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Controlling liquid crystal alignment by micro-patterned substrates

**A V Mamonova¹, M V Gorkunov^{1,2}, I V Kasyanova¹, V V Artemov¹,
and S P Palto¹**

¹Shubnikov Institute of Crystallography, FSRC “Crystallography and Photonics”,
Russian Academy of Sciences, 119333 Moscow, Russia

²National Research Nuclear University MEPhI (Moscow Engineering Physics
Institute), 115409 Moscow, Russia

Email: alen.mamon@yandex.ru

Abstract. We propose a method of controlling the liquid crystal alignment at rubbed polyimide substrates by patterning them periodically with the focused ion beam. The pattern duty factor sets the alignment conditions which determine the light phase retardation that can be precisely varied in a range from zero to that of the background. The method opens up opportunities for creating tunable optical devices.

1. Introduction

Recently it was discovered that focused ion beam (FIB) creates specific liquid crystal (LC) alignment conditions on rubbed polyimide (PI) substrates [1]. In particular, it is possible to induce periodical distribution of the main LC optical axis by patterns of a period P , consisting of alternating treated and non-treated stripes: the LC director is aligned vertically (homeotropically) above the treated areas, while the alignment above the non-treated areas remains horizontal (planar) as imposed by the rubbing.

During the FIB-patterning we can precisely control the duty factor r , which is a ratio of a width of the treated stripes to the period. It takes the values from 0 to 1, where 0 means completely untreated surface, and 1 means completely treated surface. In this paper, we report that by varying the duty factor of the micro-patterned structures one can adjust the LC alignment and, as a result, locally control such key optical property as the phase retardation. This opens up possibilities of creating versatile flat tunable LC-based optical devices.

2. Experiment

Glass substrates coated with 150 nm thin transparent ITO electrodes are used. Layers of PI or chromolane (Chr) are spin-coated onto substrates and baked for 1 hour at 190°C and 100°C respectively. A uniform planar LC aligning action is induced by mechanical rubbing of the PI layers. The substrates with Chr induce homeotropic orientation of the LC director.

PI surface prepared in such a way is then subjected to the periodic FIB patterning. The used patterns are comprised of stripes parallel to the PI rubbing direction and having fixed period and varying width, i.e., varying duty factor r (Fig.1a). LC cells are assembled as follows: the substrates with patterned PI and non-patterned Chr layers are stacked and the gap between them is filled with nematic LC Merk E7.



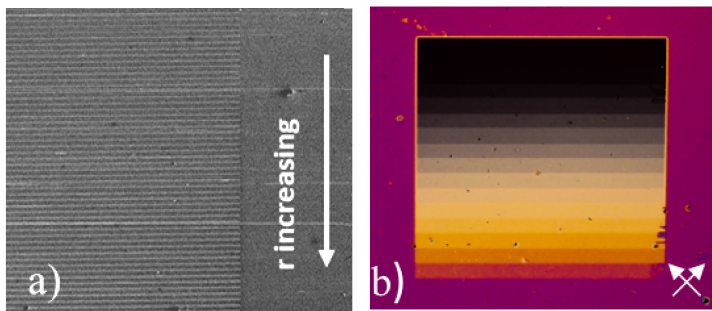


Figure 1. **a)** SEM image of a fragment of stripe pattern with a gradually varying duty factor r ; **b)** Optical image of the LC layer above the pattern with variable duty factor r as observed in crossed polarizers rotated by 45° with respect to the LC layer optical axis.

We study LC cells of a thickness d of the LC layer in a range from 3.7 to 13 micrometers upon similarly patterned substrates. Optical studies are performed using Olympus CX31PF-5 polarized-light microscope. The LC alignment determines the relative phase retardation, which is the difference of the phases accumulated by light of the two orthogonal linear polarizations. It is responsible for the color observed in crossed polarizers, see Fig. 1(b), which varies above the stripes from black (zero phase retardation) to that of the background (the same phase retardation as in the background). Precise values of the phase retardation upon each part of the stripes are measured using the Berek compensator. From these data, the relative birefringence of the LC layer above each stripe is evaluated and its dependence on the reverse duty factor $(1-r)$, is presented in Figure 2.

3. Analytical model

We apply an analytical model based on the so-called one-constant approximation, when all LC elastic modules are assumed to be equal [2]. The model relates the observed optical properties of the LC cells with the main characteristic of the FIB patterning – the duty factor.

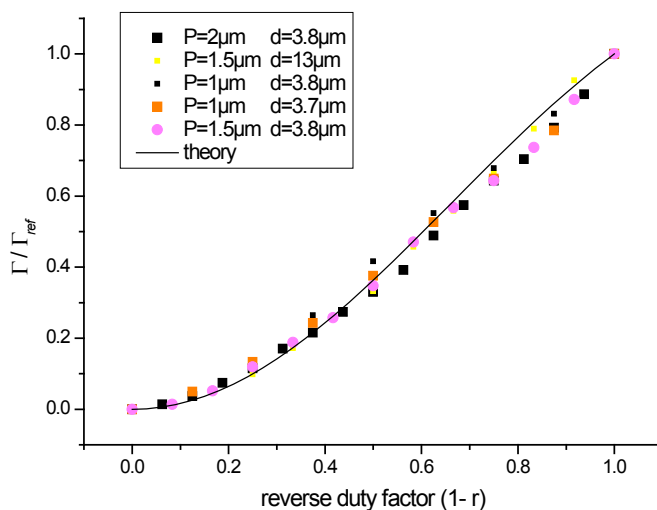


Figure 2. Universal dependence of the LC cell relative retardation on the reverse duty factor $(1-r)$ measured for stripe patterns of different periods P and LC cell thicknesses d .

In our structure we have two different areas: the background and the patterned area. The normally incident plane wave propagating through differently oriented areas of the LC cell (with different alignment conditions) travels different optical paths above the patterned area and above the background.

There is a hybrid LC orientation in the background dictated by the planar anchoring action of the PI on the lower substrate and the homeotropic anchoring action of the chromolane on the upper

substrate. We consider plane wave polarized along the y -axis, which propagates along the z -axis, and suppose that the value of the LC refractive index anisotropy $\Delta n = n_e - n_o$ is relatively small. The phase retardation is the difference of optical paths between the ordinary and extraordinary waves. So we introduce the phase retardation above the background $\Gamma_{ref} = \frac{\Delta n \pi d}{2\lambda}$.

Guided by the same logic, but taking into account that the area patterned on the lower substrate induces periodical modulation of the LC orientation, we employ the analytical model within the one-constant approximation [2] and obtain the phase retardation above the patterned area as

$\Gamma = \frac{\Delta n \pi d}{2\lambda} \left(1 - \frac{\sin(\pi(1-r))}{\pi(1-r)} \right)$. Accordingly, the relative retardation reads as:

$$\frac{\Gamma}{\Gamma_{ref}} = 1 - \frac{\sin((1-r)\pi)}{(1-r)\pi}. \quad (1)$$

We can see that the distribution Eq. (1) does not depend on the value of LC layer thickness, so we get a universal law of controlling the alignment by the duty factor. As seen from Fig. 2, the relative retardation (1) as a function of the reverse duty factor is in excellent agreement with the experiment.

4. Conclusion

FIB patterning of rubbed PI layers induces periodic modulation of the LC director orientation. At the same time, varying the pattern duty factor allows to control the optical phase retardation of the LC layer above the patterned stripes. This opens up prospects for creating LC-based optical devices.

Acknowledgments

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