors, in particular, for microprojectors using a LED light source.

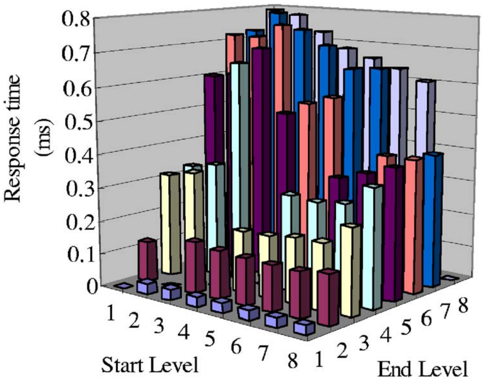

FIG. 4. (Color online) The switching times of NBB LCOS display between various gray levels.

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