Simulation of spatial phase light modulators based on the ferroelectric liquid-crystals

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Abstract. We studied the possibility for building zonal spatial phase light modulators employing quadratic electro-optical effect in ferroelectric liquid-crystals (FLC). This effect allows one to achieve modulation frequencies up to 1 KHz, but leads to a change in the ellipticity of the polarization state. We analyzed the influence of ellipticity modulation on the formation of vortex light fields by multi-pixel modulators with square configuration of cells and modulators of sector type. It was shown that for the considered FLC the resulting amplitude modulation does not have a principal essential effect and vortex light fields of good quality can be generated.

1. Introduction
Among the popular and promising applications of phase spatial light modulators (SLM) are beamsteering and optical tweezing, aberration correctors, point spread function engineering, tunable sources, optogenetics, laser communications and others. The use of orientation effects in nematic liquid crystal (LC) is traditional technique of phase-only spatial modulation. Characteristic frequencies for nematic LC are tens of Hz. This fact limits the application of SLM in systems with more fast processes. For example, the control mirrors with characteristic frequencies of 1kHz are necessary [1] for compensation of atmospheric distortion of wavefront. The units with frequency of 100 Hz and higher are needed in systems of optical micromanipulation for organization of moving multiple traps or the change of structure of traps of complex spatial configuration [2].

There are several approaches to increase fast response of LC SLMs. For example, dual frequency liquid crystals can be used [3-5]. In those crystals not only time of response but also time of LC relaxation can be controlled by means of an electric field. The time of relaxation for dual frequency LC is less than the time of natural relaxation in absence of electric field and depends on applied voltage value. The disadvantages of the approach are the difficulty of control of modulators on the base of dual frequency LCs as well as the need to use relatively high voltages. An alternative and more common method is the use of polymer-stabilized liquid crystals - polymer network liquid crystals...
(PNLCs). About the realization of the modulation from 0 to 2\pi in PNLC modulator at wavelength 4 \mu m was reported in [6, 7]. The time response of the device is 3.6 msec. It is two orders of magnitude higher than the time of response for phase modulators on nematic liquid crystals. Submillisecond response times were obtained in similar devices at the wavelengths 1.06 \mu m [8] and 1.55 \mu m [9, 10]. The authors of [11] also used polymer network liquid crystals and obtained the analogous results in visible range. That result is especially interesting because of the scattering occurs in PNLCs. The scattering decreases with the transfer from visible to IR ranges and so as a rule the modulators on PNLCs are limited of the IR range. The decrease of the scattering and reduction of control voltage are the main problems solving today during the creation of SLM on the base of PNLCs.

One of the technique to achieve fast response time of LCs is to increase their temperature [12, 13]. It is obviously that in that case the fast response time is achieved due to the decreasing viscosity of medium. Both pure LCs [13] and PNLCs [12] were used. For example, increasing the temperature from 26 °C to 43 °C decreases the time of response from 45 \mu sec to 19 \mu sec [12].

The possibility of the use polymer-stabilized blue phase liquid crystal in phase modulators were studied in the papers [14-16]. The time response of those modulators is 3 msec [15]. In the studies [17, 18] submillisecond polarization-independent phase modulation was achieved by using nanocomposite polymer-cholesterol LC with a small spiral pitch.

The increase of the fast response is possible due to an orientation effects (to the orientation Kerr effect in particular) in ferroelectric LC with subwavelength pitch of helicoidal structure [19,20]. The characteristic relaxation times in those liquid crystals are 30-100 \mu sec. The achieved reduction of the step of the spiral structure of the liquid crystal ferroelectric to the values of about 100 nanometers [21] allows to eliminate the light scattering on the spiral structure. The quadratic electro-optical effect is observed in ferroelectric LCs: an ellipsoid of refractive indices of LC layer is tilted relative to the axis of the helicoid and magnitude of its axes is changed when an electric field is applied [22]. This results in the change of the ellipticity of light transmitted through the cell.

The aim of the present study is to analyze the possibility to create the spatial modulators of various types on the base of the cell with ferroelectric LC with subwavelength helix pitch with helicoid orientation along the substrates. The possibility is estimated in terms of the efficiency of formation of light fields with complex structure and orbital angular momentum. In particular, the effect of amplitude modulation on the quality of formed light fields with orbital momentum was studied.

The dynamic generation of light fields with orbital angular momentum, both axially symmetric and more complex structures, is one of the most popular applications of phase SLMs [23-29]. Those fields are interesting for laser manipulation of microscopic objects, the information transfer in quantum communication systems, in systems of fluorescent microscopy, in STED nanolithography of 3d structures. Multi-pixel LC SLMs allow to form light fields of arbitrary structures but the modulators of sector type are interesting as inexpensive and technologically simple control devices for formation of structured light fields for practical application in biomedicine, astronomy and industry. Those devices are developed in different laboratories [30-32]. For example, the authors of [31, 32] proposed the spiral LC phase plates with the layer of nematic LC placed between two substrates with applied high – resistive electrodes and low-resisting coatings (ITO). That's why in this paper we simulate not only the multi-pixel spatial modulators but also the modulators of sector type operating in the reflectance and transmittance modes.

2. Method and materials

The operation of the multi-pixel modulators with square configuration of cells and modulators of sector type operating both reflectance and transmittance modes were simulated. The schemes of simulated modulator are presented in figure 1.

The liquid crystals FLC 587 and FLC 587-F7 synthesized in Lebedev Physical Institute by E. Pozhidaev group were considered as the ferroelectric LCs. The analytical dependencies of the refractive indexes, birefringence and effective phase delay on the value of applied electrical field were used during the simulation. They were obtained by means of approximation of experimental data for
specified crystals [20, 33]. The dependence of the deflection angle of the optical axis on the value of the applied electric field (figure 2 (a)) and dependence of the refractive index on the square of the value of the electric field, applied to the LC layer, were approximated with linear dependencies [33].

Figure 1. Types of simulated modulators: a) multipixel modulators with square configuration of cells; b) modulator of sector type.

The dependencies of phase delay for ordinary and extraordinary waves on the square of applied electrical fields value are presented in the figure 2 (b). The ordinary wave is the wave polarized perpendicular to the optical axis of the LC layer (ΔΦ parallel). The extraordinary wave is the wave polarized in parallel to the optical axis of the LC layer (ΔΦ perpendicular). The behavior of the effective phase and coordinate components of the amplitude of the light field passing through the LC cell was calculated in the framework of the model of the uniaxial crystal with the changing position of the optical axis and main refractive indices.

Figure 2. The dependence of the deflection angle of the optical axis on the value of the applied electric field (a) and the dependencies of phase delay for ordinary (blue circles) and extraordinary (red squares) waves on the square of applied electrical fields.

The computation of the light fields was performed for the following scheme. The LCM was illuminated with linear polarized light field with homogeneous intensity. The values of the voltage applied to each pixel were set in accordance of the values of the phase delay that must be formed for the passing wave. Depending on the type of the considered modulator the light transmitted through the modulator or was reflected by it. Then the light passed through the polarizer with the transmission plane coinciding with the initial polarization direction. As a result, the linear polarized light field with required wavefront but spatially inhomogeneous amplitude was formed. Then the light beam passes through the lens. The final light field in the focal plane was computed within the frame of scalar diffraction theory and had the form:

\[
E_n(x, y) = \frac{\exp(i\ell f)}{i\ell f} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A_n(x_0, y_0) \exp(i\phi_n(x_0, y_0)) \exp\left(-i \frac{2\pi}{\ell f} (xx_0 + yy_0)\right) dx_0 dy_0 ,
\]

where \(A_n(x_0, y_0)\) – the amplitude of the field after passing through the LC layer, \(\phi_n(x_0, y_0)\) – the function of phase delay of the modulator, \(\lambda\) – wavelength, \(f\) – focal distance.

The computation was performed by standard methods using fast Fourier transform.

The distributions of the phase transmittance of masks for formation of light fields in the shape of predetermined curves (triangular boundary, the Archimedes spiral) owning with orbital angular
momentum were obtained by means of the approaches of spiral light optics [34, 35] with the use of Gerchberg-Saxton algorithm.

3. Results and Discussion

3.1. The formation of light fields in the shape of predetermined curves by means of multi-pixel modulators

The examples of the generation of light fields in the shape of the triangular boundary as well as the Archimedes spiral owning the angular momentum are presented in Figure 3. The multi-pixel modulator with the resolution 1024x1024 pixels operating in the reflectance mode was simulated.

![Figure 3](image)

Figure 3. The formation of light fields in the shape of the Archimedes spiral (upper row) and the triangular boundary (lower row): the amplitude of the falling field (a, g), the distribution of the phase delay (b, h), the amplitude after polarizer (c, i), the distribution of intensity in focal plane for modulator without amplitude modulation (d, j), the distribution of intensity in focal plane for modulator with amplitude modulation (e, k) and the deflection of intensity distribution from required one normalized on its maximal value (f, l).

The obtained light field is close to required one but there is some deflection in the profile of intensity distribution. The total power is reduced by 11 % for both cases after passing the polarizer. The mean deflection of intensity from the required value relatively maximal intensity is 0.8% for light beam with intensity distribution in focal plane in the shape of the Archimedes spiral and 1% for the case of triangular boundary formation. The maximal deflections of intensity are 27% for the Archimedes spiral and 7% for the boundary of triangular. The amount of energy, that was redistributed into a different from the required distribution, was 3% of the total transmitted energy for both of the considered fields.

3.2. The formation of axial-symmetric light fields by means of the modulators of sector type

The example of the formation of axial-symmetric light field with the use of 12-sector modulator on the base of studied FLC is presented in figure 4. The thickness of the LC layer is 50 µm. The linear polarized light with polarization plane matching with the initial axis direction of non-excited helicoid falls onto the modulator.

The deflection of obtained distribution of intensity from required one (without the amplitude modulation) can be characterized as follows. The losses of output power (Pₓ/P₀) were not more than 8%, maximal intensity deflection relatively to maximal value in non-excited distribution was not more than 8%. About 4% of energy of light flow was redistributed into different from non-excited case (ΔP/Pₓ) as it followed from obtained distribution of intensity. The deflections for other values of topological charge are presented in Table 1.
Figure 4. The formation of light field: a) the amplitude of the falling field; b) the distribution of the phase delay; c) the distribution of intensity in focal plane for modulator without amplitude modulation. The modulation of the fields amplitude (d, g), the distribution of intensity in focal plane for modulator with amplitude modulation (e, h) and the deflection of intensity distribution from required one normalized on its maximal value (f, i) for SLM on the base of the FLC 587 and FLC 587-F7 accordingly.

Table 1. The deflections of characteristics of light fields forming by means of the FLC SLMs light fields from ideal.

| Topological charge | Modulator on the base FLC 587 | Modulator on the base FLC 587-F7 |
|--------------------|-------------------------------|----------------------------------|
|                    | $P_x/P_0$ | $\Delta P/P_x$ | $P_x/P_0$ | $\Delta P/P_x$ |
| 1                  | 0,89     | 0,06            | 0,92      | 0,03            |
| 2                  | 0,89     | 0,05            | 0,92      | 0,04            |
| 3                  | 0,89     | 0,05            | 0,92      | 0,04            |
| 4                  | 0,88     | 0,07            | 0,92      | 0,02            |

The similar results were obtained for the case of the simulation of the device operating in reflectance mode. Thus the effect of amplitude modulation appeared during the use of both of considered FLC as electrooptical medium in SLM of the sector type for formation of vortex axial-symmetric fields was not essential.

The considered SLM has the ideal structure in terms of the geometry of control electrodes. There are always gaps between contacts in a real device. The presence of a non-controlled region in the center of the electrode system and between sectors is typical for the modulators of sector types. The influence of the size of a circle non controlled region on the formation of the predetermined light fields for the modulator without amplitude modulation of falling light was estimated. The device with aperture diameter 1 cm was simulated. The phase delay in the center of the aperture was supposed equal to zero. The results for the case of the formation of light field with topological charge 3 are presented in figure 5.
It is clearly seen that the distribution of intensity in focal plane deformed stronger with the increasing radius. The simulation results showed that 8% of the energy of light flow was redistributed differently from ideal case for the 12-sector LC modulator with the length of the arc of the inner contacts’ boundary 200 µm. The deflection was more than 10% for the length of the inner contacts boundary 300 µm and more than 20% for 400 µm.

The influence of the presence of gaps between contacts was estimated for 12-sector LC modulator with the length of the arc of the inner contacts’ boundary 200 µm. It was assumed that in non-control regions the phase delay was equal to zero and the device operated on the base of studied FLC 587-F7, i.e. the presence of amplitude modulation was taken into account. The thickness of the LC layer was assumed 50 µm. The simulation results for the case of the topological charge 3 and the width of the contact gaps 50 µm are presented in the figure 6. We chose the width of contacts gaps equal to the thickness of the LC layer to decrease the influence of contacts on the distribution of the electric field by analogy with spatial modulators on the base of nematic LCs where this value is about of the layer thickness.

The energy deflection (the redistribution of energy of light fields differently from the predetermined intensity distribution) was 4% in comparison with the case without of amplitude modulation and 18% as compared to the case of absence of non-controlled regions for various values of beam's angular momentum. The similar results were obtained in the case of the formation of the beams with other values of topological charges.
4. Conclusion
The results of numerical modeling have shown that for the considered variants of the cell parameters, the resulting amplitude modulation using the Kerr orientation effect in LC ferroelectrics with a subwavelength pitch does not have a principal essential effect on the formation of light fields with a non-zero angular momentum in the form of predetermined curves. The quality of forming fields is determined by the complexity realized distribution for set resolution of modulator and the type of its structure.

It was shown that ring-shaped light fields with angular momentum of good quality can be formed by means of the sector modulators on the base studied FLCs. At that the taking into account of contact gaps of technologically realized sizes doesn’t qualitatively change the intensity distribution and amplitude modulation hasn’t essentially influence.

The results of study demonstrate the possibility of creating phase SLC on the base of the FLCs with modulation frequencies more than 0.5-1 KHz.

5. References
[1] Tyson R K 2000 Adaptive Optics Engineering Handbook (New York)
[2] Ananda S, Trivedi R, Stockdale G and Smalyukh I 2009 Proc. of SPIE 7232 723208
[3] Xianyu H Q, Wu S T and Lin C L 2009 Liquid Crystals 36 717-726
[4] Konshina E A, Fedorov M A, Amosova L P, Isaev M V, Kostomarov D S 2008 Journal of Optical Technology 75 670-675
[5] Lu Y-Q, Liang X, Wu Y-H, Du F and Wu S-T 2004 Appl. Phys. Lett. 85 3354-3356
[6] Peng F, Chen H, Tripathi S, Twieg R J and Wu S-T 2015 Opt. Mater. Express 5 265-273
[7] Peng F, Chen H, Tripathi S, Twieg R J and Wu S-T 2015 Proc. SPIE 9384 93840N
[8] Sun J, Xianyu H, Chen Y and Wu S-T 2011 Appl. Phys. Lett. 99 021106
[9] Fan Y-H, Lin Y-H, Ren H, Gauza S and Wu S-T 2004 Appl. Phys. Lett. 84 1233-1235
[10] Peng F, Xu D, Chen H and Wu S-T 2015 Opt. Express 23 2361-2368
[11] Love G, Kirby A, and Ramsey R 2010 Opt. Express 18 7384-7389
[12] Chien C-Y, Hsu C-J, Chen Y-W, Tseng S-H and Sheu C-R 2016 Opt. Express 24 7534-7542
[13] Zhang Z, Xu H, Yang H, You Z and Chu D P 2016 Chin. Opt. Lett. 14 111601
[14] Chen Y, Yan J, Sun J, Wu S-T, Liang X, Liu S H, Hsieh P J, Cheng K L and Shiu J W 2011 Appl. Phys. Lett. 99 201105
[15] Peng F, Lee Y-H, Luo Z and Wu S-T 2015 Opt. Lett. 40 5097-5100
[16] Yan J, Xing Y, Guo Z and Li Q 2015 Opt. Express 23 15256-15264
[17] Kobashi J, Kim H, Yoshida H and Ozaki M 2015 Opt. Lett. 40 5363-5366
[18] Maeda Y, Kobashi J, Yoshida H and Ozaki M 2017 Opt. Mater. Express 7 85-92
[19] Pozhidaev E P, Kiselev A D, Schrivastava A K, Chigrinov V G, Kwok H S and Minchenko M 2013 Phys. Rev. E. 87 052502
[20] Kotova S P, Samagin S A, Pozhidaev E P and Kiselev A D 2015 Phys. Rev. E 92 062502
[21] Pozhidaev E P, Torgova S I, Molkin V E, Minchenko M V, Vashchenko V V, Krivoshey A I and Strigazzi A 2009 Mol. Cryst. Liq. Cryst. 509 1042-1050
[22] Beresnev L A, Blinov L M, Dergachev D I, Kondrat'ev S B 1987 JETP Letters 47 413-416
[23] Rubinstei'n-Dunlop H, Forbes A, Berry M, Dennis M, Andrews D, Mansuripur M, Denz D, Alpmann C, Banzer P, Bauer T, Karimi E, Marrucci L, Padgett M, Ritsch-Marte M, Litchinitser N, Bigelow N, Rosales-Guzmán C, Belmonte A, Torres J P, Neely T, Baker M, Gordon R, Stilgoe A, Romero J, White A, Fickler R, Willner A, Xie G, McMorrain B and Weiner A 2017 Journal of Optics 19 013001
[24] Porfirov A P and Skidanov R V 2014 Computer Optics 38 243-248 (in Russian)
[25] Kotlyar V V, Kovalyov A A and Porfirov A P 2014 Computer Optics 38 658-662 (in Russian)
[26] Afanasiev K, Koroibtsov A, Kotova S, Losevsky N, Mayorova A, Patlan V and Volostnikov V 2013 Journal of Physics: Conference Series 414 01201
[27] Kotlyar V V, Kovalyov A A and Porfirov A P 2017 Computer Optics 41(3) 330-337 DOI:
[28] Kotlyar V V, Kovalyov A A, Porfiryev A P and Abramochkin E G 2017 Computer Optics 41(1) 22-29 DOI: 10.18287/2412-6179-2017-41-1-22-29
[29] Kotlyar V V, Kovalyov A A and Porfiryev A P 2016 Computer Optics 40(3) 312-331 DOI: 10.18287/2412-6179-2016-40-3-312-321
[30] Kotova S, Mayorova A, Samagin S 2018 Journal of Optics 20 055604
[31] Albero J, García-Martínez P, Bennis N, Oton E, Cerrolaza B, Moreno 2012 J. Lightw. Technol. 30 3055-3060
[32] Algorri J F, Urruchi V, García-Cámara B, Sánchez-Pena J M 2014 IEEE Electron Device Letters 35 856-858
[33] Kotova S, Mayorova A, Pozhidaev E and Samagin S 2017 EPJ Web of Conferences 161 01007
[34] Abramochkin E, Kotova S, Korobtsov A, Losevsky N, Mayorova A, Rakhmatulin M and Volostnikov V 2006 Laser Physics 16 842-848
[35] Abramochkin E, Afanasiev K, Volostnikov V, Korobtsov A, Kotova S, Losevsky N, Mayorova A and Razueva E 2008 Bulletin of the Russian Academy of Sciences: Physics 72 76-79

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