Liquid crystal spherical microlens array with high fill factor and optical power

JOSÉ FRANCISCO ALGORRI,1,* VIRGINIA URRUCHI,1 NOUREDDINE BENNIS,2 PRZEMEK MORAWIAK,2 JOSÉ MANUEL SÁNCHEZ-PENA,1 AND JOSÉ MANUEL OTÓN3

1Department of Electronic Technology, Carlos III University, Madrid 28911, Spain
2New Technologies and Chemistry Faculty, Military University of Technology, Warsaw 00-908, Poland
3CEMDATIC, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, Madrid 28049, Spain
*j.algorri@ing.uc3m.es

Abstract: A novel liquid crystal spherical microlens array with high optical power and almost 100% of fill-factor is proposed and experimentally demonstrated. The combination of a specific structure and electrical waveforms applied to the electrodes generates an array of spherical microlenses with square aperture. The manufacturing process is simple (patterned electrodes) and the microlenses are reconfigurable by low voltage signals (the electrodes are in contact with the LC layer). This device could be a key for the next generation of autostereoscopic devices based on Integral Imaging technique.

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OCIS codes: (250.0250) Optoelectronics; (230.3720) Liquid-crystal devices; (230.4110) Modulators.

References and links
1. Introduction

Liquid crystals (LC) are anisotropic materials whose optical axis (director) is parallel to the average direction of the molecular axes. By supplying a relatively low voltage, LC molecules are reoriented and the effective refractive index of the LC is modified. A gradient of the refractive index spatially distributed by the surface of a LC device will generate, correspondingly, a variation of the phase delay experienced by a wavefront of a light beam impinging on the device. By using this effect, any refractive optical element may be reproduced with the proper voltage gradient applied to the sample. Some examples are lenses [1], axicons [2], microaxicons [3], prisms [4], spiral phase plates [5], etc. Particularly, liquid crystal lenses with electrically controllable focal length have shown many feasible approaches.

Pioneers in this matter were Berreman et al. [6] and Sato et al. [7] at the end of the seventies. The first structure was composed by a cavity of glass with a certain curvature filled with LC. The main problems were a low response time and inhomogeneous molecular orientation. In the eighties, the first cylindrical lens was proposed by a group from Syracuse University [8]. The structure was composed by several electrodes. At the end of the eighties, the first LC microlenses were reported by Sato et al. [9, 10]. At the same time, the first Fresnel lenses, with reduced thickness and higher diameters, were reported [11]. At the end of the nineties, a novel technique was proposed by A.F Naumov [12,13] in order to avoid the requirement of several electrodes in lenses with high aperture. The main operation principle is based on the generation of a radial graded voltage across the lens aperture. For this, a high resistivity layer is deposited onto the pattern electrode. In consequence, only one voltage with very low value is required to create the graded refractive index in the structure (one of the main advantages). In the last years, lots of proposals have been reported. For example, based on polymer networks [14], concentration redistribution [15], carbon nanotubes [16], blue-phase LC [17], etc.

In order to fabricate LC microlens arrays, patterned electrode technique is one of the most simple and efficient. The first structures consisted on several circular holes patterned in a transparent electrode 1989 [18]. Some problems as low optical power and aberrations arose. In order to solve them, symmetrical patterned electrodes were proposed [19]. Other variations included a dielectric material between the LC layer and the control electrode. This technique, known as dual voltage, was proposed in 2004 [20]. The inclusion of this layer makes necessary a high operation voltage. To solve this problem, the use of an ultrathin glass slab was proposed [21]. In recent years, a lot of research works based on hole-patterned technique have been presented, for example, tetragonal hole-patterned electrodes [22]. Some problems are the low fill factor due to the space between electrodes of the same substrate and the asymmetry between lenses.

LC lenses share applications with conventional fixed lenses, but the first ones have some key advantages such as small size, light weight, low driving voltages, low power consumption and transmissive/reflective operation modes [23]. For instance in portable devices, at which LC lenses could work in auto-focusing systems and optical zoom systems [24]. Also, for pico-projection systems [25]. Another recent application is the correction of some defects in a holographic projection system [26]. Different fields are photovoltaics [27] or bio-optics (endoscopy [28], ophthalmology [29,30]).

Furthermore, the use of this type of lenses in array configurations is essential for image processing [31], beam steering [32], wavefront correction [33], switchable 2D/3D displays [34], etc. Specifically, the use of LC lenses for autostereoscopic devices has been a hot research topic in the last few years [35]. Most of the works are focused on spatial multiplexing technique. For example, interdigitated electrodes in both substrates with orthogonal configuration have been proposed to create cylindrical microlenses with switchable orientation. The first reference was proposed as a beam shaping device [36]. Two independent cylindrical lenses were generated by using specific voltage signals. Then, the use
of this structure in combination with a high resistivity layer was proposed to simplify the control [37]. The same voltage for one comb electrode and a ground voltage at the center of each lens is required to have a voltage gradient. This extra electrode at the center of the lens drives the voltage to zero, creating a gradient from this point to the sides of the lens. This fact indicates that the resistivity of the layer is not high enough to produce a voltage gradient by itself. In consequence it cannot be considered a modal lens. Finally, the use of this structure in combination with two phase shifted electrical signals was also demonstrated to work as cylindrical lenses with rotary capability [38]. These devices would share the same application, possible rotation between views in autostereoscopic devices based on cylindrical microlenses. The last device, use phase shifted electrical signals to achieve a proper voltage gradient. This type of electrical signals were first proposed to create axicons [39] and microaxicons [40]. In these two cases high resistivity layers were necessary. Another interesting device based on this principle consisted in six electrodes in orthogonal configuration [4]. Several optical components with millimeter size were obtained.

However, the main problems of spatial multiplexing technique are deficiencies in some significant depth cues, including full-parallax and accommodation. This causes visual strain and fatigue for the user. One solution to overcome these drawbacks is integral imaging (InI) technique. The microlens array is capable of reproducing and capturing the light from different directions (also known as light field). In this case, the microlenses have to be spherical. Some recent works have used LC arrays to improve the characteristics of InI systems. The main benefits of using this technology are the possibility of switching between 3D and 2D modes [41] and the tunability of some characteristic parameters (Depth of field [42], field of view [43], etc.). Also, in this kind of devices some parameters of the LC array are very important in terms of functionality and efficiency, as their high tunable optical power and its maximized fill factor, among them.

In this work, we propose a spherical LC microlens array with a nearly 100% fill-factor (without considering the width of the electrodes which is minimum) and high optical power (in comparison with previous techniques, hole patterned, dual voltage, etc.). An orthogonal electrode structure combined with some specific electrical driving signals allow the generation of spherical microlenses from square apertures. The use of this specific voltage allows a control of the voltage both at the sides and the center of the active area. Moreover, the problem of the LC elastic anisotropy can be solved by using different signals at each electrode. Initial test voltages have allow us to create spherical microlenses. The result is a total control over the voltage gradient and a complete filling of the active area. The device is manufactured and experimentally demonstrated. The fabrication process is simple (patterned electrodes) and the microlenses are reconfigurable by low voltage signals (the electrodes are in contact with the LC layer).

2. Structure and operation principle

The fabrication process is simple, like a typical hole-patterned structure. Two ITO coated substrates (20 Ω/sq) with two interdigitated comb-type finger electrodes patterned in each one [Fig. 1(a)] are prepared. A polyimide (PIA2000), deposited over the two substrates, acts as an alignment layer; it is rubbed in the direction of the fingers of the combs for the upper substrate and in antiparallel direction for the other one. Spacers of 40 µm diameter, mixed with optical glue, are deposited to separate the two substrates. Finally, a LC (MDA 98-1602 from Merck) fills the cavity. The electro-optical parameters are: \( n_e = 1.7779, \ n_o = 1.5113 \) (\( \Delta n = 0.2666 \) at 589nm) and \( e_e = 16.2, \ e_o = 4.3 \) (\( \Delta e = 12, \ 1kHz \)). It is important to note that other thicknesses has been fabricated with satisfactory results (maximum 100µm). Differences between them are as expected, the higher the thickness the higher the optical power and the higher the switching time. Regarding the lens pitch, maximum diameters of two times the thickness are recommended. The result is a structure with four different electrodes that can be independently addressed (\( V_1, V_2, V_3 \) and \( V_4 \)). A top view of the electrode pattern is shown in
In order to have spherical microlenses with square aperture two conditions are required. Firstly, a low resistance between electrodes in comparison with the LC impedance. This is necessary in order to have a quasi-linear voltage distribution from one electrode to another. The second one, a specific combination of phase shift between electrical driving signals. When the upper comb-type finger electrodes ($V_1$ and $V_2$) have an electrical phase shift of $180^\circ$ between them, the effective signal is cancelled at the center of the electrodes. Correspondently, when the same is driven at the bottom electrodes ($V_3$ and $V_4$) also a cross by zero is produced. In addition, the bottom electrodes have to be phase shifted $90^\circ$ with respect to the upper electrodes in order to have different complex voltages at each side of the active area. If the two previous considerations are satisfied, a conical voltage distribution is produced. The third condition, deals with the LC characteristics themselves. The LC threshold voltage and elastic anisotropy have to be compensated making some modifications to the applied signals. On the first hand, the birefringence as a function of voltage curve of the LC has three differentiated regions: for voltages lower than the threshold voltage, the molecules do not change their orientation; when this voltage is reached the molecules start to rotate; finally, there is a saturation voltage at which the molecules are completely oriented parallel to the electrical field and no more change on the birefringence is observed. As a conical voltage crossing by zero is generated with the first two conditions, a flat area at the center of the active area would be produced for a voltage gradient going from 0 to $V_{th}$. This voltage has to be compensated as it is explained in the experimental set-up section. On the other hand, the elastic anisotropy produces a displacement on the focus point caused by difference in the anchoring forces in both directions of the electrodes. This adverse effect could be compensated in two ways: by choosing the LC material with low elastic anisotropy [44] or by compensating the anchoring forces by an electrical field. For this, different voltages at each side of the active area will be necessary.

3. Experimental set-up

In order to characterize the proposed device, a basic optical set-up based on the interference of extraordinary and ordinary waveforms is used. The electrical signals are a key part of the design so a specific section addresses this issue.

3.1 Optical set-up

The system is placed in an optical table as shown in Fig. 2. The experimental set-up consists of: a He-Ne laser source (632.8nm), some neutral density filters, a linear polarizer at $+45^\circ$, a LC sample with the alignment direction at $90^\circ$, a x10 microscope objective, another polarizer at $-45^\circ$ and a B/W CCD digital camera (effective no. of pixels 1344 × 1024). All the angles
are referred to the horizontal direction of the table plane. As commented above, very specific electrical signals are required in order to generate these microlenses. For this reason, a custom electrical phase shift waveform generator that uses a sbRIO-9633 module from National Instruments is designed and programmed. This module is an embedded control and acquisition device that integrates a real-time processor and a Xilinx Spartan-6 LX25 FPGA with four 12-bit analog output channels (±10V).

Fig. 2. Experimental set-up for characterizing tunable LC spherical microlens arrays.

3.2 Electrical signals

The configuration of the driving voltage is a key to achieve spherical microlenses from square aperture. The use of phase shifted electrical signals were investigated in a previous work in order to control aberrations in rectangular apertures [45]. Difference with previous work is that in this case we have two extra electrodes at the bottom part of the device. Four alternating signals (could be sinusoidal) are required in each comb-type finger electrode (Fig. 3). Each signal will be characterized by the same frequency (ω around 1 kHz depending on the LC used), amplitude (A) and an electrical phase shift (φ). The signals are defined as:

\[ V_1 = A_1 \cdot \sin(\omega t + \phi_1), \quad V_2 = A_2 \cdot \sin(\omega t + \phi_2), \quad V_3 = A_3 \cdot \sin(\omega t + \phi_3), \quad V_4 = A_4 \cdot \sin(\omega t + \phi_4). \]

As commented before, a phase shift of 180° between electrodes of the same substrate and 90° between electrodes of upper and bottom substrates is required. For example, \( \phi_1 = 0°, \phi_2 = 180°, \phi_3 = 90° \) y \( \phi_4 = 270° \). The initial amplitude would be the same for every electrode, \( A_1 = A_2 = A_3 = A_4 = v \). This, produces a cancellation of the signals between electrodes of the same side. If it is translated to complex notation, the resulting voltage distribution in the upper side has the shape of a non-linear ramp, from \( V_1 \) to \( -V_2 \) (with a cross by zero between electrodes, at the center of the active area). The bottom electrodes (\( V_3 \) and \( V_4 \)) have an electrical phase shift of 90° with respect to the upper electrodes. In complex notation, the resulting voltage distribution is also a ramp with a cross by zero, but in the imaginary axis (from \( V_1 \cdot i \) to \( -V_2 \cdot i \)). The LC layer is affected by the difference between the upper voltage distribution and the bottom one. Considering the complex notation, \( V_1 = V_2 = V_3 = V_4 = v \), there will be an absolute value of \( \sqrt{2} \cdot v \) at each corner of the active area. However, the center of the active area has all the electrical signals cancelled. The result is a voltage distribution with a quasi-conical shape. This initial configuration could be used if some properties of the LC material are optimized, that is, it has a very low threshold voltage (Vth, the voltage at which the molecules start to move) and an optimum elastic anisotropy \( (K_{33}/K_{11}) \) [44].
Usually, LC materials have a threshold voltage higher than zero. Otherwise, a flat area in the center of the active area would be produced for a voltage gradient going from 0 to \( V_{th} \). Note that the voltage gradient generated by signals of Fig. 3 goes from 0 (at the center) to \( v \) (at the edges). Besides, the LC elastic anisotropy can induce a deviation, from the microlens center, of the focal point. That is a result of differences in the molecular anchoring when the electric field is applied parallel or perpendicular to the alignment direction. In this work, it is demonstrated how it is possible to compensate the adverse effects intrinsic to the LC features by applying specific electrical signals. In Fig. 4 it is shown an example of the designed electrical signals to overcome these drawbacks. In order to compensate the threshold voltage of the LC, it is required that voltage gradient goes from \( V_{th} \) to \( v \). To achieve this, a low frequency signal with the desired value is superimposed to the upper and bottom electrodes. During a short period of time a DC voltage (\( V_{off} \)) is applied to the upper electrodes (\( V_1 \) and \( V_2 \)). At this instant, the DC voltage at the bottom electrodes (\( V_3 \) and \( V_4 \)) is zero. Then, in the next period of time the same voltage is applied to the bottom electrodes and zero to the upper electrodes. By using this configuration, when all the amplitudes are the same (\( A_1 = A_2 = A_3 = A_4 = v \)), the voltage at the corners of the active area would be affected by two different harmonics, one with absolute value of \( \sqrt{2} \cdot v \) and other with value \( V_{off} (\sqrt{2} \cdot v + V_{off}) \). The voltage at the center will be \( 0 + V_{off} \). This solution allows the voltage gradient applied to the LC layer to be controlled exactly, avoiding unwanted zones of the LC birefringence curve. This solution allows the voltage gradient applied to the LC layer to be controlled exactly, avoiding unwanted zones of the LC birefringence curve. On the other hand, in order to compensate the elastic anisotropy, simply different amplitudes have to be applied to the electrodes as a function of the focus displacement.
4. Results

The first results show that adverse effects of threshold voltage and elastic anisotropy are compensated. For this, the same parameters of waveforms of Fig. 3 are used: Sinusoidal signals and 1 kHz frequency. The added square signal, $V_{\text{off}}$ is 1 Hz frequency. In Fig. 5 (a) the amplitudes are selected to compensate only the adverse effect of the elastic anisotropy, $A_1 = A_2 = 1.5V_p$ and $A_3 = A_4 = 1.9V_p$ (maintaining the focus in the center of the active area) and $V_{\text{off}} = 0$. Due to the threshold voltage, the voltage at the center is not enough to switch the molecules, so there is a flat area. By adding the offset signal $V_{\text{off}} = 2V_p$, molecules at the center are activated and the flat zone is suppressed [Fig. 5 (b)].
Figure 6 shows the capability of tuning the microlens focusing power by changing the voltage at the electrodes. A selection of individual microlenses for $V_{\text{off}} = 2V_p$ and different amplitudes are shown. The DC signal is inverted at a 1Hz rate. By analyzing the optical performance after several hours and days, it has not been found evidence of degradation of the alignment layer caused by the use of these specific waveforms. The tunability can be more clearly seen if the phase profiles are extracted from the interference fringes (Fig. 7). Taking the horizontal axis in the center of the active area as a reference line, the phase is estimated for Figs. 6(a)-6(c). The resulting focusing powers, taking into account the relation between the number of fringes and the focal distances are, $1/329\mu m$, $1/219\mu m$ and $1/197\mu m$, respectively.

As commented before, the horizontal axis is taken as reference to plot Fig. 7. For low voltages there is certain astigmatic aberration. This is a first demonstration of this device so several parameters can be still optimized. For example, the LC material could be chosen to have a lower elastic anisotropy, as [44] suggests there are certain materials with such small parameter. On the other hand, the estimation of a mathematical model of the electrical and phase profile could lead to know the optimum voltages required to reduce the astigmatic aberration to zero.

5. Conclusions

A novel LC microlens array with high optical power and nearly 100% of fill-factor has been proposed and experimentally demonstrated. The strategic combination of a specific electrode structure and some electrical waveforms generates an array of spherical microlenses from square apertures. The aperture of these microlenses matches perfectly with the shape of conventional pixels. The designed electrical signals can compensate the adverse effects from LC properties. Despite this, a study of the optimum LC properties for this structure has to be.
further investigated. The fabrication process is simple, only patterned electrodes are needed. The optical power is considerably high than that of other hole-patterned techniques because the voltage gradient is totally reconfigurable, both at the sides and the center of the microlenses. As the electrodes are in contact with the LC layer, very low voltages are required to tune the microlenses. The square aperture, high optical power and fill factor makes this device a good candidate for the next generation of autostereoscopic devices based on InI technique.

**Funding**

This work was supported by the Research and Development Program through the Comunidad de Madrid (SINFOTON S2013/MIT-2790), the Ministerio de Economía y Competitividad of Spain (TEC2013-47342-C2-2-R) and the funding from Agencia Estatal de Investigación (AEI) and Fondo Europeo de Desarrollo Regional (FEDER) for the Project TEC2016-77242-C3-1-R AEI/FEDER,UE. Finally, we thank the Polish Ministry of Science and Higher Education (Statutory Activity PBS-654 of Military University of Technology).