Computer analysis of the influence of technological parameters of a high–speed liquid crystal modulator on its integral characteristics

G V Simonenko
Saratov National Research State University named after N. G. Chernyshevsky
E-mail: gvsim1960@hotmail.com

Abstract. The purpose of this article is a computer analysis of various designs of LC light modulators. Based on the integrated characteristics of the LC modulator, its optimal design is found. It was shown that the LC modulator based on the LC structure with a twist angle of 270° under antisymmetric boundary conditions with small values of the pretilt angles on the orienting substrates, operating in the waveguide mode and using a phase film compensator, has optimal integral characteristics. The results of comparing the integral characteristics of the LC modulator based on various LC structures are presented.

1. Introduction
Currently, liquid crystals (LC) have found their application in various fields of science and technology: from control systems using optical elements [1] to systems for processing and displaying information [2–4]. The most famous devices based on LCDs are all kinds of modulators of the light flux: indicator systems [2, 3], displays [2–4], shutters [5]. In connection with the rapid development of 3D – systems for visualization and optical flow control systems using LC modulators, an urgent task is to improve the optical and dynamic characteristics. In the most common LC devices, nematics are used as LC substances, the main disadvantage of which is the long response time (at least 4 ms [2–4]). In such devices, as a rule, the effect of electric birefringence controlled by an electric field is used: an LC modulator based on π-cells, twist - cells, supertwist – cells. Today, there are known designs of LC modulators that have shorter response times, but they are not widely used. At the moment, there is a clear understanding of the relationship between the physical and technical parameters of such a device and its characteristics, however, the question of the optimal design of a nematic based LC modulator remains open. The parameters that uniquely determine the boundary conditions include the angle of twist of the LC structure and the angles of the incline of the LC molecules on the orienting substrates. Therefore, we performed a computer simulation of the characteristics of the LC modulator for 3D applications depending on its design parameters: the angle of twist of the structure of the LC in the cell and the angles of the pretilt of the LC molecules on the orienting surfaces of the cell?

The operation of any LC device designed to modulate the light flux is based on the dependence of its transmission on the control voltage. As a rule, in a state where the control voltage is not applied to the electrodes of the cell or below a threshold value, the transmission is maximum.
This device state is called “open”. When a control voltage is applied to the LCD cell, the transmission of the device changes, when a certain voltage is reached, it becomes minimal. This condition is called “closed”. The “closed” state is often called the “on” state, and the “open” state is called the “off” state. To describe the characteristics of LC devices in open and closed states, there is a large set of optical, electro-optical and dynamic characteristics [6], but to find the optimal design of an LC device, it is enough to use only four integral characteristics [6]:

- average transmission spectrum of the LC modulator in the “open” $T_{off}$ state;
- the average spectral contrast ratio of device $C$, which characterizes the difference in transmission of the device in the open and closed states;
- achromaticity of the $H_{off}$ device in the “open” state, provided that $H_{off} \leq 0.05$ condition for obtaining a full-color image;
- the total response time of the LC device $\tau$, which in this case is defined as follows:

$$\tau = \tau_{\text{react}} + \tau_{\text{relax}}$$

$\tau_{\text{react}}$ – device turn-on time (time required for the modulator to transition from the “open” state to the “closed” state); $\tau_{\text{relax}}$ – device shutdown time (time required for the modulator to transition from the “closed” state to the “open” state).

The search for the optimal parameters of an LC device is usually performed using the computer simulation method [6][7]. For this purpose, we used the MOUSE – LCD software package [7], which allows modeling the characteristics of various LC devices with an accuracy within the experimental error in the worst case not exceeding 10% [6][7]. It is worth noting that the modeling error is determined mainly by the accuracy of setting the physical and structural parameters of the modulator.

The main technological parameters that significantly affect the characteristics of the LC device are the boundary conditions in the working LC cell. Therefore, we investigated the characteristics of LC devices based on thin LC cells with symmetric and antisymmetric boundary conditions and various spin angles of the $\Phi_T$ structure. When modeling the characteristics of the LC device, it was assumed that the LC cell was filled with a mixture with the following physical parameters: $K_{11} = 10.5 \times 10^{-6}$ dyne, $K_{22} = 6.9 \times 10^{-6}$ dyne, $K_{33} = 16.8 \times 10^{-6}$ dyne, $\varepsilon_\perp = 4.88$, $\varepsilon_\parallel = 13.54$, rotational viscosity $\gamma_1 = 0.15$ GHS units. It was believed that the dispersion of the anisotropy of the refractive indices of the LC is weak, and its value at a wavelength of 550 nm $\Delta n = 0.2$. In all calculations, these physical parameters of the LC remained constant.

As the polarizers used film NPF – F 1205 DU. When modeling, the values of the remaining design parameters of the LC device were considered equal to the average technological values.

In order to exclude the influence of the value of the control voltage on the characteristics of the LC device, we selected the same for all boundary conditions of the LC on the substrates (for the “open” state $U_{off} \leq U_{Fred}$ ($U_{Fred}$ – is the threshold voltage of the Fredericks transition), and for the state it is “closed” $U_{on} = 12$ V). In addition, in all cases, the thickness of the LC layer $d$ in the working cell was always taken equal to 3.5 $\mu$m. For antisymmetric boundary conditions, the angle of pretilt in the absence of control voltage on one orienting substrate in the cell $\theta_{01}$, but on the opposite $\theta_{02} = -\theta_{01}$. Under symmetrical boundary conditions, the values of the angles of pretilt on both orienting surfaces were the same ($\theta_{02} = \theta_{01}$).

First of all, we note that the total response time of the LC device cannot be less than the time constant $\nu$ associated with orientation effects [8]:

$$\nu = \frac{\mu d^2}{\pi^2 K},$$

$\mu$ – the average viscosity of the LC, $K$ is the average coefficient of elasticity of the LC.
Therefore, the response time of the LC modulator in our conditions cannot be less than 100 µs and this is a fundamental limitation of the performance of these LC devices. However, at present, the minimum response time of LC modulators based on nematics is several milliseconds and, therefore, there is a fundamental possibility to reduce the response time of the LC modulator by choosing its optimal design.

2. Computer simulation

Studies have shown that of all the design parameters of the LC modulator (except for the thickness of the LC layer \(d\)), the twist angle of the LC structure in the cell has the maximum effect on its optical and dynamic characteristics. Based on LC structures with different spin angles, there are a large number of information display and processing devices that use a waveguide or interference mode for their work. However, to study the dynamics of the Fredericks transition from one state to another, the polarized-beam interference effect (interference mode) in the LC structure is usually used, since in this case the change in the optical response exactly follows the deformation distortion of the LC director without time delays.

Computer simulation of the dependence \(\tau = \tau(\Phi_T)\) showed that this function with an error of no more than 13% is linear for both symmetric boundary conditions and antisymmetric boundary conditions. The rate of change of the function \(\tau(\Phi_T)\) for antisymmetric boundary conditions is higher than for symmetric boundary conditions. Therefore, we can conclude that in order to obtain small values of the total response time of the LC modulator at high control voltages, it is necessary to use structures with a twist angle of \(\Phi_T = 270^\circ\).

Based on this, we dwell on the consideration of various designs of LC modulators based on the structure of an LC with a swivel angle of 270°. There can be eight such structures, which differ in the type of boundary conditions, in the optical mode used to implement radiation modulation, and in the presence of a phase compensator. In the table shows the main integral characteristics of various LC modulators operating on the basis of an LC structure with \(\Phi_T = 270^\circ\). Based on the analysis of the data table, we can assume that an LC modulator based on a waveguide mode in cells with antisymmetric boundary conditions and with a phase compensator has an optimal set of integral characteristics, namely, the maximum possible values \(T_{off}\) and , minimum possible values \(\tau\) and \(H_{off}\).

| \(\alpha_{in} = 0^\circ\), \(\alpha_{out} = 90^\circ\) | \(\alpha_{in} = 0^\circ\), \(\alpha_{out} = 90^\circ\) | \(\alpha_{in} = 45^\circ\), \(\alpha_{out} = -45^\circ\) | \(\alpha_{in} = 45^\circ\), \(\alpha_{out} = -45^\circ\) |
|---|---|---|---|
| without phase compensator | without phase compensator | without phase compensator | without phase compensator |
| \(\theta_{02} = \theta_{01}\), \(\theta_{02} = -\theta_{01}\) | \(\theta_{02} = \theta_{01}\), \(\theta_{02} = -\theta_{01}\) | \(\theta_{02} = \theta_{01}\), \(\theta_{02} = -\theta_{01}\) | \(\theta_{02} = \theta_{01}\), \(\theta_{02} = -\theta_{01}\) |
| \(T_{off}\) | 0.387 | 0.387 | 0.385 | 0.385 |
| \(C\) | 355 | 29 | 427 | 423 |
| \(\tau\) | 9 | 5.25 | 9 | 4.5 |
| \(H_{off}\) | 0.0324 | 0.0324 | 0.033 | 0.057 |

Let us consider the influence of technological parameters on the integral characteristics of the boundary conditions of an LC modulator based on the waveguide mode in cells with antisymmetric boundary conditions and with a phase compensator. The technological parameters include the boundary conditions: the value of the angle of incline of the LC molecules on the orienting surfaces, the adhesion energy of the LC molecules with the orienting surface, the ratio \(d/p_0\) (\(p_0\) is the chiral addition step) of the LC mixture. An analysis of the results of
Computer simulation showed that, from the point of view of the integrated characteristics of the LC modulator, the optimal value of the technological parameter \( \theta_{01} (\theta_{02} = -\theta_{01}) \) is 2\(^\circ\), which is ensured by the standard orientation technology of the nematic LC known since the mid-70s. The influence of the adhesion energy of molecules with orienting surfaces on the integrated characteristics of the LC modulator was studied in detail in the previous article, and it was shown that attenuation of the adhesion energy has little effect on the optical characteristics, but increases the total response time of the device. The influence of the energy of adhesion of molecules to orienting surfaces on the integral characteristics of an LC modulator was studied in detail earlier, and it was shown that attenuation of adhesion energy has little effect on optical characteristics, but increases the total response time of the device. The results of our modeling showed that the technological parameter \( d/p_0 \) weakly affects the values \( T_{\text{off}}, H_{\text{off}}, \) and \( \tau \), since the limits of variation of this parameter are limited to one Grange zone. Moreover, in order to avoid the appearance of undesirable dielectric domains, only the left part of the Grange zone should be used (0.5 \( \leq \) \( d/p_0 \) \( \leq \) 0.75).

An analysis of the data shows that the twist indicator is the undisputed leader in optical integrated characteristics (\( T_{\text{off}}, C, H_{\text{off}} \)), but its total response time is long (\( \tau \geq 9 \mu s \)). An LC modulator based on a \( \pi \) – cell with an angle of twist of the LC structure of 180\(^\circ\) has a very good set of all integral characteristics, the main disadvantage of which is a slightly colored “open” state (0.5 \( \leq \) \( H_{\text{off}} \) \( \leq \) 1). On the other hand, a modulator based on a structure with a swivel angle of 270\(^\circ\) has the shortest total response time, but this device has a rather low contrast ratio. Note that for most LC devices, the required level of contrast ratio is 300: 1 with achromaticity of \( H_{\text{off}} \leq 0.05 \), and the total response time of such a device should be no more than 3–5 milliseconds. Therefore, with such requirements for integral characteristics, you should choose a modulator based on a structure with a swivel angle of 270\(^\circ\), which operates on the basis of the waveguide mode in an LC cell with antisymmetric boundary conditions and with a phase compensator.

**Acknowledgements**

This work was carried out as part of the RFBR project No. 19-07-01005.

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