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Accurate modeling of a high-resolution, liquid-crystal-based, optical phased array (OPA) is demonstrated. The modeling method is extendable to cases where the array element size is close to the wavelength of light. This is accomplished through calculating an equilibrium liquid-crystal (LC) director field that takes into account the fringing electric fields in LC OPAs with small array elements and by calculating the light transmission with a finite-difference time-domain method that has been extended for use in birefringent materials. The diffraction efficiency for a test device is calculated and compared with the simulation. © 2005 Optical Society of America


1. INTRODUCTION

A multielement tunable optical phase plate, called an optical phased array (OPA), could be considered for applications including correction of wave-front aberration caused by imperfect optical elements, random-access laser beam pointing, and dynamic focusing. Liquid crystals (LCs) are useful for an OPA because they can provide a variable effective refractive index with the application of an adjustable low voltage. LC OPAs have the advantages of being non-mechanical, high resolution, low power consumption, and low size-weight-profile factor, and simple to fabricate. One-dimensional (1-D) LC OPAs have been used for nonmechanical beam steering, and two-dimensional (2-D) LC OPAs (also referred to as spatial light modulators) have been used for optical pattern recognition, active or adaptive optics, laser beam shaping, optical tweezers, etc.

One of the key performance factors of these devices is the maximum deflection angle of the incident light that can be achieved. For example, if we consider a continuous change in the effective refractive index across the device, the maximum angle (θ) that an OPA can steer the light is determined from sin θ = (∆n)/d, where ∆n is the change in the index of refraction across the aperture width w, and d is the thickness of the LC material. However, because the birefringence of the LC materials is limited, the thickness of the device may become impractically large if large-angle steering is required. For monochromatic light, this limitation is resolved by considering an approach where the phase profile generated by the OPA is a mod 2π version of the desired phase profile. The phase discontinuity associated with the mod 2π version of the phase profile is usually referred to as a phase "reset." In this case, the maximum optical path-length change required at any point on the array is only λ (λ here is the wavelength of light). The mod 2π version of a linear phase ramp will then be a grating that has m segments. Each of the segments has a shorter linear phase ramp. The maximum steering angle of the device is now determined by sin θ = mλ/w. In this case, the device performance is determined by the precision of the mod 2π version of the desired phase profile. The sharpness of the associated phase resets becomes the most critical issue.

There are two issues associated with the sharpness of the phase resets in the mod 2π phase profile. One has to do with how accurately we can produce the phase jump in the LC material, and the other has to do with the propagation of light through the vicinity of the phase reset. In a previous paper, the modeling required to analyze these issues was discussed, and some interesting aspects of the light propagation in a grating formed with a birefringent material with an inclined optical axis were pointed out. However, the connection of these modeling methods to data acquired from a test LC OPA was not made. In this paper, we will briefly review the modeling methods with which we propose to analyze a LC OPA and then compare the results of these methods with the data from a test device. The paper is organized in the following way: First, we will give a description of the director simulation and the finite-difference time-domain (FDTD) simulation method being used. Second, the measurement method used to characterize the performance of the test device is described. Finally, the results of the director simulation and the FDTD simulation are compared with the data from a test LC OPA.
a LC OPA is described. Third, the diffraction efficiency (DE) predicted by the simple model and by simulation is compared with the experimentally determined one.

2. COMPUTER SIMULATION

A. Director Simulation

According to the continuum theory, the equilibrium LC director configuration is obtained by minimizing the Frank–Oseen free energy in the presence of an electric field. We assumed infinitely strong anchoring for the polyeimide alignment layer, so the anchoring energy term is not present in the free-energy term:

\[
f_g = \frac{1}{2}(K_{11}(\nabla \cdot n)^2 + K_{22}(n \cdot (\nabla \times n) - q_0)^2)
+ K_{33}(n \times (\nabla \times n))^2 - D \cdot E).
\] (1)

Here \(f_g\) is the Frank–Oseen free-energy density, \(K_{11}, K_{22},\) and \(K_{33}\) are the splay, twist, and bend elastic constants, \(n(x, y, z)\) is the unit vector director of the LC, \(D(x, y, z)\) is the electric field displacement and \(E(x, y, z)\) is the electric field, and \(q_0\) is the chiral wave vector \(q_0 = 2\pi/p\). \(p\) is the intrinsic chiral pitch of the LC. The electric field is computed by discretization and relaxation of

\[\nabla \cdot D = 0.\] (2)

Minimization of the free energy in the bulk of the LC is carried out by time relaxation of the LC director with use of the following updating rule:

\[n_i^{t+1} = n_i^t - \frac{\Delta t}{\gamma_1} [f_g]_{n_i}, \quad i = x, y, z.\] (3)

Here \(n_i^{t+1}\) is the \(i\)th component of the director at time step \(t + 1\) and \(n_i^t\) is the \(i\)th component of the director at time step \(t\). \(\Delta t\) is the time interval, \(\gamma_1\) is the rotational viscosity of the LC material, and \([f_g]_{n_i}\) is the functional derivative, given in the 2-D case by

\[
\frac{\partial f_g}{\partial n_i} \frac{d}{dx} \left( \frac{\partial f_g}{\partial n_i} \right) - \frac{d}{dy} \left( \frac{\partial f_g}{\partial n_i} \right).
\] (4)

The simulation software used to calculate the equilibrium director configuration is based on the equilibrium calculation routine LC3D. The model assumes that a 100-nm planarization layer with a dielectric constant \(\varepsilon = 4.5\varepsilon_0\) is placed on top of the upper and lower electrodes. To proceed with the calculation of the desired director configuration, one must select the voltage that will be applied to each array element. The desired phase profile is determined by considering the voltage versus phase retardation curve that is generated by assuming an infinite-area array element. Fringing electric fields are neglected in this case, and the mod 2\(p\) version of that wave front is derived. The desired phase is assigned to the center of each array element.

As an example of our method, a wave-front tilt that would cause the beam to deflect at an angle of 4.07 mrad is considered for an eight-electrode array of 19-\(\mu\)m-wide elements separated by a 0.4-\(\mu\)m gap. The calculated voltage versus phase curve neglecting the fringing electric fields is shown as the curve in Fig. 1. Given the required phase values of each of the eight elements, the voltages required to produce such phase values are shown as the eight points on the curve. If the size of the array element is larger than 10 \(\mu\)m, the phase in the center of each array element is essentially unaffected by the fringing fields and this method of selecting the array voltages is then satisfactory.

The simulated equilibrium director configuration for an eight-element array is shown in Fig. 2. By integration of the optical path length of the extraordinary light along the cell thickness direction, the 2-D phase profile of the LC blazed grating can be obtained as in Fig. 3. For the first seven pixels, the phase profile is very close to that of the ideal stairlike blazed grating. However, a transition region exists between pixel 8 and pixel 1, which is marked as the reset region in Fig. 3. In this region, the slope of the phase profile is opposite that of the desired blaze di-
cause in experiments a reflective LC OPA is used. However, the difference between experiments and the simulation is that in the simulation a continuous mirror is used instead of a segmented mirror. This is to isolate the effect of diffraction loss from the segmented mirror and that of the LC phase profile. A single LC OPA is also used to reduce the front surface reflection of the LC OPA. The refractive index of the single-layer AR coating is chosen to be \( n_{AR} = (n_{glass} n_{AR})^{1/2} \), where \( n_{glass} = n_{e,LC} \) and the thickness of the AR coating is \( \lambda / (4 n_{AR}) \). A plane wave with Gaussian intensity distribution is propagated through 24 electrodes with three resets. The light source is turned on from the beginning time step until the first wave reaches the metal mirror. For the rest of the time step, the light source remains off. The reason for this approach is that the front surface of the LC OPA and the metal mirror located at the rear of the LC OPA will reflect the laser beam. If the light source remained on all the time, the forward-propagating light from the source and the backward-propagating light reflected by the front surface of the LC OPA and the metal mirror will spatially overlap, making the analysis more difficult. In light of this, the collection of time-averaged complex field distributions at near field is carefully chosen, so that the front surface reflection and the main reflection from the metal mirror are spatially separated. In this way, the simulated diffraction efficiency pertains to a LC OPA with no front surface reflection. For the absorption boundary, the perfectly matched layer technique is used as described in Ref. 20. The simulated electric field distribution at the final time step is shown in Fig. 4.

The time-averaged near-field complex electric field distribution is collected at the exit aperture of the LC OPA at the final time step. The far-field diffraction pattern is obtained by computing the diffraction integral as shown in Eq. (7) (Ref. 21):

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y) e^{-j2\pi \Delta x x / \lambda} e^{-j2\pi \Delta y y / \lambda} dx dy = \begin{cases} \mathcal{F}(E(x,y)), & \text{if } \Delta x = \Delta y = 1/20, \\ 0, & \text{otherwise} \end{cases}
\]

Fig. 3. Simulated phase profile of an 8 pixel per reset maximum steering grating versus an ideal eight-step stairlike blazed grating for the visible version of LCOS. The elastic constant of the LC material is the same as that in Fig. 1. The dielectric constants are \( \varepsilon_r = 12.1 \varepsilon_0 \) and \( \varepsilon_e = 4.1 \varepsilon_0 \); \( d = 4 \mu m, n_e = 1.5035, n_r = 1.6742 \), the pixel size is 19 \( \mu m \), the interpixel gap is 0.4 \( \mu m \), and \( q_0 = 0 \).

Fig. 4. Near-field intensity distribution at the final time step \( (t = 6.59 \times 10^{-13} s) \) of beam propagation in a reflective LC blazed grating obtained by 2-D FDTD simulation. \( \lambda = 632.8 \text{ nm} \), grid spacing \( \Delta x = \Delta y = 1/20 \lambda \), and \( \Delta t = \Delta x/2c \), where \( c \) is the speed of light. The input beam is a plane wave with Gaussian beam intensity distribution with \( 1/e^2 \) diameter = 140 \( \mu m \).


\[ \eta = \left( \frac{\sin(\pi/q)}{\pi/q} \right)^2, \]

where \( q \) is the number of steps in the blazed profile. However, the blazed phase profile formed by a LC OPA is not an ideal one. The LC director orientation changes discontinuously in space, which causes a flyback region to form. Such a flyback region diffracts light to an undesirable diffraction order and is the main factor for light efficiency loss. A simple model that assumes that any light passing through this region is totally lost can be derived by adding a correction factor to Eq. (9) as proposed by McManamon et al.; in this case, the approximation for the DE is

\[ \eta_{\text{total}} = \left( \frac{\sin(\pi/q)}{\pi/q} \right)^2 \left[ 1 - \frac{\Lambda_F}{\Lambda} \right]^2, \]

where \( \Lambda_F \) is the width of the flyback region and \( \Lambda \) is the total length of one period of the grating. The width of the flyback region is unknown unless the director simulation results, as shown in Fig. 3, are used to obtain this value. The criterion that we used to define the width of the flyback region in this paper is that whenever the difference between the simulated value and the desired value is greater than 1/10 wave, the region is defined as the flyback region. Following this criterion, one can determine that the width of the flyback region is approximately 5 \( \mu \text{m} \).

4. EXPERIMENT

The LC OPA used in the experiment is an electrically controlled birefringence LC-on-silicon (LCOS) device.\textsuperscript{23,24} The LCOS device consists of a thin layer of LC material sandwiched between a glass top and a silicon backplane. The clear aperture of the LCOS is 15 mm \( \times \) 20 mm. On the silicon backplane, the drive electronics of each of the 1024 \( \times \) 768 pixels are located behind a segmented aluminum mirror. Each mirror is 19 \( \mu \text{m} \) square with a 0.4-\( \mu \text{m} \) gap between successive mirrors. Both the glass top and the silicon backplane are spin coated with a polyimide alignment layer that was treated so that the LC directors on both surfaces of the cell are parallel. The LC director makes an angle with respect to the surface of approximately 2° on account of the rubbing process.

The uniformity of the LCOS across the active aperture is important for phase modulation, since small thickness variations of the LC layer could cause the voltage versus phase curve to be a function of position on the device. The thickness uniformity of the LC layer across the active area is measured by imaging the 2-D birefringence map across the clear aperture for a given voltage. The spatial nonuniformity of the 2-D birefringence map is less than 1/10x peak to valley at 632.8 nm for any given voltage, which means that the voltage versus phase curve can be assumed to be uniform across the whole clear aperture without any further correction.

A complicating factor in acquiring data is that the surface shape of the silicon backplane is not flat. While the curvature on the silicon backplane does not affect the thickness uniformity of the LC layer, the whole LCOS is

3. SIMPLE MODEL

Although the diffraction pattern for light transmitted through a clear aperture is given by the diffraction integral [see Eq. (7)], such a description is less intuitive to an understanding of the physics of a 1-D blazed grating and will require extensive numerical evaluation of the diffraction integral. An analytical expression of an ideal blazed grating that maximizes the energy of the first diffraction order is given by\textsuperscript{1}

\[ \psi_{\text{far}}(x, y) = \frac{1}{4\pi} \int \frac{d}{ds} \nabla G \cdot \psi_{\text{near}}(r') \cdot \nabla G - G \]

\[ \cdots, (7) \]

where \( G = \exp(iR)/R \) is the Green function and \( \psi_{\text{near}} \) and \( \psi_{\text{far}} \) represent, respectively, the near- and far-field electric or magnetic field distribution. This vector representation of the diffraction integral can be simplified to a scalar approximation\textsuperscript{22} for the 1-D case:

\[ \psi_{\text{far}}(x, y) = \frac{\exp\left[ (i\pi/4) \int d \exp(-iR) \right]}{\sqrt{4\pi k}} \frac{\partial}{\partial y} \psi_{\text{near}}(x', y_0) + \frac{i}{k} (y_{\text{far}} - y_0) \psi_{\text{near}}(x', y_0) \]

\[ \frac{1}{R} \int dx', (8) \]

where \( R = [(x'-x_{\text{far}})^2 + (y_0-y_{\text{far}})^2]^{1/2} \) and \( k = 2\pi/\lambda \).

The far-field diffraction pattern of eight-level LC blazed gratings is shown in Fig. 5. The portion of total energy going into the \(-1\) diffraction peak is 86.7%, and the side-lobes are very small in this case.

**Fig. 5.** Far-field diffraction peak simulated by near-field-to-far-field transformation of the FDTD simulated near field. The far-field distance is 100 km. The inset is the magnified view of the first-order diffraction peak.
bent into a curved surface, which introduces aberration into the optical system. The transmitted wave-front aberration associated with the curved silicon backplane is measured with a phase-shifting interferometer. The seven-step 60° phase-shifting algorithm is used to extract the wave-front map of the measured aberration. In Fig. 6, one frame of such an interferogram is shown. For each phase-shifting step, 30 frames of interferograms are captured and averaged to reduce the noise. The reconstructed wave front is unwrapped and filtered with a 4 × 4 2-D Wiener noise removal filter. The first 16 terms of Zernike coefficients of the measured aberration are listed in Table 1. Low-order defocus and astigmatism are dominant in this case; high-order Zernike terms are present but are of small magnitude. The magnitude of the aberration is 18.7 waves P-V. A mod 2π version of the conjugate phase ramp is generated and applied to the LCOS to compensate for the aberration. After wave-front compensation, the residual uncorrected wave-front aberration is measured again. Residual wave-front aberration smaller than 1/10 P-V or 1/30 rms is observed, which indicates that diffraction-limited performance is reached. Figure 6(b) shows the result of a fringeless interferogram after compensation. A very weak ringlike structure is observed in the residual wave-front map. This is due to the 1.4% front surface reflection as well as to the small diffraction from the reset region.

After the compensation for the surface shape of the LCOS backplane, additional tip and tilt are added to the phase map to further steer the laser beam while performing wave-front compensation at the same time. The new phase plate serves a dual purpose: correction of surface deformation due to the silicon backplane and the steering of the laser beam. In Fig. 6(c), the LC OPA is programmed to steer the beam in both horizontal and vertical directions with a steering angle of 0.6 mrad. As previously reported, the DE of an LC OPA drops as deflection angle becomes larger. A maximum steering angle exists such that if the LC OPA is programmed to an angle larger than the maximum steering angle, the DE drop very quickly. Such a maximum steering angle is defined to be the angle corresponding to having 8 pixels within one reset. For the test device, the maximum steering angle is ±4.07 mrad. More details regarding this criterion are discussed in Refs. 10 and 19.

An important parameter regarding the performance of the LC OPA is the quality of the beam transmitted through the device. This is studied by first focusing the beam reflected from the LCOS with a 3-in. clear-aperture, small-numerical-aperture lens (effective focal length = 1170 mm) and measuring the far-field beam profile at the focus of the lens. This method of measuring the far field can spatially separate high-spatial-frequency components due to diffraction from resets. Thus a more faithful representation of the beam profile at an infinite far field can be obtained. The intensity profile at focus is recorded with both a CCD camera and a beam profiler from Photo-Inc. Both the centroid of the far-field beam and the relative peak intensity are recorded for 1 min in a standard laboratory environment where air vents are blocked. With the absence of LCOS in the optical system, the far-field beam waist was 1.11 × the diffraction-limited beam waist.

### Table 1. Zernike Modes of the Transmitted Wave-Front Aberration Introduced by Surface Deformation of the Silicon Backplane

<table>
<thead>
<tr>
<th>Zernike Term</th>
<th>Order</th>
<th>Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 piston</td>
<td>0</td>
<td>4.5913</td>
</tr>
<tr>
<td>2 tilt</td>
<td>1</td>
<td>−0.0267</td>
</tr>
<tr>
<td>3 tilt</td>
<td>1</td>
<td>0.2328</td>
</tr>
<tr>
<td>4 focus</td>
<td>1</td>
<td>4.4795</td>
</tr>
<tr>
<td>5 astigmatism</td>
<td>2</td>
<td>−2.9831</td>
</tr>
<tr>
<td>6 astigmatism</td>
<td>2</td>
<td>0.1839</td>
</tr>
<tr>
<td>7 coma</td>
<td>2</td>
<td>−0.4421</td>
</tr>
<tr>
<td>8 coma</td>
<td>2</td>
<td>0.0257</td>
</tr>
<tr>
<td>9 spherical</td>
<td>2</td>
<td>−0.0573</td>
</tr>
<tr>
<td>10 astigmatism</td>
<td>3</td>
<td>−0.0204</td>
</tr>
<tr>
<td>11 astigmatism</td>
<td>3</td>
<td>−0.0679</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.0442</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>−0.0103</td>
</tr>
<tr>
<td>14 coma</td>
<td>3</td>
<td>−0.0097</td>
</tr>
<tr>
<td>15 coma</td>
<td>3</td>
<td>−0.0105</td>
</tr>
<tr>
<td>16 astigmatism</td>
<td>3</td>
<td>−0.0378</td>
</tr>
</tbody>
</table>

Fig. 6. One frame of an interferogram of a beam reflected from LCOS: (a) noncompensated beam with aberration present, (b) compensated beam with aberration removed, (c) compensated beam with aberration removed and linear tip–tilt added to the phase ramp on LCOS to steer the beam to 0.6 mrad.
is 89.6 μm.) Thus the optical system is close to aberration free. However, the beam-pointing stability of the laser beam is measured to be approximately 5 μrad, which is limited by air turbulence in the laboratory environment. The magnitude of the turbulence through the measurement optical path (1.5 m) is observed to be up to three waves.

Then the LCOS device is introduced into the system. It has been observed that once the LC OPA is programmed to have a complicated diffraction pattern, air turbulence in the laboratory environment has a strong effect on the measured peak intensity at the far field. The measured peak intensity value can vary up to 10% depending on the laboratory environment. In light of this effect, the best observed peak intensity during 1 min of recording time is considered the measured peak intensity, excluding the influence of the air turbulence. This is justified because the air turbulence will only lower the measured peak intensity and not increase the measured value.

To measure the Strehl ratio of the beam after wave-front compensation, one has to consider several losses that could reduce the peak intensity of the compensated beam. These include (1) the diffraction loss due to the segmented mirror on LCOS, which can be approximately $1 - 0.96^2 = 8\%$ of the total optical power for coherent light (96% is the filling factor of the LCOS panel) and (2) an 8%–12% absorption or scattering loss in the aluminum mirror, which is not coated with a dielectric enhancement layer. These losses are intrinsic to the device and have nothing to do with the wave-front compensation. In the experiment, the reflectivity of LCOS is measured to be 80%. When the laser is reflected by the LCOS device, only the optical power going to the zero-order diffraction peak is collected. However, in this case, the 20% loss of power will not include the loss due to front surface reflection. Although the front cover glass of LCOS is coated with broadband AR in the visible region, an approximately 1.4% loss is observed for the front surface reflection for 632.8 nm. Since the front surface reflection is spatially overlapping with the main reflection beam from the LCOS device, both contributions will be recorded by the detector.

In Fig. 7, the far-field point-spread function captured by the CCD camera is shown. Figure 7(a) shows the case when a uniform gray scale is put on the LCOS and the aberration introduced by the silicon backplane is not removed. In the presence of the strong aberration, the beam at the nominal focus has a very low peak intensity but a large spot size. In Fig. 7(b), the mod 2π version of the compensation phase plate is introduced into the LCOS. The subsequent far-field peak is sharp, and the $1/e^2$ beam waist is approximately $1.2 \times$ the diffraction-limited beam waist. In Fig. 7(c), additional tip–tilt is added to the compensation phase plate to further steer the beam by 4.07 mrad. The cross section of the laser beam in Figs. 7(b) and 7(c) is shown in Fig. 8. Peak a in Fig. 8 is for the laser beam reflected from a mirror with the peak intensity reduced by 80% to take into account the reflectivity loss of the LCOS. Peak b is for the beam after wave-front compensation. The Strehl ratio of peak b with peak a used as a reference is 0.82. Peak c is the cross section of the beam after wave-front compensation and steering. The Strehl ratio of peak c with peak b used as a reference is 0.846. Using peak b as a reference is for comparison between the DE obtained by experiments and by the simulation in the discussion in Section 5. We will use such a normalization method for the following discussion.

5. COMPARISON OF SIMULATION, EXPERIMENT, AND SIMPLE MODEL

A comparison of the DE value obtained from the simple model, the FDTD simulation, and the experimental results is carried out, as shown in Fig. 9. A 24-pixel LC blazed grating is simulated with the phase ramp programmed to steer the beam up to an angle of 12.24 mrad. The DE is obtained by normalizing the peak intensity of the steered beam with the peak intensity of the non-steered beam. The DE is obtained by normalizing the peak intensity of the steered beam with the peak intensity of the non-steered beam. Figure 10 shows the phase profile of the LC blazed grating and the corresponding far-field diffraction peak for different steering angles. Even in the cases when the steering angle is three times larger than the defined maximum angle of 4.07 mrad, the FDTD shows less than a 0.3% discrepancy with the simple model.

The DE of a test OPA is measured by programming the LCOS to steer the beam in a plane defined by the rubbing
direction and the cell normal in order to make a head-to-head comparison with FDTD simulation. DE as used here is defined as the peak intensity of the beam at the desirable diffraction order versus the peak intensity of the nonsteered beam, after all aberration is removed (see peak b in Fig. 8). The measured DE of the LC OPA is shown in Fig. 9. We limit the steering range to within the maximum steering angle of 4.07 mrad. The reason is that, for a steering angle greater than this maximum steering angle, the compensation steering phase plate will have too many resets, which makes the accuracy of

Fig. 8. Far-field beam profile: (a) aberration-free laser beam with intensity reduced by 80% to take into account the reflectivity loss of LCOS, (b) wave-front compensated but nonsteered laser beam with Strehl ratio = 0.82 using (a) as a reference, (c) wave-front compensated and maximum steered beam with Strehl ratio = 0.846 using (b) as a reference.

Fig. 9. Comparison of DE as a function of steering angle for experimental results, FDTD simulation, and simple model.

Fig. 10. Phase profile and corresponding far field of an LC blazed grating. The elastic constant of the LC material is the same as that in Fig. 1. The dielectric constants are $\varepsilon_i = 12.1\varepsilon_0$ and $\varepsilon_s = 4.1\varepsilon_0$, $d = 4\, \mu m$, $n_s = 1.5035$, $n_e = 1.6742$, the pixel size is $19\, \mu m$, the interpixel gap is $0.4\, \mu m$, and $q_0 = 0$. The steering angle is $2.04\, mrad$ for (a) and (d), $8.16\, mrad$ for (b) and (e), and $12.24\, mrad$ for (c) and (f).
the far-field peak intensity measurement vulnerable to air turbulence in the laboratory environment and to electronic noise. From Fig. 9, we can see that the overall shapes of the three curves agree excellently with each other. On the average, the experimentally measured DE is approximately 5% lower than the prediction by the simple model and the FDTD simulation. This could be due to the fact that in the FDTD simulation and the simple model, the DE is calculated for an aberration-free system. However, in the experiment, an additional correction of 18.7 waves of aberration is needed to remove the aberration introduced by the silicon backplane. Since the efficiency loss due to the introducing of additional fringes into the wave front is a function of steering angle, our normalization may be less accurate at large steering angles. Besides this effect, air turbulence could not be completely removed in the laboratory environment and electronic noise in the LCOS panel can also contribute to the 5% DE loss. In Table 2, a comparison of DE and steering angle at maximum steering angle between the simulation, the simple model, and the experimental results is shown.

With the above considerations, we concluded that the accuracy of the director simulation and the FDTD simulation is very high. The limiting factor that prevents us from getting better agreement between FDTD simulation and experiment is the accuracy of the experiments, which contain many factors that are not considered in the FDTD simulation. For example, the correction of additional aberration in the LCOS backplane, the electronic noise in the LCOS panel, the air turbulence in the laboratory environment, etc., can contribute to an observed efficiency lower than that predicted. For the current test LC OPA, we demonstrated the best possible steering efficiency predicted by the simple model and the FDTD simulation. Our previous paper discussed in more detail steering in both horizontal and vertical directions; for more information, see Ref. 23.

| Table 2. Comparison of Diffraction Efficiency and Steering Angle for Simple Model, Simulation, and Measurement at Maximum Steering Angle |
|-----------------|-----------------|
| DE              | Steering Angle  |
| Simple model    | 89.3%           | 4.075            |
| FDTD simulation | 89.1%           | 4.076            |
| Measurement     | 84.6%           | 4.071            |

6. CONCLUSION

The LC director simulation and the FDTD optical simulation can be powerful tools with which to study the LC OPA. A quantitative picture of the DE of a LCOS spatial light modulator is given. Excellent agreement among simple model, measured DE, and simulation has been shown. The full three-dimensional director simulation software used in this paper takes into account the electric field distribution between electrodes and thus can accurately determine the phase profile of the LC OPA for feature sizes smaller than the wavelength of light. The fraction of light through the phase reset region is taken into account by FDTD simulation. Thus the simulation method used in this paper is extendable to cases where the electrode size of the LC OPA is close to the wavelength of light and the fringing electric field between neighboring electrodes becomes the dominating factor of the DE of the LC OPA.26 This is experimentally shown in comparison of the DE for experimentally measured data with that of the FDTD simulation.

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