Liquid Crystal on Silicon Wavefront Corrector

Xinghua Wang (1), Philip J. Bos (1), John Pouch (2), and Felix Miranda (2)

(1) Liquid Crystal Institute, Kent State University, Kent, OH
(2) NASA Glenn Research Center, Cleveland, OH

A low cost, high resolution, liquid crystal on silicon, spatial light modulator has been developed for the correction of huge aberrations in an optical system where the polarization dependence and the chromatic nature are tolerated. However, the overall system performance suggests that this device is also suitable for real time correction of aberration in human eyes. This device has a resolution of 1024×768, and is driven by an XGA display driver. The effective stroke length of the device is 700 nm and 2000 nm for the visible and IR regions of the device, respectively. The response speeds are 50 Hz and 5 Hz, respectively, which are fast enough for real time adaptive optics for aberrations in human eyes. By modulating a wavefront of $2\pi$, this device can correct for arbitrary high order wavefront aberrations since the 2-D pixel array is independently controlled by the driver. The high resolution and high accuracy of the device allow for diffraction limited correction of tip and tilt or defocus without an additional correction loop. We have shown that for every wave of aberration, an 8 step blazed grating is required to achieve high diffraction efficiency around 80%. In light of this, up to 125 waves peak to valley of tip and tilt can be corrected if we choose the simplest aberration. Corrections of 34 waves of aberration, including high order Zernike terms in a high magnification telescope, to diffraction limited performance (residual wavefront aberration less than 1/30λ at 632.8nm) have been observed at high efficiency.
Liquid Crystal on Silicon wavefront corrector

Mark (Xinghua) Wang, Philip J. Bos
BosLab, Liquid Crystal Institute, Kent State University

John Pouch, Felix Miranda
NASA Glenn Research Center, Cleveland, OH 44135

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Outline

• LCoS SLM Vs. MEMS or Deformable Mirror
• Basics of Liquid Crystal on Silicon (LCoS) Spatial light modulator (SLM)
• Light propagation in LCoS
• Chromatic effect in diffractive wavefront compensation
• Performance of LCoS SLM for wavefront correction

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Adaptive Optics (AO) for diffractive retina imaging in Prof. David William's Lab
What is the benefit to replace DM with LCoS SLM

$10^3$ cost reduction, $10^3$ resolution increase, potential portable system, simplified driving scheme

Aberration simulator for patient to see the effect of refractive surgery before surgery.

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# LCoS SLM vs Deformable Mirror

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| LCoS SLM | Speed 50 Hz for 1 um stroke  
Speed 6.6 KHz  
Low driving voltage 0~5v  
Aperture 20mm*15mm  
stroke: up to 2.5 um (no limit with wavefront wrapping)  
no inter-pixel coupling  
light weigh, low profile  
resolution > 1024*768  
< $3000 with driver, | (good enough for aberration correction in human eye)  
> $250,000/ batch without driver  
less than 2 um  
< resolution 12*12, 32*32  
15% Inter-Pixel coupling,  
High driving voltage, expensive driver |
| MEMS DM* |  
Aperture 3.3 mm, 10 mm  
High reflectivity > 95%  
Speed 6.6 KHz  
1~2 KHz  
349 Acttuators |  
> $1000/ Actuator  
Clear Aperture 148.6mm |


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Light Propagation in LCoS

Ideal stair like blazed gratings

1st order resets

simulated stair like blazed gratings formed by LC device

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Finite Difference Time Domain Simulation of LCoS wavefront corrector

Wavefront corrector simulation

X direction (grid point)

Y direction (grid point)

Far Field intensity

Intensity (a.u.)

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Chromatic effect in diffractive wavefront compensation

Chromatic effect depends strongly on correction magnitude

Choose Secondary peak <5% criteria

At maximum correction (125 waves)

**Bandwidth=50 nm**

* Agrees with Mark Gruneisen’s experimental results of a similar LC SLM system. SPIE Proc Vol. 5162, p172, 2003

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Liquid Crystal on Silicon Spatial light modulator

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>1024*768</td>
</tr>
<tr>
<td>Pixel Spacing</td>
<td>19.4 μm</td>
</tr>
<tr>
<td>Aperture</td>
<td>20mm*15mm</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>80%</td>
</tr>
<tr>
<td>Filling factor</td>
<td>96%</td>
</tr>
<tr>
<td>Speed</td>
<td>50Hz, 25Hz, 5Hz</td>
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<tr>
<td>Effective stroke length</td>
<td>0.7 μm, 1.3 μm, 2.5 μm</td>
</tr>
</tbody>
</table>
Switching speed of LCoS

Time Response of current 4 micron device
(Switch off at room temperature 25c)

Switching on: 12.5 ms
Switching off: 20 ms

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Inter-pixel coupling is negligible
Measurement and correcting system of aberration in 8 inch mirror.
Initial wavefront aberration in 8 inch telescope

Before correction:

34 waves of aberration P-V
Strehl ratio 0.006

<table>
<thead>
<tr>
<th>Zernike term</th>
<th>Order</th>
<th>Waves</th>
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<tbody>
<tr>
<td>1</td>
<td>Piston 0</td>
<td>7.781</td>
</tr>
<tr>
<td>2</td>
<td>Tilt 1</td>
<td>1.603</td>
</tr>
<tr>
<td>3</td>
<td>Tilt 1</td>
<td>-0.583</td>
</tr>
<tr>
<td>4</td>
<td>Focus 1</td>
<td>7.751</td>
</tr>
<tr>
<td>5</td>
<td>Astig. 2</td>
<td>2.097</td>
</tr>
<tr>
<td>6</td>
<td>Astig. 2</td>
<td>0.776</td>
</tr>
<tr>
<td>7</td>
<td>Coma 2</td>
<td>0.640</td>
</tr>
<tr>
<td>8</td>
<td>Coma 2</td>
<td>-0.130</td>
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<tr>
<td>9</td>
<td>Spherical 2</td>
<td>0.0783</td>
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<tr>
<td>10</td>
<td>Astig. 3</td>
<td>0.195</td>
</tr>
<tr>
<td>11</td>
<td>Astig. 3</td>
<td>-0.052</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.295</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>-0.031</td>
</tr>
<tr>
<td>14</td>
<td>Coma 3</td>
<td>0.056</td>
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<tr>
<td>15</td>
<td>Coma 3</td>
<td>-0.045</td>
</tr>
<tr>
<td>16</td>
<td>Astig. 3</td>
<td>-0.060</td>
</tr>
</tbody>
</table>

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Residual wavefront aberration

After correction:

1/10 wave of aberration P-V
Strehl ratio=0.83

Diffraction limited performance!

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Diffraction efficiency of wavefront compensation
Dynamic Compensation/ tip-tilt/ focusing

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Conclusion

- LCoS SLM is capable of high efficiency wavefront compensation while offering:
  <3k cost, ~1M resolution, correct arbitrary high order aberration, (up to 125 waves of tip-tilt or 60 waves P-V defocus)

- Enough speed (50Hz) for tracking movement of human eyes

- Chromatic effect strongly depends on magnitude of correction, at least 50 nm bandwidth is tolerable.

- LCoS SLM seems very suitable for aberration correction in human eyes. Very attractive for:
  Obtaining diffraction limited retina image in human eyes,
  Aberration simulator for patient to see the effect of refractive surgery.

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Acknowledgement

- Dr. Ronald Krueger, Cleveland Clinic
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  For very helpful discussion regarding the application of LCoS in correction of wavefront aberration in human eyes.

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