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Polymeric Layers for Optical Structures with Controllable Waveguide Parameters

U.V. Mahilny and A.I. Stankevich

Belarusian State University, (av. Nezavisimosti, 4, Minsk, 220030, Belarus)

Abstract

Anisotropic planar waveguides based on a liquid crystal monomer with principal refractive indices n_e = 1.675 and n_o = 1.532 have been created. They were found to decrease under the influence of UV radiation, which can be used to optimize the conditions for the synchronous propagation of waveguide modes. A new photo-crosslinkable polymer is proposed for creating layers with LC controlled waveguide characteristics. The waveguide properties of the layers are investigated, the refractive index of the material (1.59) and the attenuation coefficient for λ=0.633 nm (~1 dB/cm), tens of times smaller than this value for an anisotropic waveguide are measured. The possibility of depositing on the waveguide benzaldehyde LC alignment layers is shown.

Keywords: polymer waveguide, liquid crystals, photopolymerizable LC monomer

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1. Introduction

The direct contact of the waveguide layer with the liquid crystal (LC) opens the possibility of controlling the parameters of the waveguide modes of the layer, as well as the creation of controllable waveguides of the channel type and waveguide circuits. To realize these possibilities, the waveguide layer must be included in the LC cell structure, applying it to one of the substrates. The free surface of the layer should provide the orientation of the LC molecules - homogeneous for a planar waveguide or a multidomain one, in the case of waveguide channels or circuits. In addition, the refractive index of the layer material should be sufficiently high, at least above the ordinary refractive index of the LC n_o. The required functional properties are provided by polymeric materials, the refractive index of which varies in a wide range [1], and the surface has homogeneous or multi-domain LC alignment properties [2]. In this paper, we compare the waveguide properties of highly refractive layers from a photopolymerizable LC monomer and a new photocrosslinkable copolymer with benzaldehyde, phenyl and diphenyl side groups.

2. Materials and Methods

Waveguide films from the LC monomer RMM491, Merck were formed on quartz substrates. The benzaldehyde polymer M-16 [2] was used as an alignment agent, a layer of which 0.08-0.09 μm thick was applied from the solution to a substrate, rubbed in a certain direction, and UV irradiated. Then RMM491 solution was also applied to the surface of the alignment layer by spin-coating. During the removal of the solvent, an orientation of the LC monomer took place, which then photopolymerized in a vacuum. As a result, a birefringent layer with an optical axis lying in its plane and in a direction coinciding with the director of the LC material (the rubbing direction) was created. The waveguide refractive indices of the N modes of the obtained anisotropic layers were measured with a prism pressed to the waveguide using the m-line method [3], the source of the radiation was a helium-neon laser (λ = 0.633 μm). The laser beam in the waveguide was directed perpendicular to the optical axis, then the modes can be unambiguously assigned to TE or TM type. In this case, the formation of TE modes is determined by the "extraordinary" refractive index n_e, whereas for TM modes the "ordinary" refractive index n_o plays the same role. From the measured values of N, the refractive indices n_o (TM modes) and n_e (TE modes) and the thickness of the waveguide layer h were calculated. For this, the system of equations of transverse resonance (1) was solved for two modes of the same polarization, but of different order m.

$$\frac{2\pi h \sqrt{n_e^2 - N^2}}{\lambda} - \text{arctg}\left(\sqrt{\frac{N^2 - n_s^2}{n_e^2 - N^2}}\right) - \text{arctg}\left(\sqrt{\frac{N^2 - n_c^2}{n_e^2 - N^2}}\right) = m\pi \text{ (TE modes)},$$

$$\frac{2\pi h \sqrt{n_o^2 - N^2}}{\lambda} - \text{arctg}\left(\frac{n_o^2}{n_s^2}\sqrt{\frac{N^2 - n_s^2}{n_o^2 - N^2}}\right) - \text{arctg}\left(\frac{n_o^2}{n_c^2}\sqrt{\frac{N^2 - n_c^2}{n_o^2 - N^2}}\right) = m\pi \text{ (TM modes).} \quad (1)$$

Here, n_c = 1 is the refractive index of the cover layer (air), n_s = 1.46 is the refractive index of the quartz substrate. Irradiation of the waveguide layer with the aim of photomodifying its refractive indices was carried out with the light of a mercury lamp passed through a cut filter with a short-wavelength transmission limit of about 300 nm.

We synthesized a new highly refractive copolymer with a high content of phenyl and diphenyl groups, which also includes photosensitive benzaldehyde fragments. The latter provided photocrosslinking of the material under the action of UV radiation, i.e. converting it into a reticulated polymer, resistant to the action of organic solvents. This allowed thin layers of benzaldehyde alignment materials, both planar and gradient, to be deposited on its surface without destroying the waveguide layer [2, 4]. The

isotropic layers of the photo-crosslinkable copolymer were applied by spin-coating from the solution onto glass substrates. Measurements of the waveguide refractive indices were also carried out with the help of the m lines. The refractive index of the waveguide layer n and its thickness h were calculated using equations (1), in which n_o and n_e were replaced by n. The attenuation of the light propagating in the waveguide layers was estimated from the decrease with the distance of brightness of the light trace in the photos.

3. Results

The m-spectra of fabricated LC polymer waveguides were obtained in the form of a series of bright m-lines. Their angular position made it possible to calculate the waveguide refractive indices of the excited modes. The measured values of the waveguide refractive indices along with the values of n_o and n_e calculated with the help of (1) are given in Table 1.

Figure 1a shows the trace of the laser beam in the waveguide LC layer, which rapidly decays with distance from the insertion point. Curve 1 in Figure 1c demonstrates a change in the brightness of the beam track, proportional to its intensity in the waveguide. The attenuation factor determined from this curve is 56 dB/cm.

TABLE 1: Characteristics of polymer waveguide layers.

Waveguide type	m	N_{TE}	N_{TM}	n
The layer of the LC polymer	0	1,665	1,524	n_e=1,675 n_o=1,532
	1	1,639	1,501	
	2	1,594	1,461	
	3	1,533	-	
	4	1,462	-	
Copolymer layer	0	1,587	1,585	n=1,591
	1	1,576	1,573	
	2	1,555	1,553	
	3	1,528	-	
	1	1,572	1,571	
	2	1,553	1,551	
	3	1,526	1,525	
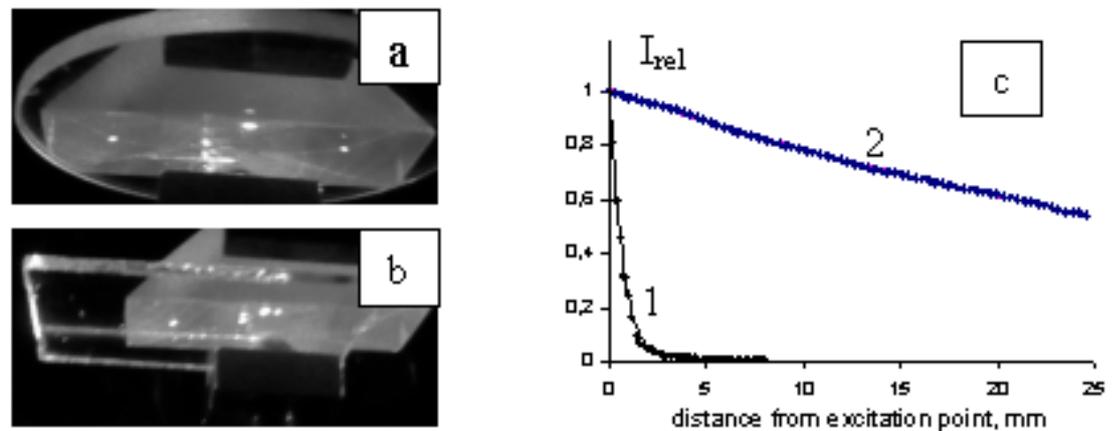
Figure 1: Photos of light beams in LC polymer (a) and copolymer (b) layers and the dependence of the brightness of the light track on the distance (c).

In the process of prolonged UV irradiation of the polymer LC layer, a shift in the m-spectrum lines is observed, indicating a decrease in the refractive indices of the waveguide layer and consistent with the concepts of the photolysis of mesogenic fragments of the LC polymer. Figure 2a shows the time dependences of the calculated values of n_e (upper curve) and n_o (lower curve).

The layers of the new copolymer were probed with a conical laser beam. After reflection from the base of the prism, pressed to the waveguide, dark m-lines appeared in its cross section, according to which the waveguide refractive index of the modes was calculated. Table 1 shows the magnitudes of the waveguide refractive indices of the copolymer layer and the refractive index of the new material calculated on the basis of these data. Obvious in visual observation, the much weaker attenuation of laser radiation compared with the polymer LC layer (Figure 1a, b) is confirmed by the curves of brightness decrease of the beam trace in the layers under investigation (Figure 1c). The attenuation coefficient for the layers of the copolymer is about 1 dB/cm

4. Discussion

The obtained results indicate that the polymeric materials used to form the waveguide layers upon contact of the surface of their layers with the LC in the cell can provide conditions for the total internal reflection of the laser radiation at the waveguide layer-LC interface. The change in the direction of the LC director under the action of the electric field will affect the critical angle of total internal reflection, and hence also the parameters of the waveguide modes. In addition to the effect of mode cutoff, this control action in the case of LC polymeric layers can lead, for example, to the creation or violation of synchronism conditions for modes of different polarization, just

a

b
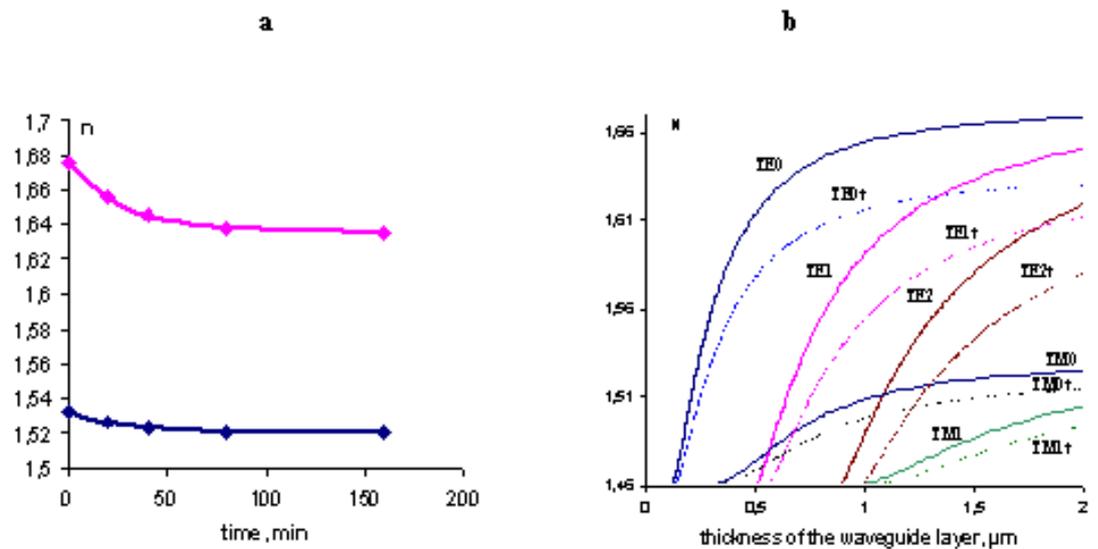
Figure 2: Variation in the refractive indices (a) of the LC polymer waveguide layer under UV irradiation and dispersion curves (b) for the unirradiated (0, 1, 2) and UV irradiated (0t, 1t, 2t) waveguide.

as it occurs when the refractive indices of an anisotropic waveguide layer change. An example of the transformation of the dispersion curves for the photoinduced variation of n_e and n_o is shown in Figure 2b. The synchronous propagation of light beams in optical waveguides provides an energy exchange between them, a controlled change in the polarization state of the leakage beams, and nonlinear transformations of the light characteristics. "Turning on" or "turning off" this or that effect creates additional opportunities for converting light signals. At the same time, serious limitations can arise due to large attenuation, which significantly reduces the interaction length of light beams in the waveguide (Figure 1a).

The high anisotropy of the LC polymer surface guarantees a planar orientation of the LC in the cell parallel to its own director and makes it practically possible to fabricate a controlled waveguide structure. The benzaldehyde alignment agent used in the formation of the LC polymer layer is suitable for fabrication of multi-domain LC polymer layers with a locally changeable director [5]. The multi-domain orientation of the LC monomer on benzaldehyde-based orientations can become the basis for manufacturing technologies of controlled channel waveguide circuits.

The synthesized photocrosslinkable copolymer has the refractive index lower than the LC polymer (Table 1). Nevertheless, the value of n is greater than n_o for a number of types of LC materials. A significant positive difference feature of the copolymer layers is the much lower attenuation of light beams in waveguide (Figure 1). The main problem preventing the direct use of copolymer layers as waveguides with controlled parameters is associated with the absence of the effect of orientation of

the LC on their surfaces. Experiments to create a photostimulated rubbing orientation and photoorientation [6], characteristic for benzaldehyde polymers, have not revealed the effect. Photosensitive benzaldehyde fragments provide photocrosslinking of the material under the influence of UV radiation, making it resistant to the action of organic solvents. This allowed the thin (~50-100 nm) benzaldehyde alignment layers, both planar and gradient [2, 4], to be deposited on its surface without destruction of the waveguide layer. We tested the application of a single and double alignment layer, because such an operation is part of multi-domain technology [2]. After the application of the alignment layers, the waveguide refractive index of the modes changed insignificantly by 0.001-0.002.

Variations in the direction of the LC director on the surface of the copolymer layer with a multidomain planar alignment layer and the creation of different pretilt angles by gradient alignment layers open the possibility of creating various schemes for controlled transformation of laser radiation propagating in plane and channel waveguides.

5. Summary

The created polymer waveguide layers are characterized by sufficiently high refractive indices to ensure complete internal reflection at the interface with the LC in the cell and controlled waveguide propagation of the laser radiation. Anisotropic waveguides based on LC monomer have a surface that align LC, can provide synchronous mode propagation, but exhibit strong radiation attenuation (~ 50 dB/cm). Much less attenuation (~ 1 dB/cm) is characteristic for glassy layers of the new photocrosslinkable copolymer with phenyl, diphenyl and benzaldehyde groups. It is shown that benzaldehyde materials can be applied to create an LC alignment on the surface of copolymer layer without a significant effect on the waveguide parameters.

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