Contributed paper

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Liquid crystals as active elements of sensors based on planar waveguide

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A system LC–waveguide may be applied in different devices for physical values registration, and optical signal controlling devices. It is important to use a planar waveguide in combination with peculiarity of liquid crystal (LC) materials that are characterised by a high sensitivity to physical values of external influence liquid crystal materials. At present, time waveguides are widely used as elements for signals processing and transmission in optical systems that are realised on different optical effects. The using of planar waveguide as backplane of LC cell alleviate orientation process of LC layer in contrast to fibre waveguide.

Keywords: nematic mixtures, induced cholesteric, waveguide, sensor.

1. Introduction

The task of present work was to research liquid crystal (LC) materials for new constructive design of sensor sensible element. This allows to provide temperature, pressure, electric and magnetic fields registration and leads to extend the functional sensor applications.

The registration of physical values is based on turn of LC molecules orientation under the action of an external field. The changes of applied external field intensity leads to changes of LC medium refraction index. That leads to changing of total reflective conditions inside waveguide–LC system.

For cholesteric mixtures external influence leads to changing of induced spiral pitch that in turn causes the change in the conditions of selective reflection. The external factors such as pressure, temperature, microwave and electromagnetic fields change a pitch of induced spiral.

2. Nematic LC mixtures

When nematic liquid crystal mixes are used for filling capsule of an active sensor element, the dominant role is played the choice of values of the refraction parameter $n_\perp$ and $n_\parallel$. The initial orientation of nematic should be homeotropic what allows to provide internal refraction condition, that is $n_\perp < n_c$, where n_c is the core refraction parameter.

The action of the external factor (temperature, pressure, electrical or magnetic fields) results in infringement of condition of complete internal de-excitation, as $n_o = 0$. As an example, we choose five members of homological 4-alkyl-4'-methoxsytolan series with such refraction parameters as $n_\perp = 1.495$ $n_\parallel = 1.669$. For sensor functioning, according to the above-mentioned condition, we choose a core material FLG – KNd_4O_{12}/KLa_4O_{12} with $n = 1.5$. For maintenance of homeotropic orientations, the polymer–oktametyltrycyclohecsane is chosen that also responds to the imposed condition $n = 1.49... 1.525$.

The sensor with nematic mixture sensibility depends on birefringence value and on length of removed region of core with LC. In Fig. 1, the dependence of refraction index on temperature is shown. For material selection, the table is represented with parameters of nematics of 4-alcil-4'-methoxytolanes series.

The homeotropic orientation process is difficult and it becomes more complex for radial light guide core, at the region of which the LC layer is placed. It is an essential disadvantage of their using.

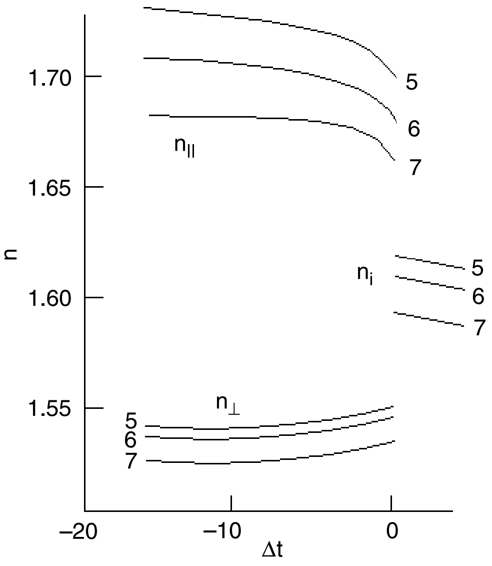

Fig. 1. Dependence of the refraction indices $n_\perp$, $n_\parallel$, n_i of 4-alcil-4'-methoxytolanes on $\Delta t = t_{lnl} - t$.

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3. Cholesteric liquid crystals

The situation essentially changes with the use of induced cholesteric as active substance. For sensor functioning it is necessary to provide execution of such demands: radiation wavelength of the same order that the pitch of induced spiral $p = \lambda/n$, planar texture of LC film, and material of wave guide material with refraction index less than induced cholesteric refraction index.

The planar texture destruction, under action of external factors, leads to the selective distribution of refraction conditions. In order to obtain a planar texture, it is necessary to create a homogeneous molecules orientation that is technologically simply to provide.

The width of a maximum reflection index stripe is defined by $\Delta\lambda = nP$ relationship, so, the divergence of wavelenght value, which are reflected is known, the value Δn varies from 0.08 to 0.2. For LC material selection it is possible to define the spectral width of reflection on LC layer.

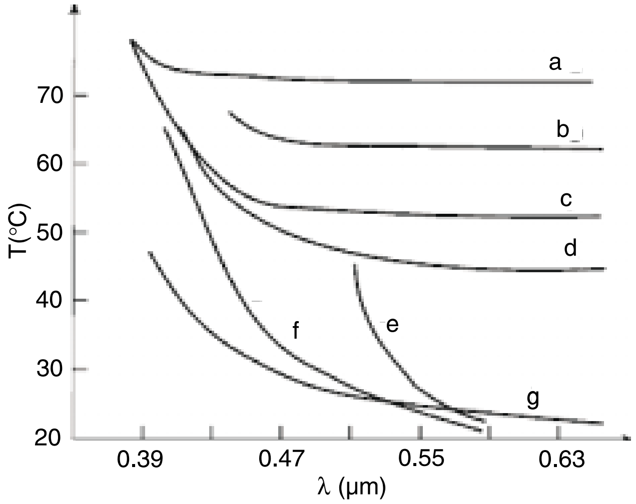

Fig. 2. Temperature dependencies of light wavelength in maximum reflection for number of cholesteryl ethers mixture and cholesteryl nonanoate (CN): (a) pure CN; (b) 20% cholesteryl hydro cyanate, 80% CN; (c) 20% cholesteryl butyrate, 80% CN; (d) 20% cholesteryl propionate, 80% CN; (e) 20% cholesteryl chloride, 80% CN; f) 20% cholesteryl acetate, 80% CN; g 20% cholesteryl methylcarbinate, 80% CN.

Several works were devoted to study pressure influence on cholesteric spiral pitch. As shown in Fig. 4, the spiral pitch increasing fast at the increasing pressure and critical values are 0.8 and 1.2 kbar. The cholesteric spiral pitch changing at the magnetic field influence well exposures in cholesteric-nematic mixtures with spiral pitch $P_0 = 26$ μm (Fig. 5). The value of critical field is calculated from the equation

$$H_c = \pi^2 \left(\frac{K_2}{\chi_a}\right)\frac{1}{P_0}$$

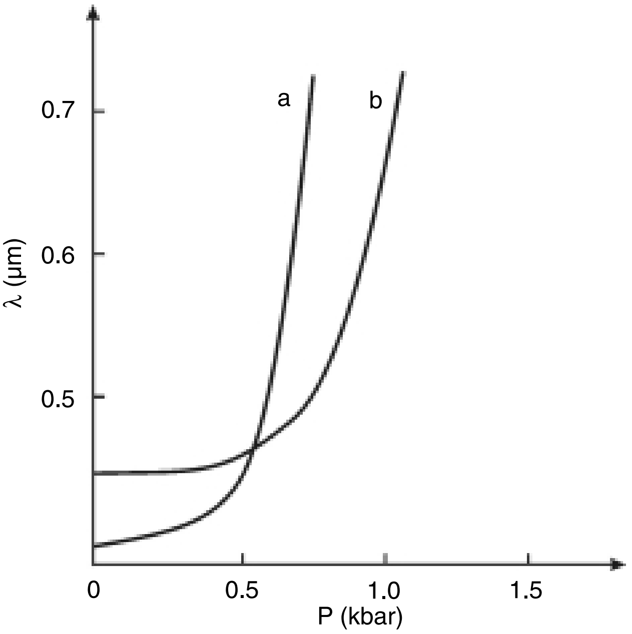

Fig. 3. Dependence of light wavelength of maximum dispersion on pressure for mixture cholesteryl propionate and cholesteryl chloride at room temperature for the different mixture contents.

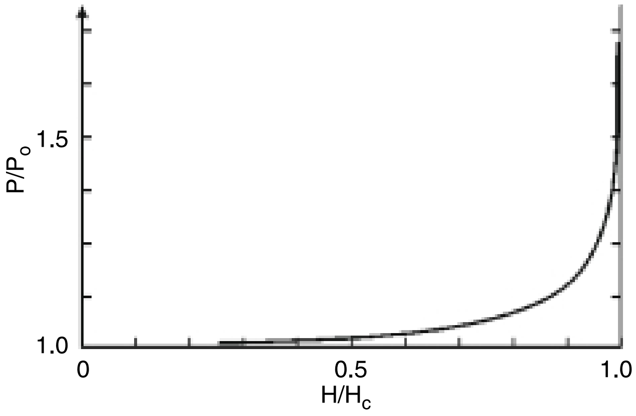

Fig. 4. Dependence of spiral pitch on magnetic field in mixtures PAA with low molar consistent of cholesteryl acetate.

for fixed K_2 and χ_a. The critical field value H_c is inversly proportional to the cholesteric pitch and for different LC mixtures are 8–10 kGs.

4. Example of planar waveguide sensor calculation

In the optical sensor, designed as scheme of controlled waveguide, the light transmittance depends on surrounding refraction index (in this case – depends on LC refraction index).

The mathematical model for this case defines the dependence output light intensity on refraction index changes, waveguide surface, and the condition of light propagation. This model is composed of the change of reflection capability of waveguide at the change of refraction index

$$I(n_2) = 0.5S_{fd}\sum_{k=k_{\min}}^{k=k_{\max}} \int_{arctg[(L-I)/2kd}^{arctg(L/2kd} C(1-R_{\perp r})^2 + R_{IIn}^{k}(\theta_1,n_2)(1-R_{\|r})^2 \times \exp(-\chi L/\cos\theta_1) f_1[\arcsin(n_1\sin(\theta_1-\alpha_0))] f_{fd}[\arcsin(n_1\sin(\theta_1-\alpha_0)) + \Delta\beta] d\theta_1 . \qquad (1)$$

For the calculation of sensor based on controlled waveguide responses it is necessary to define both input energy parameters of light and geometrical position of the polar pattern of light source which is characterised by axial and boundary beams. The optical scheme of planar waveguide is presented in Fig. 5.

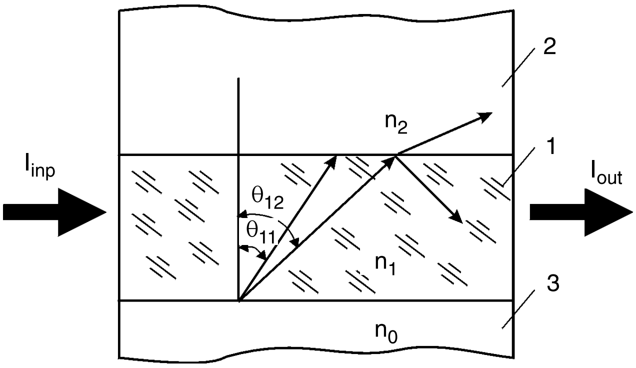

Fig. 5. Optical scheme of a planar waveguide.

$$R_{\perp n}(\theta_1,n_2) = \left[\frac{n_1\cos\theta_1 - \sqrt{n_2^2 - n_1^2\sin^2\theta_1}}{n_1\cos\theta_1 + \sqrt{n_2^2 - n_1^2\sin^2\theta_1}}\right]^2, \qquad (2)$$

$$R_{\| n}(\theta_1,n_2) = \left[\frac{n_2^2\cos\theta_1 - \sqrt{n_2^2 - n_1^2\sin^2\theta_1}}{n_2^2\cos\theta_1 + \sqrt{n_2^2 - n_1^2\sin^2\theta_1}}\right]^2, \qquad (3)$$

where $R_{\perp n}(\theta_1,n_2)$, $R_{\| n}(\theta_1,n_2)$ are the Frenel reflectivity factors.

The modulation factor m of such sensor is defined from

$$m = (I_{\max} - I_{\min})/I_{\max} = 1 - \tau_{\min}/\tau_{\max}, \qquad (4)$$

where I_{max}, I_{min}, τ_{min}, τ_{max} are max and min values of output intensity and light transmittance at the changes of surrounding properties correspondingly

$$\tau(n_2,\varphi) = \frac{1}{2}\left(\sin\left(\frac{\pi}{2}\arcsin\left(\frac{n_1}{n_0}\sin\left(\arcsin\frac{n_2}{n_1} - \alpha_0\right)\right)\Big/\varphi_{dn}\right)\right), \qquad (5)$$

where α_0 is the input beam angle and φ_{dn} is the polar pattern angle.

The intensity I_{max} is defined at $n_2 = n_{20}$, and the intensity I_{min} – at $n_2 = n_{20} + \Delta n$

$$I_{\max} = \int_{l\min}^{l\max} \frac{dI_{out}}{d\theta_1} d\theta_1 \Big|_{n_2 = n_{20}}. \qquad (6)$$

This integral can be divided in the angle range from $\theta_{lcr} = \arcsin(n_{20}/n_1)$ till θ_{lmax}, within the condition of full internal reflection is fulfilled

$$\frac{dI_{out}}{d\theta_1} = \frac{dI_{inp}}{d\theta_1}, \qquad (7)$$

and in the angle range from θ_{lmin} till θ_{lcr}, where the condition of full internal reflection is disturbed

$$\frac{dI_{out}}{d\theta_1} = \frac{dI_{inp}}{d\theta_1} R_\Sigma(\theta_1,n_{20}), \qquad (8)$$

$$R_\Sigma(\theta_1,n_2) = 0.5[R_{\perp n}^{k}(\theta_1,n_2) + R_{\| n}^{k}(\theta_1,n_2). \qquad (9)$$

Correspondingly

$$I_{\max} = \int_{\theta_{l\min}}^{\theta_{lcr}} \frac{dI_{inp}}{d\theta_1}[R_\Sigma(\theta_1,n_{20})]d\theta_1 + \int_{\theta_{lcr}}^{\theta_{l\max}} \frac{dI_{inp}}{d\theta_1} d\theta_1. \qquad (10)$$

The intensity is defined analogously

$$I_{\min} = \int_{l\min}^{l\max} \frac{dI_{out}}{d\theta_1} d\theta_1 \Big|_{n_2 = n_{20}+\Delta n_2}, \qquad (11)$$

or

$$I_{\min} = \int_{\theta_{l\min}}^{\theta_{lcr\Delta}} \frac{dI_{inp}}{d\theta_1}[R_\Sigma(\theta_1,n_{20}+\Delta n_2)]d\theta_1 + \int_{\theta_{lcr\Delta}}^{\theta_{l\max}} \frac{dI_{inp}}{d\theta_1} d\theta_1. \qquad (12)$$

Substituting the values I_{max}, I_{min} into Eq. (4) and taking into account the polar pattern we can calculate the modulation factor or sensor sensitivity.

At the condition of equal angular intensity of light source within angle range from θ_{11} till θ_{12}, that is $dI_{inp}/d\theta_1 = I_0$

$$I_{\max} = I_0 \int_{\theta_{12}}^{\theta_{lcr}} [R_\Sigma(\theta_1,n_{20})]d\theta_1 + I_0(\theta_{11} - \theta_{lcr}), \qquad (13)$$

$$I_{\min} = I_0 \int_{\theta_{12}}^{\theta_{lcr\Delta}} [R_\Sigma(\theta_1, n_{20} + \Delta n_2)] d\theta_1 + I_0(\theta_{11} - q_{lcr\Delta}) . \qquad (14)$$

5. Example of temperature sensor construction

The construction of the temperature sensor based on cholesteric LC for integral performance is shown in Fig. 6.

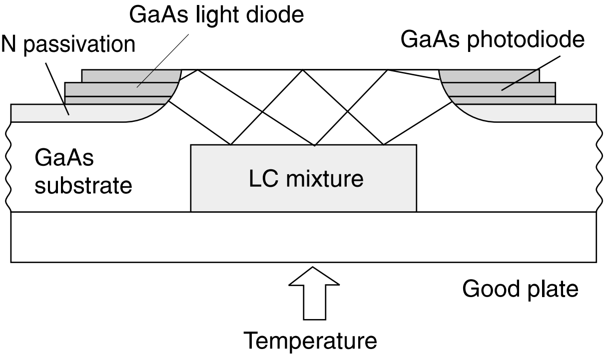

Fig. 6. Construction of the planar temperature sensor filled in cholesteric liquid crystal.

Sensor is based on GaAs–substrate. The sensor creation is compatible with silicon microtechnology. IR light diode and photodetector is created directly on the GaAs substrate. On the backplane the ditch can be grooved or bited and filled with LC mixture and cover by gold plate.

Refractive indexes of LC mixture and waveguide are chosen to confirm condition $\arcsin n_{LC}/n_{substrate} < \theta_{cr}$. Thus, the total reflection is violated but due to selective reflection on spiral structure of cholesteric light return to waveguide.

It is necessary to choose sensitive LC mixture in given temperature range of sensor operation. The propagated light in waveguide passes the region of LC cell due to selective reflection. The wavelength of reflected light depends on spiral pitch $\lambda = nP$, which in turn has temperature dependence.

6. Conclusion

The attempt to analyse characteristics of liquid crystal materials with aim to its application for modern optoelectronic sensor schemes was done. The example of calculation and construction of such type sensor are shown. The advantage of presented sensor structure is possibility of its creation in one production cycle of optoelectronic integral circuit.

Due to high sensitivity of LC materials to external influences we can conclude that LC applications in sensor devices are perspective and advisable.

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