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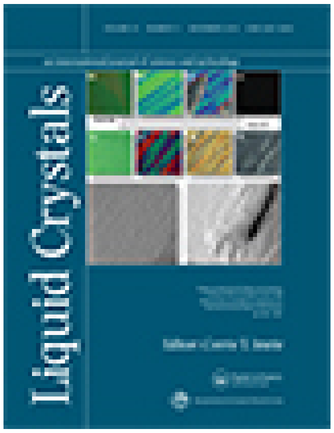

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The optimal cell gap determination of a liquid crystal wavefront corrector from a single photoelectric measurement

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It has been a crucial technique to improve the dynamic response characteristics of a liquid crystal wavefront corrector (LCWFC) with optimal cell gap since the LCWFC needs at least 2π (or π) phase modulation in adaptive optics systems (AOSs). We have given a complete process for obtaining the optimal cell gap accurately from a single photoelectric measurement, which can be conducted with a liquid crystal (LC) cell of any known thickness. This method has been analysed theoretically and confirmed experimentally by using a wedge-shaped cell; the experimental results match very well with the theoretical analysis. The response time of an optimal gap cell can be a novel evaluation method of response performance of LC materials.

Keywords: liquid crystal; response time; optimal cell gap; wedge-shaped cell; photoelectric measurement

1. Introduction

In a liquid crystal adaptive optics system (LCAOS), liquid crystal wavefront corrector (LCWFC) is a critical component. It is used to improve the performance of large-aperture telescopes by reducing the effect of wavefront distortions.[1,2] Many researchers have devoted themselves to exploring LCWFCs from the 1970s onwards.[3–7] After the solution of diffractive efficiency and fitting error of LCWFC, correction speed improvement is a primary task, and a fast response will significantly increase the bandwidth of LCAOS.[8] For the moment, there are many approaches to improve the response speed of LCWFC: dual frequency [9] and ferroelectric [10] LCs have been utilised to fabricate LCWFCs; however, due to its high voltage requirement and the complexity of the control method, the dual frequency LCWFC is improper to be applied to large-aperture telescopes. The binary phase modulation of ferroelectric LCs limits their effectiveness in LCWFCs. Compared with dual frequency and ferroelectric LC materials, high performance nematic LCs should be a nice choice.[11–13] So in this paper, only nematic LC materials will be considered. In addition, we can also speed up LCWFCs by using overdrive,[14,15] temperature-elevating,[2] a concurrent control technique,[8] etc. However, these methods can only be applied on the premise that the LCWFCs are well fabricated.

Cell gap plays a pivotal role for improving the response speed of LCWFCs .Many researchers have studied the response mechanism concerning the LC cell gap.[16–19] In the meanwhile, Wu et al. pointed out that in the large signal regime the optical decay time is independent of the cell gap.[20,21] Wang et al. discussed the physical picture of the optical response time as a function of the cell gap in different voltage regions.[22] For nematic LCWFCs, we show more concern about the response time at a specific modulation quantity; due to the kinoform technique, transmissive LCWFCs require at least 2π phase modulation, and reflective LCWFCs are π. Peng et al. have recently analysed the response time as a function of the cell gap at a specific phase retardation.[23] They indicate that the response time of 2π first decreases and then increases with the LC cell gap increasing, and there is an optimal cell gap to obtain the shortest response time. Then, Wang et al. derive the optimal cell gap of a nematic LCWFC by a finite difference iterative method.[24] We find that this method is a useful tool to achieve the optimal cell gap of nematic materials with known parameters, e.g. 5CB; however, for the newly synthesised liquid crystals with unknown parameters, we have to get various parameters, e.g. refractive indices, elastic constants, and rotational viscosity in order to utilise this method, consequently the measuring error is produced; what's more, this job is a little time-consuming

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and inefficient. In this paper, we will explain that we can obtain the optimal cell gap accurately from a single photoelectric measurement of an arbitrary thickness LC cell and this process does not need a material parameter measurement. A theoretical explanation has been given for this phenomenon and experimental results from a wedge-shaped cell agree well with the theoretical analysis.

2. Theory

The configurations as a prototype of an LCWFC are shown in Figure 1. They are both parallel-aligned and homogeneous-thickness LC cells, d is the cell gap, and θ is the tilt angle measured from the surface towards director. If the backflow and inertial effects are ignored, the dynamics of the LC director reorientation is described by the following Erickson–Leslie equation [25–27]:

$$\gamma_1 \frac{\partial\theta}{\partial t} = \left(K_{11}\cos^2\theta + K_{33}\sin^2\theta\right)\frac{\partial^2\theta}{\partial z^2} + (K_{33}-K_{11})\sin\theta\cos\theta\left(\frac{\partial\theta}{\partial z}\right)^2 + \varepsilon_o\Delta\varepsilon\left(\frac{\partial U}{\partial z}\right)^2\sin\theta\cos\theta \qquad (1)$$

where K_{11} and K_{33} are the elastic constants associated with spray and bend deformation, respectively, $\Delta\varepsilon$ is the LC dielectric anisotropy, $\partial U/\partial z$ is the electric field strength, and γ_1 is the rotational viscosity.

The time-dependent phase change associated with this angle change is described as follows:

$$\delta = \frac{2\pi}{\lambda}\int_0^d \left[\frac{n_e n_o}{\left(n_e{}^2\sin^2\theta + n_o{}^2\cos^2\theta\right)^{1/2}} - n_o\right]\mathrm{d}z \qquad (2)$$

where n_e and n_o are the refractive indices for the extraordinary and ordinary rays, respectively, and λ is the wavelength.

Here numerical approximation is available to solve Equations (1) and (2). Utilising finite differences, Equations (1) and (2) can be converted to another form:

$$\theta_{i,j+1} = \theta_{i,j} + \frac{\Delta t}{(\Delta z)^2}\frac{1}{\gamma_1}\left[\begin{array}{c}\left(K_{11}\cos^2\theta_{i,j} + K_{33}\sin^2\theta_{i,j}\right)\left(\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j}\right) + (K_{33}-K_{11}) \\ \sin\theta_{i,j}\cos\theta_{i,j}\left(\theta_{i+1,j} - \theta_{i-1,j}\right)^2 + \frac{1}{4}\varepsilon_o\Delta\varepsilon\left(U_{i+1,j} - U_{i-1,j}\right)^2\sin\theta_{i,j}\cos\theta_{i,j}\end{array}\right] \qquad (3)$$

$$\delta_j = \frac{2\pi}{\lambda}\sum_{i=1}^{N}\left[\frac{n_e n_o}{\left(n_e{}^2\sin^2\theta_{i,j} + n_o{}^2\cos^2\theta_{i,j}\right)^{1/2}} - n_o\right]\Delta z \qquad (4)$$

where $\theta_{i,j}$ denotes the tilt angle of the ith layer and the jth moment, and $\theta_{i,j+1}$ denotes the tilt angle of the next moment. Δt is the minimum time interval, Δz is the thickness of each layer, $\Delta z = d/N$, and N is the number of layers, e.g. $N = 100$.

Figure 1 depicts the calculated transient phase changes of two LC cells with the same initial conditions and boundary conditions; the only difference is their thickness. In order to describe visually, the response line of LC cell 2 is displayed from right to left and the x-axis lies on the top of this figure. Both cells are divided into N layers, from Equation (3), if $\Delta t/(\Delta z)^2$ remains constant, i.e. $\Delta t_1/(\Delta z_1)^2 = \Delta t_2/(\Delta z_2)^2$ the average tilt angles of corresponding layers are the same (shown schematically in Figure 1). According to Equation (4), the relationship between the phase changes of two cells at the same moment is linear, which is a simple multiple relation, that is, $\delta_{d_2 j} = (d_2/d_1)\delta_{d_1 j}$. Since the value $\Delta t/(\Delta z)^2$ keeps invariant, the minimum time intervals of the two cells share a one-to-one mapping, i.e. $\Delta t_2 = (\Delta z_2/\Delta z_1)^2\Delta t_1$. After such a transform for each

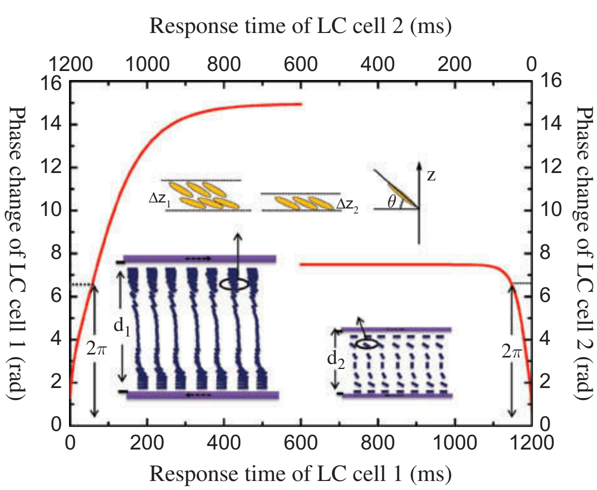

Figure 1. (colour online) The calculated transient phase changes of two LC cells with 1° pretilt angle at λ =730 nm released from V = 5 Vrms. Also the configurations as a prototype of an LCWFC are included.

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moment, the two response lines coincide well with each other. Based on the analysis above, if the transient phase change of a planar LC cell has been given, the transient phase changes of other cells with an arbitrary thickness can be achieved (on the basis of two premises: the same initial conditions and boundary conditions). This process can be realised by using one expansion of coordinate axes, x-axis and y-axis multiplied by a constant $(d_2/d_1)^2$ and (d_2/d_1) respectively are converted to new ones. Afterwards, the response time of each thickness LC cell at a specific modulation quantity can be gotten, naturally, we will know the optimal cell gap of LCWFC at this modulation quantity.

3. Experiment and discussion

3.1 Experimental details

To verify the results of analysis, the electro-optic measurement of a wedge-shaped cell [28–30] with LC synthesised by ourselves at T = 25°C is carried out, the schematic of the experimental set-up is shown in Figure 2. The LC has the following parameters: the birefringence Δn = 0.26, the clearing point $T_m = 105°\text{C}$, the dielectric anisotropy $\Delta\varepsilon = 15$, the elastic constants $K_{11} = 6.1 \times 10^{-12} N$, $K_{33} = 10.0 \times 10^{-12} N$, the rotational viscosity $\gamma_1 = 160 mPa.s$. The wedge-shaped cell is glued by spacers of thicknesses 2 and 15 μm. The other processes are the same with common homogeneous cells.[23,24] The cell is placed in a thermostatic stage between the polariser and analyser crossed in the measurement system, the linear polariser is orientated at 45° with respect to the LC rubbing direction. A laser of wavelength 730 nm is used as a light source. A simple shrinking beam system with lens of focal length 40 cm, 100 cm, 25 cm is used to get a narrow beam. The driving voltage is provided by a signal generator (Tektronix AFG 3022), the data are detected and recorded by photodetector (New Focus Model 2031) and oscilloscope (Tektronix MSO 3032) respectively.

There is a wedge angle α in the LC cell because of different spacers, $\alpha = \tan^{-1}(\Delta d/l)$, Δd is the difference value of thickness, l is the length of glass. We can calculate the angle approximately and find that it is small enough. So in the small neighbourhood a wedge cell can be treated as a planar one on the premise of a narrow incident beam. The normalised intensity of incident light in different areas is recorded as a function of response time. Since the rise time is much shorter than the decay time, we only focus on the decay time. Corresponding experimental results are illustrated below.

3.2 Results and discussion

Figure 3 gives the experimental results of point A and point B (shown schematically in Figure 2), the top and bottom lines represent normalised light intensity and phase changes respectively. Also included are the response times of point A and B at the phase retardation of 2π ($t_{A\_2\pi}$ and $t_{B\_2\pi}$), $t_{A\_2\pi}$ = 31.06 ms, $t_{B\_2\pi}$ = 35.12 ms. Obviously, the cell gaps of point A and B are different and the response lines differ from each other. We can obtain the ratio d_A to d_B using the phase changes at the last moment: If the buffing induced pretilt angles are small, the equalities hold: $\delta_{A\_\infty} = (2\pi/\lambda)(n_e - n_o)d_A$, $\delta_{B\_\infty} = (2\pi/\lambda)(n_e - n_o)d_B$, δ_{A_∞} and δ_{B_∞} are phases after a sufficiently long time or at the last moment, so we can know the ratio: $\chi = d_A/d_B = \delta_{A_\infty}/\delta_{B\_\infty}$, $\chi = 0.66$ here. According to the foregoing part, the response line of point A should coincide with that of point B undergoing such a

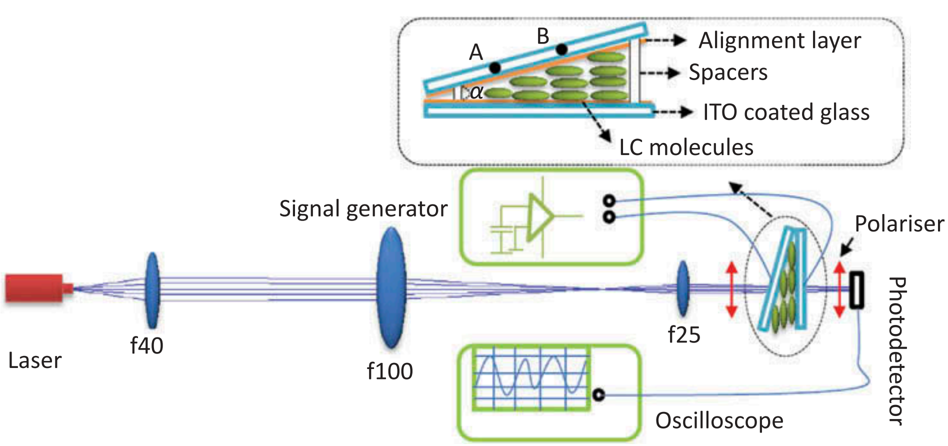

Figure 2. (colour online) Schematic of the experimental set-up used for recording photoelectric dates of a wedge-shaped cell.

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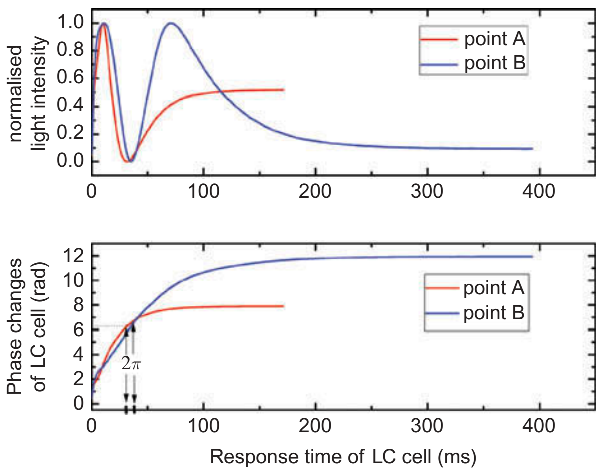

Figure 3. (colour online) The normalised light intensity and phase changes of a wedge-shaped LC cell as a function of response time; red lines represent the response characteristic of point A and blue lines refer to another point.

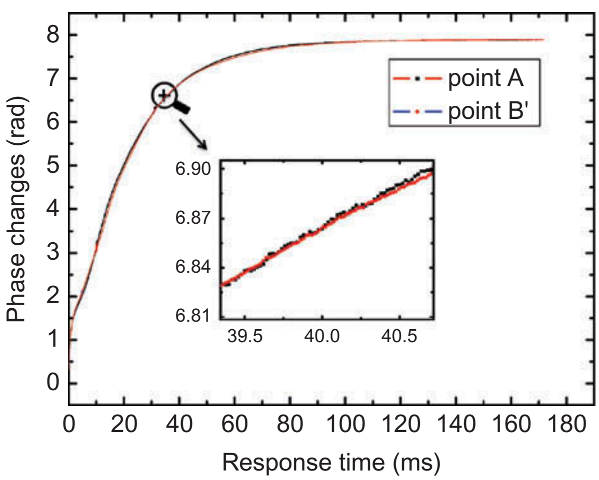

Figure 4. (colour online) The phase changes of point A and converted point B (point B′) as a function of response time. These lines have been enlarged to show details.

transform: x-axis of point A is multiplied by χ^2, y-axis of point A is multiplied by χ. The results are shown in Figure 4. Part of lines has been enlarged to show details. It is clear that these lines coincide with each other very well. We have also measured the characteristics of other points; that is other LC cells with varying thickness and those results are all consistent with the expectation. It illustrates that the presupposition of obtaining optimal cell gap from a single photoelectric measurement is reliable. That is to say, if the delay process of a homogeneous LC cell with known gap has been measured, we can get the response time of each thickness LC cell at 2π (or π) modulation quantity, the optimal cell gap can also be obtained.

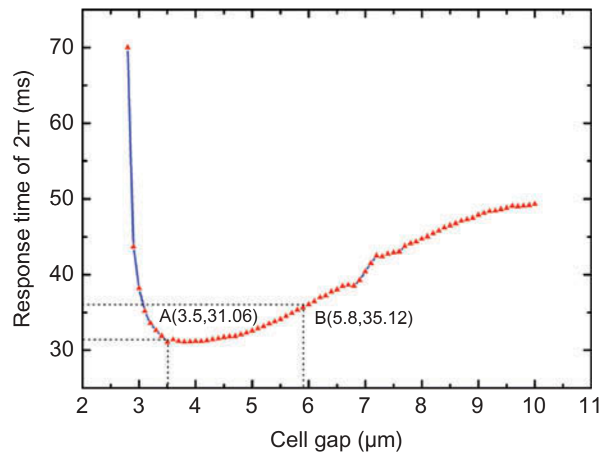

Figure 5. (colour online) The response times of different points as a function of cell gap.

In this experiment, since the refractive indices of the materials used are known, $\Delta n = 0.26$, the cell gaps of point A and B can be directly derived, $d_A = 3.5$ μm, $d_B = 5.8$ μm. What is mentioned that the achievement of optimal cell gap using this method above does not need such a reverse deduction value d, we can conduct a measurement directly on an LC cell with standard gap, e.g. 5 μm. Figure 5 lists the response times of 2π for different points as a function of cell gap, including these of point A and B. It is easy to see from this figure, the optimal cell gap for this LC is 3.5 μm by coincidence.

At present, the decay time $\left(\tau_{\text{decay}} = \gamma_1 d^2/K_{11}\pi^2\right)$ [31,32] and the figure-of-merit $\left(FoM = K_{11}\Delta n^2/\gamma_1\right)$ [33,34] are the most important evaluation methods to judge the response performance of LC materials. By measuring the decay time for a controlled phase change, the viscoelastic coefficient (γ_1/K_{11}) can be calculated, and then the FoM that takes the refractive indices and viscoelastic coefficient into account is used to compare the performance of LCs. These methods are important and straightforward. What should be emphasised is that, for LC materials synthesised to fabricate nematic LCWFCs, it is also relatively intuitive to characterise their performance using the response time of 2π (or π) at the optimal cell gap from a single photoelectric measurement. What's more, this special response time can help us estimate the potentialities of high birefringence and low viscosity LC materials in improving the response speed.

4. Conclusions

In summary, we have demonstrated a method to obtain the optimal cell gap of an LCWFC, which

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only needs a single photoelectric measurement and one expansion of coordinate axes. This measurement can be conducted on a homogeneous LC cell with an arbitrary known cell gap. A theoretical base for this method has been provided utilising finite differences of the Erickson–Leslie equation. The response time at an optimal cell gap is intuitive to characterise the performance of an LC material. We believe that combining with the development of high performance nematic LC materials and other techniques, this method can be helpful to decrease the response time of a nematic LCWFC and improve the performance of large-aperture telescopes ultimately.

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