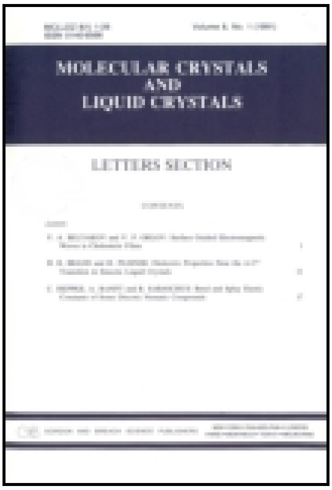

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Detailed Modeling of the Effect of Gap Between Ring Electrodes on the MTF of Liquid Crystal Lenses and Comparison with a "Floating" Electrode Design

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Numerical modeling of the effect of the gap between electrodes on the MTF of an example liquid crystal lens is presented. The results are compared with those of a lens using a layer of "floating" electrodes above the addressed concentric ring electrodes.

Keywords Liquid crystal; electronic lenses; modeling of LC lenses

Introduction

Liquid crystal based lenses, with their ability to make fine corrections to their phase profile, have the potential to be of exceptional quality. However it has been observed that these lenses can have a "haze" that lowers the zero frequency MTF value. Summary results of the cause of this haze has been published [1, 2] and has shown the effect of the gaps between the electrodes can be a major contributor to this problem. Here are shown detailed results of the effect of the gap between the electrodes on the MTF.

In a liquid crystal lens with using a discrete ring electrodes, gaps are needed to separate electrodes in order to apply different voltages and tune the optical power of a liquid crystal lens. Obviously, as the electric field in gap areas is different from the adjacent electrodes, the director orientation distribution is different, and an index of refraction variation is expected. In order to minimize the index change and resulting phase aberration, the gaps between electrodes should be small. The efficiency can be calculated as a function of gap width from both an analytical estimation and numerical modeling methods. As an example consider a LC lens with a diameter of 2.4 mm with 33 ring electrodes, and a focal length of 400 mm. Analytically, the diffraction efficiency for different gap widths can be roughly expressed as:

$$\eta \propto \left(1 - \frac{\Lambda_F}{\Lambda}\right)^2 \tag{1}$$

Here, Λ is the total area of the lens, and Λ_F is the area of gaps. Using this expression, the efficiency can be estimated for the specific lens design considered.

However, the exact effect of gap width on the efficiency can only be obtained with accurate numerical modeling of phase variations in gap areas, by simulating the electric field distribution and the resultant LC director profile.

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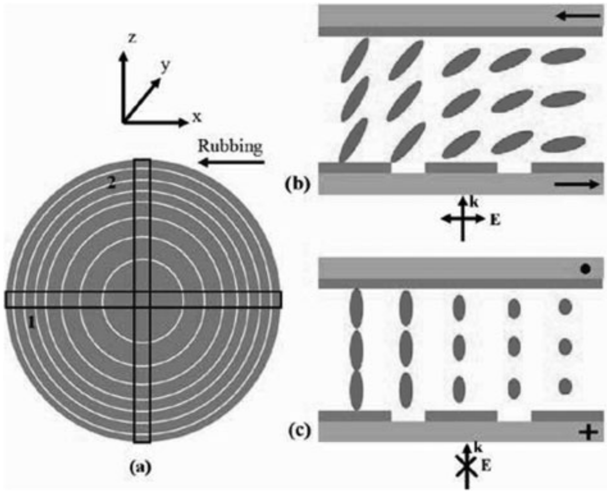


Figure 1. (a) Top view of lens areas (1 and 2) where a tangent to the electrodes is perpendicular or parallel to the rubbing direction; (b) LC director 2D plane as a cross section of area 1, projection of LC directors on cell surface is perpendicular to the electrode axis; (c) LC director 2D plane as a cross section of area 2, projection of LC directors on cell surface is parallel to the electrode axis.

Efficiency Losses Due to Electrode Gaps

Due to the concentric electrode ring structure, the fringing field between electrodes is always in the radial direction; however, the projection of the LC directors onto the plane of the cell is aligned uniformly in one direction (Fig. 1(a)). Because of this, there are two

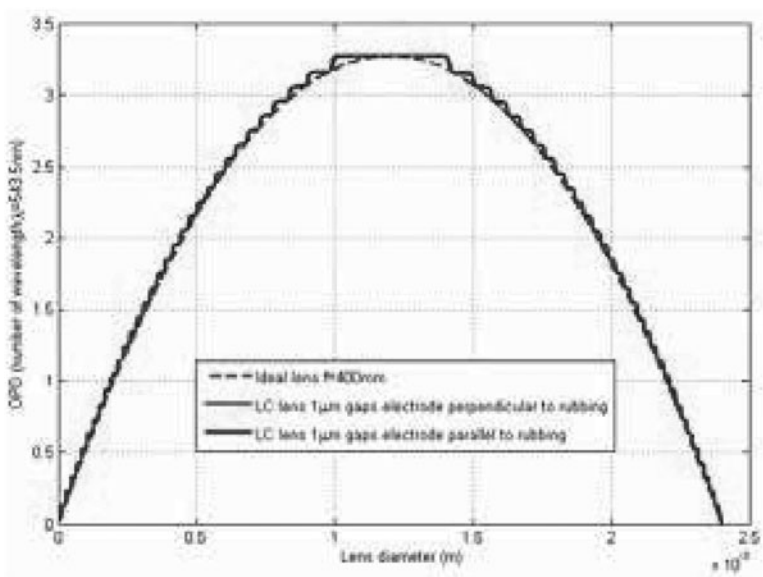


Figure 2. Calculated phase profile for both parallel and perpendicular cases with 1 μm gaps, compared to ideal lens case

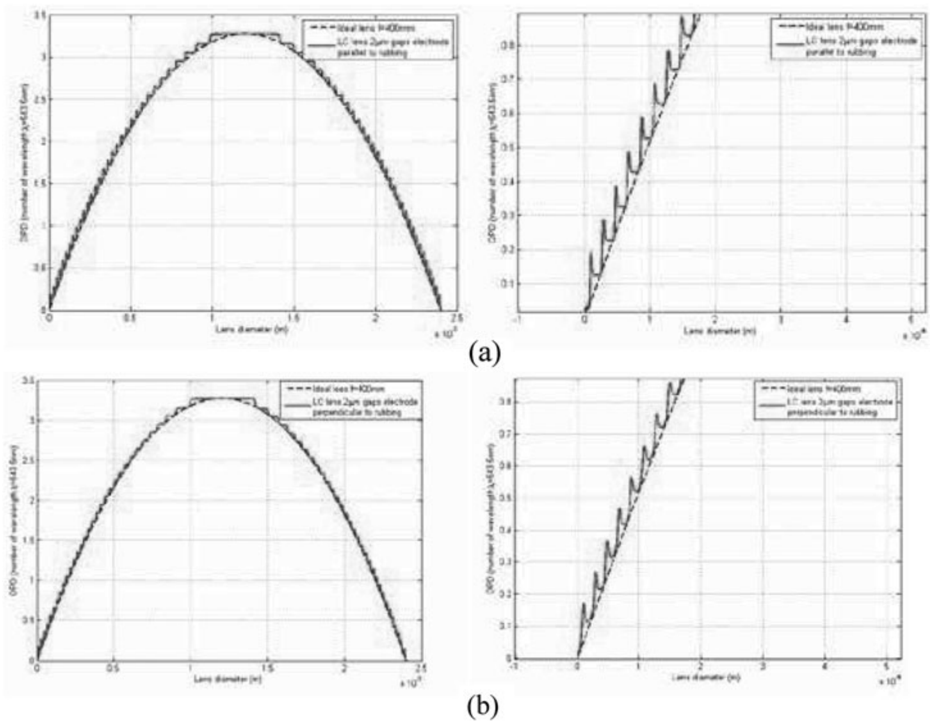


Figure 3. (a) Calculated phase profile for the parallel case with 2 μm gaps and the close-up in outermost areas; (b) Calculated phase profile for the perpendicular case with 2 μm gaps and the close-up in outermost areas.

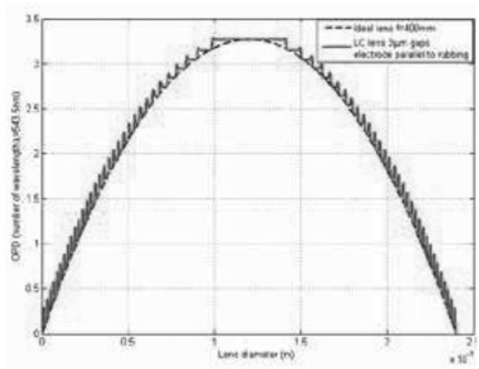
typical lens areas where the tangent of the electrodes is perpendicular or parallel to the rubbing direction (Fig. 1(b) and 1(c)).

Using previously described methods [2] we have modeled the director field for lenses with different gap widths. In these calculations, an example lens is considered where the: lens diameter is 2.4 mm; number of rings is 32; cell thickness is 10 microns; LC material birefringence is 0.27; considered lens focal length is 400 mm; and the considered wavelength of light is 543 nm. In the 2D liquid crystal director calculation, for the case that rubbing direction is perpendicular to the electrode in y direction, the initial orientation of the directors has $n_y = 0$; when calculating the director profile where the rubbing direction is parallel to the electrode, the directors initially have no components in x axis $n_x = 0$.

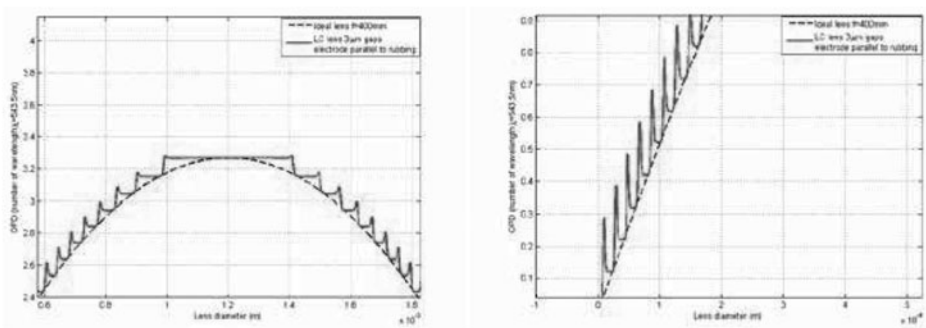
Director and Near Field Phase Profile

With the cell thickness of 10 microns, when the gap width is only 1 μm, the phase profile has no obvious phase bumps associated with the gaps. (Fig. 2). When the gap width becomes 2 μm, the phase bumps have a magnitude of about 0.1 λ (from bump peak to the ideal phase value at the same position in the ideal phase profile) in the outermost area of the lens (Fig. 3).

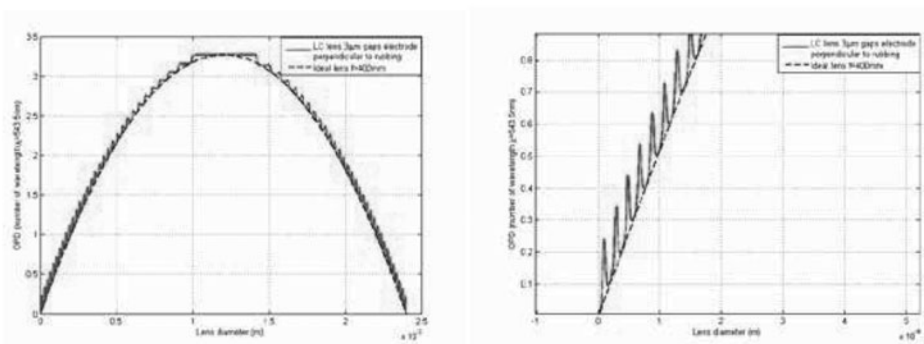
When the gap width becomes 3 μm, the magnitude of the phase bumps increases, and it is a little higher in the parallel case. Specifically, for the parallel case, phase bumps are observable in the center area while no bumps are seen in the perpendicular case. The phase



(a)



(b)



(c)

Figure 4. (a) Calculated phase profile for the parallel case with 3 μm gaps; (b) close-up in center and outermost areas; (c) calculated phase profile for the perpendicular case with 3 μm gaps and the close-up in outermost areas.

bumps in outermost areas for parallel case have a magnitude of about 0.2 λ and 0.18 λ for the perpendicular case (Fig. 4).

In the case of 4 μm gaps, the magnitude of phase bumps significantly increases. In the parallel case, the phase bumps are about 0.1 λ in the center and 0.3 λ in outermost areas.

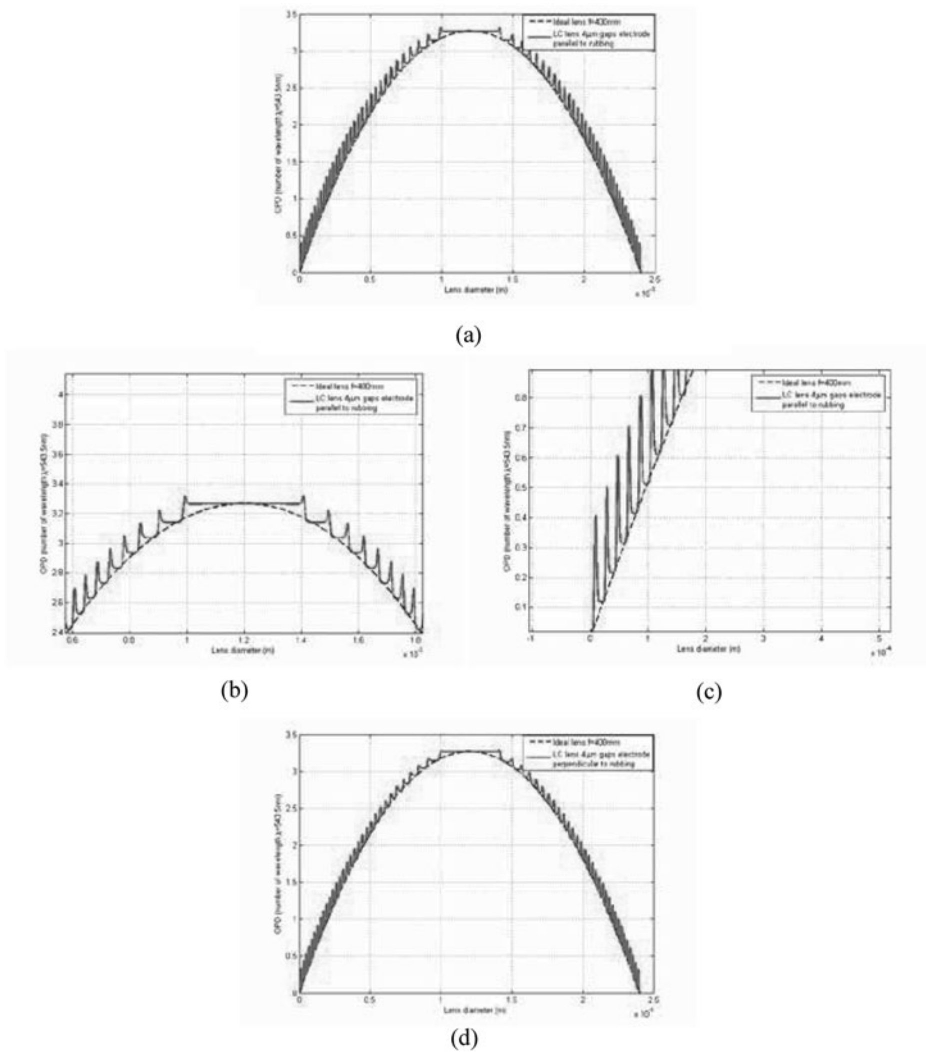


Figure 5. (a) Calculated phase profile for the parallel case with 4 μm gaps; (b) close-up in center and outermost areas; (c) calculated phase profile for the perpendicular case with 4 μm gaps; (d) close-up in outermost areas.

In the perpendicular case, the phase bumps are small in the center (0.05 λ) and 0.25 λ in outermost areas (Fig. 5).

Calculation of the Modulation Transfer Function

The PSF (normalized to the peak irradiance of the ideal lens) and MTF are calculated as a function gap width for the parallel and perpendicular cases (Fig. 6). Table 1, 2.

The optical performance of the whole lens expressed by the PSF is calculated as the average of the previously discussed two cases, based on phase profiles as a function of gap width. It is found that the Strehl ratio in the focal plane drops significantly as the gap width increases to 3 or 4 μm (Table 3) for our 10 micron example device.

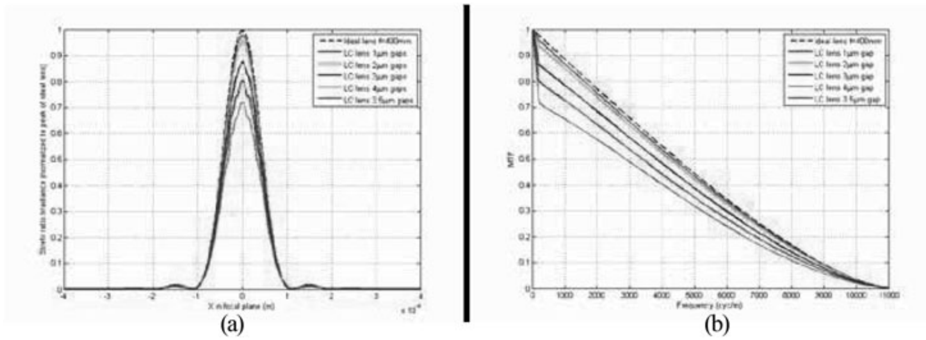


Figure 6. (a) Calculated PSF and MTF as a function gap width (1 μm, 2 μm, 3 μm, 3.5μm, 4μm) for the parallel case; (b) Calculated strehl ratio and MTF as a function gap width (1 μm, 2 μm, 3 μm, 3.5μm, 4μm) for the perpendicular case

However the radius of the center lobe in the focal plane for LC lens is the same as ideal lens (Fig. 4(a), 4(b), 4(c)); and consistent with the analytical prediction determined by the expression $1.22 f \cdot \lambda / D = 110.5\ \mu m$ (Here, f is the focal length and D is the lens diameter). Accordingly, the cutoff frequency for the LC lens is the same as ideal lens (indicating the same resolving ability), but there is a sharp drop at low frequencies in the MTF (Fig. 4(d)), due to the large angle light scattering from the effect of the electrode gaps.

Therefore, we expect the effect of an inhomogeneous electric field to be an issue of concern in a LC lens using the discrete electrode structure. For a better image quality, the electrode gaps should be as small as possible.

Discussion

The calculation shows that for both cases, the basic shape of phase profile is a parabola (Fig. 3). However, in the gap areas between the electrodes, once the gap becomes larger than 1 μm, the calculated phase profile shows noticeable phase bumps, and a further increase in gap width induces higher bumps. Particularly, in the case of 3 μm gaps, the phase bumps in gaps of outermost lens areas are larger than 0.2 λ; in lens center areas, the bumps are smaller than 0.1 λ.

The phase variation in the gap areas is due to the fact that the lower electric field in the gap area causes the director to be at a lower angle to the cell surface and to have a larger effective index of refraction. The magnitude of phase variation in gaps is dependent on the radial location of the cell, because the voltage on the electrodes near the outside of the lens ($V_{edge} = 2.36$ volts) is much larger than that near the inside ($V_{center} = 0.9$ volt), the relative decrease of the electric field and the phase variation due to gaps are larger.

Table 1. Analytical diffraction efficiency for different gap widths

Gap width	1 μm gap	2 μm gap	3 μm gap	4 μm gap
Area ratio	2.67%	5.33%	8%	10.67%
Analytical Efficiency	94.6%	89.3%	84.2%	79.2%

Table 2. Calculated Strehl ratio of the LC lens as a function of gap width including the factor of 10 phase steps per wave, for director plane with electrodes perpendicular to rubbing direction, parallel to rubbing direction, and the average

	1 μm gap	2 μm gap	3 μm gap	4 μm gap
Ratio of gap to thickness (g/d)	10%	20%	30%	40%
Strehl Ratio (director plane with electrodes perpendicular to rubbing direction)	98.35%	96.59%	91.01%	78.74%
Strehl Ratio (director plane with electrodes parallel to rubbing direction)	97.78%	95.59%	87.73%	71.89%
Strehl Ratio of whole lens (in average)	98.07%	96.09%	89.37%	75.32%

In the previous section it was shown that the gaps in the electrodes add "haze" to the image and degrade the zero frequency MTF, and it was shown that gaps that are less than 2 microns where needed for the example lens that was modeled. However it is often not possible to obtain small gaps with high yield, low cost manufacturing. A proposed solution to this problem is to consider "floating" electrodes. [3]

With this approach, the voltage profile is applied on the bottom layer of addressed ring electrodes, and each of the floating electrodes is placed over each gap area overlapping with small part of the neighboring pair of addressed electrodes on both sides of the gap. The potential on the floating electrode becomes the intermediate value of that on both electrodes on the bottom layer by the dielectric coupling and capacitive voltage division. Moreover, another advantage is that the addition of the floating electrodes effectively increases the phase sampling across the lens plane, which is able to further improve the efficiency.

Numerical calculations allow the optical performance in the focal plane to be estimated. [2, 3] The Strehl ratio (peak intensity calculated in focal plane for the LC lens as compared to that for the ideal lens) of the LC lens becomes as high as 98.64%. In addition, MTF of the LC lens becomes almost the same as the diffraction-limited ideal curve, and there is almost no contrast drop at low frequencies (Fig. 7).

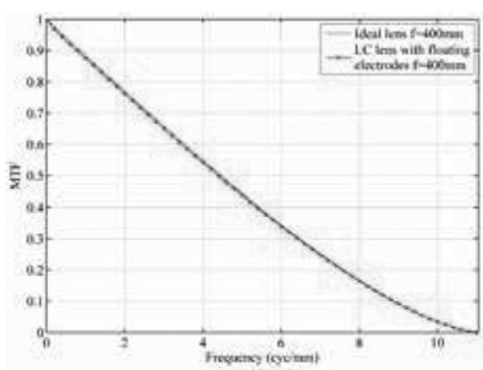


Figure 7. Numerically calculated MTF for the performance of LC lens with floating electrode, compared to an ideal lens of same power.

Summary

We have shown numerical results of the effect of gaps between the electrodes on the MTF of a liquid crystal lens using circular electrodes. The results show that for practical values of those gaps, there is significant haze introduced that lowers the zero frequency MTF values. To solve this problem we consider a liquid crystal lenses where "floating" electrodes are placed over the gaps and show a large improvement in its MTF.

References

[1] Li, L., Bryant, D., vanHeugten, T., Duston, D., & Bos, P. (2013). "Near-diffraction limited tunable liquid crystal lens with simplified design" *Optical Engineering 52*, p035007-1.

[2] Li, L., Bryant, D., vanHeugten, T., & Bos, P. (2013). "Physical limitations and fundamental factors affecting performance of liquid crystal tunable lenses with concentric electrode rings" *Applied Optics 52*, p1978.

[3] Li, L., Bryant, D., vanHeugten, T., & Bos, P. (2013) "Near Diffraction limited and low haze electrooptical tunable liquid crystal lens with floating electrodes" *Optics Express 21*, p8371.