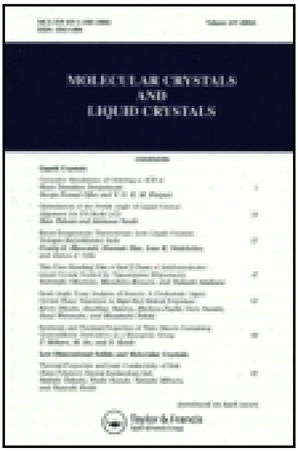

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Tunable Microlenses Optically Recorded in Dye-Doped Liquid Crystals

Liana Lucchetti [a] & Jordanka Tasseva [b]

[a] Dipartimento di Scienze e Ingegneria della Materia, dell'Ambiente e Urbanistica and CNISM , Università Politecnica delle Marche, via Brecce Bianche , 60131 , Ancona , Italy

[b] Institute of Optical Materials and Technologies "Acad. J. Malinowski," Bulgarian Academy of Sciences , Acad.G.Bonchev Street, block 109, 1113 , Sofia , Bulgaria

Published online: 14 Jun 2013.

To cite this article: Liana Lucchetti & Jordanka Tasseva (2013) Tunable Microlenses Optically Recorded in Dye-Doped Liquid Crystals, Molecular Crystals and Liquid Crystals, 576:1, 8-14, DOI: 10.1080/15421406.2013.789394

To link to this article: http://dx.doi.org/10.1080/15421406.2013.789394

Mol. Cryst. Liq. Cryst., Vol. 576: pp. 8–14, 2013

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2013.789394

Tunable Microlenses Optically Recorded in Dye-Doped Liquid Crystals

LIANA LUCCHETTI[1,*] AND JORDANKA TASSEVA[2]

[1]Dipartimento di Scienze e Ingegneria della Materia, dell'Ambiente e Urbanistica and CNISM, Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy
[2]Institute of Optical Materials and Technologies "Acad. J. Malinowski," Bulgarian Academy of Sciences, Acad.G.Bonchev Street, block 109, 1113 Sofia, Bulgaria

We report on optically recorded microlenses in conventional liquid crystal cells doped with the azo-dye methyl-red. The focal length can be tuned electrically with low external voltage and changed in a wide range with just a small variation of the applied dc field. No patterned electrodes, built-in polymeric lens or patterned molecular reorientation are required.

The effect underlying the proposed fabrication method is connected to the surface induced nonlinear effect (SINE) observed a few years ago in dye doped liquid crystals.

Keywords Liquid crystals microlens; surface-induced nonlinear effect; optical nonlinearity

1. Introduction

Since the first report in 1979 [1], liquid crystal (LC) lens of various structures have been proposed, given their advantages which include tunable power, small size and low cost [2–5].

It is well known that conventional lenses are made by the radial shaping of materials like glass or plastic that exhibit a constant refractive index. Typically these systems have one fixed focal length. The standard way of varying the focal length of an imaging system is to use a number of lenses such that the focus position is changed by mechanically moving components that adjust the distance between lenses. This approach makes the system bulky and unsuited for some applications. It appears clear that optical systems small in size and weight, low in cost and where the focal length can be varied without moving parts, are desirable and LC lenses can address all these requirements.

The different methods to fabricate LC lenses can be divided into two main types. One type is based on patterned electrodes to generate a special distribution of electric field, which is then used to align LC molecules; the other is based on the patterned relief surface structure using polymer or photoresist [6,7].

*Address correspondence to Liana Lucchetti. Tel.: +39 0712204259. E-mail: l.lucchetti@univpm.it

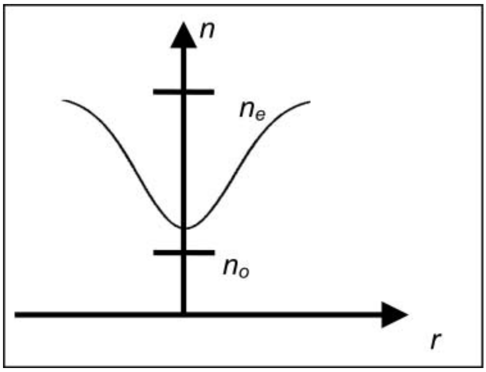

Figure 1. Sketch of the refractive index profile induced in the LC cell by the common action of light and external dc field. n_e and n_o are the extraordinary and ordinary refractive indexes, respectively; r is the radial coordinate: r = 0 corresponds to the centre of the Gaussian distribution of the incident optical beam.

It is known that the nematic liquid crystal pentyl-cyanobiphenil (5CB) doped with the azo-dye Methyl-Red (MR) can exhibit colossal nonlinear response due to a light-induced modification of the surface conditions known as Surface Induced Nonlinear Effect (SINE) [8], the full reproducibility of which can be obtained by means of an external low frequency electric field [9]. We have recently demonstrated that the huge nonlinear response of this system can be controlled in a single beam experiment under application of a dc voltage, opening the way of potential exploitation of the effect for optical processing devices [10]. Based on this result, we propose here a fast and simple method to fabricate LC lenses based on nematic liquid crystals doped with MR. The lens is obtained in conventional cells with not-patterned ITO electrodes coated on the two glass substrates.

2. Preliminary Considerations

According to the SINE, a Gaussian laser beam is able to create a modification of the irradiated surface through the light-induced adsorption and desorption of dye molecules from this surface. In our experimental configuration, light-induced desorption is expected to be dominant on adsorption [11]. This effect reduces the surface density of dark adsorbed dye molecules [12]. Since there are several experimental demonstrations that dye-doping forms charge complexes in liquid crystals [9], this layer is expected to have a polar character. Therefore the light-induced desorption reduces the surface charge density. As a consequence one gets a lowering of the screening effect, thus increasing the effective internal voltage. In this way the reduction of charge screening gives rise to a reduction of the actual Freedericksz threshold so that an external dc field is able to reorient the LC director just in the region where light impinges and the reorientation degree varies with light intensity [10]. If LC cell are homogenously aligned the reorientation induced by the dc field produces an index profile with the shape sketched in Fig. 1, giving rise to a negative lens in the sample.

The new idea here is the following: if the surface modification induced by the optical field is permanent one has an electrically tunable lens without the need of patterning the electrodes or of using patterned relief surface structure. The focal length can be tuned on a wide range acting on an external dc bias, requiring a very small variation of this latter parameter. The lens can be erased applying an external bias exceeding the electric Freedericksz threshold of the cell and reconfigured simply by lowering again the external voltage. This method allows making LC lenses of very small size. Specifically, since the beam waist on the sample is of the order of 100 μm, the obtained lenses will be referred to as LC microlenses.

It is worth noting that all-optical recording of LC lens has already been reported in several papers [3, 13–18]. In particular, electrically tunable lens based on polymer network liquid crystals [16] and Polymer Dispersed Liquid Crystals [13] have been proposed. However, while comparing with these optically written lens, our approach has several advantages. Due to the writing method, which requires neither masks nor UV pre-curing, several lens with different aperture can be obtained in a single cell with a single exposure (e.g. by using a Spatial Light Modulator); the writing time is much lower being on the order of seconds; the fabrication method is simpler. Moreover, the proposed LC lens can in principle be erased with a plane wave and rewritten with a Gaussian beam.

3. Experimental Details

The samples used to fabricate the microlenses are conventional sandwich cells with planar alignment and thickness of 3, 11, and 23 μm. The planar alignment has been obtained by treating one glass substrate with polyvinyl alcohol and then rubbing it while leaving the other substrate uncoated. In this way one gets cells with a good planar alignment and a surface with very low anchoring which, according to the SINE, increases the nonlinear response of the cell [8]. As mentioned both glass substrates have an ITO coating. Cell thickness has been controlled by Mylar spacers and carefully measured by means of spectroscopic techniques. Cells are filled with a mixture of the nematic LC 5CB and the azo-dye MR. Three values of dye weight concentration have been used: 0.2%, 0.5%, and 1%.

A linearly polarised pump beam from a cw He-Cd laser ($\lambda = 442$ nm) is focused by a 15 cm plano-convex lens on the sample untreated surface. The beam is polarised in order to impinge the sample as a pure extraordinary wave. The beam waist on the sample is 100 μm. The incident power was varied between 0.5 to 2.5 mW. A dc voltage below the electric Freedericksz threshold is applied perpendicular to the cell substrates.

4. Results and Conclusions

The presence of the microlens in the irradiated region is highlighted by the appearance of the typical Self-Phase-Modulation (SPM) rings in the far field easily observable for each value of the used power, when both the optical and the electric fields are switched on. SPM is due to the surface modulation produced by the incident optical field which decreases the electric Freedericksz threshold allowing the LC molecules to be reoriented by the dc field just in correspondence of the induced surface modulation [9–10]. The number of SPM rings increases by increasing V until the bias exceeds the Freedericksz threshold value and the whole sample becomes uniformly reoriented. In this situation the SPM pattern collapses. This indicates that the phase shift $\Delta\phi$ increases with the external bias leading to a change in the focal length according to the relation [18]:

$$f = \frac{\pi w^2}{\lambda \Delta\phi} \tag{1}$$

where w is the radius of the lens aperture and λ is the wavelength of the light beam.

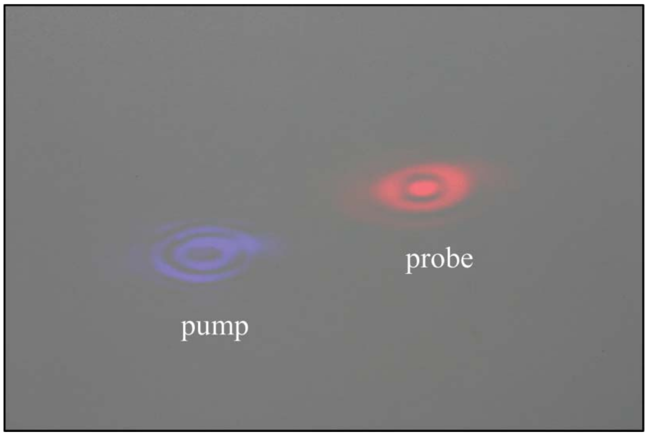

Figure 2. Self Phase Modulation pattern observed with both the pump and the probe beams in a 3 μm LC cell with 0.2% MR concentration. The optical power is 1 mW and the external bias is 1V.

It is worth noting that $\Delta\phi$ is the phase difference between the region of the cell corresponding to the centre of the Gaussian beam, and the periphery. Since the refractive index decreases in the centre (see Fig. 1), $\Delta\phi$ is negative and so is the focal length f.

The minimum value of the bias V required to observe the effect is related to the incident optical power and increases with increasing the dye content, ranging between 0.3 and 2 V. The SPM pattern can also be visualised with a low power probe He-Ne beam, polarised parallel to the pump, as shown in Fig. 2 for a 3 μm cell with 0.2% MR concentration. If the pump beam is switched off, the red ring pattern stays visible and can be modulated by the dc field, as long as the external bias is applied. We underline that microlens formation is demonstrated by the observation and modulation of the red ring pattern when the pump beam is switched off.

In order to evaluate the focal length of the described microlenses and its dependence on the external bias and on the pump optical power, we made use of the SPM pattern to measure the divergence of the pump beam. It is known that the beam divergence θ is related to the focal waist w_f through the relation [19]:

$$\theta = tg\frac{\lambda}{\pi w_f} \tag{2}$$

that is a measurement of the divergence is a measurement of the focal waist. This latter is then connected to the focal length f by the usual relation [19]:

$$\frac{w_f}{w_0} = \frac{f/_{z_0}}{\sqrt{1 + (f/_{z_0})^2}} \tag{3}$$

where w_0 is the beam waist on the sample (100 μm in our case) and z_0 is the confocal parameter. We prefer using the described method to calculate the focal length instead of using equation (1), since the phase shift calculated by counting the number N of SPM rings suffers of a large error when N is lower than ten. The typical dependence of f on the external bias V is reported in Fig. 3 for five different cells with the same characteristics: 1% MR concentration and 11 μm thick. The incident pump power is P = 0.5 mW. It is evident that

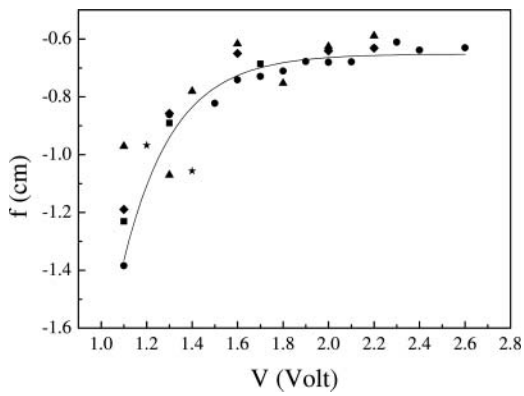

Figure 3. Typical dependence of f on the external bias V for five different cells with the same characteristics: 1% MR concentration and 11 μm thick. The incident pump power is P = 0.5 mW. The solid line is just a guide for the eyes.

the obtained data are well reproducible. The focal length of the induced microlens can be varied within almost 1 cm with a voltage variation of 1 V. As mentioned, the microlens can be erased applying an external bias exceeding the electric Freedericksz threshold of the cell and reconfigured simply by lowering again the external voltage.

Cells with a lower MR content (0.2% and 0.5%) seem to allow a wider range of variation of f and require a lower voltage for the onset of the effect. However, further experiments are needed to clarify the relationship between MR concentration and range of tunability. Concerning cell thickness, the lower the parameter the lower is the range of microlens tunability.

The dependence of f on the pump beam power P is shown in Fig. 4, where f is plotted as a function of P for a 23 μm cell with 1% MR concentration. The external bias is fixed at 0.5 V. In these conditions, the focal length f varies with the optical power, as expected.

The aberration estimation would require the evaluation of the spatial profile, which is a difficult task due to the low size of the lens diameter. However, preliminary results obtained with a theoretical model based on the light-induced modulation of the anchoring energy

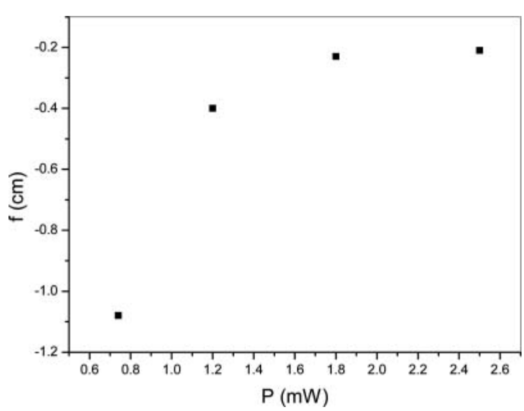

Figure 4. Focal length f versus pump beam power P for a 23 μm cell with 1% MR concentration. The external bias is fixed at 0.5 V.

show a good agreement between the experimental data discussed here and the focal length calculated by assuming a parabolic phase profile. This suggests that the aberration of our microlens is weak. Details on the theoretical model will be reported in a forthcoming paper. It is worth mentioning that the described microlens are still far from being optimized. We believe that by improving the quality of the intensity profile of the writing beam and the cell preparation method we can easily get microlens with very good performance.

As mentioned, the proposed microlens fabrication method is connected to the SINE. In this model the origin of the huge nonlinear response of MR doped LCs is considered to be the light-induced modulation of the surface conditions that in turn affects the director orientation in the bulk. Namely there is no direct optical torque on the LC molecules, but reorientation occurs due to the elasticity of the medium. The possibility of controlling this effect in different configurations, with an external dc field, due to the dependence of the effective internal voltage on the surface charge density of ions, has been demostrated [9–10]. In these papers we exploited the dynamic nature of SINE, whereas in the present case the light-induced modification of the surface conditions is written in the cells, and the external electric field produces a bulk director reorientation that follows the surface modification created by the incident light.

The range of focus variation is lower with respect to other type of LC lens reported in literature [18–20], however we believe that the simplified design and reconfigurability make the proposed LC microlenses very promising in the field of optical systems. Moreover, their performance can be optimized acting on dye content and cell thickness, in particular we expect that increasing cell thickness and decreasing dye concentration can lead to a wider range of tunability. Work is in progress also in this direction.

Finally, we would like to underline that by using a LC with negative anisotropy in homeotropic configuration, the described mechanism can in principle be used to obtain positive LC microlens.

Acknowledgments

Authors are grateful to Professor Victor Reshetniak for valuable discussions and to Professor Francesco Simoni for both valuable discussions and support.

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