Improvement in rise time of liquid crystals with patterned benzocyclobutene as alignment layer for photonic applications

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Liquid crystal (LC) response time plays a crucial role on the switching of the LC-based devices in photonic applications. It is significantly influenced by the surface structure of the substrate. Therefore, an alignment layer is typically deposited to give a preferred direction to the LC molecules in contact to the surface. In this paper, the rise time of LC on a patterned benzocyclobutene (BCB) was studied and compared with that on a conventional rubbed polyimide (PI) alignment layer. A faster rise time was achieved for the LC cell with patterned BCB alignment layer than that of PI alignment layer. The shortest rise time (τ_r) reached in our study is 0.06 ms for LC aligned on the patterned BCB layer and 0.18 ms for rubbed PI layer under a field strength of 3.3V/μm for a LC film thickness of 3μm. Therefore the patterned BCB as alignment layer is very potential in the LC based polymer waveguide devices. When the BCB can act both as waveguide materials and alignment materials, the technique also can reduce a fabrication step of LC based polymer waveguide devices. Thus the study can enhance the application of LC based optical waveguide devices for photonics technology.

1. Introduction

Planar lightwave circuit (PLC) technology based optical communication offers the advantages of low cost, ease in handling, highly reliable, multi-functionalities, low loss characteristics and high production through-put. In typical planar optical waveguide devices, the thermo-optic effect is used to tune the refractive index of the waveguide material, thus changing the optical properties of a guiding layer. The main concern for this method includes power consumption, heat dissipation and potential geometric deformation of waveguide structure under high heater temperature [1, 2]. As an alternative, electro-optic (EO) effect of the liquid crystals (LC) can easily overcome such issues. Liquid crystals, due to their large electro-optic response, anisotropy, mature and inexpensive technology, are quite appealing for many applications in optical devices. Especially, nematic liquid crystal (NLC) have many attractive features; such as large area formation, low driving voltages, and low power consumption. However, the NLC based devices have some limitations with respect to response characteristics and rely on active alignment of the LC molecules. The typical response speed of NLC is only in the order of tens of milliseconds [3-5] and faster speed is highly required for photonic applications. Another alternative is the use of smectic C* Ferroelectric Liquid Crystals (FLC) for faster EO response. However, it has several drawbacks and difficulties in the fabrication process. The layered structure of smectic LC is rather sensitive to mechanical and thermal stress and often needs special protective housings. Therefore this study focused on improving the rise time or switch-on time of NLC for photonic applications.

In order for such devices to function optimally, microscopic control over the director movement of the LC molecules within the device is highly required. This is enforced by the boundary conditions of the LC layer, and is preferably realized through the alignment layers. The presence of alignment layer on the surfaces enclosing the LC thin film is required to induce the desired molecular orientation. It could be postulated that the surface structure greatly influences on the molecular orientation of LC, which is controlled by the shape of surface, the elasticity and viscosity of LC and the interaction energy. Several techniques have already been demonstrated to align the LC on an alignment layer. Traditionally, surfactants or mechanical rubbing methods on polyimide (PI) are employed as it is a convenient and easy process to induce microstructures on the alignment layer surface. In the rubbing process, a giant roller wrapped in velvet cloth is rubbed on the surface of the polymer alignment layer. This technique is of high throughput and very appropriate for large area substrates in display industry.

However, the rubbing technique has some limitations in case of waveguide based optical devices. The requirement of direct mechanical contact, which introduce defects (scratches on the surface of alignment layer) and is a source of electrostatic charge and dust [6, 7]. The technique is also somewhat unreliable because the rollers can degrade unevenly, causing defects and degradation of the rubbing fabric, which lead to non-uniformity of the alignment layer surface. In case of irregular structure of waveguide devices, rubbing is also undesired as it may damage the device structure [8]. Fig. 1 is such an example of damaged optical channel waveguide by rubbing. To overcome the demerit of rubbing method, the

lithographically patterned alignment layer can be potentially used in the fabrication of LC based waveguide devices.
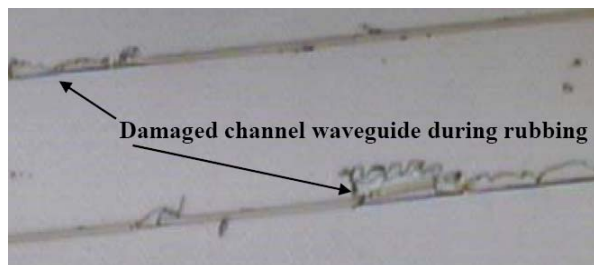

Fig. 1. The damaged waveguide channels by rubbing technique.

Polymers, as waveguide materials are very attractive due to their advantages, such as, simple fabrication processes of using embossing or UV technique, easy formation of multi-layer structure by spin-coating on any surface of interest and low cost. Therefore, it is also very appealing for patterned alignment layer on the same waveguide structure to reduce one fabrication step if the waveguide structure itself can effectively act as the alignment layer for the devices. No additional polymer layer need to deposit only as alignment layer. Among various polymers, benzocyclobutene (BCB) has been widely used in optical waveguides for its versatility of material properties, such as low moisture absorption, low optical loss, and high thermal & chemical resistance [8]. However, cured BCB is also excessively hard and ineffective for mechanical rubbing.

Therefore, we proposed to lithographically pattern of the top surface of BCB to act as alignment layer for the LC based polymer waveguide devices. The aims of this paper are to study and understand the influence of patterned BCB alignment layer on the rise time or switch-on time of NLC. A comparison was made between the rise time characteristics on patterned BCB and on traditionally rubbed PI alignment layer. Alignment layer of both BCB and PI was deposited on ITO coated glass slide and then BCB layer was patterned using photolithography and PI layer was rubbed using velvet cloth. To measure the rise time of LC molecule, two ITO coated glass slides with identical alignment layer were assembled for making the homogeneous LC cell. The rise is studied as a function of the applied field strength and applied frequency. The clearer understanding of the alignment layer effect on rise time is very important for manufacturers to develop better performance LC based optical waveguide devices.

2. Experiments

2.1 Materials

The materials for liquid crystal cell are mainly ITO coated glass substrate, polymer based alignment layer and liquid crystal film.

2.1.1 Substrate

Indium Tin Oxide (ITO) coated glass is used as a substrate for preparing the LC cells. The thickness of glass is about 1.1 mm and the ITO coating is few tens of nm. The ITO layer can acts as transparent electrodes. The substrate is cleaned by ultrasonic in solvents and then dried before the deposition of polymeric alignment layer.

2.1.2 Polymer materials used for LC alignment

Polyimide (SE130) from Nissan Chemicals is used for making rubbed PI alignment layers. It is a yellowish material of liquid state and the viscosity is about 50 cP at 25°C. The material has an average transparency of 94% within visible range and also shows excellent adhesive force to ITO coated glass substrate. On the other hand, benzocyclobutene (Cyclotene 3022) from Dow Chemical Company is used for making patterned BCB alignment layer. BCB is widely used as core material in polymer based optical waveguides due to its good material properties, such as low moisture absorption, low optical loss, high thermal and chemical resistance, and low dielectric constant. It is also a yellowish material of liquid state and the viscosity is about 60 cP at 25°C. The material has the thermal stability in excess of 350°C and good adhesion to various substrates.

2.1.3 Liquid crystal material

The use of nematic liquid crystal (NLC) for photonic applications is still of great interest. Therefore, NLC (E7 – commercially available and purchased from Merck) is used in the experiments. E7 nematic mixture exhibits a nematic phase from -10°C to $+58$ $^{\circ}$C, and so it can be electrically modulated within this wide working temperature range. E7 has ordinary (n_o) and extraordinary (n_e) refractive indices 1.522 and 1.747, respectively at 20°C and wavelength 589.3nm.

2.2 Alignment layers preparation

Two types of alignment layer were prepared on the ITO coated glass substrate: conventionally rubbed PI alignment layer and patterned BCB alignment layer. The detail of the preparation techniques are as follows:

2.2.1 Mechanically rubbed PI alignment layer

The technique for preparing a rubbed PI alignment layer is shown in Fig. 2. A thin layer of polyimide (PI) is deposited on ITO coated glass substrate as alignment layer by spin coating. After the pre-baking at 90°C for 10min, it is hard cured at 175°C for 45min. When the cured film is rubbed by a velvet cloth, microscopic groves are generated on the surface of polyimide (PI) layer so that the LC molecules can be aligned along the rubbing direction.
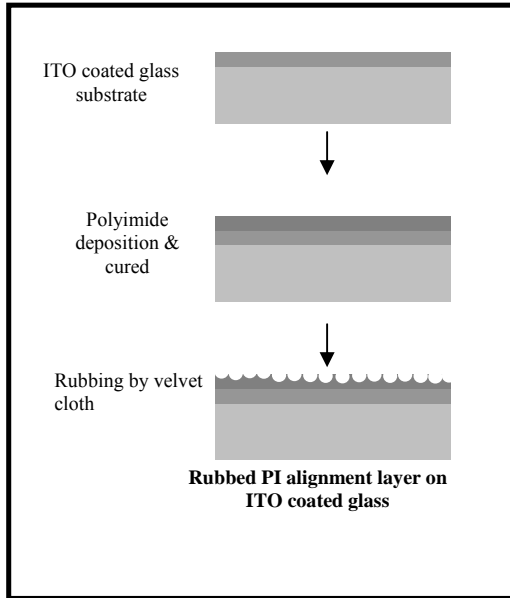
Fig. 2. The process of making a rubbed PI alignment layer.

2.2.2 Patterned BCB alignment layer

Photolithography is considered to be a clean non contact technique with high throughput and low cost. Therefore, photolithography based patterning technique is used to prepare the benzocyclobutene (BCB) alignment layer. The patterning steps of BCB layer are shown in Fig. 3. Firstly, a thin film of BCB is deposited by spin coating on ITO coated glass substrate. The deposited film is thermally cured at 275°C for 45min in N_2 environment to avoid oxidation. For Patterning the BCB a positive photo-resist SPR6112B film is deposited over the BCB layer and patterned by a UV mask aligner. After developing, the film is etched by Reactive Ion Etching technique (RIE). The etching depth of the grating patterned structure is controlled by controlling the etching time together with the N_2 and O_2 gas mixing ratio and flowing rate. After the etching process the patterned surface is washed again by developer.
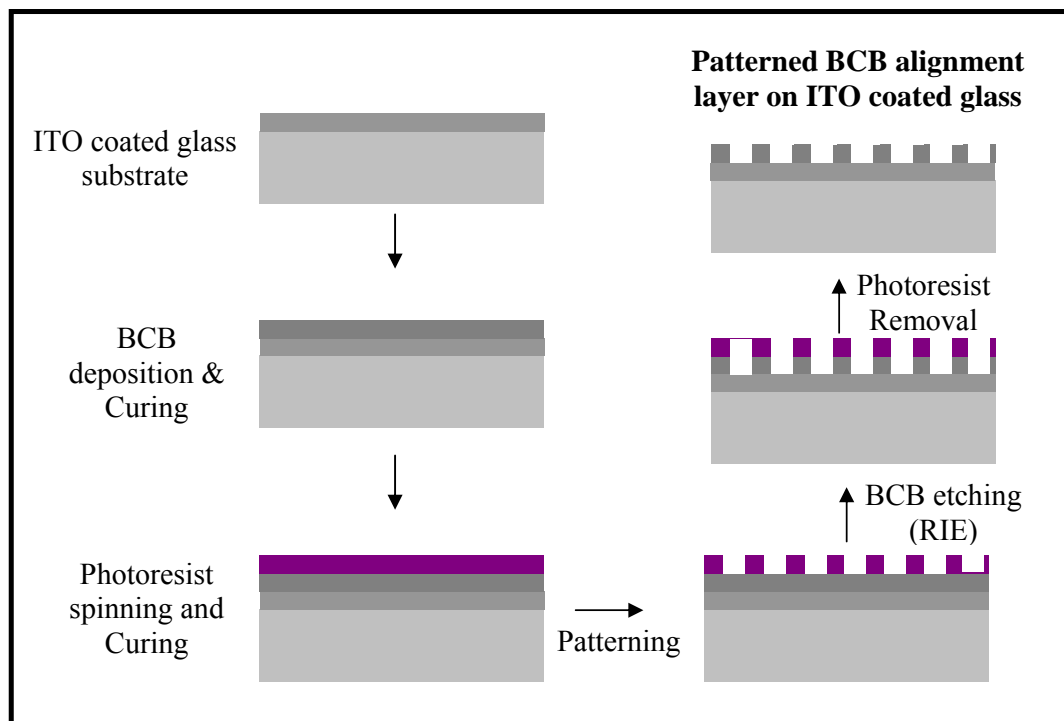

Fig. 3. The patterning steps of the BCB layer.

2.3 Surface analysis

The surface structure of both BCB and PI alignment layer was characterized by using contact mode of atomic force microscopy (AFM) (AUTOPROBE CP-Research).

The average grating period and depth are measured by the image analysis program.

2.4 Anchoring energy measurement

In order to compare the EO performance of the two cells relative to each other, the azimuthal anchoring energy (W_a) was calculated for the patterned BCB layer according to Berrman theory, [9, 10]. The Berreman theory is given by:

$$W_a = \frac{2\pi^3 a^2 K}{\lambda^3} \tag{1}$$

where; a, is the grating height, λ, is the grating period, and K, is the mean of the splay and bend elastic constants. Berreman has made a theoretical study of the interaction of nematic LC molecules with undulating surface structure. He assumed a planar anchoring that is completely isotropic in the local tangent plane to the surface, and calculated the resulting elastic energy as a function of the azimuthal orientation of the LC director in the bulk relative to the direction of the grooves. Berreman's topological model is only applicable for shallow grating surface, and for the sinusoidal grating structures [11]. The calculated anchoring energy of BCB layer was then compared with that of the PI layer [12, 13].

2.5 Cell fabrication

The LC cell assembling procedure is shown in Fig. 4. Two ITO coated glass slide with identical alignment layers (either the rubbed PI or patterned BCB) are assembled together to form a cell. The cell gap spacing (d) of 3μm of the LC cell is controlled by making a photoresist spacer over the alignment layer of one slide. Then glue is used for sticking two opposite side edges of the two substrates together. The nematic LC (E7) was heated to isotropic phase, and then was filled into the cell by capillary effect and gradually cooled down to room temperature. The two types of fabricated LC cells are:

PI cell: cell with a rubbed PI alignment layer on both the upper and lower substrates.

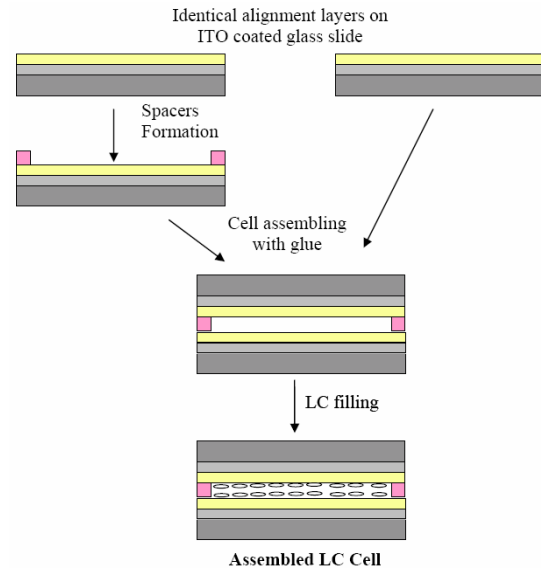**BCB cell**: cell with a patterned BCB alignment layer on the upper and lower substrates.

Fig. 4. LC cell assembling procedure.

2.6 EO measurement of the Rise time

Fig. 5 shows the measurement set-up for measuring the rise time or switch-on time of two LC cells**.** He–Ne laser beam with a wavelength 632nm as the input signal and the transmitted output optical signal is detected by a New Focus 2001 detector connected directly to an oscilloscope. A square a.c. signal voltage is applied to the cell by using HP HEWLETT PACKARD 33120A function generator. The cell is set at angle 45° between crossed linear polarizer and analyzer for ensuring maximum output transmittance, so that the cell works as a phase retarder thereby altering the polarization of the light. When a voltage is applied, the LC molecules are aligned in the applied field direction. Again when the voltage is switched off the LC molecules relax back on their own to return back to their initial state.
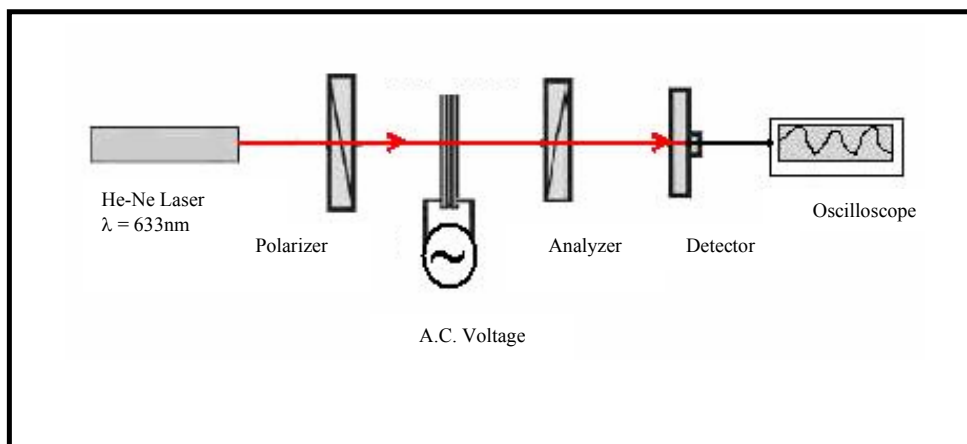

Fig. 5. The experimental setup for measuring the EO response of the LC cells.

3. Results and discussion

3.1 Surface properties

In general, the alignment layer greatly affects the electro-optic properties of liquid crystals [14-16]. The more confined & uniform alignment quality leads to a better liquid crystal device performance. Therefore, the surface structure was studied using the Atomic Force Microscopy (AFM). Fig. 6 shows the 3D AFM image of the rubbed PI and the patterned BCB surface topography. From the figures, it is clear that the BCB patterned grating structure, Fig. 6 (b), is more ordered with periodical microgrooves compared to the surface structure of the rubbed PI layer, Fig. 6 (a). For the PI alignment layer, the average spacing between the grooves is 0.58μm and the average groove depth is 20nm. However, for the BCB alignment layer the average grating period (λ) is 1.92μm and average grating height (a) is 0.93μm.
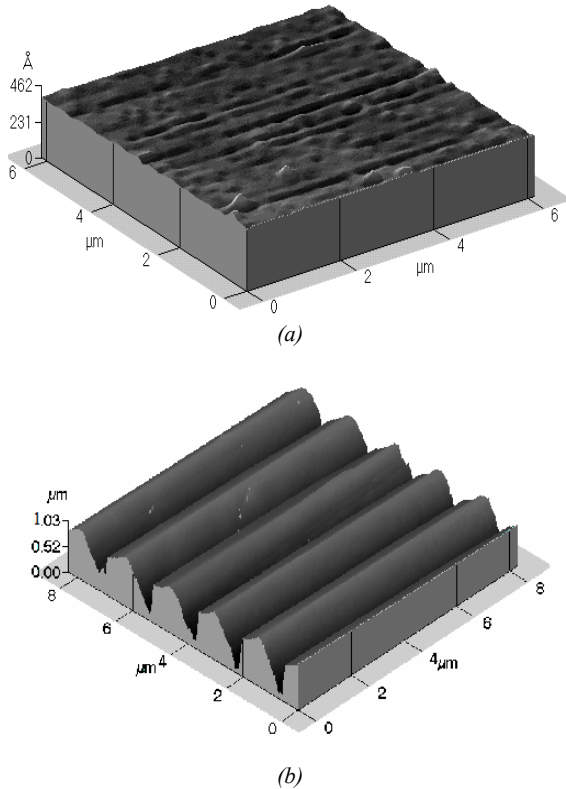

(a)

(b)

Fig. 6. The 3D AFM image of (a) the rubbed PI and (b) the patterned BCB layers.

3.2 Surface anchoring energies

It is known that at any applied external field, EO response of LC is related to the surface anchoring energy which depends on the boundary surface energy [17-19]. The alignment of the LC molecule director is determined by the competition among the surface interactions, bulk interactions, visco-elastic properties and the externally applied electric field.

As the surface anchoring strength decreases the LC response time also decreases; the EO switching speed becomes faster [20]. On the other hand, the LC cell with higher surface anchoring strength provides more homogeneous LC thin film. For the E7 the value of splay elastic constant is K_{11} =12 x 10^{-12}N, and the bend elastic constant is K_{33} = 19.5 x10^{-12}N, and so K = 15.75 x 10^{-12}N [21]. According to equation (1), The calculated anchoring energy for the patterned BCB cell is 0.12X10^{-3} J/ m^2, which is in the same order of magnitude as that reported for rubbed PI layers [12, 13]. Regarding the material properties; it was reported that polyimide (PI) induces stronger anchoring strength compared to BCB [22]. Therefore, the BCB alignment layer should provide faster LC rise time than that of PI alignment layer.

3.3 Comparing the EO response

Theoretically, the LC rise time (τ_r) is given by [3, 23]:

$$\tau_r = \frac{\gamma d^2}{k_{ii}\pi^2}\left[\left(\frac{V}{V_{th}}\right)^2 - 1\right]^{-1} \qquad (2)$$

where, K_{ii} is the LC material effective elastic constant, γ is the LC viscosity, V and V_{th} are the applied driving voltage and the LC threshold voltage, respectively. The threshold voltage is expressed as:

$$V_{th} = \pi\sqrt{\frac{k_{ii}}{\varepsilon_o \Delta\varepsilon}} \qquad (3)$$

where; ε_o is the permittivity of free space, $\Delta\varepsilon$ is the LC dielectric anisotropy,($\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$), and K_{ii} is the LC material effective elastic constant. From the equation 2, the rise time (τ_r) dependant on both the applied voltage and threshold voltage (V_{th}). However, the threshold voltage (V_{th}) depends on the LC dielectric anisotropy $\Delta\varepsilon$, which is dependant on applied frequency. Thus, the rise time is ultimately depends on the applied frequency as well. Therefore for a cell of fixed thickness and specific LC, the rise time (or the switch-on time) depends mainly on driving frequency and applied field strengths.

3.3.1 The effect of driving frequency on the LC rise time

Fig. 7 shows the rise time (τ_r) as a function of the applied frequency up to 1 kHz under a driving a.c. square voltage to the cells.
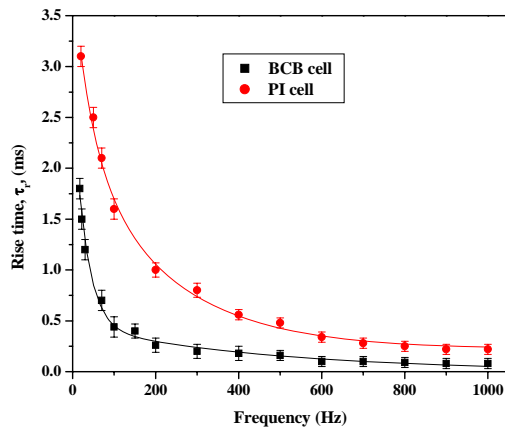
Fig. 7. The rise time (τ_r) as a function of the applied frequency with an applied peak voltage of 7.1V.

In order to achieve a faster switching speed, much higher voltage (V_p = 7.1V) than the threshold voltage ($V_{th} \sim$ 1.8V) is applied. The rise time (τ_r) of the two cells decrease nonlinearly with the applied frequency reaching 0.08 ms for the BCB cell compared to 0.22 ms for the PI cell at 1 kHz. The important facts of the measurement results are discussed as follows:

Faster response in BCB alignment layer

The faster response of BCB cell compared to that of the PI cell could be due to material and surface properties of the two different alignment layers. Since BCB surface promote a weaker anchoring energy than PI and thus should have faster response to LC molecules [22]. The patterned BCB layer also provide more uniform surface structure that confines the LC molecules in parallel orientation relative to each other. The grating patterned structure also promote a relatively higher pre-tilt angles and lower anchoring strengths and thus leads to faster LC response speed [11, 22, 20, 24].

Faster response at higher frequency

The rise time also decrease with the increase of applied frequency. Initially the rise time decrease very sharply up to the applied frequency of 200 Hz and then decrease slowly over the frequency. Theoretically the dielectric anisotropy ($\Delta\varepsilon$) decreases with increasing of applied frequency. As a results, the threshold voltage (V_{th}) increases with the applied frequency according to equation 3. When the threshold voltage is increased, the rise time is also decrease with applied frequency according to equation 2. The nonlinear drop of rise time is due to applied higher peak voltage (almost four times of threshold voltage). Because, theoretically, the rise time (τ_r) is directly proportional to (d^2). However, there is a theoretical deviation of such quadratic dependence of the rise time on the cell thickness (d) at higher applied

voltage. The theoretical expression of the rise time (τ_r) is valid only in the low voltage region; $V_{th} < V < \sqrt{2} \, V_{th}$, while at higher applied voltage the rise time (τ_r) become faster and independent of the cell gap thickness (d) [20, 25]. A similar behavior of the decrease of rise time (τ_r) of nematic LC as a function of the applied frequency up to 1 kHz was also reported [26].

Charging effect at low frequency

At frequencies lower than 100Hz the output transmitted signal was not stable. This in fact is due to the effect of free charges and ions motion that arise from the impurities in LC or from the alignment layer. These free charges and ions lead to change the actual applied field strength to the LC molecules, since this charge motion between the two electrodes induce an additional field component which affects the actual value of the applied field strength on the LC thin film.

3.3.2 The effect of field strength on the LC rise time

The rise time (τ_r) is also measured as a function of the applied field strength. Fig. 8 shows the field strength effects for the two cells at frequency 1 kHz. The field strength is increased from 1.0 V/μm to 3.3V/μm. The rise time strongly depends on the applied voltage according to Eq.2. When the applied voltage is only just above the threshold voltage V_{th} (0.6 V/μm), the rise time is comparatively higher. However, the rise time is reduced effectively just by increasing the applied driving voltage. The shortened rise time (τ_r) found in this study are 0.06 ms for the BCB cell and 0.18 ms for PI cell.
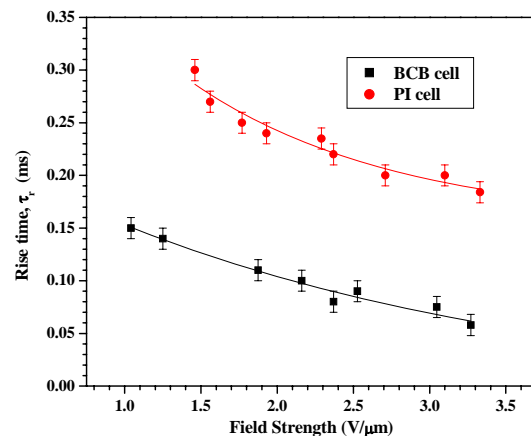

Fig. 8. The rise time (τ_r) as a function of the applied electric field strength at 1 kHz.

In summary, the liquid crystals response is governed by

(i)   The electric field that orients the LC director in the bulk.

(ii)   The surface anchoring of the alignment layer that keeps the director aligned at the bounding substrates together.

(iii)   Visco-elastic properties of LC material that's also influenced by the applied frequency [27].

4. Conclusions

Patterned benzocyclobutene (BCB) is demonstrated as the alignment materials for liquid crystal (LC) based optical devices. It is an alternative of traditionally rubbed polyimide (PI) alignment layer, also potential for waveguide based optical devices as BCB is extensively used as waveguide materials. By using BCB as both the waveguide materials and alignment layer, a fabrication step can be reduced. Photo-Lithography is used as a clean non contact technique for patterning a periodical grating structure on the BCB layer. A systematic study have done to compare the patterned BCB and rubbed PI alignment layer. The rise time is measured as a function of the driving frequency and field strength in characterizing the LC cells.   The shorter rise time and faster response was found for LC film with patterned BCB alignment layer than that of rubbed PI alignment layer. The fastest rise time in our study was found 0.06ms for BCB alignment layer and 0.18ms for rubbed Polyimide (PI) alignment layer under applied field strength 3.3V/μm at 1 kHz. Therefore, the patterned BCB can potentially replace the PI alignment layer in fabricating the optical waveguide devices. Hence the study can gives important dictations in the fabrication of LC based planar light wave circuit devices.

Acknowledgements

References

[1] M. A. Uddin, H. P. Chan, J. Optoelectron. Adv. Mater. **10**(1), 1 (2008).

[2] J. T. Kim, J. J. Ju, S. Park, M.-H. Lee, IEEE J. Sel. Top. Quant. Electron. **13**(177), 2007.

[3] Iam-Choon Khoo, John Wiley & Sons, Inc., 2007.

[4] A. Muravsky, A. Murauski, V. Chigrinov, I. Goncharenko, ICTON, 2007.

[5] Y. Okamura, K. Kitatani, S. Yamamoto, J. of Lightwave Technology **LT-4**(3), 360 (1986).

[6] S. Mias, H. Camon, J. Micromech. Microeng **18**, 083001 (2008).

[7] F. Yang, G. Zoriniants, L. Ruan and J.R. Sambles, Liquid Crystals, **34**, No. 12, 1433, (2007),.

[8] Y. Xu, M. A. Uddin, P. S. Chung, H. P. Chan, Sydney, OECC, 2008.

[9] D. W. Berreman, Phys. Rev. Lett. **28**, 1683 (1972).

[10] C. J. Newsome, M. O'Neill, R. J. Farley, G. P. Bryan-Brown, Applied Physics Letters **72**(17), 1998.

[11] Munehiro Kimura, Yasuyuki Ohta, Tadashi Akahane, Journal of materials online **1**, 2005. http://www.azom.com/details.asp?ArticleID=3096

[12] S. Faetti, P. Marianelli, Physical Review E **72**, 051708 (2005).

[13] Shug-June Hwang, Hsin Her Yu, Min-Hua Hsu, Journal of Display Technology **3**(3), 259 (2007).

[14] S. Frunza, T. Beica, R. Moldovan, I. Zgura, L. Frunza, J. Optoelectron. Adv. Mater. **7**(4), 2149 (2005).

[15] T. Betca, S. Frunza, I. Zgura, R. Moldovan, A. Dinescu, J. Optoelectron. Adv. Mater. **10**(3)**,** 558 (2008).

[16] A. G. Petrov, Y. Marinov, S. D'Elia, S. Marino, C. Versace, N. Scaramuzza, J. Optoelectron. Adv. Mater. **9**(2), 420 (2007).

[17] V. Barna, G. Strangi, E. S. Barna, J. Optoelectron. Adv. Mater. **10**(12), 3403 (2008)**.**

[18] Dumitrascu I, Dumitrascu L, Dorohoi Do, J. Optoelectron. Adv. Mater. **8**(3)**,** 1028 (2006).

[19] P. Jagemalm, L. Komitov, G. Barbero, Appl. Phys. Lett. **73**(12), 1616 (1998).

[20] X. Nie, R. Lu, H. Xianyu, T. X. Wu, S.-T. Wu, J. of Applied Physics **101**, 103110 (2007).

[21] J. Beeckman, K. Neyts, X. Hutsebaut, C. Cambournac, M. Haelterman, IEEE Journal of Quantum Electronics **41**(5), (2005).

[22] C. Desimpel, F. Beunis, H. Desmet, K. Neyts*,* The 16th Conference on Liquid Crystals, Chemistry, Physics & Applications, 69 (2005).

[23] S. Musikant, MARCEL DEKKER, INC., 1990.

[24] J. Cliff Jones, S. Beldon, SID Symposium Digest of Technical Papers **35**(1), 140 (2004).

[25] H. Wang, X. Nie, T. X. Wu, S.-T. Wu, Mol. Cryst. Liq. Cryst. **454,** 285 (2006).

[26] C. H. Choi, S. H. Kim, E. Y. Hong, B. K. Kim, Eur. **33**(4), 565 (1997).

[27] Y. Yin, Ph.D. Thesis, Kent State University, 2007.

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