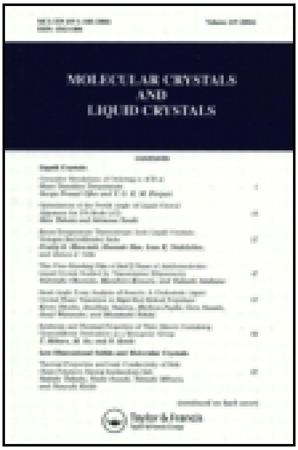

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Comparison of the Electrooptical Properties of Asymmetrical Liquid-Crystal Microlenses

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Comparison of the electrooptical properties of asymmetrical liquid-crystal (LC) microlenses with various types of alignment is carried out. It is shown that LC-microlenses with planar alignment have the best performance in case of focusing properties, and homeotropically-aligned LC-microlenses – in case of defocusing properties.

Keywords: liquid crystal microlens

INTRODUCTION

Recently the LC optics of adaptive optical elements with parabolic phase profile controlled by voltage is developed. The effect of reorientation of nematic molecules in an inhomogeneous electrical field created by means of special geometry of electrodes is used to control a phase of light wave in these elements . After emergings in 1989 of the first article in which the Japanese researchers offered a construction of a LC-microlens [1] a lot of work on study of electrooptical properties of these devices was carried out and the various types of LC-microlenses [1-4] are investigated. Now LC-microlenses can be used in fiber optics, converters of light beam polarization and raster systems.

We investigated electrooptical properties of asymmetrical LC-microlenses with homeotropical [4], planar and hybrid [5] alignments. In this paper the comparison of electrooptical properties of

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asymmetrical LC-microlenses with various types of alignment is carried out.

EXPERIMENT

The asymmetrical LC-microlens is a cell the upper electrode of which has round hole produced by means of photolithography (see Figure 1) and the lower one is coated by a transparent layer of indium oxide (In_2O_3). The thickness of a LC - layer d in the cell is set by teflon spacers.

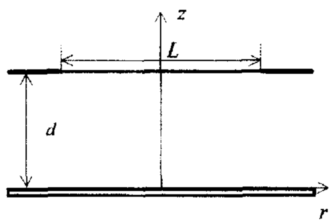


FIGURE 1. The asymmetrical LC-mirolens

The hole diameters L had values from 170 to 800 μm. Under a voltage applied to the LC-cell an axially-symmetrical electrical field causing a deformation of a nematic director is produced. In result the radially symmetrical refractive index distribution is formed and LC-cell obtained the properties of a lens.

Nematics used for experiments are following:
for the homeotropical alignment – a mixture of *MBBA* and *EBBA* (*N*-8) with dielectric anisotropy $\Delta\varepsilon$=-0.43 and optical anisotropy Δn = 0.25;
for the planar alignment – *GhKM*–1289 with $\Delta\varepsilon$=9.8, Δn = 0.17;
for the hybrid alignment – *5CB* with $\Delta\varepsilon$=12.6, Δn = 0.18.

All experiments were carried out in red light (wavelength of light λ= 0.637 microns).

The experiments have shown that under low voltages the LC-microlenses with a homeotropical alignment have defocusing properties and the microlenses with planar and hybrid alignments possess focusing properties.

The research of various microlenses focal lengths dependency on voltage were carried out. It is obtained that these dependencies for all microlenses in the range of low voltage values are simular: under voltage increasing the focal length at first decreases attaining the minimum at certain voltage value and after that it increases. The further magnification of voltage causes the inversion of optical properties of LC-microlens and hybrid- and planar-aligned LC-microlenses obtain the defocusing property.

Figure 2a represents the typical focal length dependency on voltage for LC microlenses with homogeneous alignment (the focusing properties), and Figure 2b shows the dependency for the defocusing properties.

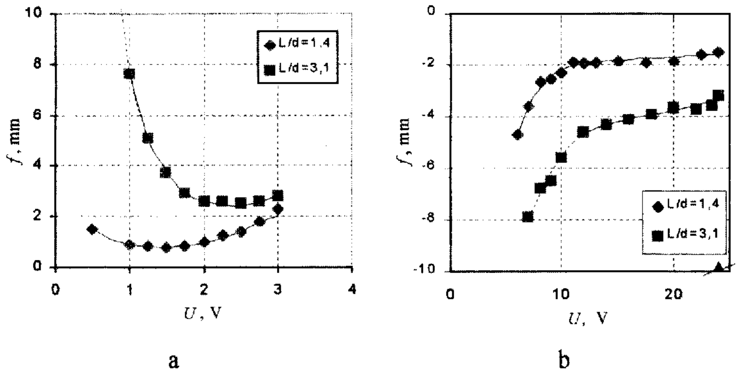


FIGURE 2. Dependence of the focal length on voltage for the LC-microlenses with planar alignment (a – focusing optical properties, b – defocusing properties).

The most important parameters of the LC-microlens are the numerical aperture, operation voltage and resolution. The comparison of properties of the LC-microlenses was carried out based on these parameters.

The analysis have shown that voltage U_m at which the numerical aperture reaches maximum value linearly depends on the LC-microlens geometric parameter L/d

$$U_m = \beta_i U_0 L/d,$$

where U_0 - threshold voltage of Fredericks effect, and β_i – dimensionless factor dependent on the type of alignment. It reaches the maximum value for the LC-microlens with planar alignment and the minimum value – for homeotropically-aligned LC-microlenses (see Figure 3; the data on a symmetrical LC-microlens are taken from [3, 8]).

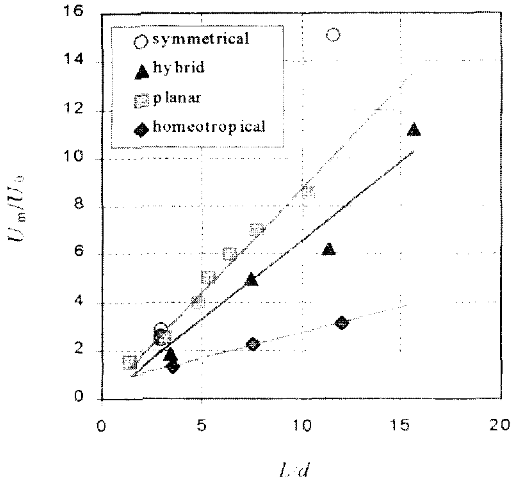


FIGURE 3. The voltage of numerical aperture maximum U_m dependency on the geometrical factor of LC-microlens L/d

The maximum value of the numerical aperture NA_{max} (in focusing regime) decreases with the increase of the geometric parameter L/d (see Fifure 4). Values for symmetrical LC-microlenses investigated by the Japanize researchers, [7] also are shown on the Figure 4.

The comparison of focusing ability $NA_{max}/\Delta n$ for various asymmetrical LC-microlenses has shown that LC-microlens with planar alignment have the maximal focusing ability (its numerical aperture reaches value NA_{max} = 0.11 at L/d = 1.4) at focusing regime and homeotropically-aligned LC-microlens – for defocusing regime (NA_{max}= 0.11 at L/d = 3.5).

The dependence of the numerical aperture NA_{max} on the geometrical factor L/d for planar LC-microlenses has the maximum at L/d = 3 at large voltages (at defocusing regime) (see Figure 4b). The value observed by $(U/U_0)/(L/d)$=8 are shown on Figure.

The visual observations as well as the measurement of a resolution have allowed to select ranges of operational voltage in which microlenses have good optical properties. It was assumed that the resolution of a LC-microlens is satisfactory if the ratio of Airy radius to weadth of element l resolved in a focal plane was not below 0.7: $R_a / l = (1.22\ \lambda f / L) / l > 0.7$.

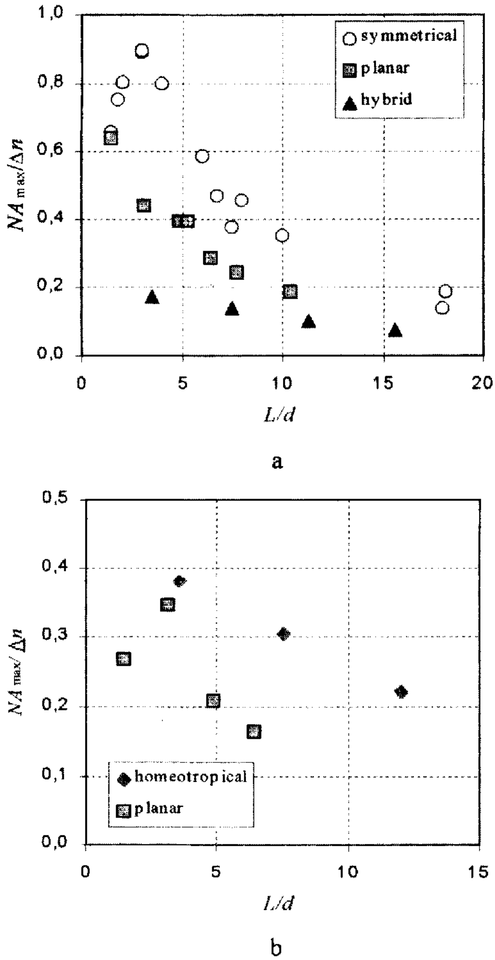


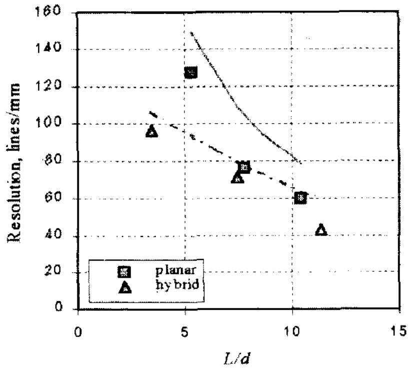
FIGURE 4. Dependence of focusing (a) and defocusing (b) properties of various LC-microlens on geometric parameter *L/d*

The obtained values are listed in the Table. The variation ranges of the numerical aperture corresponding to operation voltage are also shown in the Table. For the LC-microlenses with planar and hybrid alignment these voltages correspond to a descending branch of the focal length dependence on voltage as well as they correspond to the minimum (at the focusing properties). In case of defocusing properties it corresponds to the area at this curve when focal distance start to increase slowly with the voltage increasing.

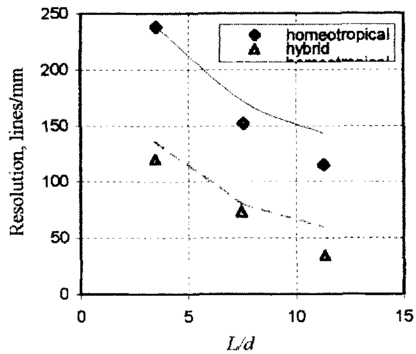
TABLE Comparative characteristics of LC-mirolenses

Alignment	Optical properties	*L/d*	Range of numerical aperture	Range of operational voltages, V	Optimal voltage, V
Homeotro-pical	defocusing	3.5	0.03 – 0.11	5 – 8; (5–7)	7
		7.6	0.08 – 0.07	9.5–13; (10)	10
		11	0.10 – 0.06	12.5–15;(14)	14
Planar	focusing	1.4	0.06–0.11–0.04	0.5 – 3	1.5
		3.1	0.02–0.074–0.066	1 – 3	3
		4.8	0.03–0.066–0.050	3 – 4	3.5
		6.3	0.022-0.048	3 – 6	4
		5.3	0.046–0.066–0.046	2 – 7	4
		7.7	0.041–0.038	5.5 – 8	6
		10	0.024–0.032–0.027	6 – 12	8
	defocusing	1.4	0.024–0.057	7 – 25	maximal
		3.1	0.040–0.058	12 – 25	
		4.8	0.022–0.038	16 – 70	
		6.3	0.019–0.029	20 – 70	
		5.3	0.025–	10 –	
Hybrid	focusing	3.5	0.006–0.030–0.017	0 – 2	1.2
		7.4	0.012–0.025–0.019	1 – 6	4
		11	0.012–0.019	2.5 – 6	5
		15	0.010–0.013	5 – 11	8

The voltages at which the maximum resolution was observed (see table) at planar and hybrid LC-microlenses is slightly smaller than the voltage of a maximum of the numerical aperture U_m. The phase profiles of homeotropically-aligned LC-microlenses at these voltages well coinside with parabolic approximating function and deviations from them did not exceed $\lambda/4$ at microlenses with L/d = 3.5; 7.3. Then the optical properties of microlenses correspond to the Rayligh's criterion. In spite of the fact that the consent of phase profiles with square-law dependence was observed for homeotropical LC-microlenses only at voltages indicated in brackets (thus strictly speaking, only microlens with L/d = 3 is adaptive) the research have shown that the focal point is observed in broader voltage limits.



a



b

FIGURE 5. The resolution of LC-microlenses with different alignment: a – focusing regime (solid and dotted lines show diffraction limits for LC-microlenses with planar and hybrid alignment consequently), b – defocusing regime (solid line is diffraction limit for LC-microlens with homeotropical alignment, dotted line corresponds ones with hybrid alignment).

The Figure 5 shows the resolution of LC-microlenses. It is clear that the resolution decreases with increasing *L/d* that is due to the decrease of the numerical aperture. The LC-microlenses with planar alignment have the greatest resolution in the focusing regime (up to 130 lines/mm at $L/d = 5.3$) and homeotropically-aligned LC-microlens - in focusing one (up to 200 lines/mm at $L/d = 3.1$). The curves show the diffractional limit of the resolution.

CONCLUSION

The comparison of electrooptical properties of asymmetrical LC-microlenses with various types of alignment is carried out in this paper. The following results are obtained.

1. It is shown that the numerical aperture NA_{max} and resolution decrease with the growth of the geometric parameter L/d. The optimal value in defocusing regime is obtained for planar LC-microlenses: $L/d_{opt} = 3$.
2. It is established that the voltage of the maximum of the numerical aperture U_m linearly depends on the geometric parameter of the LC-microlens L/d.
3. It is shown that LC-microlenses with planar alignment have the best performance in case of focusing properties (numerical aperture $NA_{max} = 0.11$ at $L/d = 1.4$, resolution up to 130 lines/mm). In case of defocusing properties the LC-microlenses with homeotropical one show the best performance ($NA_{max} = 0.11$, resolution up to 200 lines/mm at $L/d = 3.1$).

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