

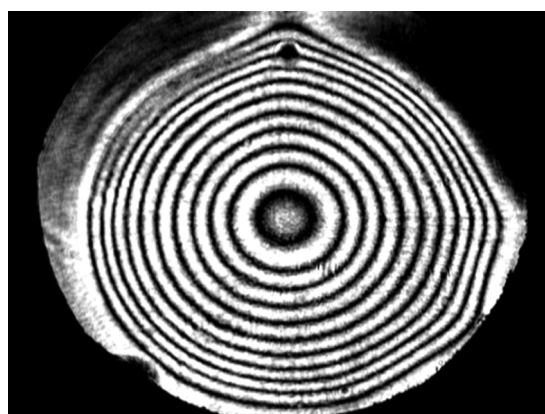
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Abstract: This study is dedicated to the design of a new negative liquid crystal (LC) lens with multiple ring electrodes in unequal widths. The number and widths of the multiple ring electrodes are designed to offer online tunability on focusing length by predetermined individual electrode voltages. This aims to render a smooth refraction index distribution that mimics well a divergent lens based on the theory of a gradient refraction index (GRIN) lens. Finally, the proposed negative LC lens is fabricated with the capability of realizing different focus lengths in a relatively large aperture of 5 mm and a thickness of 0.7 mm. Experiments are conducted to verify expected light-diverging performance. The effective focus length (EFL) is measured based on interference patterns. It is shown that the proposed negative LC lens is able to realize light-divergent effects with an EFL as short as -357.9 mm.

Index Terms: Divergent (negative) lens, liquid crystal (LC) lens, electrodes in unequal widths.

1. Introduction

Liquid crystal (LC) molecules are known of substantial optical and electrical anisotropies such that the refractive indices along different directions across an LC molecule are different and can be changed by molecule rotations. These LC molecule rotations can be attained by applying different electrical fields across the LC molecules. The earliest presentation of the relationships among effective refractive indices, gestures of LC molecules, and electric fields was given in 1972 [1]. Following this, an LC lens with a lens-shaped cell was first proposed by Sato in 1979 [2]. The invention of this LC lens impacted the design and fabrication of traditional solid spherical lenses, since the focus length of the LC lens can be tuned in an online fashion via changing the applied voltage level. With the online tunability on the focus length of the LC lens, a lens module formed by some LC lenses is able to be downsized for given tasks of focusing or zooming.

Following Sato's work in 1979 [2], a number of studies were dedicated to varied designs of the LC lens to maximize the focusing performance. Most of them are related to optical positive LC lenses but with different structures in electrodes, such as hole [2]–[7], spherical [8], stacked structure [9], [10], cylindrical [11] and hole-and-ring [12]. Most recently, multiple ring electrodes were proposed which are used to create the electric field smoothly for generating a required gradient index distribution that mimics well a focusing lens [13]–[16]. All the studies were devoted for a better index distribution that is as close as possible to a perfect gradient refraction index

(GRIN) lens. Some works used high-dielectric materials to be part of electrode structure [13], while others used zone-pattern electrodes to design a diffractive lens [17]–[20], unlike refractive lenses designed by other past studies. In additions, some studies about LC lenses are designed to be applied in nonimaging optics like technologies of autostereoscopic displays [21], [22].

As all the aforementioned studies focused on positive lenses, very few studies are dedicated to negative LC lenses, since it requires a particular electric field that is strongly present in the center area while weakly in the fringe area of the lens, the design principles of which are totally the opposite of the positive lens. In 2005, Sato [23] proposed a negative LC lens with one hole and one plane electrodes. With a predesigned two-voltage driving scheme, the designed electrodes with voltages applied are able to generate required electrical fields for effects of a negative lens. The design presents an LC lens with a small aperture of 3 mm and a thickness of 1.3 mm. Other than this proposed lens, two related works on the negative LC lens are also reported by Sato [24], [25], presenting a lens capable of tuning the focus length from positive to negative.

The largest aperture among all the aforementioned negative LC lenses presented in [23]–[25] is 3 mm, while the smallest thickness of dielectric layer is 1.3 mm. This aperture of 3 mm is in fact too small to constitute a commercial lens module for cameras in mobile phones. To render larger apertures, a new refractive negative LC lens is designed by this study with multiring electrodes in unequal widths for a large aperture up to 5 mm. The designed multiring electrodes is theoretically able to arbitrarily shape the electric field for a desired refractive index distribution, as opposed to a fixed profiles for the index distribution offered by the hole-type lenses presented in [23]–[25]. Furthermore, with the ring electrodes directly shaping the desired index distribution, the glass layer between electrodes and the LC layer can be thinner than the hole types in [23]–[25], making the lens module much more compact to be fit in a commercial cameras in mobile phones. The lens design process is started with calculating the distribution of the applied voltages that are required to result in a perfect index distribution for a negative GRIN lens. This is followed by determining the number and width of ring electrodes based on a rule that the electrode widths should be proportional to gradients of the desired index distribution for the least number of electrodes and a smooth index distribution. With the negative LC lens successfully designed with eight ring electrodes in unequal widths, the associated fabrication process is devised in this study. A high-dielectric material layer is placed between the LC layer and the electrode layer, thus, the electric field is well smoothed in the LC layer to create a near-perfect index distribution. Finally, a fabrication process is developed to bury the bus lines under the ring electrodes in order to avoid undesired electric field distortion near the bus lines. The proposed negative LC lens is realized and its performance is validated by interference patterns obtained in experiments. This designed lens is able to decrease its total thickness to 0.7 mm with the aperture up to 5 mm and the focus length of -357.9 mm.

2. Design Principles

2.1. Required Applied Voltage Distribution

A negative LC GRIN [26] lens, like a conventional diverging negative lens, has the capability of diverging collimated light beams. This can be achieved if the effective refraction index, n_{eff} , of the LC layer has its smallest value at the center (around the optical axis), while the largest on the fringe area of the lens. In order to design the proposed lens to result in a desired diverging index distribution along the radial direction of the negative lens, a basic negative GRIN lens principle is first considered, which is

$$n_G(r) = n_{G,\min} - \frac{r^2}{2fd_G} \quad (1)$$

where $n_{G,\min}$, r , f , d_G , and $n_G(r)$ are the minimum refractive index, the radial position, the focal length, the thickness, and the index distribution of the GRIN lens along its radial direction, respectively. Note also that the focal length in (1) is a negative value. Based on (1), a desired

TABLE 1

Parameters for LC material of MERCK E7 at 20 °C ($\lambda = 633$ nm)

Symbol	Parameters	Value/Unit
n_e	The refractive index of e-ray	1.7371
n_o	The refractive index of o-ray	1.5183
Δn	Refractive anisotropy	0.2188
K_{11}	Elastic constant of splaying	11.1/pN
K_{22}	Elastic constant of twisting	5.9/pN
K_{33}	Elastic constant of bending	17.1/pN
$\epsilon_{\parallel}$	Dielectric constant in the direction parallel to the director	19.28
$\epsilon_{\perp}$	Dielectric constant in the direction perpendicular to the director	5.21
γ	Rotational viscosity	233/mPa . Sec

focal length of a negative LC GRIN lens in a negative value f_{LC} can be achieved as small as

$$f_{LC} = \frac{r_{LC}^2}{2d_{LC} \cdot [n_{LC,min} - n_{LC}(r_{LC})]} \quad (2)$$

where subscript LC denotes the LC lens; r_{LC} is the LC lens radius (half of lens aperture size); $n_{LC}(r_{LC})$ is the local index on lens' fringe; and $n_{LC,min}$ is the minimum index possibly achieved by a rotated LC molecule, which is, in fact, the o-ray index n_o . With a predesigned distribution of $n_{LC}(r)$ matching closely to that of a GRIN lens along the aperture radius, a diverging negative lens can be well attained. Furthermore, to achieve minimum possible focusing length $n_{LC}(r_{LC})$ could be initially designated as the e-ray index n_e , the maximum possible index of a rotated LC molecule. The LC material offered by Merck Inc., E7, is used in this study to design and realize the negative LC GRIN lens. The parameters of LC material E7 are listed in Table 1. For an initial example study, the radius of the lens aperture is designed as large as $r_{LC} = 2.5$ mm, while the cell gap of the LC lens is chosen as $d_{LC} = 50$ μ m for better focusing capability. In results, the LC lens reaches a minimum focal length $f_{LC} = -286$ mm based on the calculation following (2). Note that different designs on the aperture size lead to different minimum focal lengths. The relation between different designated aperture radii and the resulted effective focal lengths (EFLs) is depicted in Fig. 1(a), where it is seen that as aperture radius is demanded to be larger, the minimum EFL decreases. This shows that a large aperture comes with a price of deceased EFL. This study intends to design a negative LC lens with a large aperture and a satisfactory EFL. Substituting the minimum refractive index of E7 (n_o as given in Table 1), the minimum focal length calculated by (2) and the designed LC layer thickness of 50 μ m into (1), the function of the index distribution along the radial position of the designed negative LC lens could be rewritten as

$$n_G(r) = n_{LC}(r) = 0.035008r^2 + 1.5183 \quad (3)$$

which is, in fact, a desired index distribution for a perfect GRIN diverging lens. The refractive index distribution resulted from (3) versus the radial position is plotted in Fig. 1(b). Seen from this figure is a hallow index distribution that leads to effects of a negative, diverging GRIN lens.

It should be carefully noted herein that in a realistic LC lens there are a number of LC molecules across the thickness of the LC layer in a lens, forming LC columns. An example of an ILC column is illustrated by Fig. 2. The desired GRIN distribution (3) is preliminarily derived based on an assumption that all the LC molecules could be rotated to the same final gesture throughout the columns, even to vertical gestures for all LC molecules in a column. Note that the vertical gesture corresponds to minimum possible index along the long axis of a single LC molecule, n_o . However, with a voltage applied to an LC column, the final rotation gestures of LC molecules through the

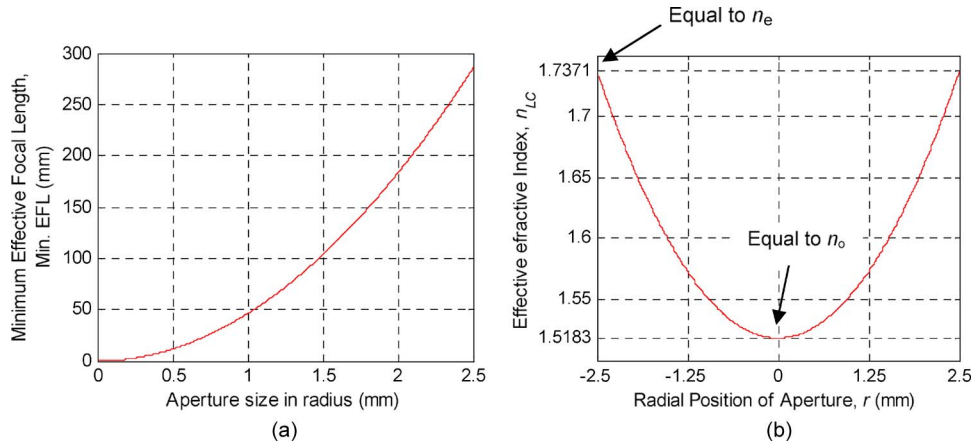


Fig. 1. (a) The effective focus length as a function of aperture size and (b) the desired refractive index as a function of radial position in lens' aperture.

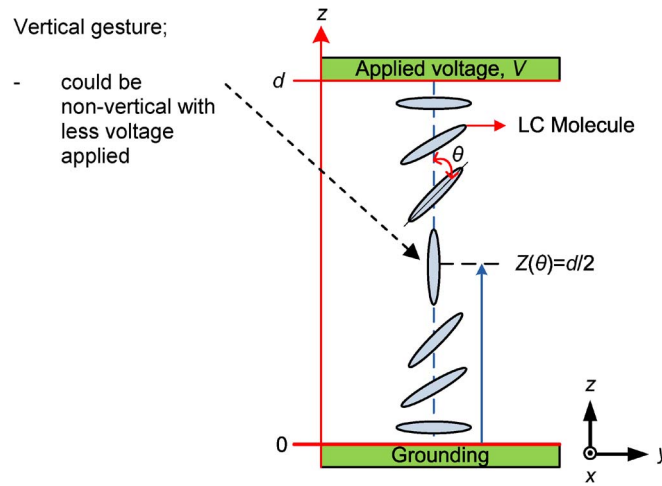


Fig. 2. Gestures of liquid crystal molecules along one LC column subjected to a driving voltage.

column are gradually changed from almost horizontal ones at boundaries of the LC layer to a tilted gesture in the middle, the minimum possible of which is the vertical one as shown in Fig. 2 while enough voltage is applied. With different LC gestures along the LC column, it is impossible to achieve an effective index at the lens' center as a minimum possible index along long axis of a single LC molecule n_o as requested by (3). Therefore, the actual focus length achieved by the later-fabricated LC lens would be larger in magnitude than the focus length of -286 mm, which is preliminarily targeted based on the theoretical (2).

With the desired index distribution for a given minimum focal length, the required electric field and electrode voltages are derived in the followings. This is started from deriving required LC molecule rotations and their applied voltages needed. Considering first a single LC molecule, the effective refractive index of the LC molecule $n_{s,eff}$ can be calculated by

$$n_{s,eff}(\theta) = \frac{n_o n_e}{\sqrt{n_e^2 \cos^2 \theta + n_o^2 \sin^2 \theta}} \quad (4)$$

where θ is the rotational angle of the single LC molecule, which is the one relative to the direction across the LC layer. Considering next a single column of LC molecules which is in fact also along the optical axis of the LC lens across the LC layer at a given radial position of the LC lens, as shown in Fig. 2, based on Huygen's principle [27], [28], the effective refractive index through this column $n_{c,\text{eff}}$ can be obtained by the integration

$$n_{c,\text{eff}}(r) = \frac{1}{d_{\text{LC}}} \int_0^{d_{\text{LC}}} n_{s,\text{eff}}(r, z) dz \quad (5)$$

where z is the radial position in the lens aperture. To design a negative or positive GRIN lens, the index distribution obtained by (5) should be equal to the effective index distribution of a perfect GRIN lens calculated by (1), i.e.,

$$n_{c,\text{eff}}(r) = n_{\text{G}}(r). \quad (6)$$

In order to satisfy the above (6), a particular distribution of applied voltage along the radial position of the LC lens, which is denoted by $V(r)$, is next searched to lead to a specific $n_{c,\text{eff}}(r, z)$ such that the $n_{c,\text{eff}}(r)$ calculated by (5) satisfies (6). Based on the deformation theory of an LC molecule column due to an applied voltage, $V(r)$, can be derived by first finding $\theta(r, z)$, where $\theta(r, z)$ is the rotational angle of a single molecule in a given LC column of an LC GRIN lens. This can be accomplished by solving sequentially a combination of two equations, as follows, for a given applied voltage V [1]

$$V = V_{\text{th}} \cdot 2/\pi \sqrt{1 + \gamma \cos^2 \theta_m} \cdot \int_0^{\theta_m} \left\{ \frac{1 + \kappa \cos^2 \theta}{(1 + \gamma \cos^2 \theta)(\cos^2 \theta_m - \cos^2 \theta)} \right\}^{1/2} d\theta \quad (7)$$

$$z = \frac{d_{\text{LC}}}{2} \cdot \frac{\sqrt{1 - \gamma \cos^2 \theta_m} \int_0^{\theta} \left(\frac{(1 + \gamma \cos^2 \theta)(1 + \kappa \cos^2 \theta)}{\cos^2 \theta_m - \cos^2 \theta} \right)^{1/2} d\theta}{\sqrt{1 + \gamma \cos^2 \theta_m} \int_0^{\theta_m} \left(\frac{(1 + \gamma \cos^2 \theta)(1 + \kappa \cos^2 \theta)}{\cos^2 \theta_m - \cos^2 \theta} \right)^{1/2} d\theta} \quad (8)$$

where V_{th} denotes the LC threshold voltage at which an LC molecule starts to rotate, and θ_m is the rotational angle of the LC molecule at the center position of the LC column. V_{th} is equal to

$$V_{\text{th}} = \pi \left(\frac{k_{11}}{\varepsilon_o(\varepsilon_{\parallel} - \varepsilon_{\perp})} \right)^{1/2} \quad (9)$$

where the parameters γ and κ are

$$\gamma = \frac{\varepsilon_{\parallel} - \varepsilon_{\perp}}{\varepsilon_{\perp}} \quad \text{and} \quad \kappa = \frac{k_{33} - k_{11}}{k_{11}}. \quad (10)$$

where $\varepsilon_{\parallel}$, $\varepsilon_{\perp}$, k_{11} , and k_{33} are the relative dielectric permittivity parallel to the director of LC molecules, the relative dielectric permittivity perpendicular to the directors of LC molecules, and the elastic curvature constants of splay and the elastic curvature constants of bend, respectively. With a given voltage at a particular radial position of the lens, i.e., a given $V(r)$ for V in (7), the rotational angle of the LC molecule at the center position of the LC column θ_m can be first solved based on (7). The obtained θ_m is then substituted into (8) to find θ for the LC molecule in different vertical position of z across the LC layer, which can be denoted by $\theta(r, z)$.

Using the approximation on the effective index as an LC molecule rotates, as given by (4), the corresponding $n_{s,\text{eff}}(r, z)$ can be attained. The attained $n_{s,\text{eff}}(r, z)$ is then used to calculate $n_{c,\text{eff}}(r)$ by (5) to see if $n_{c,\text{eff}}(r)$ matches the desired $n_{\text{G}}(r)$, as given by (6). The aforementioned computation

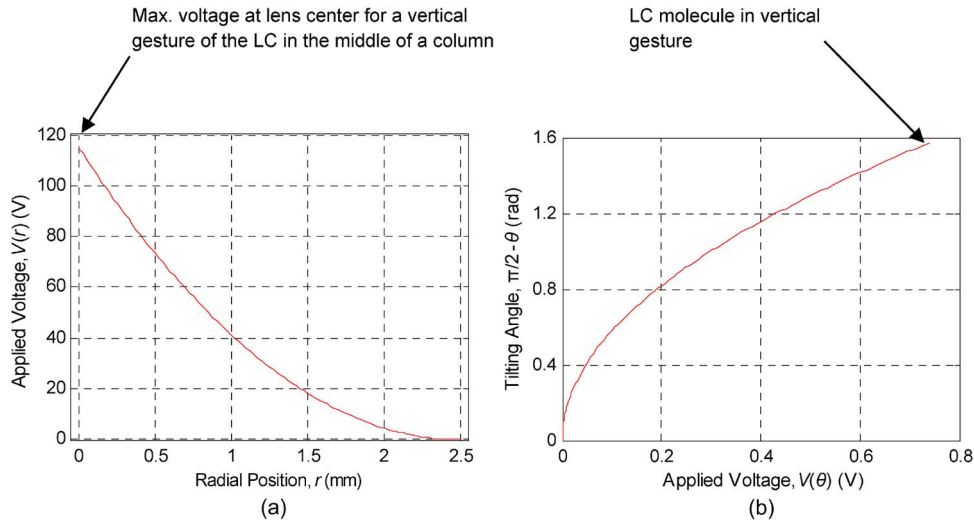


Fig. 3. (a) Required applied voltage at varied radial position of the lens' aperture. (b) The tilting angle of the LC molecule at the middle of an LC column.

process from $V(r)$ to $n_{c,eff}(r)$ can be reversed via known numerical tools, especially for integrations in (7) and (8). This way, for a given index distribution mimicking a GRIN lens, $n_G(r)$, the required voltage distribution along the radial position of the LC lens, $V(r)$, can be found. Based on the recommended computation process, the required applied voltage distribution on LC columns along the radial direction of the lens can be calculated. Considering the desired index distribution in (3) and the typical impedances of the LC layer and the glass substrate in thickness of $700 \mu\text{m}$ between the LC layer and the electrodes, the required voltage distribution can be obtained and then depicted in Fig. 3(a). It is seen from this figure that the required voltage distribution has its maximum in the middle of the lens while minimum on the fringe of the lens. The trend of the voltage distribution is obviously and reasonably opposite to a positive LC lens [11], [12]. In the previous computation process, the tilting angle of the LC molecule in the middle of an LC column, θ_m , was also calculated as a function of lens' radial position, which is depicted in Fig. 3(b). It is seen from this figure that, as expected, the tilting angle in the middle of the LC layer is able to reach its maximum, i.e., 90° , with the maximum voltage applied.

2.2. Electrode Widths

The required voltage distribution that was successfully calculated in the previous section is next approximately realized by applying calculated voltages to a finite number of multiple ring electrodes that fully fill lens' aperture. In order to approach the continuous voltage distribution required and calculated, the applied voltage on each finite-width electrode is chosen as the evaluation value of the voltage distribution function shown in Fig. 3(a) at the center across each electrode width. In addition, the widths of ring electrodes are determined to be proportional to gradients of the desired index, as illustrated by the chart in Fig. 4, which is in fact a half profile of the refraction index distribution for a GRIN lens shown in Fig. 1(b). The total index ranging from $n_o(n_{\min})$ to $n_e(n_{\max})$ along the ordinate in Fig. 4 is first divided to N equal segments. The resulted single index increment is

$$\Delta n = \frac{n_{\max} - n_{\min}}{N} = \frac{n_e - n_o}{N}. \quad (11)$$

The lens radii r_i 's as denoted on the abscissa of Fig. 4 are designated as the edges of ring electrodes, since they correspond to those segmenting indexes $n_{LC,i}$'s on the ordinate. The electrode rings are designed to be placed between r_i 's with widths limited by these adjacent r_i 's. The resulted widths for the case if eight electrodes are also given in Fig. 4. This way, each electrode

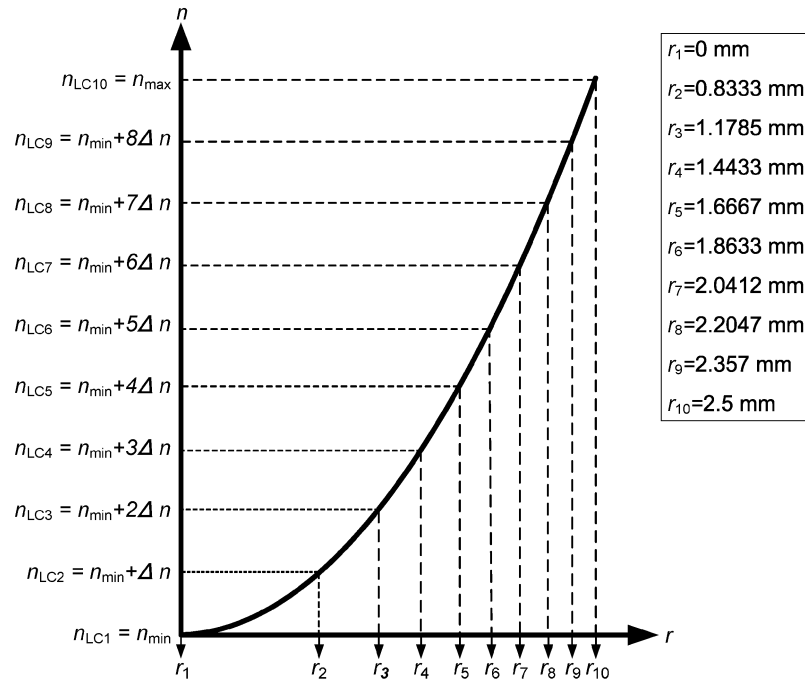


Fig. 4. Width designation for electrodes.

is responsible for the same index increment Δn . The applied voltage differences between adjacent electrodes are also responsible for the same index increment. Thus, it is highly plausible that the required set of applied electrode voltages to achieve a GRIN-lens-like distribution in Fig. 4 is linearly distributed over a finite range, making it much easier to realize an external drive circuit. It is also pertinent to note herein that wider electrodes are placed in the center region of the lens aperture to realize large voltages while narrower at edge. This particular design aims to result in larger lens apertures with smoother electrical field distributions in the center region of the lens.

It is pertinent to note herein that the negative LC lens in this study is polarization dependent, since the expected varied refractive property of LC molecules is only applicable to those light polarized along with the LC lengths as seen from top to bottom of the lens (along the optical axis of the lens). Polarization dependency of the LC lens should be considered to be solved for applications because optical efficiency decreases by a polarizer. However, it should be mentioned that in experiments it is constantly found that the alignment agent layers as shown in Fig. 5(b), e.g., the agent layers processed by rubbing, could provide moderate effects of polarization.

A common remedy for polarization dependence is to integrate two lenses with orthogonal alignment directions [17], regardless of a decrease in optical efficiency. In addition, several LC phase modulations were recently demonstrated or proposed for achieving polarizer-free LC lenses, such as the residual phase modulations [32], optical isotropic materials (blue phase LC) [15], [33], or double-layered structure [9], [10].

2.3. Baseline Lens Structure

The structure of the negative LC lens is next designed, which is illustrated by Fig. 5(a) and (b), top and side views of the lens, respectively. In this structure, an upper glass topped with patterned indium tin oxide (ITO) electrodes is placed upon the LC layer, and below this, there is another ITO glass substrate. Note that the material of ITO is commonly chosen as the transparent electrodes due to their satisfactory conductivity and high optical transmittance of 94%. In the lens' structure as shown in Fig. 5(b), the upper ITO glass is patterned with designed multiring electrodes, while the

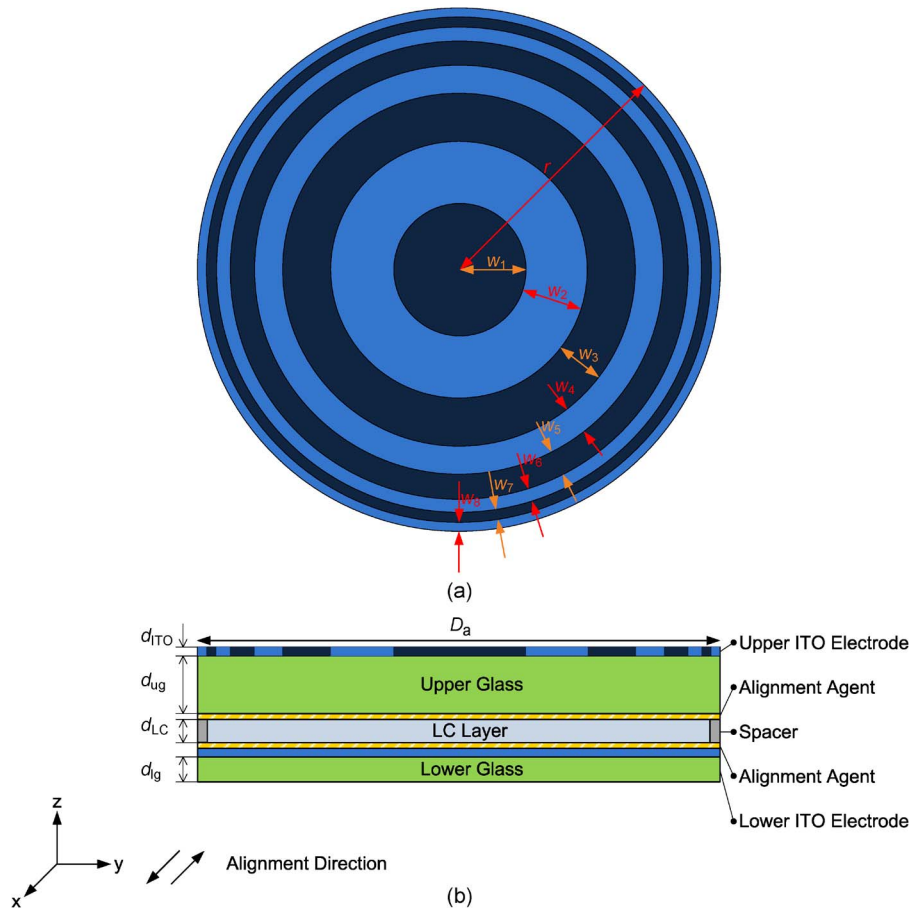


Fig. 5. Structure of the negative LC lens. (a) Top view. (b) Side view.

TABLE 2

Sizes and properties of the designed negative LC lens

Symbol	Parameters	Value/Unit
D_a	The aperture of the negative LC lens	5/mm
d_{ITO}	Thickness of ITO	100/nm
d_{ug}	Thickness of upper glass	0.7/mm
d_{LC}	Thickness of spacer	50/ μ m
α_0	Pre-tilt angle	2/deg

lower glass substrate remains unpatterned as a single electrode. In operations, this single electrode is connected to ground to create a required voltage difference between top multiple ring ITO electrodes and the lower single ITO electrode. In addition, there are two layers of alignment agent between the LC layer and two glass substrates. The thickness of the LC layer is well controlled by spacers. D_a the aperture size of the lens. d_{ITO} is the thickness of the ITO electrodes. d_{ug} is the thickness of the upper glass. d_{LC} is the thickness of the LC layer. d_{lg} is the thickness of the lower glass substrate. All the parameters of the designed negative LC lens for the current study are summarized in Table 2.

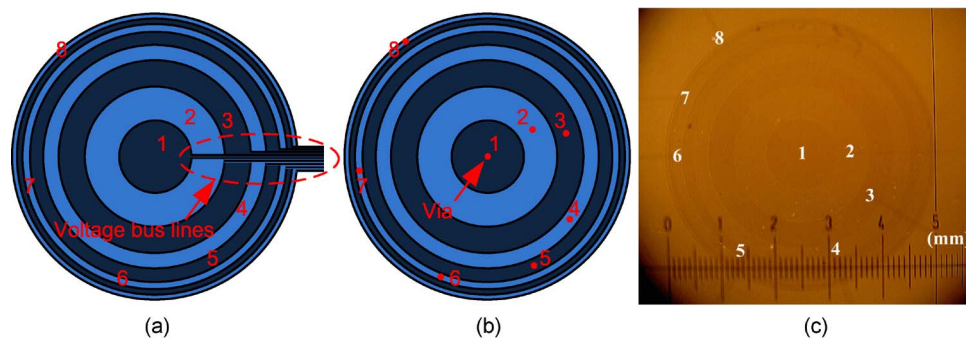


Fig. 6. (a) The electrode pattern with all electrodes in the same layer. (b) With buried bus lines. (c) A photo on a lens sample with multiring electrodes.

3. Fabrication

The essence of the fabrication process for the LC negative lens with ITO ring electrodes on a glass substrate is elaborated in the followings. Eight ring-type ITO electrodes are chosen for experimental study herein. Smoothness of the refractive index distribution offered by the LC lens fabricated is expected to be seen from experimental data. The preliminary design of the lens with eight electrodes for fabrication is shown in Fig. 6(a), where the rings in deep color are odd-numbered electrodes while others in light color are even-number electrodes. Following the baseline structure as shown in Fig. 5(b), these electrodes are made possible by a single patterned ITO layer. Therefore, it is inevitable to extend the electrodes to cross rings to form bus lines for applying external voltages, as shown in Fig. 6(a). These bus lines would definitely cause undesired distortion in the electric fields in its local area covering part of the LC layer, in results of undesired LC rotations for mimicking a perfect GRIN lens. In addition to the aforementioned problem, it is also reported from [13] and [17] that the space between adjacent electrode rings ought to be large enough to avoid possible effects of short cuts. To remedy the aforementioned problems, a new structure and a corresponding fabrication process are proposed in this study, as illustrated by Figs. 6(b) and 7, respectively. In this fabrication process, the odd- and even-numbered electrodes are deposited and patterned at two different layers and separated by an insulator SU-8. The bus lines are buried beneath the two electrode layers with VIA holes [which is denoted as red dots in Fig. 6(b)] to be connected their corresponding electrodes.

The details for fabricating different layers of electrodes are illustrated by Fig. 7 and elaborated in the followings. First, from steps (1) to (2), the ITO layer is patterned for the bus lines of all electrodes. These electrode bus lines are in radial extension to the outmost region of the glass substrate to be wire bounded. They do not cross each other in this layer. From (3) to (7), odd-numbered electrodes are patterned and connected to ITO VIA holes, the thickness of which is 1000 Å. The electrodes are connected to the foundation and encapsulated by insulating SU-8, the thickness of which is about 5 μm . In step (8), the SU-8 layer is patterned for exposing external electrode pads for wire bounding. Steps (9) to (12) repeat a similar subprocess but for even-numbered ring electrodes and their external pads for wire bonding. Following the aforeproposed fabrication process, the bus lines can be buried beneath the conductive electrode rings without crossing bus lines, as shown in Fig. 6(b). In this way, possible distortions of electric fields in the local area around the bus lines, as shown in Fig. 6(a), are avoided. Another advantage is that the neighboring electrodes need no spacing and the upper even-numbered electrodes could even be a little wider than originally designed in order to avoid over-etching in the process and also control the resistance to a lower value for a fast response of LC molecule rotations. Samples of LC lenses with multiring electrodes are successfully fabricated following the aforeproposed process. Fig. 6(c) shows one of fabricated samples under a microscope, where ring electrodes and VIA holes can be seen.

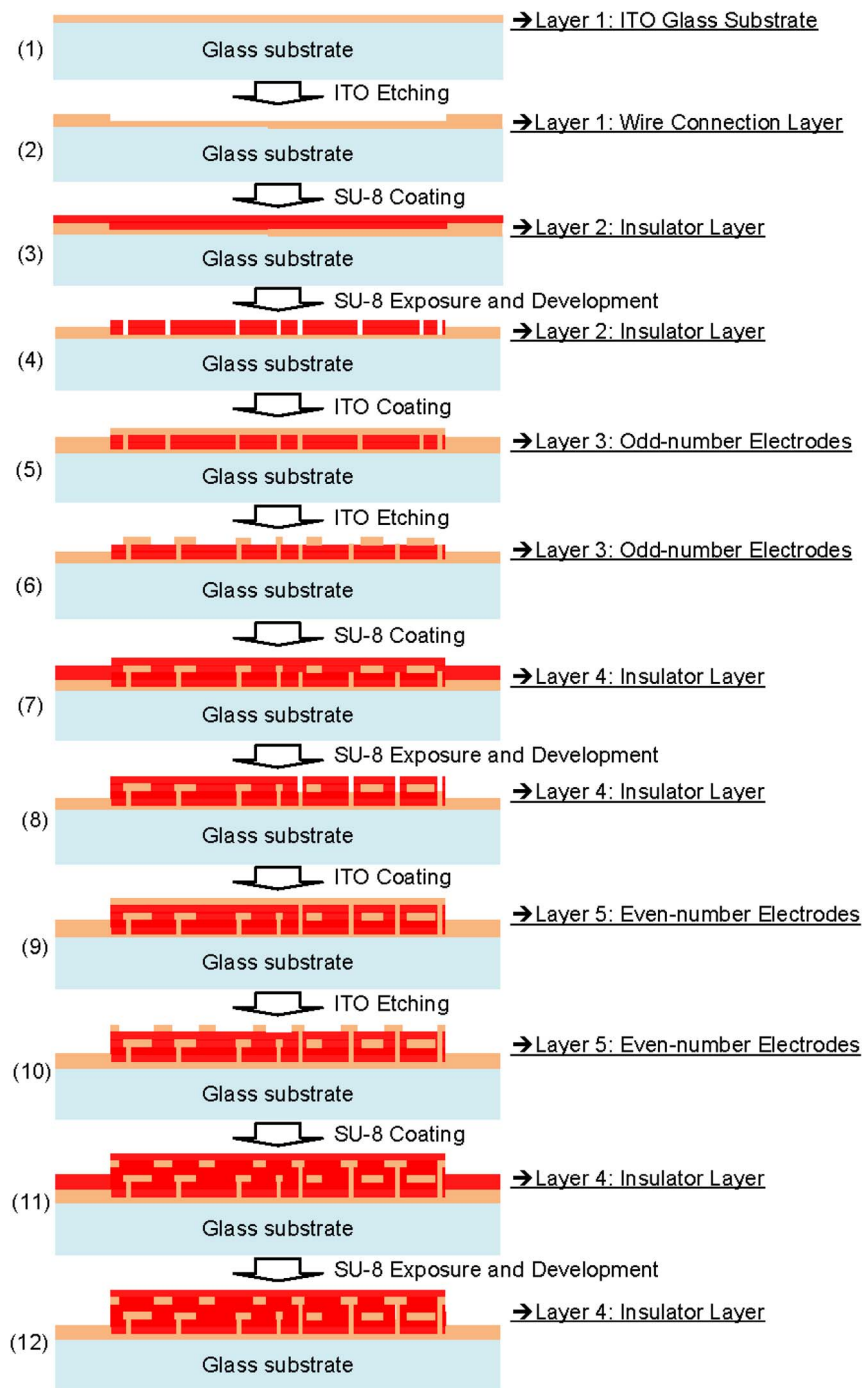


Fig. 7. The fabrication process for multiring electrodes and buried bus lines.

It is pertinent to note herein that the lens proposed in this study is expected to act as a refractive lens even with multiple ring electrodes. In this refractive lens, as voltages applied, the LC molecules are only allowed to be rotated to different tilting angles (from cross-sectional view of the lens) relative to the optical axis of the lens (perpendicular to lens' aperture surface). The angles of LCs projected on aperture surface are always aligned with the direction of the alignment layer and are not allowed to be changed. Therefore, transmission efficiency does not change noticeably with voltages applied as for a conventional LC display; thus, no zone plate effects are present. In

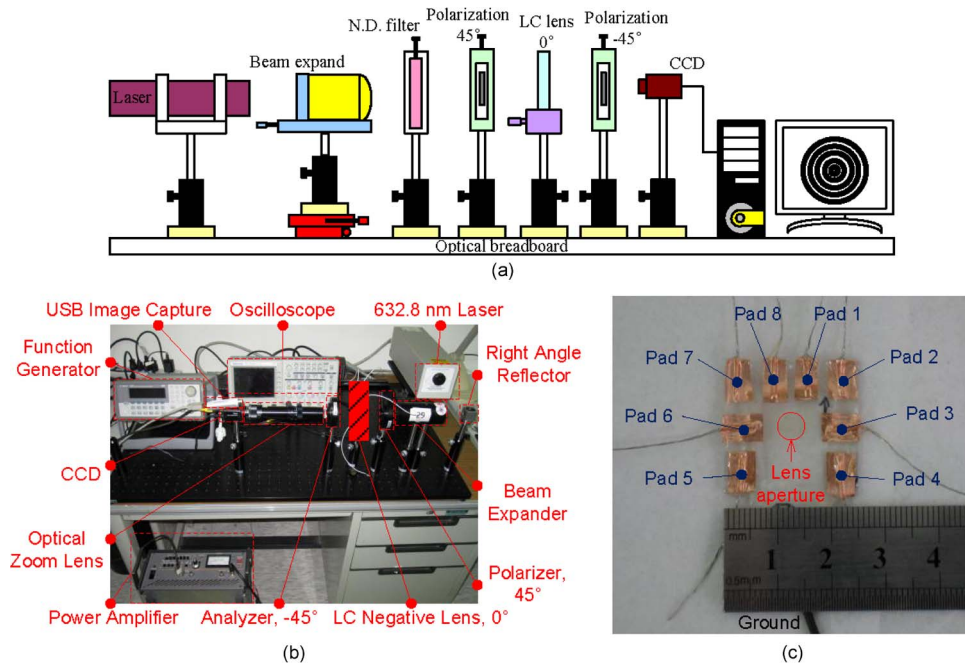


Fig. 8. The (a) schematic and (b) photo of the experimental setup for measuring interference patterns. (c) A photo of the fabricated LC negative lens with multiring electrodes.

addition, the fabricated ring electrodes are near transparent, which are evident from Fig. 6(c), where the levels of transparency via different electrodes are very close. Therefore, the diffraction effects are very limited, i.e., no zone plate effects induced, either. Ring electrodes are adopted widely by other studies for a refractive LC lens without noticeable diffraction effect, like [14]–[16].

4. Experiment and Simulation

4.1. Analysis for Interference Patterns

With designed negative LC lenses fabricated, experiments were conducted to validate the expected performance. For measuring interference patterns, an experiment system is orchestrated. A schematic of the experiment is shown in Fig. 8(a), while Fig. 8(b) shows in a photo the experimental setup for observing the focusing quality. The fabricated lens which is shown in a photo in Fig. 8(c). As illustrated by Fig. 8(a), a He–Ne laser beam with 632.8-nm wavelength is employed. The beam passes through a right angle reflector, a polarizer, the negative LC lens in radius 5 mm, an analyzer, an optical zoom lens and finally into a charge-coupled device (CCD). The CCD is utilized to capture the transmitted light intensity patterns. The polarizing direction of the polarizer, rubbing direction of the PI layer and that of the analyzer are in 45° difference subsequently, in order to generate a clear white and black rings pattern which looks like an interference patterns. The pattern presented herein in fact results from varied degrees of phase retardation that is experienced by the light passing from input polarizer to aligned LCs and finally to the analyzer. The differences of 45° among polarizer, rubbing direction of PI alignment layer and analyzer makes the total changes in polarization across the LC cell in proportional to total phase retardation of a given column of tilted LCs. If the change in retardation is 2π , meaning no change, the crossness between polarizer and analyzer leads to the case with no light passing through. On the contrary, with retardation π , the change of 180° in polarization makes 100% of input light passing through. Note that the interference herein is by no means the usually defined interference [6]–[10], [14], [25].

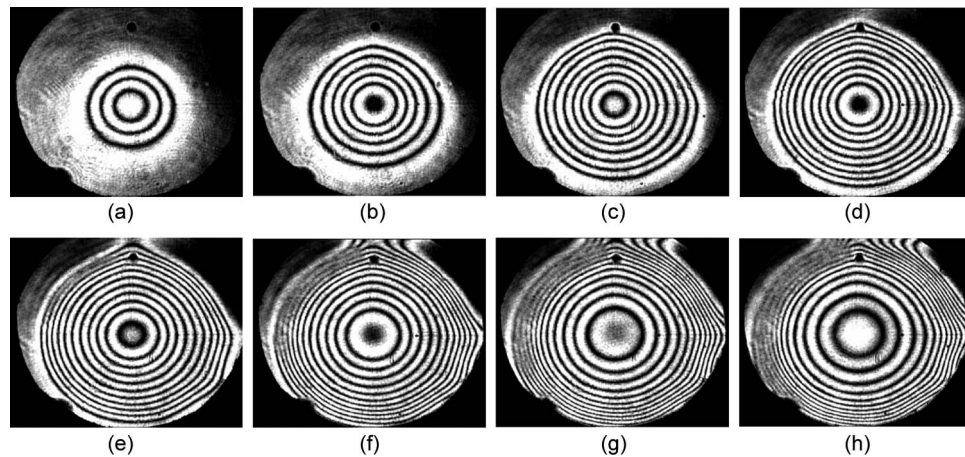


Fig. 9. Experimental interference patterns with different driving voltages of Ring 1, i.e., V_{ring1} , at (a) 20 V, (b) 30 V, (c) 40 V, (d) 50 V, (e) 60 V, (f) 80 V, (g) 100 V, and (h) 120 V.

TABLE 3

Driving voltages at each electrodes for different focus lengths

Number of Electrodes	1	2	3	4	5	6	7	8
Figure 8 (a)	20 V	12 V	9 V	6 V	5 V	3 V	2 V	0 V
Figure 8 (b)	30 V	16 V	12 V	9 V	7 V	4 V	3 V	0 V
Figure 8 (c)	40 V	22 V	17 V	11 V	8 V	5 V	4 V	0 V
Figure 8 (d)	50 V	27 V	21 V	14 V	10 V	6 V	4 V	0 V
Figure 8 (e)	60 V	32 V	24 V	16 V	12 V	7 V	5 V	0 V
Figure 8 (f)	80 V	43 V	32 V	21 V	16 V	9 V	6 V	0 V
Figure 8 (g)	100 V	53 V	40 V	26 V	19 V	11 V	7 V	0 V
Figure 8 (h)	120 V	64 V	48 V	31 V	23 V	14 V	9 V	0 V

Fig. 9(a)–(h) shows the experimental interference patterns of the proposed negative LC lens with different voltage combinations applied to eight electrodes. Note that based on previous theoretical study in Section 2.1 and shown in Fig. 3(a), the voltage applied to the central electrode is the largest among eight voltages applied to all ring electrodes. For the eight cases corresponding to resulted interferences in Fig. 9(a)–(h), the largest voltages applied to the central electrode are 20 V, 30 V, 40 V, 50 V, 60 V, 80 V, 100 V, and 120 V at 1 kHz, respectively. The voltages for other electrodes are listed in Table 3, which are determined based on the voltages calculated by (7) and (8) at a given radial position of the LC lens. It is clearly seen from Fig. 9(a)–(h) that the interference rings are more densely present as the applied voltages increases, rendering shorter focus lengths of the negative LC lens.

The measured interference patterns as shown in Fig 9(a)–(h) are next deciphered to extract the effective focus lengths (EFLs) with different applied voltages. At first, a submodule of the experimental setup in Fig. 8(a), which consists of a polarizer, the LC lens, and an analyzer, can be in fact recognized as a standard crossed-polarizer setup. According to the basic principles about LC optics [29], [30], the phase delay between two adjacent bright or dark rings in Fig. 9 correspond to a

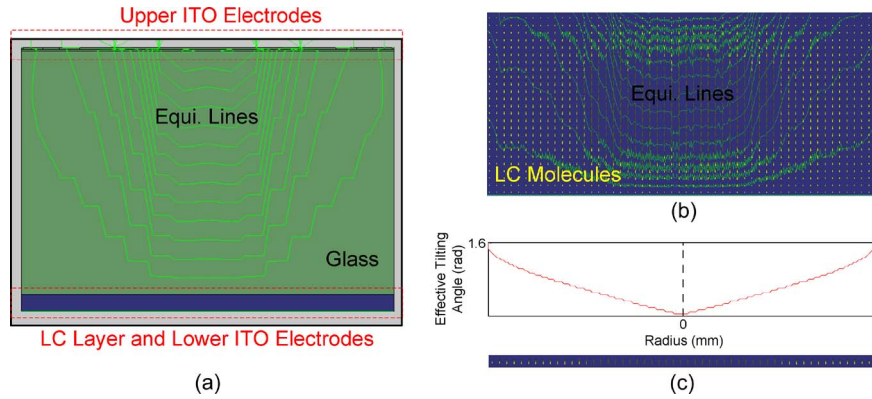


Fig. 10. Simulation results via DIMOS. (a) Equipotential. (b) Rotational angles of LC molecules. (c) Effective rotation angles of LC molecules.

phase change of 2π . Thus, the resulted effective index difference between two adjacent rings in Fig. 9(a)–(h) can be calculated by

$$\Delta n_{c,\text{eff}} = \frac{\lambda}{d_{\text{LC}}} \quad (12)$$

where $n_{c,\text{eff}}$ is in fact the effective anisotropy across LC lens thickness along an LC column across the LC layer, which was already defined by (5). The index difference identified from the interferences in the photos in Fig. 9 are compared to their counterpart results simulated by the software DIMOS. The simulation results by this software provide equipotential lines in the glass substrate and the LC layer, respectively in Fig. 10(a) and (b). Steady-state LC rotation angles with voltages applied are presented in Fig. 10(b), while Fig. 10(c) does the effective LC rotation angles along the radial direction of the lens. The angle was geometrically defined in Fig. 2. This effective LC rotation angle is actually defined as the equivalent angle of a single LC molecule, the effective index of which is the same as that of the corresponding LC column across the LC layer thickness, as calculated by (5). Note that the LC angles shown in Fig. 10(b) and (c) are displayed from the axis x defined in Fig. 2. Thus, the LC rotational angles are proportional to the lengths of LC molecules displayed in Fig. 10(b) and (c). It should also be noted in Fig. 10(b) that the displayed color of the molecules change from yellow in lower tilted angles to dark ones in larger angles (leaning to vertical). It is seen from these figures that even though the equipotential lines in the glass presents a “stairway” distribution due to a finite number of voltages applied in Fig. 10(a), the final effective LC rotation angles in Fig. 10(c) presents a rather smooth distribution over the lens aperture.

The effective index distributions are next calculated based on the previously calculated effective LC angles. Along each LC column at a given radial position of an LC lens, one can find the effective index by (5). Based on (12), the experimental index distributions can be also obtained. They are shown in Fig. 11, where the simulated indices are denoted by “+,” while the experimental counterparts by “•.” In addition, the index distributions predicted by the theories presented in Section 2.1 [primarily based on (5), (7), and (8)] are also depicted in these four subfigures. A general closeness among three sets of data is clearly seen in four subfigures with the central largest voltage increased from 20 to 120 V, showing the validness of the design principle presented in Section 2.1 and associated numerical DIMOS simulations.

Assuming the LC lens acts like a GRIN lens, the experimental indices extracted from Fig. 9 are fitted into a parabolic curve for estimating the experimental EFL of the lens. The results are shown in Fig. 12, where the achieved focus lengths are recorded as a function of the applied voltage at Ring 1, the largest among all electrode voltages. The details in all required electrode voltages as a function of the resulted EFLs are plotted in Fig. 13. Note that the electrode voltages leading to a given EFL are determined to fit the voltage distribution recommended by (7) and (8). It

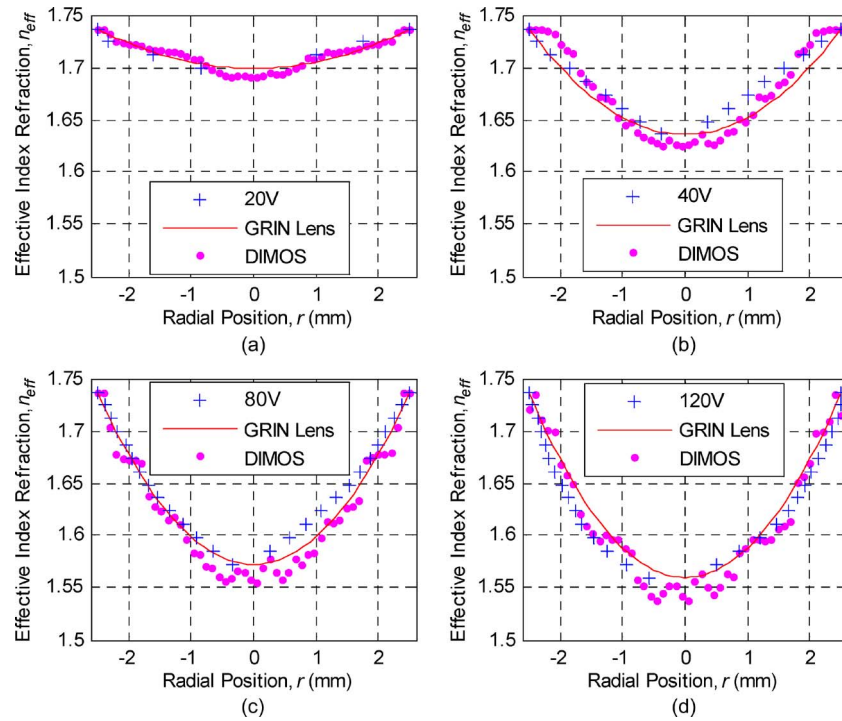


Fig. 11. Refractive index distributions of the designed LC negative lens from experiment, GRIN lens theory, and DIMOS simulations, with different driving voltages of Ring 1, V_{ring1} , at (a) 20 V, (b) 40 V, (c) 80 V, and (d) 120 V.

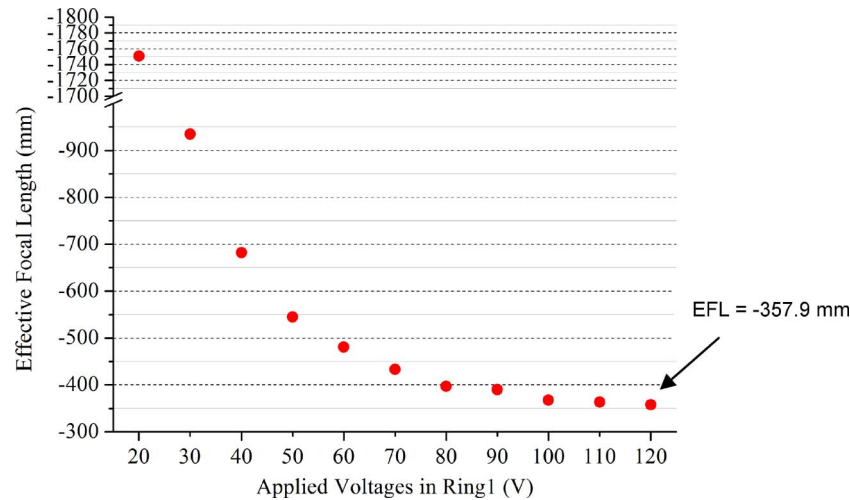


Fig. 12. Effective focal length (EFL) versus the voltage applied to Ring 1 electrode.

is seen from either Fig. 12 or Fig. 13 that the dynamic range of the focus length is from -357.9 to -1760 mm, showing an online tunability offered by the LC lens. Note herein that the obtained focus length of -357.9 mm is short of -286 mm, the focus length designed originally in Section 2.1, where all LC molecules across the LC layer are assumed capable of being rotated to vertical gestures.

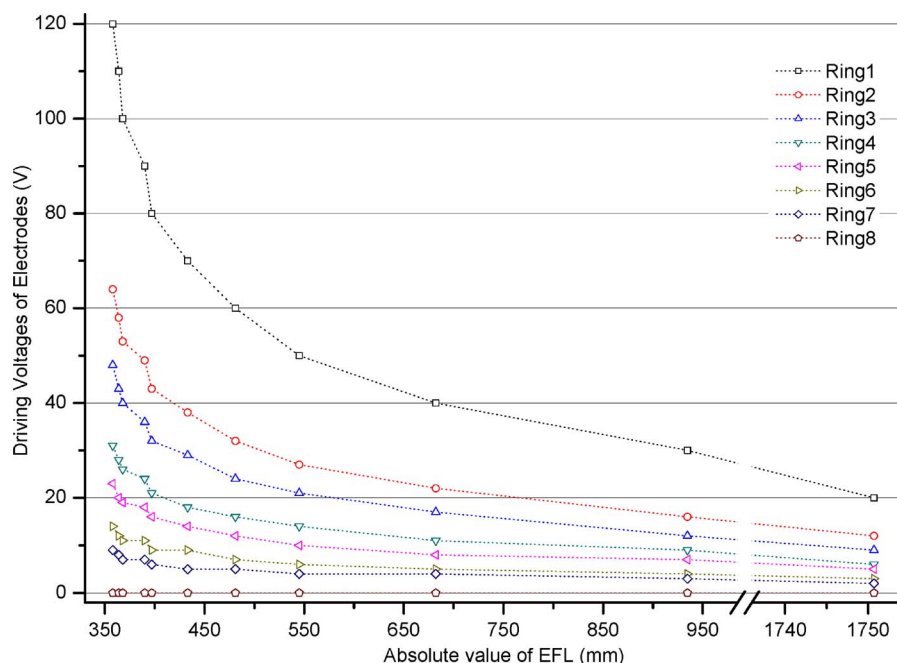


Fig. 13. Driving voltages to electrodes at different EFLs from experiment.

4.2. Measurement of Light Intensity Distribution

To measure distribution of light intensity, an optical experiment system is orchestrated, as shown in Fig. 14(a). A He-Ne laser with 632.8 nm wavelength, a right angle reflector, a beam expander, an IRIS, the designed LC lens and a beam profiler on a slide. The laser beam is emitted through the beam bender for reflecting light in 90° such that the light is inputted to the beam expander directly. The light is outputted from beam expander and then through the IRIS with 5 mm aperture and the designed LC lens to the beam profiler. The light intensity distributions are shown by a computer graphic interface. When the light intensity is measured, the distance between the beam profiler and the designed LC lens is set close to the shortest focal length of 357.9 mm. The measuring results are shown in Fig. 14(b) and (c). In Fig. 14(b) and (c), they show the distributions of light intensity without/with driving voltage 120 V at the observing distance 357.9 mm. As seen from Fig. 14(b) and (c), the light intensity distribution with driving voltage applied is found doubled as compared with that without voltage applied. It validates the lens performance of desired defocusing. The designed LC lens is proven able to offer divergent effect at the possible minimum focal length close to -357.9 mm. A new Section 4.2 is added for this experiment.

5. Conclusion

A new negative LC lens with multiring electrodes in unequal widths is successfully designed and fabricated in this study. This lens owns the merits of a larger aperture of 5 mm, and a smooth refractive index distribution that mimics well a theoretical GRIN lens. In the study, eight ring electrodes are considered in fabrication for the proposed negative lens. The electrodes fill the lens aperture as much as possible for forming a smooth distribution of electric field. The electrode widths are determined in proportional to the gradients of the required index distribution for a general diverging GRIN lens. The applied voltages on each electrode were also designated based on the theoretical analysis and computation on LC columns. In addition, the DIMOS software is used to build an electrooptical model of the designed negative LC lens, and then, it is used to simulate this model with a finite number of electrodes to ensure that the index distribution of the proposed LC lens is close to the perfect one.

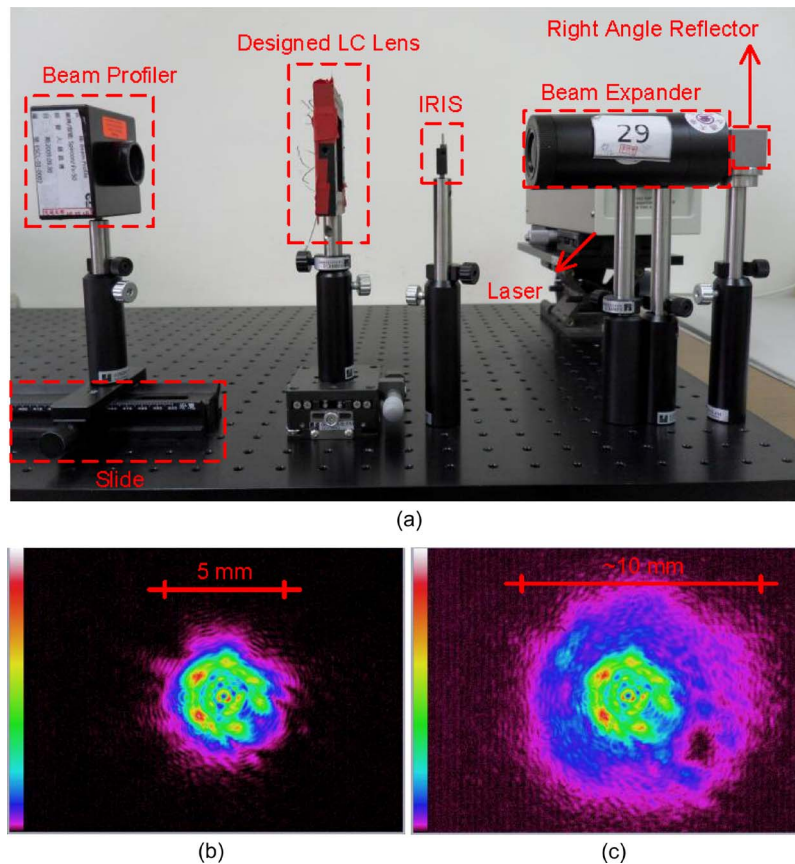


Fig. 14. (a) The experiment system for measuring light intensity distribution and the measured results (b) without and (c) with driving voltage.

Moreover, a fabrication process for double-layer ring electrodes in the negative LC lens is successfully designed to render a desired smooth field over the lens aperture. The thickness of dielectric layer in designed LC lens is 0.7 mm and the total thickness of the designed LC lens is about 1.05 mm. The measurement setup for capturing interference patterns is established in order to measure the interference patterns, and furthermore, the focal lengths are able to be extracted from the interference patterns. A general closeness among experimental, simulated and theoretical data is clearly seen for varied focus lengths, showing the validness of the design principle presented and associated numerical DIMOS simulations. The extracted minimum focal length of the fabricated negative LC lens is able to reach -357.9 mm, while a driving voltage of 120 V is applied in the center electrode.

In future works, a small-sized PCB with an inductor-type boost DC-DC converter circuit for high-voltage drive should be developed to offer high-voltage drive to the LC lens. The PCB size is able to be minimized since an LC cell acts like a capacitor, and it does not consume too much power while driving. Furthermore, an application-specific integrated circuit chip along with the aforementioned boost converter can be developed for driving the LC lens easily to different focusing lengths.

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