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## ELECTRO-OPTICAL MODULATION IN PLANAR ALIGNED FERROELECTRIC LIQUID CRYSTALS WITH SUBWAVELENGTH HELIX PITCH

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*We study experimentally electro-optical modulation in a planar aligned deformed-helix ferroelectric liquid crystal (DHFLC) with subwavelength helix pitch that is less than 100 nm, while thickness of the liquid crystal layer is around 50 μm. The electrically tunable phase shift of light from 0 to 2π and the ellipticity of the transmitted light were measured at the electro-optical response frequency of more than 1 kHz as functions of time and voltage applied across the cell. It is shown experimentally that under the conditions indicated above, the modulation of the ellipticity attenuates with decreasing wavelength of the incident light. It has been shown theoretically that even the maximum modulation of the ellipticity observed in experiments does not have a significant effect on the formation of light fields with nonzero angular momentum. Therefore, the planar aligned DHFLC cells with a thick liquid crystal layer can be used in those areas of optics where the pure phase modulation of light is required at frequency of more than 1 kHz.*

**Key words:** ferroelectric liquid crystals, phase shift of light, ellipticity, subwavelength helix pitch.

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## ЭЛЕКТРООПТИЧЕСКАЯ МОДУЛЯЦИЯ В ПЛАНАРНО-ОРИЕНТИРОВАННЫХ СЕГНЕТОЭЛЕКТРИЧЕСКИХ ЖИДКИХ КРИСТАЛЛАХ С СУБВОЛНОВЫМ ШАГОМ СПИРАЛИ

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*Мы экспериментально исследуем электрооптическую модуляцию в планарно ориентированной ячейке на основе эффекта деформированной спирали сегнетоэлектрического жидкого кристалла (DHFLC), у которого шаг спирали менее 100 нм, а толщина слоя жидкого кристалла около 50 μm. Электрически управляемый фазовый сдвиг света от 0 до 2π и эллиптичность прошедшего света измерялись на частоте электрооптического отклика более 1 кГц в зависимости от времени и напряжения, приложенного к ячейке. Экспериментально показано, что при указанных выше условиях модуляция эллиптичности ослабляется при уменьшении длины волны падающего света. Теоретически*

показано, что даже максимальная модуляция эллиптичности, наблюдаемая в эксперименте, не оказывает существенного влияния на формирование световых полей с ненулевым угловым моментом, поэтому планарно ориентированные DHFLC-ячейки с толстым жидкокристаллическим слоем могут использоваться в тех областях оптики, где чисто фазовая модуляция света требуется на частоте более 1 кГц.

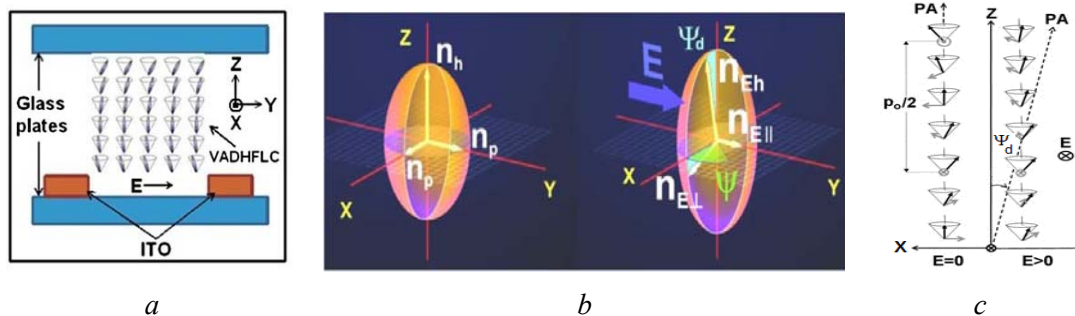
**Ключевые слова:** сегнетоэлектрические жидкие кристаллы, фазовая модуляция света, эллиптичность, субволновой шаг спирали.

## Introduction

High-speed light modulation is in high demand for a variety of display devices, which can be based, in particular, on ferroelectric liquid crystals (FLCs). A detailed description of fast electrooptical effects in FLCs, which are appropriate for development of displays of a new generation, such as field sequential colors displays [1, 2], can be found, e.g., in Ref. [3].

One of important challenges of modern photonics is to increase the speed of adjustment of the spatial characteristics of light fields. This task is relevant both to traditional areas of optics, including

adaptive optics and holographic storage devices, and also for intensively developing fields of science and technology such as holographic displays or optical manipulation of microscopic and nano-scale objects [4–9]. Pure phase modulation of light, when the phase shift can be smoothly tuned from zero to  $2\pi$  in electric field  $\mathbf{E}$  at frequency around 1 kHz or more and without any essential change of the light ellipticity, is required for development of such modern photonic devices. These requirements can be satisfied using vertically aligned deformed helix ferroelectric liquid crystal (VADHFLC) with sub-wavelength helix pitch [10, 11], under conditions illustrated in Figure 1



*Fig. 1. a* – is VADHFLC cell with ITO electrodes, *b* – are ellipsoids of effective refractive indices of a VADHFLC with sub-wavelength helix pitch. Left: at  $\mathbf{E} = 0$ , the field-free effective ellipsoid is uniaxially anisotropic with the principal optical axis parallel to the helix axis. Right: applying an in-plane electric field  $\mathbf{E} \parallel \mathbf{Y}$ , makes the optical anisotropy biaxial with the two optical axes rotated by the angle  $\Psi_d \propto \mathbf{E}$  about the electric field vector  $\mathbf{E}$  [10, 11], *c* – is an illustration of the VADHFLC principal axis (PA) deflection due to deformation of the helix with the pitch  $p_0$  in the presence of electric field

If the linearly polarized in  $XZ$  plane light propagates along the  $Z$  axis (Fig. 1, *b*, *c*) then no change of the light ellipticity happens because the PA deflection plane coincides with the light polarization plane in the same manner as for S- and B-effects in nematic liquid crystals, which are in use for manufacturing of photonic devices with the pure phase modulation of light. But characteristic frequencies of S- and B-cells are several tens of Hz, while of VADHFLC is about 1 kHz [3, 10, 11]. Thus, VADHFLC in principle has greater applications potential compared with S- and B-effects in nematic liquid crystals for development of photonic devices, where the pure phase modulation of light is required.

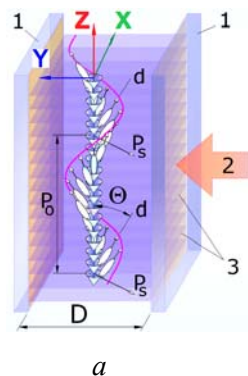
At the same time, the VADHFLC advantages are largely depreciated by the complex technological problems associated with the need for the strip structure of the ITO-electrodes in VADHFLC cells (Fig. 1, *a*), and these problems must be solved in the design of phase matrices.

On the contrary, all technological problems are solved for planar aligned FLCs, when both directions of the applied electric field and the light propagation are along the  $Y$  axis (see Fig. 1, *b*, *c*), since in this case the ITO-electrode in each pixel of the matrix should be continuous rather than striped [12, 13]. However, the optical axis PA, which sweeps in  $XZ$  plane (Fig. 1, *b*, *c*), produces undesirable changes in the ellipticity

of light that propagates along  $Y$  axis. Modulation in electric field of the ellipticity in planar geometry of the deformed helix ferroelectric liquid crystal (DHFLC) [14] with subwavelength helix pitch, which provides the phase shift up to  $2\pi$ , has been not reported so far. Therefore, a goal of this work is to carry out the ellipticity measurements in all visible spectral range in order to understand under what conditions the modulation of the ellipticity becomes so small that electro-optical modulation can be regarded as almost pure phase modulation of light.

### Experimental

In our experiments we use the FLC mixture FLC-587-F7 (developed by the authors in P. N. Lebedev Physical Institute of Russian Academy of Sciences)



as the material for the DHFLC liquid crystal layer. The FLC-587-F7 is an eutectic mixture of the three compounds. The phase transition sequence of this FLC during heating from the preliminary obtained solid crystalline phase is:  $Cr \xrightarrow{7.5^\circ C} Sm C^* \xrightarrow{78.3^\circ C} Sm A^* \xrightarrow{103.2^\circ C} Is$ . The spontaneous polarization this mixture  $P_s \cong 110 \text{ nC/cm}^2$ , the tilt angle of the FLC director in smectic layers  $\Theta \cong 33$  degrees, and the helix pitch  $p_0 \cong 50 \text{ nm}$  at room temperature ( $23^\circ C$ ). The liquid crystal is sandwiched between two glass substrates covered by indium tin oxide (ITO) and aligning films with a thickness of 20 nm, and the gap is fixed by spacers at  $D \cong 56 \mu\text{m}$ . The geometry of the cell is schematically depicted in Fig. 2, *a*, and the experimental set-up is shown in Fig. 2, *b*.

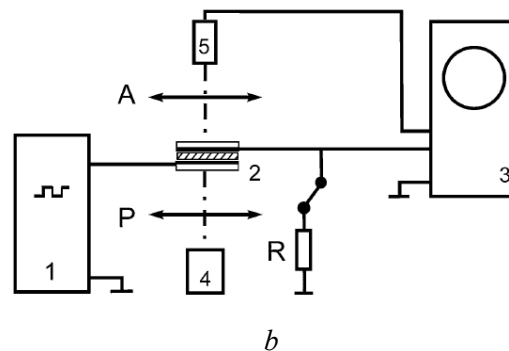


Fig. 2. *a* – represents geometry of planar aligned DHFLC cell: 1 – indicates the cell substrates, 2 – is incident light beam, 3 – shows smectic layers,  $D$  – is the liquid crystal layer thickness,  $d$  – is the director,  $\Theta$  – is the tilt angle of the director in smectic layers; *b* – shows a design of the experimental set-up: 1 – generator, 2 – planar aligned DHFLC cell placed on rotating table, 3 – oscilloscope, 4 – photo-detector, P – polarizer, A – analyzer, R – is a resistor for registration of the polarization reversal current

High-quality planar alignment yielding a contrast ratio more than 100:1 in white light is achieved using 4,4-oxydianiline dianhydride (PMDA-ODA) as 20 nm thick aligning layers according to the technique, which has been described in details in [15, 16]. The obtained alignment was inspected by observing of textures within the cell in a polarizing microscope POLAM-P-312.

### Results and discussion

The condition of electrically controlled phase shift of light by  $2\pi$  was defined in our experiments

according to [17] as the transition between two light transmission minima of the electro-optical response when the cell is placed between crossed polarizers. This condition was achieved, for instance, under applied voltage of  $\pm 45$  volt and at the incident light wavelength  $\lambda = 456 \text{ nm}$  (Fig. 3, *a*, lower solid curve). Similar experiments were performed in the measuring set-up shown in Fig. 2, *b* also at wavelengths of incident light of 543 nm and 659 nm.

In all experiments of this type, the principal optical axis of the DHFLC cell ( $Z$ -axis in Fig. 2, *a*) was directed along the polarizer axis, and the polarizer and the analyzer were either crossed or parallel.

The electro-optical response of the same cell when it is located between the parallel polarizer and the analyzer is shown by the upper solid line in Fig. 3, *a*.

The measurement results shown in Fig. 3, *a*, allow us to calculate the change in the ellipticity  $e$  of transmitted light within a change in the phase shift by  $2\pi$ . According to [15], this calculation is carried out according to the simplest formula:

$$e = \sqrt{\frac{I_{cr}}{I_{par}}}, \quad (1)$$

where  $I_{cr}$  and  $I_{par}$  (see Fig. 3, *a*) are intensities of light transmitted through the DHFLC cell placed between crossed and parallel polarizers, respectively. The results of calculating the ellipticity from the measured values of  $I_{cr}$  and  $I_{par}$  are shown in Fig. 3, *b*.

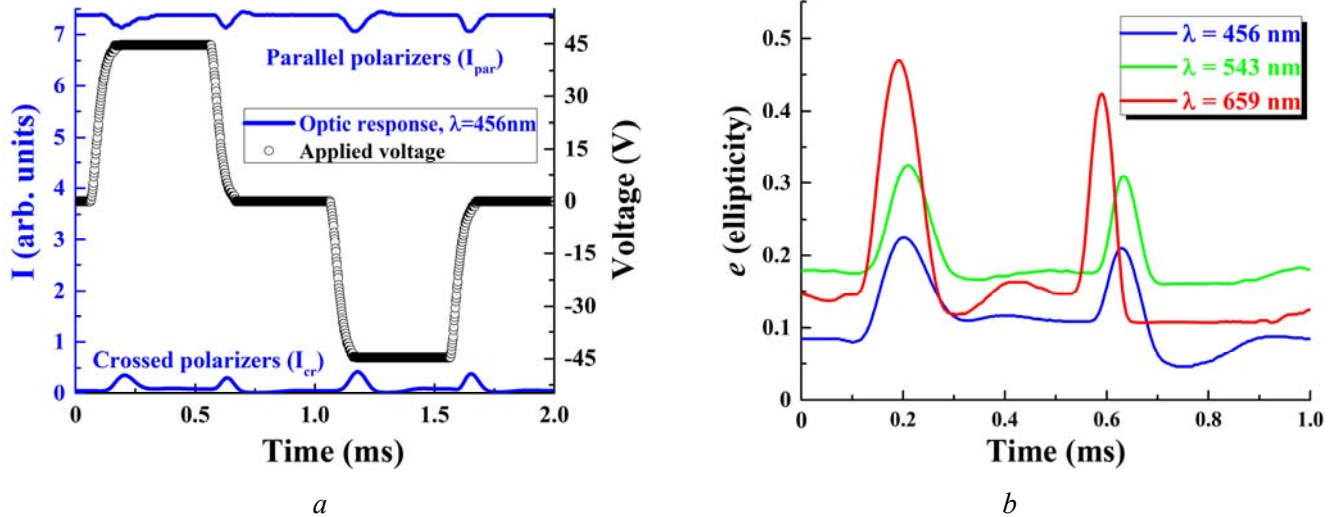


Fig. 3. *a* – Open circles represent the voltage applied to the DHFLC cell with the FLC-587-F7 layer thickness 50  $\mu\text{m}$ . Lower and upper solid curves show the electrooptical response when polarizers are crossed or parallel, respectively. In both cases, the principal optical axis of the DHFLC cell is directed along the polarizer axis, *b* – Dependence of the transmitted light ellipticity on time at the phase shift of light  $0-2\pi$  and vice versa, wavelengths are 456 nm, 543 nm and 659 nm. All measurements were carried out at temperature 23  $^{\circ}\text{C}$

We note that the electro-optical response of the 56  $\mu\text{m}$  thick planar aligned DHFLC layer located either between crossed or between parallel polarizers is characterized by a very weak modulation of the intensity of transmitted light, which does not exceed 3 % of the intensity of light passing through the structure, see Fig. 3, *a*. In other words, the amplitude modulation in this case is insignificant. As for the value of the phase shift under the action of the applied voltage, it can be roughly estimated by the shape of the curves of the electrooptical response. Note that after the transient process, caused by the application of the electric field pulse to the DHFLC layer is completed, the light transmission of the structure becomes approximately the same as it was in the absence of the electric field. This electrooptical behavior is equivalent to introducing a wave  $\lambda$ -plate

(which provides a phase shift of  $2\pi$ ) between crossed or parallel polarizers, and the duration of the transient process is determined by the insertion time of this plate, as it was proved in [17] both theoretically and experimentally.

Based on the above considerations, it is easy to estimate the time after application of the voltage to the DHFLC layer during which the phase of light shifts to  $2\pi$ . Obviously, this time will be equal to the duration of the electro-optical response pulses measured at the base of these pulses. As can be seen from Fig. 3, the time during which a phase shift of  $2\pi$  is achieved after applying the electric voltage pulse to the DHFLC layer is about 220  $\mu\text{s}$ , while after switching off the pulse, the same phase shift occurs in about 130  $\mu\text{s}$ . Hence, the phase shift from 0 to  $2\pi$  and vice versa, from  $2\pi$  to 0, can be obtained at frequency till 2.85 kHz.

The considered phase shift is accompanied by a modulation of the ellipticity of light, which varies quite strongly within the phase shift process, and the longer is the wavelength of the incident light the stronger the ellipticity modulation, Fig. 3, *b*. This phenomenon can be explained by the birefringence dispersion of the liquid crystal, on the basis of the approaches developed earlier in [10, 11, 15, 18], according to which the helical nanostructure of the DHFLC cell in the optical sense is equivalent to the ellipsoids of the refractive indices shown in Fig. 1. This means that the light transmission  $T$  of the DHFLC layer placed between crossed polarizers can be described as [18]:

$$T = \sin^2 2\Psi_d(E) \cdot \sin^2 \frac{\pi \Delta n_{eff}(\lambda, E) D}{\lambda}, \quad (2)$$

where  $\Delta n_{eff}$  is an effective birefringence of the DHFLC layer. At small  $\Psi_d$  the effective birefringence can be expressed as [15]:

$$\Delta n_{eff}(\lambda, E) = 4\Delta n(\lambda) \left( 1 - \frac{3}{2} \sin^2 \Theta \right) \Psi_d^2(E). \quad (3)$$

Here, in (3),  $\Delta n(\lambda)$  is the molecular birefringence dispersion, which does not depend on electric field while  $\Psi_d$  is linear function of  $E$ , as it is shown in Fig. 4, *a*. Dependencies of  $\Delta n_{eff}(\Psi_d^2)$ , which confirm the validity of the relation (3), are presented in Fig. 4, *b*.

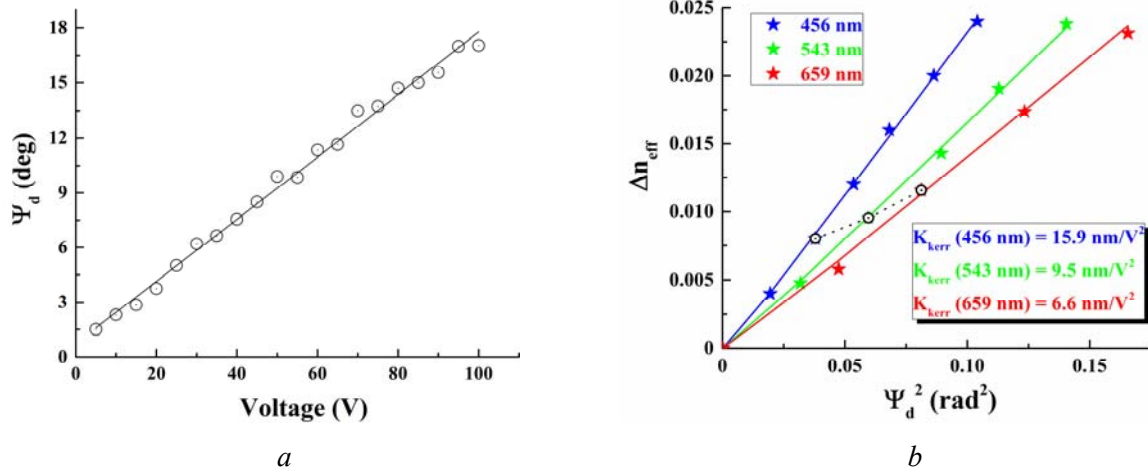


Fig. 4. *a* – Dependence of the  $\Psi_d$  angle on voltage applied to the planar aligned 56  $\mu\text{m}$  thick layer of the FLC-587-F7; *b* – the effective electrically controlled birefringence of the planar aligned 56  $\mu\text{m}$  thick layer of the FLC-587-F7 versus square of the principal axis deflection  $\Psi_d^2$ . All measurements were carried out at temperature 23  $^\circ\text{C}$  and wavelengths  $\lambda_b = 456 \text{ nm}$ ,  $\lambda_g = 543 \text{ nm}$ ,  $\lambda_r = 659 \text{ nm}$ . Open circles indicate conditions of the  $2\pi$  phase shift at different wavelengths

Taking into considerations Figs. 3, *a* and 4, *a* one can conclude that at the driving voltage amplitude  $V_{2\pi}^{456 \text{ nm}} = 45 \text{ V}$ , which provides the  $2\pi$  phase shift at  $\lambda = 456 \text{ nm}$ , the principal axis deflection is  $\Psi_{d-2\pi}^{456 \text{ nm}} = 8.4$  degrees at  $E = 45 \text{ V} / 56 \mu\text{m} = 0.8 \text{ V}/\mu\text{m}$ . The value of  $\Delta n_{eff}(\lambda, E)$ , which provides the  $2\pi$  phase shift at  $\lambda = 456 \text{ nm}$  is  $\Delta n_{eff-2\pi}^{456 \text{ nm}} = 0.0082$ , as it follows from Fig. 4. Acting similarly, we find  $\Psi_{d-2\pi}^{543 \text{ nm}} = 13.8$  degrees at  $E = 77 \text{ V} / 56 \mu\text{m} = 1.375 \text{ V}/\mu\text{m}$  (because of  $V_{2\pi}^{543 \text{ nm}} = 77 \text{ V}$ ), and  $\Delta n_{eff-2\pi}^{543 \text{ nm}} = 0.0096$ . At  $\lambda = 659 \text{ nm}$  we have  $V_{2\pi}^{659 \text{ nm}} = 89 \text{ V}$ , as it was measured experimentally. Hence, according to the same

procedure we have  $\Psi_{d-2\pi}^{659 \text{ nm}} = 15.7$  degrees, and  $\Delta n_{eff-2\pi}^{659 \text{ nm}} = 0.0122$ .

The simple calculations given above show that as the wavelength increases, the angle  $\Psi_d$  of the principal optical axis deflection, which is necessary to ensure the phase shift  $2\pi$ , also increases: from 8.4 degrees at  $\lambda = 456 \text{ nm}$  to 15.7 degrees at  $\lambda = 659 \text{ nm}$ . That means, according to (2), that the contribution of amplitude modulation to the electro-optical response also increases with the wavelength increasing, which at a qualitative level explains the increase in the ellipticity modulation depth with increasing wavelength of light (Fig. 3, *b*).

The above discussed effects of ellipticity modulation may affect the quality of the resulting light field formed by phase matrices. We estimated theoretically the possibility of formation of light fields with the required spatial parameters in such conditions, based on the calculation method described in [16, 19], at  $\lambda = 632.8$  nm and  $D = 50$   $\mu\text{m}$ . Special attention was paid to the formation of light fields in the form of specified curves possessing orbital angular momentum.

Multi-pixel spatial light modulators (SLM) with a square configuration of pixels and sector type modulators operating both in transmission and reflection were considered. Calculations of the light fields were made for the following scheme. The SLM was lightened with the linearly polarized light beam of homogeneous intensity. The value of the voltage fed to each pixel was determined in accordance with the required value of the effective phase delay which should be formed for the transmitted wave. The light transmitted or reflected by the modulator (depending on the modulator type) passed through the polarizer with the plane of transmission coinciding with the initial direction of polarization and was focused by the lens.

The light fields with nonzero orbital angular momentum and the distribution of intensity in the form of ring, curve (Archimedes spiral) and a closed curve (triangle) were obtained. Fig. 5 shows an example of the formation of axially symmetric fields with the topological charge of 3 by means of a modulator of the sector type (12 sectors, the DHFLC layer thickness of 50  $\mu\text{m}$ , diameter 1 cm).

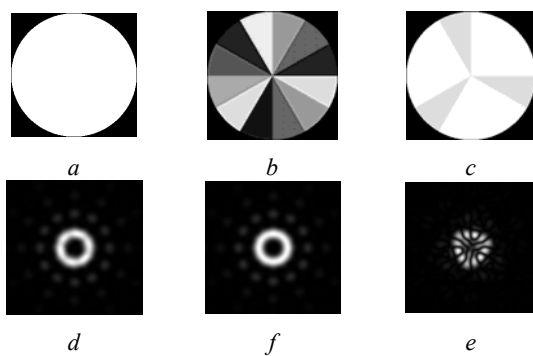


Fig. 5. *a* – initial distribution of the light field amplitude, *b* – phase delay profile, *c* – amplitude of the light field obtained by the polarizer, *d* – intensity distribution in the focal plane, *f* – required intensity distribution (without amplitude modulation), *e* – deviation of the obtained intensity distribution from the desired normalized by its maximum value

Both for this case and other ones it was found that the total energy losses reached approximately 11 %, the average deviation of the intensity did not exceed 5 %.

## Conclusion

Thus it can be concluded that the resulting ellipticity modulation has no significant effect on the formation of light beams with nonzero angular momentum in the form of specified curves even with red impinging light, when the total energy losses reached approximately 11 % at the ellipticity modulation depth from 0.12 to 0.45 within the phase shift from 0 to  $2\pi$  (Fig. 3). The results of experiments and calculations indicate the possibility of constructing the phase SLM based on planar aligned DHFLC with modulation frequencies more than 1 kHz. It can be expected that as the depth of modulation of ellipticity decreases with decreasing wavelength of the incident light, the energy losses during the formation of light fields with a nonzero orbital angular momentum also decrease. So, decrease of the incident light wavelength is a very suitable option for diminishing of the total energy losses at forming light fields with nonzero orbital angular momentum, using planar aligned DHFLC spatial light modulators.

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