Near-Diffraction-Limited Tunable Liquid Crystal Lens with Simplified Design

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Abstract. A high-efficiency tunable refractive lens based on liquid crystals with concentric electrode rings and a simple unique design of a resistor network is reported, and used to assess the performance of an optimized electrically tunable lens. It has a large number of phase control points to be able to accurately control the phase profile and produce high efficiency. The lens design uses resistors between neighboring electrodes to minimize external connections. The lens optical path difference is measured as a near perfect parabolic shape and the Strehl ratio of about 80% is obtained (comparing to a high-quality glass lens). Image evaluations show a good image quality with diffraction limited resolution, but the contrast is lowered by a large-area haze. The lens design also shows a good switching speed, and adjustable power, allowing it to be used in many applications. An example lens with a diameter of 2.4 mm and a 5 diopter tunable range is used in the evaluations.

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1 Background

Tunable electro-optical lenses have been considered as a potential candidate for replacing, simplifying, or correcting passive imaging systems, with the advantages of adaptable corrections and lens power. Liquid crystal (LC) materials have been used for tunable lenses because of their advantage of being able to vary effective refractive index with external field. Many approaches have been reported, such as refractive lenses, diffractive lenses, polymer-dispersed liquid crystal (PDLC) based lenses, hybrid lenses,

Generating the desired index profile of the LC layer with proper electric field distribution is the key for best performance. Various electrode structures and addressing approaches have been introduced to control the index profile, such as the spatial distribution of electric field by a hole-patterned electrode plate; the electrode with a spherical shape which can be addressed to tune the power continuously; discrete ring-patterned electrodes addressed individually with different voltages.

Diffractive LC lenses with ring electrode design have been reported, but chromatic aberration is a serious issue; also, the design of continuously tunable diffractive lenses is difficult. Refractive lenses have less chromatic aberration and the continuously tunable designs are able to be easily considered. For simple electric driving, ideas of inter-ring resistors have been demonstrated; however, the performance of the lenses was not well controlled or fully characterized.

Therefore, there is a need to fully characterize a highly optimized refractive LC lens to be able to assess the current state of the art in electrically tunable lenses.

2 Example Optimized Lens Design

The LC lens presented in this report has a diameter \( D = 2.4 \text{ mm} \) with a 5 diopter tunable range from \(+2.5D\) to \(-2.5D\). The electrode pattern on one substrate consists of 33 discrete Indium tin oxide (ITO) rings, the width of each electrode is determined by its phase step between each electrode of \( 1/10\lambda \) with a design wavelength \( \lambda = 543.5 \text{ nm} \), to reduce the phase aberration due to the discrete nature the electrodes to a low level. As the slope of lens optical path difference (OPD) increases from center to edge, the width of electrodes decreases accordingly. The central electrode disk has a radius about 200 \( \mu \text{m} \), and the width of the outermost electrode is about 15 \( \mu \text{m} \).

In order to minimize the index aberration within the interstitial space between electrodes, the gap between electrodes should be small compared with thickness of the cell. In this design, the gap between two adjacent electrodes is 3 \( \mu \text{m} \), and the cell has a thickness of 10 \( \mu \text{m} \). It is filled with a LC material with large birefringence, which gives enough phase retardation for the targeted tunable range.

Adjacent electrode rings are not completely isolated but connected by a simple inter-ring resistor, which has a rectangular shape with a resistance of two squares [Fig. 1(a)]. The constant inter-ring resistors placed and aligned across the lens radius are used as voltage dividers so that the complexity of electrical connections can be reduced. In this example design, only eight of rings are addressed individually with external bus lines (1st, 5th, 10th, 14th, 19th, 23rd, 28th, and 33rd ring from the lens center), and there are totally seven regions of linear voltage drop. The number of bus lines is chosen to provide sufficient control of the shape of phase profile across the lens for the targeted lens power [Fig. 1(b) and 1(c)]. The voltage profile for a desired focal length can be accurately calculated by the previously introduced LC director simulations, taking into account the specific electrode locations, LC material properties, and thickness of the cell.
The fabrication process for the main substrate needs three major steps with standard thin-film deposition and photolithography. First, a photomask is used to create the electrode ring pattern with inter-ring resistor network from ITO-coated glass (0.4 mm thick, 100 Ω/□). Next, a SiO$_2$ layer is deposited on the ITO layer. Over each addressable electrode, a small via (diameter 10 μm) is patterned through the SiO$_2$ layer. Last, Nickel material is deposited and patterned as eight bus lines connecting the addressable electrodes to the external voltage driver through the vias (Nickel was chosen for its high conductivity so that the bus line width could be minimized) [Fig. 2(a)].

After the patterning process, a polyimide alignment layer is coated and rubbed on the patterned substrate along the bus line direction as well as the common ITO substrate. Cells are assembled by using standard LCD fabrication processes: a thermal epoxy perimeter seal is dispensed on one substrate, while high-precision 10 μm silica sphere spacers are dispersed on the opposing substrate. The two substrates are optically aligned facing each other’s interior surface with an opposite rubbing direction, then mated, and vacuum bagged before final thermal cure of the epoxy [Fig. 2(b)]. Most importantly, the thickness variation across the cell is controlled down to a small fraction of the wavelength. Finally, the cell is filled with a LC material (liquid crystal mixture 18349) with a large birefringence $\Delta n = 0.27$, a flex connector is bonded over the Nickel bus lines with one side, and connected to the voltage driver with the other side [Fig. 2(c)].

For the desired focal length, the voltage profile for eight bus lines is first calculated, and manual adjustment of the voltages might be needed in the phase profile measurement until a perfect parabola basic shape is obtained.

3 Characterizations

3.1 Interferometry

The LC lens actual OPD is measured with phase-shifting Mach-Zehnder interferometer and wavefront analysis software. A linearly polarized green laser light ($\lambda = 543.5$ nm)
is expanded to 10 mm in width by a spatial filter and a
collimator, and used with its polarization along the cell
rubbing direction. An imaging glass lens \( f = 75 \) mm in
front of the high speed charge-coupled device (CCD)
(size: \( 8.7 \times 6.9 \) mm\(^2\); resolution: \( 1300 \times 1030 \)) is used to
image the LC lens surface on the CCD.

Without voltages, the interferogram of the LC lens shows
a uniform cell (across the lens aperture area, the thickness
variation is about \( 0.1 \lambda \)). Once the calculated voltage profile
for \( f = 400 \) mm is applied with a slight adjustment, the
interferogram map shows a very good parabolic shape of
the phase profile along the lens diameter [Fig. 3(a), 3(b),
and 3(c)]. In the following characterization, we compare
LC lens to a high quality commercial glass lens \( f =
400 \) mm with an aperture attached on the lens center.
The glass lens has an excellent parabolic OPD profile and
will be considered as an ideal lens [Fig. 3(d)].

It is clear that the phase profile measured for LC lens
has more noise than that for the glass lens. However, as
the CCD’s resolution is not high enough (pixel size
\( 6.7 \times 6.7 \) \( \mu \)m\(^2\)), the OPD details particularly for gaps areas
(3 \( \mu \)m in width) are not captured and analyzed well with
the setup for measuring the phase profile of entire lens
aperture.

In order to measure the phase of gap areas, a microscope
objective 10× is added in the interferometer and placed
behind the imaging lens and the image plane of the LC
lens to optically magnify the image of LC lens’s interfero-
gram onto the CCD.

The measured phase profile clearly shows that there are
phase bumps in gap areas with a magnitude of approximately
\( 0.1 \lambda \) (Fig. 4) near lens center area. Also, the phase steps
of the electrodes are observed. Furthermore, similar phase
bumps are found in all gap areas across lens aperture with
increasing magnitude toward the edge. In outermost areas
where over 2 V are applied, the phase bumps are larger
than \( 0.2 \lambda \) (Fig. 5).

To evaluate the phase distortion due to the electrode gaps,
same voltage is applied to all electrodes. In this case, the
magnitude of the phase bumps in gaps is almost independent
of the location. To measure the phase bump in gaps as a func-
tion of voltages, uniform voltages (1 to 5 V) are applied. It is
found that the phase variation in gaps reaches highest when
2 to 3 V are applied (Table 1).

3.2 Light Intensity and Strehl Ratio Measurement in
the Focal Plane

Light distribution measurement in lens focal plane requires a
method being able to capture not only a very high dynamic
range (center peak versus side lobe minimums), but also a
relatively large area as light scattering is an important aspect
of the analysis as well. For these measurements, we use the
imaging device of a commercial digital single lens reflex

![Fig. 3](https://example.com/fig3.png)

**Fig. 3** (a) Interferogram of actual LC lens when the voltage profile is applied; (b) measured OPD in 2D of LC lens; (c) measured 1D phase profile for the LC lens, and (d) a high-quality commercial glass lens.
(DSLR) camera. The DSLR’s CCD is $14.8 \times 22.2 \text{mm}^2$ in size and has a pixel size of $5.2 \mu \text{m}$, small enough to construct airy disk patterns for lens with 400 mm and longer focal lengths. An efficient method of recovering high dynamic range intensity distribution is adopted.\(^{16}\)

In the measurement, the linearly polarized laser light ($\lambda = 543.5 \text{nm}$) expanded to a collimated beam with 10 mm in width, passes through a circular aperture with 2.4 mm in diameter and the LC lens with its rubbing direction along the incident light polarization. When the voltage profile for $f = 400 \text{mm}$ is applied on LC lens, the DSLR CCD in manual mode is placed in the focal plane, and multiple exposures are taken with full-stop time increments. The images show that forward scattering is caused by the LC lens. To display the problem, the longest available exposure time is used. In the image, the area around the center lobes is over saturated and a large-scale halo of scattered ring pattern almost fills in the entire CCD sensor; also, there is a long horizontal line pattern due to the diffraction of the straight bus lines that are vertically aligned [Fig. 6(a)]. When the glass lens of the same power is in replace of the LC lens, less scattering is observed with the same exposure time [Fig. 6(b)].

Normalized to the peak intensity for glass lens, the Strehl ratio for the LC lens is measured as about 80% [Fig. 7(a)]; both lenses have the same center lobe width about 220 $\mu \text{m}$, which is theoretically predicted by $r = 1.22f/\lambda/D$.\(^{17}\) The light distribution in the focal plane can be considered as the response of the lens to a point source at infinity, so that the point spread function (PSF) of both lenses is obtained.
Modulation transfer function (MTF) is typically obtained by taking Fourier transform of the PSF in the focal plane and normalizing it to the transform’s zero frequency value (equal to the area under the PSF curve). However, experimentally, if the lens being considered has large angle scattering that results in a haze in the image, this method may not provide a useful quantification of the lens performance because the scattered light may not be completely collected by the limited detector acceptance angle.

To account for this possibility, we start with the idea that the sum of the area under the PSF curve, and the intensity of reflected light for each lens should be equal to the incident light intensity, and therefore the same for both lenses. With this thought, we normalize the curves for the LC lens to a number that is equal to the area under the glass lens’s PSF (assuming no scattering measured for glass lens), corrected for the measured differences in the reflectivity of the glass and LC lens. Specifically, the normalization factor for the LC lens with our modified normalization is: 

\[ \text{Int (PSF, glass lens)} \times (1 - R_L)/(1 - R_G) \] 

where Int (PSF, glass lens) is the area under the PSF for the glass lens; \( R_L \) is the percentage of the total light reflected by the LC lens, measured as about 16%; and \( R_G \) is the percentage of the total light reflected by the glass lens, measured as about 8%. Therefore, this method assumes that the incident light intensity is the same and the measurements of intensity of the reflected light are quite precise. Because these assumptions can be questioned, we have plotted the MTF curves normalized by the typical method, and our modified method [Fig. 7(b)]. In fact, the area of PSF of LC lens is measured as about 80% of that measured for glass lens, same as its measured Strehl ratio, indicating that the light is scattered out of the detector collection angle, the modified normalization method should give more accurate result. With the typical normalization, MTF curve of LC lens is very similar to glass lens; with the modified normalization approach, MTF for LC lens drops to about 0.85 at zero frequency, resulting from the scattering of the light. In addition, the cutoff frequency is measured as about 10.5 cycles/mm, close to the theoretical prediction for a diffraction-limited lens 

\[ \varepsilon_{\text{cutoff}} = \frac{D}{f \cdot \lambda} \] 

(Here, \( f \) is the focal length and \( D \) is the lens diameter). Therefore, in terms of imaging details, the LC lens can be said to be diffraction limited.

### 3.3 Imaging Test Grouped with a High-Quality Glass Lens \( f = 125 \text{ mm} \)

A 1951 USAF resolution chart (7.6 cm x 7.6 cm) with chrome pattern is attached on a uniform light table as the object with high contrast. White light passes through a linear polarizer with its polarization axis parallel to LC lens rubbing direction. The test lens (\( f = 400 \text{ mm} \)) is placed about 400 mm away from the chart with an aperture (diameter \( d = 2.4 \text{ mm} \)) attached. A high-quality glass lens \( f = 125 \text{ mm} \) is placed behind the test lens to increase the power (about 0.5 cm separation), and the best focus is found at about \( z_2 = 125 \text{ mm} \) behind the lens group, where the DSLR CCD is placed. The magnification of the image is about 0.3 of the object size. Measurements are done using the LC lens as the test lens and the glass lens (\( f = 400 \text{ mm} \)) for comparison. The images are taken in a dark room and most of the stray light is eliminated by the additional hood and cover.

Figure 8 shows images taken using the 125 mm glass lens in conjunction with: the 400 mm glass lens; the LC lens with voltage profile applied to yield a 400 mm focal length; and the LC lens with no voltage applied to yield an infinite focal length. With a long exposure time, the images formed through LC lens show a large-scale haze. However, the details are well resolved almost the same as the glass lens. Therefore, the images formed through the LC lens are degraded by the large-scale scattering, which lowers the overall contrast; but it is still very good in terms of detailed resolution.

In order to quantify and further assess the imaging performance, we have attempted to measure the image contrasts (image modulation depth, defined as the amplitude of the intensity variation between \( I_{\text{max}} \) and \( I_{\text{min}} \), divided by the bias level) as a function of spatial frequencies defined within each bar element in the resolution chart from the multiple images obtained with the same imaging setup and image intensity recovery method (Fig. 9).

The figure quantifies what is seen in the image pictures and shows general agreement with Fig. 7(b). It is shown that relative to the glass lens, the LC lens shows a contrast drop at low frequencies due to light scattering and haze, and that the resolving ability is about the same (however, the cutoff...
frequency of both the LC and the glass lens compared here, as well as the shape details of the curve, is not expected to provide an accurate portrayal of the MTF curve because of measurement limitations of our imaging system).

3.4 Variable Power

As the LC lens is designed to have an optical power swing from positive \((f = 400 \text{ mm} \) to infinity) to negative \((f = -400 \text{ mm} \) to infinity), several voltage profiles for longer focal lengths are calculated and applied on the lens, the phase profiles are all measured as good parabola (Fig. 10).

3.5 Switching Time

The time response study is conducted by placing the lens between crossed polarizers with its rubbing direction 45-deg to them, and detecting the transmitted light intensity as a 5 V field is suddenly applied. The time duration for the 10 \(\mu\)m cell to switch from 90% to 10% of the maximal retardation is only about 35 ms. When the voltage is promptly removed, it takes about 0.7 s to relax back to 90% of the maximal retardation.

4 Conclusion

We have demonstrated a high-efficiency electro-optical tunable lens design based on LCs, along with fabrication and complete characterization methods. The simple and unique resistor network design has simplified the driving method, and the lens phase profile can be accurately controlled as a perfect parabola. The images formed through the LC lens show a good resolving ability the same as a high-quality commercial glass lens. However, the large area contrast is slightly reduced by the scattering. Chromatic aberration is less of an issue because our design is a refractive lens with no phase resets, which exist in diffractive lenses and could cause great chromatic aberrations. With the solid PSF and MTF measurement, the performance of the LC lens is comparable to the high-quality glass lens. All these above give a quantified picture of the performance of an optimized LC lens.

References


Biographies and photographs of the authors are not available.