Properties of Optically Addressed Liquid Crystal Spatial Light Modulators Studied by Mach-Zehnder Interferometry

Katarzyna Komorowska,[1] *Andrzej Miniewicz,**[1] *Janusz Parka*[2]

[1] Institute of Physical and Theoretical Chemistry, Wroclaw University of Technology,
Wybrzeze Wyspianskiego 27, 50-370 Wrocław, Poland
[2] Institute of Technical Physics, Military University of Technology, 00-908 Warszawa, Poland

Summary: In this work optically addressed liquid crystal spatial light modulators are experimentally investigated. Local reorientation of molecules in the modulator and local changes of effective refractive index $n_{eff}(x,y)$ are induced by modulated light intensity $I(x,y)$. We present preliminary results of measurements of phase shifts in optically addressed liquid crystal panels using a Mach-Zehnder interferometer. Experiments were performed for the panels filled with nematic and dye-doped nematic liquid crystals. Optical addressing was realized by Ar+ laser beam (λ = 514.5 nm) while the reading beam was supplied by He-Ne laser (632.8 nm). The operation voltage was in the range 4 - 20 V. The total phase shift under the influence of addressing light for the studied systems was 2 - 6 π, sensitivity to the addressing light ~ $\mu W/cm^2$ per 2π phase change and speed of response to the light was 20 ms - 30 s with total recovery time 0.5 - 120 s.

Keywords: conducting polymers; liquid-crystalline polymers (LCP)

Introduction

Liquid crystalline materials are attractive for many applications because of their high optical birefringence $\Delta n = n_e - n_o$. Electrically addressed pixelated liquid crystal spatial light modulators (EA LC SLM) are widely used in modern optics [1]. The main drawback of EA LC SLM is that coherent light is diffracted on the well-defined pixelated structure of these modulators limiting optical resolution of system [2]. Optically addressed liquid crystal spatial light modulators (OA LC SLM) were proposed in order to overcome these disadvantages [3]. In such devices phase shift is a function of the externally applied voltage and intensity of addressing light. Spatial controlling and shaping of the wavefront are the main tasks of adaptive optics, for example, a nonlinear Zernike filter wave front sensor based on an OA LC SML has been recently extensively studied [4,5]. The interest in liquid crystalline materials is associated with their suitability for construction of many photonic devices with high speed and high resolution such as optical processors, light amplifiers, etc.

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The phase shift introduced in OA LC SLM $\delta\phi(x,y)$ under the influence of addressing light can be calculated for extraordinary polarized wave using the formula:

$$\delta\phi\,(x,y) = \frac{1}{L}\int_{0}^{L}\frac{2\pi\delta n_{\mathrm{e}}(I(x,y),z)}{\lambda}\,\mathrm{d}\,z, \tag{1}$$

where L - thickness of liquid crystal layer, λ - wavelength of the normally incident light beam, $\delta n_{\mathrm{e}}(I(x,y), z)$ - light induced $I(x,y)$ extraordinary refractive index local change: $\delta n_{\mathrm{e}}(z) = n(I(x,y) \neq 0,z) - n(I'(x,y) = 0,z)$. We measure phase shift $\delta\phi(x,y)$ in nematic LC systems employing a Mach-Zehnder interferometer fed with an expanded collimated He-Ne laser beam.

Experimental

The measurements of light induced refractive index changes were performed in two types of planar liquid crystal panels: dye-doped nematic (fourteen-component cyanoester mixture) confined between two transparent ITO/glass electrodes with polyimide layers, and a panel with single photoconducting polymeric layer filled with pure E-7 nematic. Characteristic parameters of the studied LC panels are presented in Table 1.

Table 1. Characteristic parameters of the studied LC panels.

LC Panel	d [μm]	$\Delta\varepsilon$	Δn	Other features
Dye-doped nematic	30	>10	0.34	anthraquinone dye: 1%
Hybrid photoconducting polymer nematic LC structure	10	+13.8	0.225	PVK:TNF 100 nm

d - thickness of LC layer, $\Delta\varepsilon$ - static dielectric anisotropy, Δn - optical birefringence at $\lambda = 589$ nm

The active areas of the presented modulators were 1.5 cm^2. Local phase shifts were monitored at the output of a Mach-Zehnder interferometer (Fig.1).

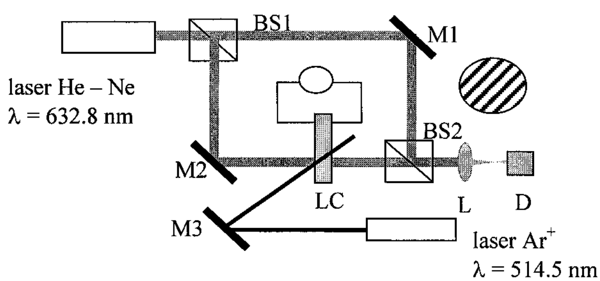

Figure 1. Experimental setup: M1, M2, M3 - mirrors, BS1, BS2 - beamsplitters, LC - liquid crystal modulator placed in one arm of a Mach-Zehnder interferometer, illuminated by addressing beam, D - detector, L - lens.

Optical addressing was realized by monochromatic beam from argon-ion laser (INNOVA 90, coherent, $\lambda = 514.5$ nm) with Gaussian distribution of intensity, extended and filtered to obtain a plane wave. The reading beam was supplied from He-Ne laser (632.8 nm). Operation voltage was in the range 4 - 20 V. All measurements were carried out at room temperature (about 22 °C). Response and recovery times of the samples were measured using a photodiode connected to a digital oscilloscope. Interference patterns showing light-induced phase modulation were captured by a CCD camera connected via a frame grabber to computer.

Results and discussion

The mechanism of light-induced refractive index change in LC modulators is associated with electric-field-driven reorientation of molecules. The internal electric field in LC layer is a superposition of the static field applied externally to the sample and the field induced by the addressing light. In dye-doped LC this external electric field is diminished by a bulk photoconductivity induced by an incoming addressing light [6,7]. In systems with photoconducting polymer layer, the incident spatially modulated light generates the respective surface charge distribution $\rho(x,y)$ in the photoconductor. Then the electric space charge field together with the externally applied static field induces reorientation of liquid crystal molecules [8,9]. The surface space charge field amplifies the externally applied electric field in the bright regions. The dynamic performance of optically addressed LC modulators were measured in a Mach-Zehnder interferometer by monitoring the temporal movement of interference fringes after a sudden opening of the addressing light. The results of recording and decay times for the presented LC modulators are shown in Table 2.

Table 2. Results of recording and decay times for the presented LC modulators.

	Dye-doped nematic	Hybrid photoconducting polymer nematic structure
t_B [s]	3 - 10	30×10^{-3}
t_D [s]	5 - 10	50×10^{-3}

t_R - recording time, t_D - decay time

During measurements we noticed considerable depolarisation of the reading He-Ne laser beam after traversing the LC panel. Especially for externally applied voltage slightly higher than the threshold voltage for the electric Freedericksz transition [10,11], the fringe contrast is decreased. We define the fringe contrast, which depends on external voltage applied to the panel, $C(V)$, by the following formula:

$$C(V) = \frac{I_b(V) - I_d(V)}{I_{max}} \quad (2)$$

where I_b and I_d - intensities of light in the bright and dark regions of interference pattern respectively, I_{max} - maximum intensity of light in the bright region of interference pattern at V=0. In Fig. 2 we present the relation between phase shifts and applied voltages for the described modulators (solid line)

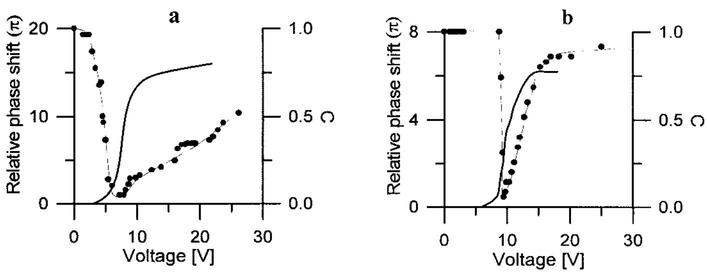

Figure 2. Electrically obtained phase shift (solid line) and contrast C (dashed line) of interference patterns measured for (a) LC modulator filled with dye-doped nematic and (b) hybrid photoconducting polymer nematic LC modulator.

Dashed lines in Fig. 2 represent the changes in interference pattern contrast as function of the applied voltage. In order to determine the usable range of voltages (for $C > 0.8$), we performed our experiments without the addressing light. The interference pattern amplitude $I_b(V) - I_d(V)$ as function of voltage and the phase shift were measured in the same experimental run. Just above the threshold voltage, even a small change of the applied field causes large changes of the effective refractive index (large phase shift in the reading beam). At the same time, the contrast of interference pattern significantly decreases. With a further increase in the voltage, one can observe how the LC undergoes transition to a more ordered state, and the contrast of interference pattern again rises. The spatial light modulator should work within the voltage range where the contrast is high (i.e. $C > 0.8$), so the usable voltage range is limited to several volts. Under this criterion the maximum phase shift under the influence of addressing light for the dye-doped nematic phase modulator is 0.4 π and for the panel with photoconducting polymer layer it is about 1.5 π. The panel filled with dye-doped liquid crystal has a too small interference pattern contrast (less than 0.9) in almost the whole range of voltages, so it is useless as a spatial light modulator. In Fig. 3 we present the dependence of light-induced phase shift on its intensity (λ = 514 nm) in high-contrast voltage regions for the nematic with photoconducting layer.

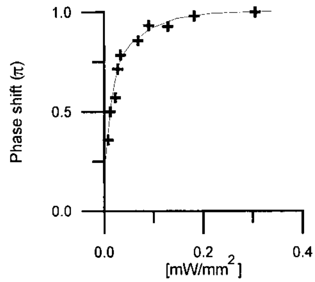

Figure 3. Dependence of phase shift on the intensity of addressing laser beam 514 nm for hybrid photoconducting polymer nematic LC modulator (15 V).

The presence of photoconducting layer allowed to obtain 1π phase shift in reading beam at writing light intensities 0.4 mW/mm^2. In order to demonstrate the phase change abilities of LC spatial phase modulators, we present photographs (Fig. 4) of interference patterns obtained for addressing beam with Gaussian distribution (a,b) of intensity and uniform distribution of intensity (c-f).

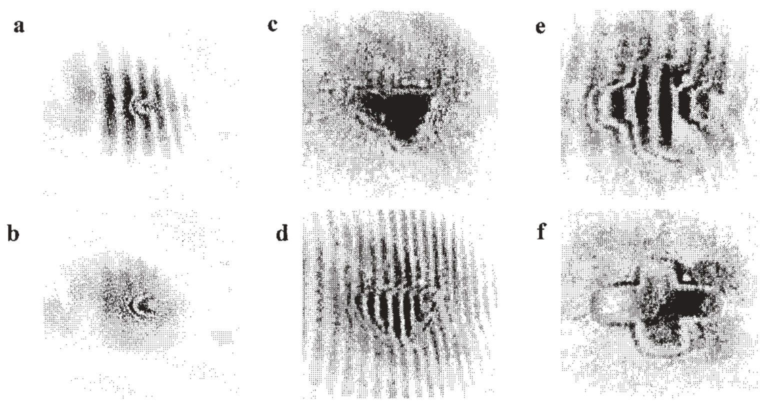

Figure 4. Local changes of phase obtained in nematic liquid crystal modulator with photoconducting layer for different distribution of intensity: (a,b) for Gaussian distribution, (c-f) for plane wave cut by a cross (c,d) and a triangle (e,f) mask.

The experiments were carried out with different values of light intensity and applied voltage. In the first experiments we did not use expanded laser beam (Fig. 4a, b). The phase shift seen by the reading beam can be larger than 2π (a), with the contrast in the illuminated region a little higher than outside it. In Fig. 5a we applied such a value of voltage, for which the contrast was very weak. In the illuminated region the interference pattern is better visible because of a higher value of electric field induced by the addressing light. In Fig. 4 c-f we present results of SLM addressing with expanded laser beam, passing through amplitude masks, a cross and a triangle. Fringe shifts were observed for different values of voltage applied to the LC panel as well as for different conditions of observation in Mach – Zehnder interferometers. The results clearly indicate how the light intensity changes locally the refractive index of LC and the $\Delta n{\cdot}d$ – changes optical path for the reading plane wave. From the practical point of view, it is necessary to study spatial resolution of the presented systems using different shapes and sizes of amplitude masks.

Conclusions

In this paper we presented preliminary experimental results for optically addressed liquid crystal phase modulators (OA LC SML), which seem to be capable of overcoming some of the limitations of electrically driven phase modulators or conventional phase filters. OA LC SLM offer interesting potentials in this field. No pixelation and high sensitivity allow to create an effective device able to modulate (or correct) the phase of laser beam or even filter it in the Fourier plane. The presented results show a potential for optimization of these systems with respect to their performance as phase modulators.

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