Binary Phase Mode

Short Tutorial & Applications

ForthDD 2019
• Diffraction
• Binary Phase Theory
• Binary Diffraction from Ferroelectric Liquid Crystal on Silicon -FLCoS-
• Measurements, Results, Demo Unit
• QXGA – SLM and interface options
• Application References
• Diffraction is an interference effect due to changes in the wavefront

• Far field diffraction – when the distance from the obstacle, a, to screen is $> a^2/\lambda$

• We will only be considering far field diffraction
• Diffraction grating with coherent illumination

- Constructive interference at angles such that:
  \[ \sin(\theta_m) = \frac{m\lambda}{a} \]

- Destructive interference at angles such that:
  \[ \sin(\theta_m) = \frac{(m + 0.5)\lambda}{a} \]
• You don’t just have to block the wavefront to create diffraction

• Diffraction can be created by introducing phase difference between parts of the wavefront

  - Phase difference now created by $\Delta n$ and path length (which makes things more complex!)

  - If $\Delta n \cdot d = (c+1)\lambda/2$, destructive interference occurs at $\theta = 0$ ($c =$ integer) i.e. no zero order

  - It is possible to create grating with multiple phase levels (e.g. several $d$’s or $n$’s)

  - Forth Dimension Displays’ SLM can only create 2 levels (binary), so that is what will be considered
Why binary: FLCoS Structure

Top view of microdisplay

Cross-section of pixel

Incident Light (Illumination)

Reflected Light (Image)

Cover Glass

Front Electrode

Pixel Mirror

FLC

Silicon
Why binary: FLC Switching

- Rod-like molecules (~3 nm)
- Layered structure: layer normal $\mathbf{z}$
- Molecular long axis $\mathbf{n}$
- Just two tilt positions with tilt angle $\pm \Theta$

- FLC Polarisation couples with E-field
- FLC layer thickness <1 µm
- Optimised for 555 nm
- Binary in-plane switching
- Dynamic switching angle (DSA) = $2\Theta$
- Switching time ~40 µs @ 2.5V/µm
• For diffraction gratings, the *diffraction efficiency*, $\eta_m$, of each diffracted order (m) is the ratio of the power in the order to that of the incident beam.

• For a binary phase grating the diffraction efficiencies are calculated as:

Zero order (n=0) \[ \eta_0 = \left( \frac{b}{a} \right)^2 4\cos^2(p\pi) \]

$\pm$-m order \[ \eta_m = \frac{4\sin^2\left( \frac{b}{a} \frac{m\pi}{m\pi} \right)}{(m\pi)^2} \sin^2(p\pi) \]
- So, for a binary phase grating with $\pi$ ($p = 0.5$) phase difference, the theoretical diffraction efficiencies are:

<table>
<thead>
<tr>
<th>Order</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\pm 1$</td>
<td>40.5</td>
</tr>
<tr>
<td>$\pm 2$</td>
<td>0</td>
</tr>
<tr>
<td>$\pm 3$</td>
<td>4.5</td>
</tr>
<tr>
<td>$\pm 4$</td>
<td>0</td>
</tr>
<tr>
<td>$\pm 5$</td>
<td>1.6</td>
</tr>
<tr>
<td>$\pm 6$</td>
<td>0</td>
</tr>
</tbody>
</table>
Binary Phase Gratings (3)

• The efficiency is related to the phase difference by a $\sin^2$ term:

$$\eta_m = \frac{4 \sin^2 \left( \frac{b - m \pi}{a} \right)}{(m \pi)^2} \sin^2(p \pi)$$

• For ForthDD’s SLM, (a nominal half wave plate i.e. $\pi$ phase difference), the efficiency will be wavelength dependent and also dependent on the cell gap thickness:

$$Display\ phase\ difference = \frac{2\pi \cdot d \cdot \Delta n\lambda}{\lambda}$$  
Where $d = 2 \times Cell\ Gap$
Binary Phase Gratings (4)

• No need for an output polarizer or alignment.

Diffraction Efficiency is proportional to $0.5 \cdot (1 - \cos(2\text{DSA})) = \sin^2(\text{DSA})$

• So, max efficiency for DSA = 90°
• In case of ForthDD’s FLC the DSA = 33°, so $\sin^2(33) = 30\%$
• So (assuming true HWP performance), $\eta_{\pm1} = 30\% \cdot 40.5\% = 12.2\%$
• The polarization state of the constructively interfering light is the same as the input polarization state (phase only) if aligned to bisected angle of DSA (i.e. 33°/2) +45°.
Binary Phase Gratings (5)

- Relative efficiency versus DSA from 0° to 90°

100% equals 40.5% efficiency into each +1st and -1st order

DSA of ForthDD’s FLC
543.5nm HeNe
Unexpanded beam diam. = 124 pixel

Power meter

Glan-Thomson polarizer

Output polarizer (absorption)

SLM @ 40°C
Angle of incidence on display = 9.1°
• What are the fixed patterns and where do they come from?

QXGA SLM fixed patterns
(distortion due to angled view)

- Zero order
- Inter Pixel Gap
Demo unit
Demo unit

QXGA Microdisplay

Polarizer

Mirror

Diffuser

Beam Expander

Laser Diode 532nm
Note the mirror point of +1st & -1st diffractive order at the zero order.

Zero order and hexagonal diffraction pattern due to interpixel gaps are visible.

Speckle contrast reduction option by coherent temporal summation (averaging) proportional to $\sqrt{N}$ phase masks showing the same far field image.

Inherent phase stability.

Transmission function calculated using LightTrans „VirtualLab Fusion“

$\text{www.lighttrans.com}$
Other optical functionalities

Transmission function can be programmed to show

- Grey-scale images (example: 8 bit)
- Offset of 1st order
- Wavefront correction up to $1/\pi$ (33%)
- 2 Vortex beams of opposite helicity:

Schematic representation of transmission function (Ronchi linear diffraction grating with a „fork“ dislocation and resultant vortex beams, image to the left)

Transmission function calculated using LightTrans „VirtualLab Fusion“
www.lighttrans.com
Other optical functionalities

- Beam Shaping & Polarisation Control
### Properties of QXGA SLM

<table>
<thead>
<tr>
<th>SLM Property</th>
<th>QXGA data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>2048 x 1536</td>
</tr>
<tr>
<td>Pixel number</td>
<td>3.1 M Pixel</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>94 %</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>8.2 µm</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>430 – 800 nm*</td>
</tr>
<tr>
<td>Active Area</td>
<td>16.8 x 12.6 mm</td>
</tr>
<tr>
<td>+/-1st diffracted order efficiency @ 20°C</td>
<td>10% @ 544 nm</td>
</tr>
<tr>
<td></td>
<td>8.2% @ 488 nm</td>
</tr>
<tr>
<td>Tested Power (cw)</td>
<td>1.3W @ 550 nm</td>
</tr>
<tr>
<td></td>
<td>3.5W @ 1064 nm</td>
</tr>
</tbody>
</table>

Option: Extended Storage Temperature

-40°C - +80°C

* Near-IR possible at reduced efficiency
<table>
<thead>
<tr>
<th>SLM Model</th>
<th>QXGA-3DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 bit Refresh Rate</td>
<td>40 Hz - &gt; 4.5 kHz</td>
</tr>
<tr>
<td>On-board Storage</td>
<td>1024 bit planes</td>
</tr>
<tr>
<td>Trigger ports</td>
<td>RS232, RS485 + 3 user-defined</td>
</tr>
</tbody>
</table>
## Video Interface: QXGA-R10-AUX

<table>
<thead>
<tr>
<th>SLM Model</th>
<th>QXGA-R10-AUX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refresh Rate via DisplayPort</td>
<td>Max 100 Hz, 24 bit @ 2048 x 1536 resolution</td>
</tr>
<tr>
<td></td>
<td>Max 240 Hz, 24 bit in SXGA 1280 x 1024 window</td>
</tr>
<tr>
<td></td>
<td>Max 400 Hz, 18 bit in XGA 1024 x 768 window</td>
</tr>
<tr>
<td>Sync ports</td>
<td>1 IN, 6 OUT</td>
</tr>
<tr>
<td>Thermal Management</td>
<td>included</td>
</tr>
</tbody>
</table>
2k x 2k SLM

New Product
• 2k-R10 (video interface) in Q1 2020
• 2k-3DM (memory based interface, pictured right) in Q3 2020
• Pixel pitch 8.2 \( \mu \text{m} \)
• Optical performance identical to QXGA
• Interface performance tbd.
Super Resolution Microscopy: Structured Illumination for LLS, TIRF, SPIM, SMLM, Scanning

- “A guide to structured illumination TIRF microscopy at high speed with multiple colors“, Young *et al*.* JoVe*  [https://doi.org/10.3791/53988](https://doi.org/10.3791/53988) (2016), In depth guide for the assembly and operation of a structured illumination TIRF microscope.
- „Super-resolution using speckle illumination microscopy“, A. Negash *et al*., *Imaging and Applied Optics 2017* (OSA Technical Digest) paper MTh1C.2 , [https://doi.org/10.1364/MATH.2017.MTh1C.2](https://doi.org/10.1364/MATH.2017.MTh1C.2)
Super Resolution Microscopy: Structured Illumination for LLS, TIRF, SPIM, SMLM, Scanning

- „Compressive sensing for fast 3-D and random-access two-photon microscopy“, C. Wen et al., Opt. Lett. 44 (17), 4343-4346 (2019) [https://doi.org/10.1364/OL.44.004343](https://doi.org/10.1364/OL.44.004343)
- „Spatially resolved random-access pump-probe microscopy based on binary holography“, C. Wen et al., Opt. Lett. 44 (16) 4083-4086 (2019) [https://doi.org/10.1364/OL.44.004083](https://doi.org/10.1364/OL.44.004083)
Applications

Optogenetics

Holographic Optical Tweezers / Vortex Beam / Real Time
- „Dynamical hologram generation for high speed optical trapping of smart droplet microtools“, P. M. P. Lanigan et al., *BIOMEDICAL OPTICS EXPRESS* 3 (7), 1609 (2012)

Beam Shaping & Polarisation Control

Spatial Filtering
Surface quality by Interference


2D Binary Holograms


3D Binary Computer Generated Holograms


Holographic Projection

Free space optical communication

Optical Computing