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# LC acousto-optical transducer for nondestructive holographic control systems

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**Abstract.** The construction of acousto-optical display based on the hysteretic in cholesteric liquid crystals (CLCs) is proposed for nondestructive holographic test systems. The influence oblique reactive sputtering deposited thin films of $In_2O_3$, $Al_xO_y$, $SiO_x$, upon alignment properties of CLC, which are used as ultrasonic holographic recording media, is investigated. The technical characteristics and properties of developed acousto-optical display (AOD) are represented. The high sensitivity and planar texture reproducibility CLC are shown to be implicit advantages of AOD developed.

**Keywords:** cholesteric liquid crystal, acousto-optical display, ultrasonic hologram.

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## 1. Introduction

Both fundamental and applied research of nondestructive control techniques attracted very much attention recently [1, 2]. Acoustic holography technique, which is a good supplementary technique for traditional nondestructive control techniques, play a special role in nondestructive research techniques.

The usability of acoustic holography techniques for nondestructive testing and defectoscopy lies in the very fact that the majority of materials and constructions are nontransparent for electromagnetic field in its optical range and, as a consequence, the internal structure of tested materials is invisible for visual observation. However, the optically nontransparent solid media may be transparent for ultrasonic acoustic waves of an appropriate frequency range. Therefore, interaction of ultrasonic acoustic waves with the defects and inhomogeneities in the media may provide information on structure and properties of defects. The success in further development and application of acoustic holography techniques depends very much on availability of a good sensor, which fulfill the numerous requirements like threshold sensitivity, resolution, reversibility, *etc*.

Cholesteric liquid crystals (CLCs) attract very much attention in that sense due to their periodic helical structure of molecular layers, which gives Bragg selective reflection accompanied by circular dichroism and strong rotation of the polarization plane for short pitch CLCs. The strong helical pitch dependence of above factors and the influence of other various external factors make it possible to use CLCs for visualization of acoustic, thermal and other kinds of fields.

The general construction of acousto-optical display (AOD) is enough simple. It consists of an optically transparent substrate and ultrasonically transparent but optically opaque substrate with the layer of CLC (*e.g.*, mixture of cholesterolpelargonate and cholesterol-chloride [3]) arranged between them. The theoretical threshold sensitivity for AOD of above described construction is calculated to be about $10^{-12}$ W/mm$^2$, whereas the practically achieved value is only about $10^{-4}$ W/mm$^2$ [4]. There are several constructions of above described AOD known for today [5-7]. The general feature of such devices is impossibility to erase recorded information quickly as well as to restore the planar texture of CLC. The recorded information erase and a planar texture restoration is performed by mechanical shift between substrates. This technique imply a significant disadvantage because LCs could not be hermetically sealed, which result in lifetime restrictions and reproducibility of the results. The other shortcomings of such construction represent the thickness variation of LC after each sequential shift of glass substrates, which results in variation of reflection intensity for selected wavelength.

In order to avoid above mentioned shortcomings, we have developed a new type of AOD based on hysteretic properties in CLC [8]. It features uniform high quality planar texture and possibility to erase information and restore the planar texture. Another feature of proposed AOD is CLC in fully hermetic and sealed volume, which prevents any contact of LC with testing object and any aggressive environment for LC.

## 2. Experimental setup

The developed AOD is made up of the following parts (Fig. 1): the ultrasonically transparent substrate (1) with the optically dark opaque layer on top (8) and CLC film arranged between those substrates. Both substrates have embedded transparent electrodes (7) connected to a power source and transparent alignment layers (6). The sensor sandwich is sealed from opposite sites, whereas the remaining two opened sides are directly connected to incoming (9) and outgoing (4) reservoirs sealed with LC. There is a heater (5) embedded into LC feeder, reservoir of which has a piping with a plastic membrane (11). The total erase of recorded information is performed by the application of voltage from the power source (12).

The proposed AOD operates in the following way. In order to prepare the sensor for information recording, the voltage from the power source (12) is applied first. The transparent electrode is made of $In_2O_3$:Sn thin film deposited on top of the glass substrate by the cathode reactive sputtering deposition technique in the Ar:$O_2$ atmosphere. The ingot has the standard 95/5 ratio for In/Sn. Passing through the $In_2O_3$:Sn electrodes, the electric current produces heat sufficient for isotropic phase transition of CLC. The temperature set both inside the drain and source must be below the isotropic temperature of CLC. After the power source (12) is turned off, the heater (5) launches the power source (13) at the very moment of the reverse phase transition of LC from isotropic to cholesteric state. The heater has enough power to transfer the content of reservoirs from LC phase to the isotropic state within a few seconds. Due to a natural thermal expansion of liquid in the source, it is flown through the sensor capillary into the

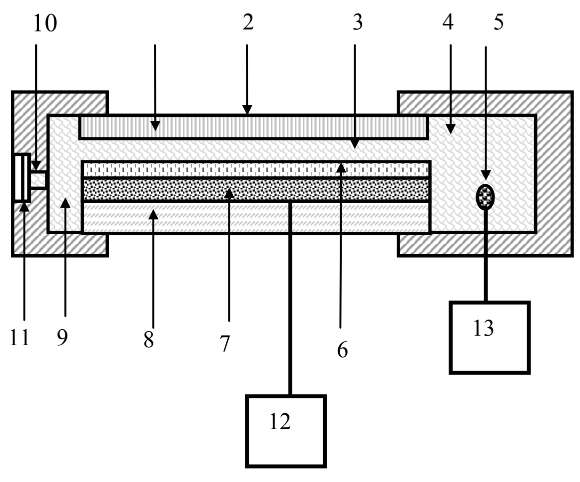


**Fig. 1.** The construction of AOT: 1 – acoustic transparent substrates, 2 – opaque layer, 3 – CLC thin layer, 4 – source, 5 – heater, 6 – alignment layer, 7 – transparent electrode, 8 – optically transparent substrates, 9 – drain, 10 – piping connection, 11 – membrane, 12, 13 – power supply units.

drain. Unidirectional transportation of LC via the capillary with the alignment layer creates a good planar texture. The heating power and operation time is adjusted to provide isotropic phase transition completed by 30–60 % of overall volume of LC in the source and to avoid the isotropic phase in sensor capillary. The LC flowing out of the sensor capillary comes to the drain. Excessive pressure is compensated by the membrane (11) via the floating of LC passing through the piping system (10). The membrane is made of a flexible elastic material covering the edge of the pipe system. The LC is cooled down after turning off the heater (5) in the source and the volume of LC is shrinked into the original one at the room temperature. An excessive spread of CLC is moved through the piping into the drain and eventually comes to the source via the sensor capillary. A good planar texture is reached after the complete cooling down operation at the room temperature and AOD is considered to be fully functional for information recording.

One should mention that the located flow of LC in the sensor capillary due to a natural thermal compression facilitate the alignment of CLC via friction interactions at the boundary layer. The alignment of CLC is forced by the boundary alignment layer (6) having microgrooves like structure. Similar structures may be obtained in the different manner, *e.g.,* oblique deposition in vacuum such materials $SiO_x$, $In_2O_3$, $MgF_2$, $GeO_x$, Pt, Au, *etc.*; unidirectional rubbing of organic polymer films and so on.

The optimum dimensions of the drain and source for normal operation of AOD were defined in the following way. At the room temperature, the volume $V_{t_1}$ of CLC in the source is equal [9]:

$$V_{t_1} = V_0(1 + \beta_1 t_1),$$

where $V_0$ is the volume at $t = 0$ °C, $t_1$ is the room temperature, $\beta_1$ is the volume expansion coefficient of CLC in the range between 0 °C and $t_1$.

While heating up to $t_2$, the volume of CLC rises and reaches the value $V_{t_2}$:

$$V_{t_2} = V_0(1 + \beta_2 t_2),$$

where $\beta_2$ is the thermal expansion coefficient of CLC in the range $(t_1 - t_2)$ °C. The difference between two volumes $(V_{t_2} - V_{t_1})$ is equaled to the CLC volume $\Delta V$, forced out the sensor capillary:

$$V_{t_2} - V_{t_1} = V_0(\beta_2 t_2 - \beta_1 t_1) = \Delta V.$$

If $k_i$ is a part of volume which is necessary to pump through the capillary for reliable planar alignment ($k_i$ is defined experimentally), and the capillary has a definite cross-section $s$ and thickness $d$, then

$\Delta V = sdk_i$ .

Consequently,

$$V_0 = \frac{sdk_i}{\beta_2 t_2 - \beta_1 t_1},$$

substitution of $V_0$ into expression for $V_{t_1}$ results in

$$V_{t_1} = \frac{sdk_i(1+\beta_1 t_1)}{\beta_2 t_2 - \beta_1 t_1}.$$

The thermal expansion coefficients $\beta_1$ and $\beta_2$ for our CLCs were experimentally determined by PICNOMETR technique and gave the following values:

$$\beta_1 = 9.1\cdot 10^{-4} K^{-1},\ \beta_2 = 8.5\cdot 10^{-4} K^{-1}.$$

The experimental samples of AOD have been performed with the operation field area 7×7 cm$^2$. The cell gap in the capillary was selected to be 50 μm. The experimental value defined for $k_i$ coefficient was found to be 0.3. The thermal source was made of NiCr wire and allow to reach the ambient temperature in the source around 50 °C in 7 s. Both the source and drain were made of PMMA Plexiglas. The optically transparent substrate was made of K8 optical glass with optically transparent $In_2O_3$:Sn electrodes deposited by cathode reactive sputtering technique on the substrate top. The conductivity of transparent electrodes was measured to be 50 Ω/□ at the electrodes thickness ~0.1 μm. The strip wiring (1-mm width) of Cr:Cu was attached to the electrodes. The alignment layer was cathode reactive sputtering oblique deposited at 15 deg. angle with respect to surface plane. The sensor was assembled to have the coincidence of LC flow direction in the capillary with the groove easy action direction of the alignment layer. Acoustically transparent substrate was made of PMMA Plexiglas 1-mm thick and painted black from ultrasonic input side. The cell gap between two substrates was performed by mylar spacers of calibrated 50-μm thickness. The overall sealing of AOD was made using T-111 glue with the addition of L-20 hardener.

### 3. Result and discussion

It is indispensable to know exactly and to control the wavelength of maximum selective reflection when using AOD of acousto-holographic registration element. It is very important to know the reflection intensity width, scattering cones and circular dichroism parameters additional to acoustic waves parameters like frequency, intensity and its relation to the information recording efficiency. There have been carried out studies of selective reflection spectra as well as the other parameters and characteristics of AOD.

We have found that selective reflection spectra taken from seemingly identical substrates have the different reflection intensity and its angular dependence. Some samples show the narrow peak of the high intensity, whereas the others offer the low intensity but the broader spectral width (Fig. 2).

In the course of studying the influence of substrate preparation and further treatment on selective reflection spectra, we have found that the reflection intensity is associated with the helical axis ordering. The higher the ordering the higher reflection intensity and more narrow the peak. It could be understood from the Bragg diffraction conditions:

$$2d\sin\theta = m\lambda ,$$

where $d$ is the helical pitch, $\theta$ is the angle of incidence, $\lambda$ is the wavelength, $m$ = 1, 2, 3, …

For ideal planar texture, where the helical axes are strictly parallel to the surface plane, the diffraction conditions are satisfied for a single wavelength under the fixed angle of incidence. The disordering of helical axes results in broadening of the wavelength interval to fit the Bragg diffraction conditions. Eventually, there is no selective reflection in the case of extreme focal conic texture, and any wavelength is scattered in the similar way.

We have studied the influence of various substrate treatment techniques on texture uniformity of LCs. In the very first turn it was tested the mechanical treatment of alignment layer by means of unidirectional rubbing. It was also investigated the influence of various alignment layers like $SiO_x$, $In_2O_3$, $MgF_2$, $Al_xO_y$, *etc*., deposited by oblique cathode reactive sputtering technique described in [10, 11]. All above investigated techniques create microgrooves on aligning surface and result in a special ordering of LC molecules at the boundary. In order to check alignment properties of CLC, we measure the scattering cones that are shown in Figs 2-6.

Fig. 3 demonstrates the angular dependence of the intensity reflected from the LC layer for four different wavelengths and 20 deg. oblique light incidence with respect to the surface plane. The substrate had no treatment in that case.

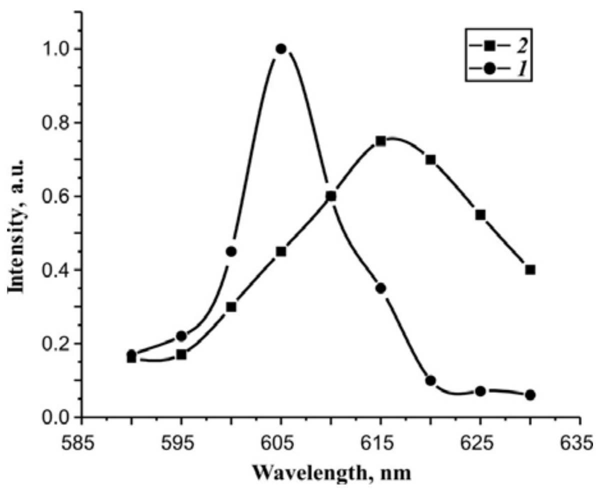


**Fig. 2.** Scattering cones of CLC for aligned (1) and non-aligned (2) CLC layers.

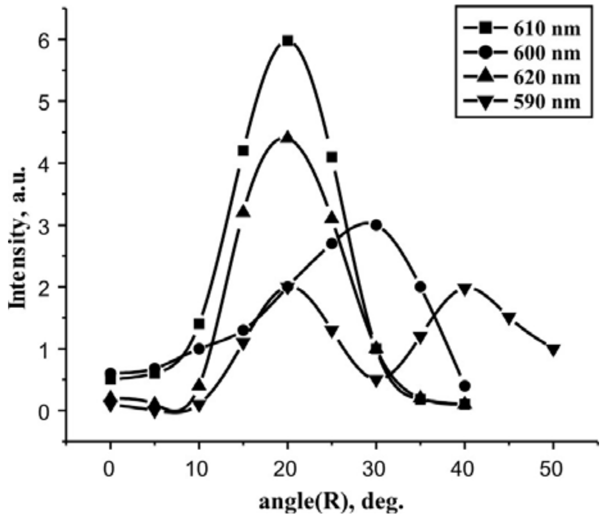


**Fig. 3.** Scattering cones of CLC for untreated surfaces.

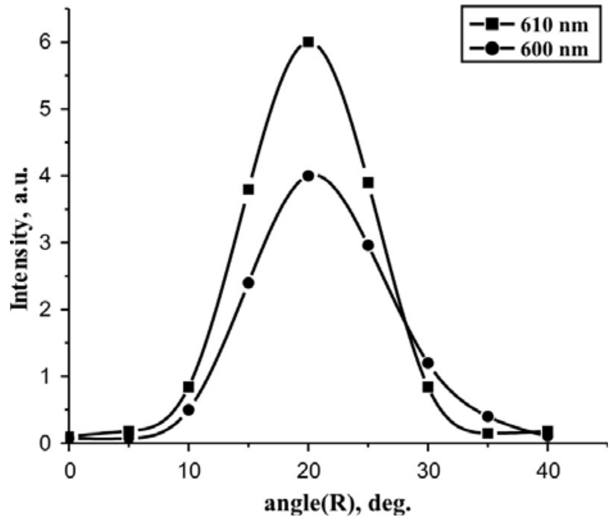


**Fig. 5.** Scattering cones of CLC for rubbed substrates.

As it could be seen from Figs 2-6, the intensity peak of selective reflection is around $\lambda = 610$ nm. For the other angles of incidence, the peak of the selective reflection intensity is shifted.

The resemble lines in Fig. 4 show somewhat higher reflectance intensity for the $SiO_x$ alignment layer.

For $In_2O_3$, $MgF_2$, $Al_xO_y$ alignment layers as well as for various unidirectional rubbed materials on the substrate surface, the intensity of selective reflection falls down (Figs 5-7). It is still pronounced for $In_2O_3$ layers and almost completely vanishes for mechanically rubbed layers.

Hence, it is shown from our measurements that the best results for alignment of CLC are provided with oblique reactive sputtering the deposited $SiO_x$ alignment layers.

As to the other alignment layers and unidirectional mechanical rubbing of virgin surfaces with the different materials, we cannot consider the results of our studies to be comprehensive and possibly more detailed studies should be performed in the future.

The selective reflection spectra taken for 1, 2, 5, 20 and 60 min followed the beginning of the planar texture restoration process. As seen from Fig. 8, the intensity of reflection is low and the peak is wide at the onset. The reflection intensity rises shifting into the shorter wavelength range and the reflection band narrows while the time growth. In 60 min following the onset, the reflection peak achieves its maximum, and the peak width becomes narrow. Further changes in the reflection spectrum are minor and mostly invoked by the ambient temperature fluctuations. Hence, the sample was ready for measurements in 1 hour after reset.

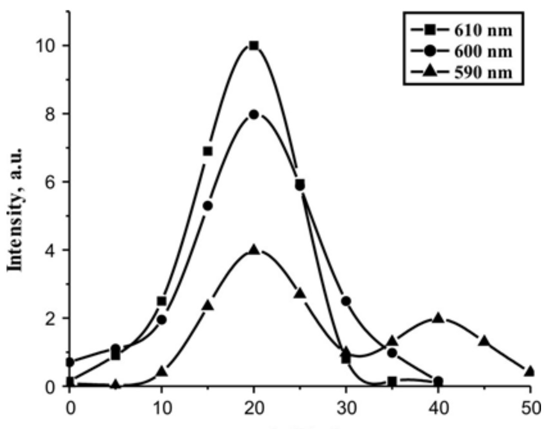


**Fig. 4.** Scattering cones of CLC for $SiO_x$ deposited alignment layers

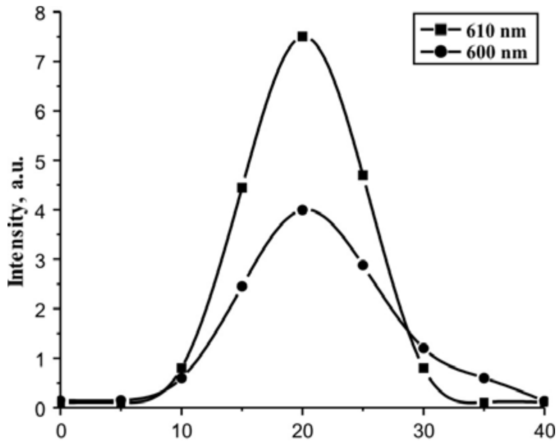


**Fig. 6.** Scattering cones of CLC for $In_2O_3$ deposited alignment layers.

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Fig. 9 shows some characteristics of reflection spectra for AOD developed and their comparison with the conventional AOD facility according to the literature data. Both AODs use the same cholesteric LC material, and spectral characteristics are measured for the same measurement conditions.

The curves 1-3 correspond to the different peaks of erase-restoration and emphasize on a good reproducibility of our AOD. Besides the significantly lower intensity and wider reflection peak, the curves 4-6 are characterized by different peak wavelengths, which confirms poor reproducibility of measurements for AOD that employs mechanical shift between upper and lower substrates for planar texture restoration.

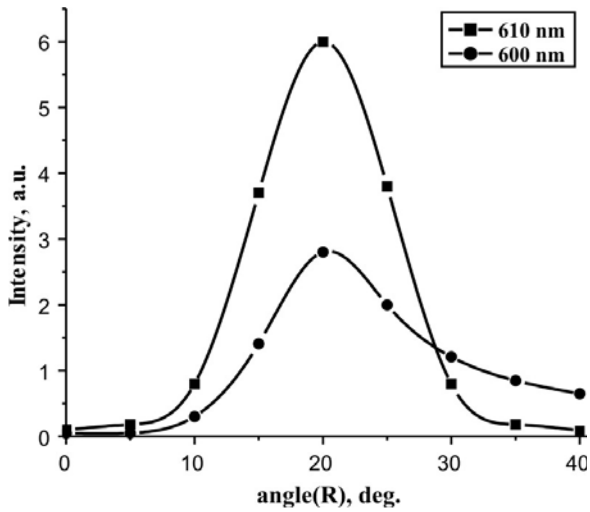


**Fig. 7.** Scattering cones of CLC for $Al_xO_y$ deposited alignment layers.

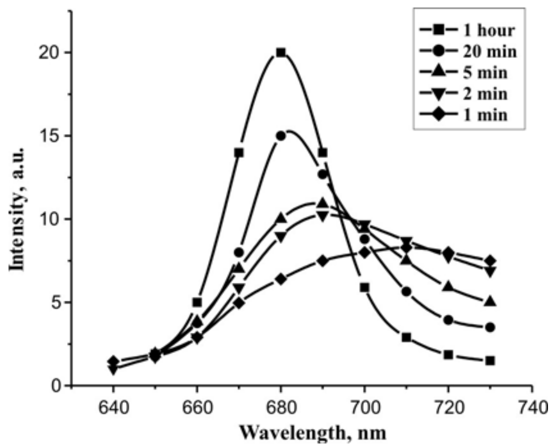


**Fig. 8.** Reflection spectra of CLC during the restoration of planar texture (the time legend after onset is shown next to reflection curves).

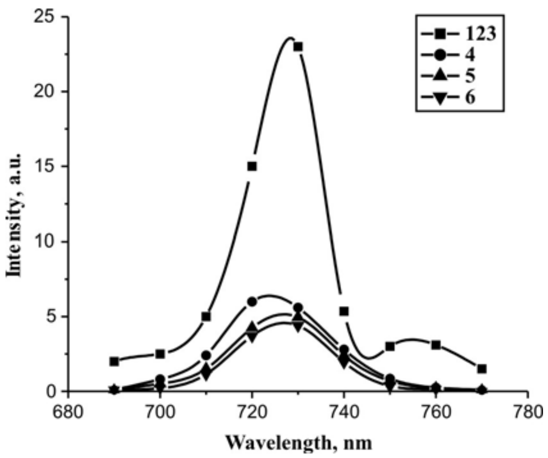


**Fig. 9.** Spectral characteristics of our AOT (curves 1, 2, 3) and AOT built according to the known scheme [7] (curves 4, 5, 6).

Numerous tests performed for our AOD have shown the high reliability in the hard operation conditions. The measured lifetime resource was at least 2500 hours and the central wavelength shift was not more than $\Delta\lambda =$ = 5…10 nm after a year of permanent exploitation. The average erase and restore times for the planar texture did not exceed 2 and 18 s, respectively.

## 4. Conclusions

The AOD based on a hysteretic properties in CLC featuring fast information erase time and recreation of planar texture, fully sealed CLC geometry that except LC contact with ambient atmosphere, has been developed.

The influence of oblique reactive sputter deposited $In_2O_3$, $Al_xO_y$, $SiO_x$ thin film upon the alignment properties of CLCs, which are used for ultrasonic holograms recording, has been investigated.

Being based on studies of selective reflection spectra, it has been shown that the high quality and uniformity of planar alignment over the whole operation area as well as good reproducibility of the planar texture of CLC is an implicit advantage for our developed AOD over existing counterparts.

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