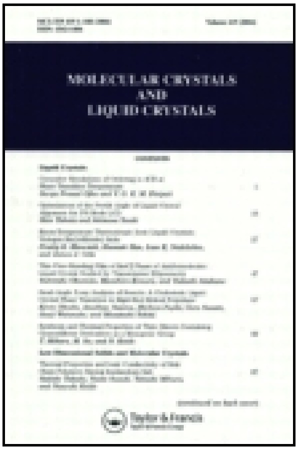

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Pi-cells for Telecoms

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Pi-cells for Telecoms

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In this paper, we present a comparison of the response times of pi-cells with that of uniform pretilt cells and confirm that the pi-cell switches faster than uniform pretilt cells possessing similar phase retardation. In order to design a 2π phase modulator with a fast response time at 1550 nm, an optimized combination of cell thickness d and pre-tilt angle θ_p was found using computer simulations. With this cell parameter combination, the condition for a pi-cell possessing maximum effective phase retardation and the smallest cell thickness and hence fastest response times for a given voltage were found.

Keywords: nematic liquid crystal; pi-cell; telecoms; uniform pretilt cell

1. INTRODUCTION

Pi-cells, in which the molecular director bends symmetrically by 180° through the cell [1], have been intensively studied due to their fast response times [2]. As well as being used in displays [3], it also has potential applications in telecommunications [4]. Owing to the long wavelength (1550 nm) of the IR light source used in telecommunications, devices used are quite thick (>10 μm) and thus have a slow optical relaxation for conventional cell configurations. Pi-cells are therefore considered very attractive in this case. Bos *et al*. [1] have

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related the fast electro-optical response to the symmetrical director configuration in the pi-cell producing no "backflow" near the center of the cell. However, when applying a voltage, a pi-cell will go through 3 director configurations:

i. With no applied voltage, a pi-cell stabilizes in the symmetrical splay state.
ii. With an applied voltage lower than a certain voltage which is known as the critical voltage V_{st}, a pi-cell stabilizes to give an asymmetric splay state.
iii. With a voltage above V_{st}, a pi-cell stabilizes in the bend state.

As the critical voltage V_{st} is needed to eliminate the unstable and slow switching splay state and maintain the bend state [5], part of the phase is lost in a pi-cell [6] when compared with a uniform pretilt cell. Consequently a larger cell thickness is required to maintain the same phase level, and thus a slower response times will be expected. A question that arises is whether the optical response time of a device is improved when using a pi-cell instead of using a uniform tilt cell in such a case.

Although we have confirmed that pi-cells indeed switch faster than uniform pretilt cells, their practical application is still of concern because of the instability of the desired bend configuration at certain voltages. This results in complicated relationships between cell parameters. Therefore when designing a pi-cell, trade-offs between the stability of the bend configuration and other electro-optical properties need to be addressed. In order to design the fastest possible 2π phase modulator at 1550 nm, we systematically investigate the pi-cell parameters in terms of cell thickness d and pre-tilt angle θ_p and try to find out the optimum combination of such parameters.

2. COMPARISON BETWEEN PI-CELL AND UNIFORM PRETILT CELL

2.1. Experiment

In order to compare the response times of the pi-cell, the non-pretilt cell and the uniform pretilt cell with similar phase retardation (2π), four cell conditions were chosen. The data is as shown in Table 1.

A convenient way to evaluate retardation δ is by measuring the I_c/I_P ratio [7]. I_c and I_p correspond to the cell optical transmission when the two polarisers are crossed and parallel respectively. To measure the transmittance of these cells, we inserted the LC cell between two crossed or parallel polarisers with the rubbing direction of the

TABLE 1 Test Cell Data

Cell	Alignment	Type	Liquid crystal	Thickness d (μm)	Pretilt angle(□)
Cell1	AM4276	P-AP	BLO48	7.66	<1
Cell2	SE610	P-AP	BLO48	8.92	11.431
Cell3	SE610	P-P	BLO48	14.79	11
Cell4	SE610	P-P	BLO48	19.91	11

Note:
P-AP—Planar aligned, antiparallel uniform pretilt cell;
P-P—Planar aligned, parallel pi-cell;

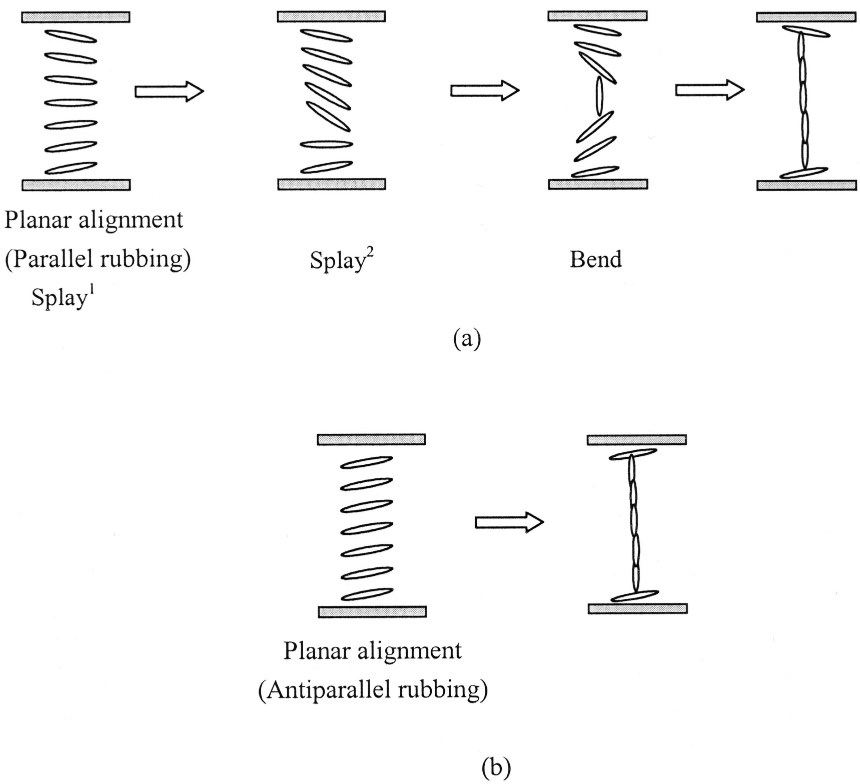

FIGURE 1 (a) Director configurations in a pi-cell for symmetrical splay (Splay^1), asymmetrical splay (Splay^2) and bend structure when applied voltage increases. (b) Director configurations in a uniform pretilt cell without voltage and with high voltage.

front substrate rotated 45° from the transmission axis of the first (fixed) polariser. The transmittance vs voltage curves were measured by using a computer-controlled system with a 1550 nm laser beam propagating normal to the substrates. A square waveform ac electric field was applied with a frequency of 4 kHz. Effective retardation is defined as $\delta_e = \delta_{Vst} - \delta_{V\max}$ where $\delta_{Vst}, \delta_{V\max}$ are the retardations at the critical voltage and maximum applied voltage respectively. The maximum applied voltage was 5 v because of the program restriction however the simulation showed that 5 v is enough to scan all the peaks in optical transmission. Experimentally, the critical voltage of a pi-cell was defined as the voltage at which a disclination can be observed in the polarizing microscope due to transforming from the splay state to the bend state.

The response time is determined according to the transmittance-time curve $t_{on}(100\% - 0\%) + t_{off}(0\% - 100\%)$ which was measured by using an oscilloscope with crossed polarisers. The set-up was similar to the one used to evaluate retardation except that the light source was white light.

2.2. Results and Discussion

The measured effective retardation result is shown in Figure 2. It can be seen that:

1) Effective retardation decreases as temperature increases. This is due to the change of birefringence with temperature.
2) From the data shown in Table 1 and Figure 2, it's easy to see that to produce the desired effective retardation, the pi-cell needs to be thicker.

Figure 3 shows the measured switch-on time of a pi-cell and a uniform pretilt cell with the same effective retardation at different operating temperatures. The switch-on time of a uniform pretilt cell is faster than for a pi-cell. However the switch-off time of the pi-cell is much faster than a uniform pretilt cell. Since the switch-off time dominates the overall switching time in a nematic liquid crystal cell, the overall switching time of a pi-cell is faster than a uniform pretilt cell. The result is shown in Figure 4.

3. OPTIMAL DESIGN FOR A 2π PHASE MODULATOR

3.1. Simulation

The commercial simulation package LCDMaster was used to investigate the effects of cell construction parameters on the main

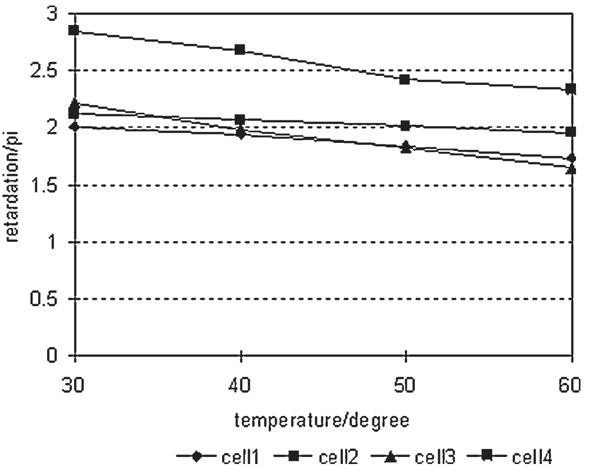

FIGURE 2 Measured Effective Retardation δ_e of the cells. For the uniform pretilt cell and the non-pretilt cell $\delta_e = \delta_{v=0} - \delta_{v=5}$. For the pi-cell, $\delta_e = \delta_{Vst=1.5} - \delta_{v=5}$. $\delta_{v=0}, \delta_{Vst=1.5}, \delta_{v=5}$ are the retardations at 0 v, 1.5 v and 5 v. The measured critical voltage Vst of cell 3 is 1.3 v and cell 4 is 1.4 v. 1.5 v is chosen to ensure enough driving margin above the critical voltage.

electro-optical properties of the pi-cell: critical voltage, effective retardation and response time. The simulation parameters are listed in Table 2.

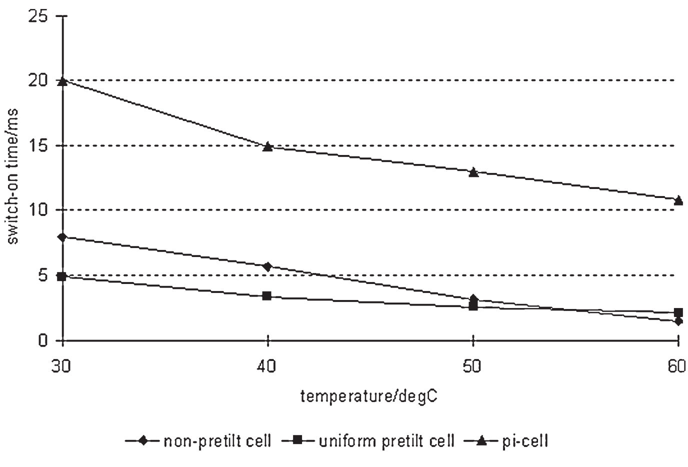

FIGURE 3 Measured switch-on time of uniform pretilt cell, non-pretilt cell and pi-cell with 2π effective phase retardation.

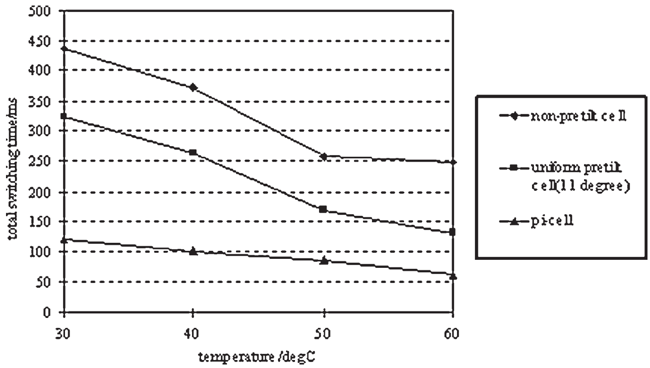

FIGURE 4 Measured total switching time ($t_{on} + t_{off}$) of Uniform Pretilt Cell, non-pretilt cell and Pi-cell all of which have 2π effective phase retardation.

3.2. Vst (Critical Voltage) Optimization

Vst is one of the most important parameters of a pi-cell. Only when operated entirely above this critical voltage, can the pi-cell show the fast switching characteristic of the bend state. When optimizing it, we should consider the interdependencies among various parameters, such as material parameters and cell construction parameters.

Figures 5–6 show the Vst dependency with pretilt angle and cell thickness respectively. In Figure 5, it is observed that the critical voltage is inversely proportional to the pretilt angle. When the pretilt angle is 50° the pi-cell can stabilize in the bend state without applying a voltage. This is similar to the result obtained by Acosta *et al*. [8] Figure 6 shows that the critical voltage is independent of cell thickness, as previously shown by Lee *et al*. [9].

3.3. Effective Retardation Optimization

From the above result, it seems that by increasing pretilt angle, we can reduce the critical voltage which means we obtain a larger

TABLE 2 Simulation Parameters: Liquid Crystal Material is BLO48

K33$^{(1)}$	K11$^{(1)}$	K22$^{(1)}$	$\Delta n^{(2)}$	$\Delta\varepsilon^{(3)}$	$\gamma^{(4)}$	$\lambda^{(5)}$
28	15.5	15	0.216	16.8	0.1	1550 nm

(1) Oseen-frank elastic constant, (2) birefringence at $\lambda = 1550\,\text{nm}$, (3) dielectric permittivity anisotropy, (4) rotational viscosity, (5) light source wavelength.

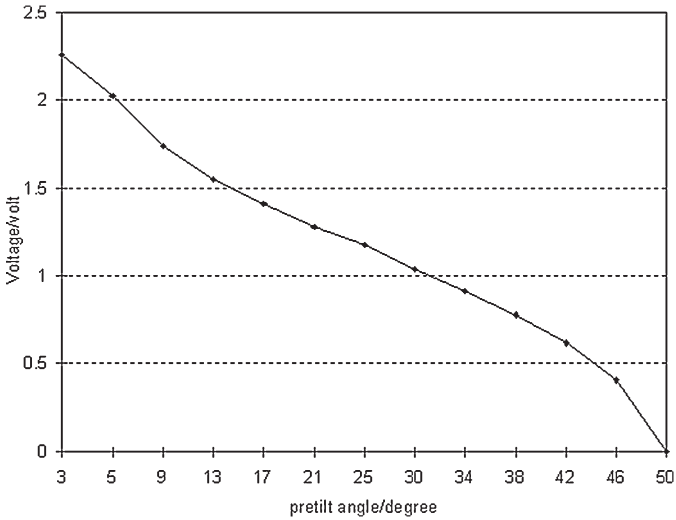

FIGURE 5 Critical Voltage v pretilt angle in a cell with thickness fixed at 10 μm.

effective retardation. However, increasing the pretilt angle results effectively initially in a smaller effective retardation. Consequently an extreme point can be expected in the relationship between effective retardation and pretilt angle.

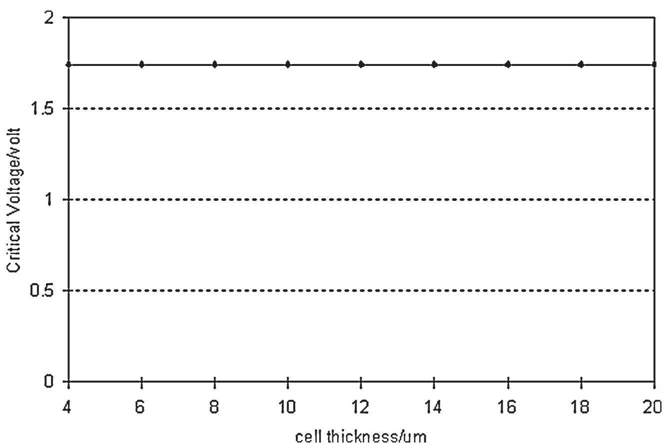

FIGURE 6 Critical voltage v cell thickness in a cell with pretilt angle fixed at 10°.

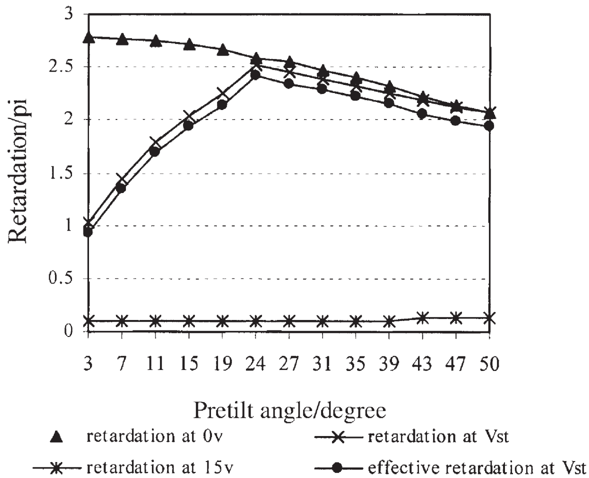

FIGURE 7 Effective retardation vs pretilt angle in a cell with thickness fixed at 10 μm. The effective retardation is defined as $\delta_e = \delta_{Vst} - \delta_{V\max}$. Here $V_{max} = 15$ v.

The extreme point is indeed found in simulation results as shown in Figure 7. The optimum pretilt angle corresponding to the maximum retardation is 24° for BLO48.

When the pretilt angle $\theta_P < 24°$, effective retardation increases sharply as the pretilt angle increases. When $\theta_P > 24°$, the effective retardation slightly decreases as the pretilt angle increases. The optimum angle depends on the choice of liquid crystal material.

Additionally, Figure 7 also shows that:

(i) The retardation at 0 V is inversely proportional to the pretilt angle;
(ii) The retardation at V_{max} is relatively stable as the pretilt angle increases.

3.4. Results and Discussion

Since the critical voltage is independent of thickness as shown in Figure 6, Figure 7 can be easily transformed into a thickness v pretilt angle curve for the designed effective retardation. Our aim is to get a 2π phase modulator with the fastest response times at 1550 nm. The required cell thickness d to produce 2π effective retardation with different pretilt angles are shown in Figure 8. It indicates that for LC material BLO48, when the pretilt angle is 24°, the smallest cell thickness is required and the fastest response times can be achieved.

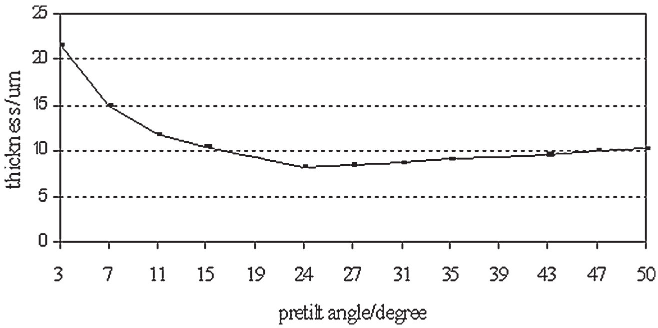

FIGURE 8 Required cell thicknesses to produce 2π effective retardation v pretilt angle.

4. CONCLUSION

We have systematically compared the response times of pi-cells with that of uniformly pre-tilted cells which possess equal phase excursions. It was found that that the pi-cell switched faster than uniformly pre-tilted cells since the switch-off time of a pi-cell is much shorter than that of a uniformly tilted cell. We also simulated the effect of cell parameters (cell thickness d, pre-tilt angle θ_p) and the driving voltage on the critical voltage, the effective retardation and the response time. Computer simulation has shown that there exists an optimized combination of such parameters, with which a pi-cell can possess the maximum effective phase retardation. As a result, the smallest cell thickness and therefore fastest response times can be achieved. The optimization result provides a valuable design rule for pi-cells.

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