Laser treatment of ITO thin films with Carbon Nanotubes for Liquid Crystal Devices

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Abstract. In this paper, the influence of laser ablation on the refractive properties of indium tin oxides (ITO) thin films with deposited single-wall Carbon Nanotubes (CNTs) was considered. Sputtering of CNTs was preliminary based on the laser-oriented method with application of the external electric field. The laser ablation of ITO-CNTs coatings allows changing the electric, optical and mechanical properties dramatically. Moreover, this technical operation permit to switch the topology of the surface, thus it leads to the conversion of the refractive index. The possibility of index-matching due to the laser treatment contributes to the expansion of the technical capabilities of LC devices.

1. Introduction

Liquid Crystal – is a mesophase that combines the optical anisotropy and properties of liquids. These molecules have no regularity of the centre mass; however, their orientation can be controlled with external exposure (optical beam, electric and magnetic field, acoustic waves). These features allow constructing the devices for the optical modulation issues such as electro-optical and spatial light modulators, optical switching elements, lenses with the variable focus point, etc. In the common case, electro-optical LC devices require high optical transmittance in the operating spectra range and low electric consumption. Spectral properties of mesophase depend on the LC modifications and the materials of sensitizers. One of the most perspective ways for optical optimizing of LC is structuring with the nanoparticles, such as fullerenes, nanotubes, quantum dots, and others [1-3]. Moreover, they are able to increase the local polarizability of media which correlated with the temporal characteristics of devices [4-5]. Another approach for tuning of parameters is connected with the topology and composition of the adjacent layers to the LC phase in the construction of the device. In order to decrease the response time of LC molecules, variable approaches can be used. The deposition of single-wall carbon nanotubes (CNTs) permits not to use high-resistive orienting layers and increases the laser strength [6]. It should be noticed, that these nanoparticles can realize anti-reflection functions that depend on the deposition parameters, such as density, penetration depth, and tilt angle.

In the current research, we processed via the CO2 laser the surface of ITO with the deposited CNTs. Its influences the topology of films, thus refractive properties can be modified under irradiation. In this paper, we compare the refractive indices of two groups of samples — with the laser ablation and without the laser ablation.
2. Materials and methods
For deposition of the CNTs on the ITO surface, we used a laser-oriented deposition (LOD) method based on a CO$_2$ laser ($\lambda = 10.6$ $\mu$m, $P = 30$ W, $d = 5$ mm and speed of treatment $v$ was 1-3 cm$^2$/s). The supply grid with the electric field $100$ V$\times$cm$^{-1}$ was in LOD scheme as well. The laser ablation was performed with the laser system «C-Marker C30» ($\lambda = 10.6$ $\mu$m, $P = 5$ W, the beam diameter is 100 $\mu$m, $f = 1$ kHz, $v = 3$ cm$\times$s$^{-1}$, the distance between laser grooves was 500 $\mu$m). The refractive index of structures was measured with the ellipsometry method (J.A. Woollam M-2000RCE) in 26 points for each sample per aperture 20 mm. The thickness of ITO was approximately 100 nm. The diagnostic of relief was performed through the atomic-force microscope (AFM) Solver Next NT-MDT in semi-tapping mode. The aperture was 50 $\mu$m and the scan rate was 1 Hz.

3. Results
During the laser ablation process, besides the absorption of the beam in media, the part of optical flux can propagate along the surface. In this case, induced surface electromagnetic wave (SEW) has the same wavelength. However, the intensity of SEW is dramatically decreased in comparison with the incident wave. According to these features, it is possible to realize the secondary laser ablation technique with SEW (Figure 1). This phenomenon was considered in detail by M.N. Libenson in papers [7-8].

![Figure 1. The scheme of laser ablation of ITO surface through the SEW propagation](image)

In the case of the smooth surface of pure ITO, the described waves produce periodic lattice in relief with the following period coinciding with the wavelength. The diffuse reflection becomes higher and the measured effective refractive index for ITO with SEW processing is higher in range the from 1280 nm to 1700 nm (Figure 2a).

When the ITO structure is modified with the CNTs, the relief roughness is increased. Two against mechanisms exist. The first one is connected with the material aspect and based on the antireflective properties of CNTs due to the less value of the refractive index. However, the new geometry of the surface can provide higher reflection losses in comparison with the smooth structure.

The properties of the new interface can be changed and improved via the SEW processing with the further decrease of refractive index and rise of transmittance (Figure 2b).
Figure 2. (a) Spectral dependences of refractive index for ITO modification on glass substrate; (b) Optical transmittance for ITO with CNTs before and after laser treatment.

Moreover, SEW treatment of ITO with CNTs is an additional mechanism for liquid crystal orientation. The order of cavities height is tens of nm and the size of the LC molecule is approximately 1.5 nm (Figure 3). These features allow to control and to set the initial orientation of mesophase molecules in the construction of LC cell.

Figure 3. (a) 3D AFM image of ITO with deposited CNTs after the laser treatment; (b) 1D image of ITO with deposited CNTs after the laser treatment

4. Conclusion
In this article, the refractive properties of the various modifications of ITO thin films were discussed. During the interaction of the incident laser beam and the ITO surface, the SEW is produced. Induced waves have the same wavelength, however, the intensity is dramatically decreased. This technological process has not contradicted with the one shown previously in paper [9] and can be applied for several reasons in the construction of LC cell:

1). Probability to high precise control the effective refractive index of ITO films via the geometry of relief. It allows creating an index-matched ITO-LC interface with small reflection losses.

2). SEW processing is an additional mechanism for the orientation of LC molecules. In this case, we influence the initial conditions for the director of LC, thus temporal parameters of LC cells can be improved.
3). In addition, the cavities after SEW can perform the orientation functions for CNTs deposition inside the laser-oriented deposition technique. Its influences the tilt angles of CNTs and their penetration depth. The discussions of this phenomenon will demonstrate in the further articles.

The described features of SEW treatment perform to increase the transmittance of LC devices via the index-matching of conductive layers and LC mesophase.

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References

[1] Kamanina N V 2005 Physics-Uspekhi 48(4) 419
[2] Chausov D N, Kurilov A D, Kazak A V, Smirnova A I, Velichko V K, Gevorkyan E V, Rozhkova N N and Usoltseva N V 2019 Liquid Crystals 46(9) 1345
[3] Petrescu E and Cirtoaje C 2018 Beilstein J. Nanotechnol. 9 233
[4] Kamanina N V, Zubtsova Yu A, Toikka A S, Likhomanova S V, Zak A and Tenne R. 2020 Liq. Cryst. and their Appl. 20(1) 34
[5] Toikka A S and Kamanina N V 2020 J. Phys.: Conf. Ser. 1695 012071
[6] Kamanina N, Toikka A and Gladysheva I 2021 Nano Express 2 1
[7] Bonch-Bruevich A M, Libenson M N, Makin V S and Trubaev V V 1992 Optical Engineering 31(4) 718
[8] Libenson M N, Makin V S, Shiryaev V A and Soileau M J 1994 Proc. SPIE 2428 676
[9] Vasilyev P Ya and Kamanina N V 2007 Technical Physics Letters 33(1) 8