Liquid crystals electro-optical structure with conducting layers modified by carbon nanotubes

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Abstract. Due to their unique properties and scalable technology, optical devices based on the liquid crystals are widely used in industry. In optoelectronics, an LC is used to design the optical limiters, switches, and spatial light modulators. Response time, electrical consumption and optical transmittance are the most important parameters of an electro-optical modulator. Temporal parameters substantially depend on the level of the applied supply voltage and on the number of layers used in the structure of the LC device. In this paper, it is proposed to compare the reflection losses level of samples with pure ITO and samples with ITO conducting coating modified by carbon nanotubes (CNTs).

1. Introduction

The operation of the electro-optical modulator is based on the birefringence effect. Under external exposure, for example, when an electric field is applied, the LC molecules begin to orient along it, since they have anisotropy of the refractive index and other important parameters as well [1-3]. Therefore, the phase difference between the two components is formed, the plane of polarization of the resulting beam is changed, after it modified wave from the LC cell passes through the analyzer. When switching the parameters of the control voltage, it is possible to control the phase shift. As a result, intensity of the modulated signal by analyzer is changing. With these features it is possible to design the electro-optical and spatial light modulators, optical switches and limiters.

In addition, birefringence effect of the liquid crystals and exposure of the electric field allow controlling the distribution of the refractive index. This factor is fundamental for processing of the adaptive lenses and the wave front correctors, which might be realized by the liquid crystals.

Structurally, the LC cell consists of an LC mesophase, two conductive coatings (ITO), two orienting layers, and also two quartz or glass substrates. Materials based on polyimide, polyvinyl alcohol, lecithin, and other are used as the orienting coatings. These layers have high electrical resistance, many times higher than the resistance of the active LC layer, which is a problem because it is necessary to work with the higher voltage values. ITO coatings modified with the carbon nanotubes (CNTs) simultaneously perform the contact and orienting functions, as a result, it isn’t necessary to use the high resistive orienting layers [4]. This allows creating LC cells with less electrical consumption and better switching times [5].

Notice that the smaller quantity of functional layers in construction of LC cell also reduces the optical losses of devices. In this work, we continue research aimed at studying ITO coatings, which structured with the carbon nanotubes, and take into account the reflection losses.
2. Materials and methods

To modify the conducting ITO coating by the CNTs, we used a laser-oriented deposition (LOD) technique based on a CO\textsubscript{2} laser (\(\lambda = 10.6\ \mu m\)), which operated in continuous regime with \(P = 30\ \text{W}\) and a beam diameter of 5 mm. The beam moved at a speed of 1-3 cm\(\times\)s\(^{-1}\) during surface processing. To orient CNTs in the deposition process, an electric field in the range of 100-600 V\(\times\)cm\(^{-1}\) was used. To avoid the chemical interaction with the media, the process took place in a vacuum chamber. This approach, in contrast to the widely used CVD and PVD methods, has the advantage of not requiring a large amount of the substance, and also ensures the purity of the deposited material. The difference between the samples is in the conductive layers. First group has pure ITO films (figure 1,a); samples of the second group have the ITO + CNT modification (figure 1,b). Additionally, the obtained surface topography of the structured ITO contact was investigated by Solver Next AFM.

![Figure 1 (a,b). (a) Design of LC cell with orienting layers; (b) Design of LC cell with modified ITO.](image)

3. Results

Notice that the sizes of CNTs with a refractive index of 1.1 are of the order of ten nanometers, and the average ITO film thickness is 0.1 \(\mu m\) (figure 2). During their interaction, a covalent bond is formed and the optical properties of the conductive layer change significantly [6].

![Figure 2 (a,b). (a) Surface of pure ITO layer; (b) Surface of ITO layer modified by CNTs.](image)

For the LC cells, there are two main types of losses: reflection (Fresnel) and absorption (Bouguer-Lambert-Beer). We limit ourselves to Fresnel reflection losses. Nevertheless, the resulting transmission for \(j\) interfaces can be divided into the Fresnel (\(T_{Fr,total}\)) and Bouguer-Lambert-Beer (\(T_{BLB,total}\)) components [7]:

\[
T_{total} = \left[ \prod_{i=1}^{j-1} \frac{4n_i n_{i+1}}{(n_i+n_{i+1})^2} \right] \cdot \exp \left[ -\sum_{i=1}^{j-1} k_{i+1}(\lambda)L_{i+1} \right] = T_{Fr,total} \cdot T_{BLB,total} \quad (1)
\]
Where $n_i$ — refractive and $k_i(\lambda)$ — absorption indices of the respective medias; $L_i$ — medium length. For conductive coatings, a significant dispersion of the refractive index is observed, which affects the spectral dependence of the Fresnel transmission in the LC cell.

### Table 1. Transmittance estimation (using the Fresnel losses) for 2 types of the samples

| Wavelength, nm | Pure ITO |       | ITO+CNTs |       |
|---------------|---------|-------|----------|-------|
|               | Refractive index | Total transmittance, % | Refractive index | Total transmittance, % |
| 340           | 2.10    | 84.71 | 1.75     | 91.46 |
| 370           | 2.31    | 79.31 | 1.92     | 88.69 |
| 400           | 2.03    | 86.36 | 1.67     | 92.29 |
| 500           | 1.40    | 91.80 | 1.40     | 91.80 |
| 600           | 1.42    | 92.05 | 1.42     | 92.05 |
| 720           | 1.49    | 92.63 | 1.51     | 92.71 |

The resulting transmission, using Fresnel losses taken into account, for the LC cell was obtained from the calculation that $n_{air}$=1, $n_{glass}$=1.46, $n_{LC}$=1.65. The dispersion of the refractive indices in the considered wavelength range is negligible.

Notice that in the violet-blue region of the visible spectrum, the Fresnel transmission for samples with a modified ITO coating is several percent higher. This is due to the fact that CNTs affect the optical properties of the conductive coating via covalent bonding formation, which allows them to be better conformed to the LC mesophase.

The procedure proposed leads to decrease significantly the temporal parameters of the current LC up to 1 ms and less (figure 3).

![Figure 3. Optical response of LC with structured conducting layer and sensitized LC.](image-url)
When the control pulse is applied, the LC molecules change orientation, as a result the optical response of the cell is changed. Here we used lower voltage values (15.5 V), since the electrical resistance of the new cell is less. It can be determined that visible changes in the research sample occur during the 0.2 ms from the oscillogram. As one of the ideas discussed in order to explain the little value of the control bias voltage is based on the fact that the additional electrons from the core of the CNTs can increase dramatically the conductivity of the structured ITO.

4. Conclusion

By carbon nanotubes ITO coatings complete the functions of contacts and orienting layers. Also it allows improving the matching of functional layers and decreasing their quantity. As a result, we reduced absorption and reflection losses of LC cell in visible wavelength range. Moreover, in addition, we use less level of control voltage and receive the better temporal parameters of LC cells, due to the absence of the high-resistive orienting layers.

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