Voltage dependent director of a homeotropic negative liquid crystal cell

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Thin layers of obliquely (60° to normal) thermally evaporated SiO_x lead to homeotropic alignment of a nematic liquid crystal (LC) having negative dielectric anisotropy. Under application of an ac voltage the director, as characterized by the fully leaky waveguide technique, is found to realign with a voltage controlled tilt along the evaporation direction. This behavior is in complete contrast with that of a LC having positive dielectric anisotropy and may have important implications for modern LC display technology. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2963977]

Liquid crystals (LCs) with negative dielectric anisotropy (NDALC) have recently seen extensive use in flat panel display applications, especially in the vertically aligned (VA) mode.[1] Because such a structure has good contrast combined with quite fast switching times, this type of display has substantial potential. Clearly to obtain good operation it is important to be able to control the director orientation in such a structure incorporating a NDALC. However, it is well known that these materials can be rather difficult to align homeotropically. Poor alignment of course leads to a low contrast ratio and the advantages of using a NDALC are lost. Because of this several different methods for achieving homeotropic alignment with a NDALC have been developed.[2–5] Lu *et al.*[5] explored in some detail the use of obliquely deposited SiO_2 produced using electron beam evaporation. They found that, depending on the angle of evaporation and the nature of the LC (positive or negative $\Delta\varepsilon$), alignments from homogeneous through to homeotropic could be obtained. Other works, which form the basis of US patents,[6,7] also provide methods for homeotropic alignment of negative nematics.

In this letter, we provide a simple and inexpensive method for aligning a NDALC in a uniform homeotropic orientation in a thin (<4 μm thick) cell and show, using optical waveguide studies, how upon application of an ac voltage across the cell a uniform tilted structure is obtained with the LC director tilted along a single direction which lies in the plane conatining the intitial SiO_x evaporation direction and the surface normal.

First a wedged cell with a thickness varying from $\sim$0 to 3 μm has been built using glass plates on the inside of which has been deposited thin SiO_x layers by oblique vacuum evaporation (60° to normal). Such a layer gives homogeneously aligned LC for a positive dielectric anisotropy nematic. The cell was assembled with the evaporation directions antiparallel to each other and then vacuum filled with a NDALC (MLC-6884, Merck), which has a reasonably high dielectric anisotropy of $\Delta\varepsilon=-5$. When this cell was observed between two crossed polarizers, there was a very uniform dark figure at all twist angles. However, if the cell is tilted from being normal to the incident light then at certain angles it appears uniformly bright. This means that the director within the cell is everywhere homeotropically aligned. Thus it appears that the 60° to normal evaporated SiO_x layer causes *homeotropic* alignment of this NDALC for this range of thickness.

Next a cell of $\sim$3 μm thickness was assembled, again using two glass plates ($n=1.5170$ at 632.8 nm), each having on their inside surfaces thin layers of indium tin oxide as electrodes, on top of which are deposited the surface aligning layers of obliquely evaporated SiO_x. The cell was then filled with NDALC (MLC-6884, Merck). Observing the cell between two crossed polarizers shows that it is homeotropically aligned. However, on application of an ac electrical field it was observed that for voltages below about 1.5 V rms nothing changes. However, above this voltage the cell is observed to become uniformly bright as the cell is rotated around the normal to the polarizers. This shows that the director within the cell is tilted out along a single direction, either parallel or perpendicular to the plane containing the evaporation direction and the surface normal (the evaporation plane).

In order to explore the detail of this director structure, the fully leaky guided wave technique has been used.[8] The cell is inserted between the two equilateral glass prisms with optical contact being established with the glass plates of the cell using matching fluid, the prisms and matching fluid all having the same index as that of the cell substrates. The experimental setup is a typical θ-2θ rotating system as described elsewhere.[8] The cell has been set so that the SiO_x evaporation plane is perpendicular to the incident plane. A p (or s)-polarized beam with $\lambda=632.8$ nm (He–Ne laser) enters through one face of the input prism and the incident angle dependent reflectivity signals are recorded using a detector with a p (or s)-polarizer placed in front of it. Data in the form of R_{pp} and R_{ss} are recorded with various voltages applied to the cell at a frequency of 1 kHz. The polarization conversion reflection signal R_{ps} with no applied voltage is also taken. As noted there is a threshold voltage for the cell since the waveguide modes do not significantly alter until the applied voltage reaches $\sim$1.8 V. Two typical R_{pp} and R_{ss} signals, taken at 3.6 V, are shown in Fig. 1 by the crosses.

Using multilayer optics theory,[9] together with a continuum elastic theory for the nematic, the reflectivity data are fitted to a model giving the full director profiles within the cell at different voltages. For no applied field, a uniform nearly homeotropic structure with a surface pretilt angle less than 2° is found. The optical parameters of the LC MLC-6884 are found to be $\varepsilon_\perp=2.1870+i0.003$ and $\varepsilon_\parallel=2.4650+i0.003$ with a thickness of 3.07 μm.

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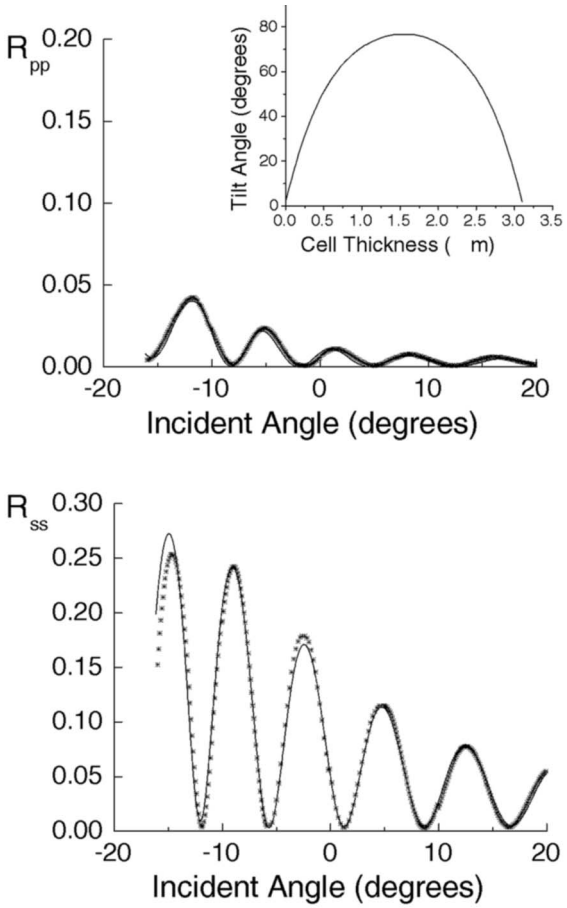

FIG. 1. The experimental data (crosses) (a) R_{pp} and (b) R_{ss} for 3.6 V ac applied to the cell compared with the theoretical fits (solid lines). The insert is the director tilt profile in the cell.

The change in R_{ss} under application of an electric field is fitted by a model of the director which is simply tilted within the evaporation plane. This is quite different to the case of a positive nematic where the director aligns perpendicular to the evaporation plane.[10] The change of the director orientation after applying a field to the cell is shown schematically in Fig. 2. By fitting all of the data the director profiles for different applied voltages are obtained. Figure 1 shows the fitting results for R_{pp} and R_{ss} (solid lines) with the experimental data (crosses) at 3.6 V, the insert being the director tilt profile in the cell at this voltage. The voltage dependence of the director tilt at the cell center is plotted (as dots) in Fig. 3.

According to the continuum elastic theory of LCs,[11] there is a threshold voltage independent of the cell thickness, the Freedericksz transition voltage. Our experiments confirm the existence of this threshold voltage for this NDALC. The

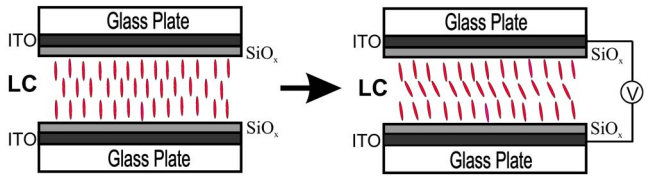

FIG. 2. (Color online) Schematic of the cell structure and the change of the director orientation after applying an electric field.

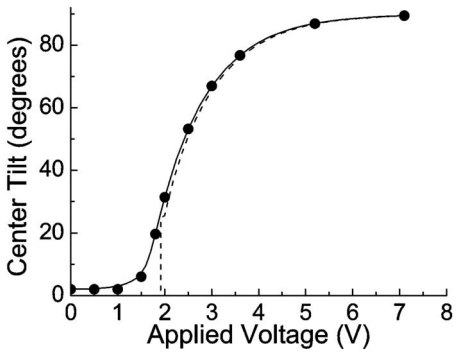

FIG. 3. The change of the director tilt at the center of the cell (dots), from fitting data, as a function of applied voltage compared with the theoretical model (solid line). The dashed line is the model for zero pretilt angle on the cell surfaces.

threshold voltage for a cell with perfect homeotropic alignment is given by[12]

$$V_t = \pi \sqrt{\frac{K_{33}}{\varepsilon_0 |\Delta\varepsilon|}}.$$

Substituting values for $K_{33}=14.8$ pN and $\Delta\varepsilon=-5$ gives a threshold voltage of about 1.82 V. Bearing in mind that there is a 2° surface pretilt angle in our cell, this simple analytic value is in very good agreement with our experiment result. Using a full theoretical model with these parameters and a 2° pretilt on both surfaces gives the director tilt in the cell center for different applied voltages, as shown in Fig. 3 by the solid line. Because of the small surface pretilt there is no longer a sharp threshold voltage and the model compares extremely well with the experimental data. For comparison we have also calculated the director profile in the cell center if the surface pretilt was zero; this is shown in Fig. 3 as a dashed line; now there is a clear threshold voltage.

In conclusion, a thin layer (of order 20 nm) of 60° (from normal of the substrate) obliquely evaporated SiO_x has been found to produce good homeotropic alignment of a NDALC. The fully leaky guided wave technique has then been used to characterize as a function of applied voltage the director profile in a 3 μm thick cell having these surface aligning layers. A threshold voltage is found above which the director tilts along one single direction, which lies in the plane containing the SiO_x evaporation direction and the surface normal. This orientation control of the director in such cells may be very useful for further application of NDALCs.

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[1] D. Pauluth and K. Tarumi, J. Mater. Chem. **14**, 1219 (2004).
[2] J. L. Janning, Appl. Phys. Lett. **21**, 173 (1972).
[3] C. Chen, J. E. Anderson, and P. J. Bos, Jpn. J. Appl. Phys., Part 2 **44**, L1126 (2005).
[4] C. H. Wen, B. Wu, S. Gauza, X. Y. Nie, and S. T. Wu, Mol. Cryst. Liq. Cryst. **454**, 315 (2006).
[5] M. Lu, K. H. Yang, T. Nakasogi, and S. J. Chey, SID Int. Symp. Digest Tech. Papers **29**, 446 (2000).
[6] N. Kato, R. Sekura, and T. Iwaki, U.S. Patent No. 5745205 (28 April 1998).
[7] M. G. Samant and J. Stöhr, U.S. Patent No. 6519018 (11 February 2003).
[8] F. Yang and J. R. Sambles, J. Opt. Soc. Am. B **16**, 488 (1999).
[9] D. Y. K. Ko and J. R. Sambles, J. Opt. Soc. Am. A **5**, 1863 (1988).
[10] J. Cognard, Mol. Cryst. Liq. Cryst. **I**, 1 (1982).
[11] F. C. Frank, Discuss. Faraday Soc. **25**, 19 (1958).
[12] J. Nehring, A. R. Kmetz, and T. J. Scheffer, J. Appl. Phys. **47**, 850 (1976).