LCOS Spatial Light Modulator Technology

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SLM Workshop
27.10.2017, EPFL Lausanne

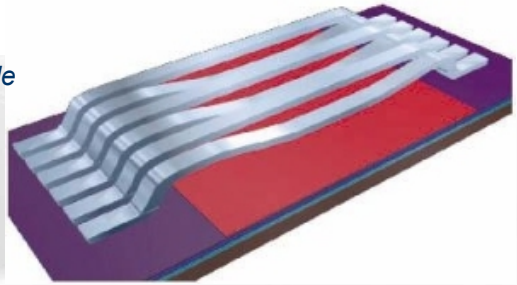
SLMs Variety Today

MEMS (one- or two dimensional)
- Piston-like (e.g. GLV)
- DMD
- Membrane

LCD (one- or two dimensional)
- Trasmissive LCD
- LCOS
- OASLM

Other

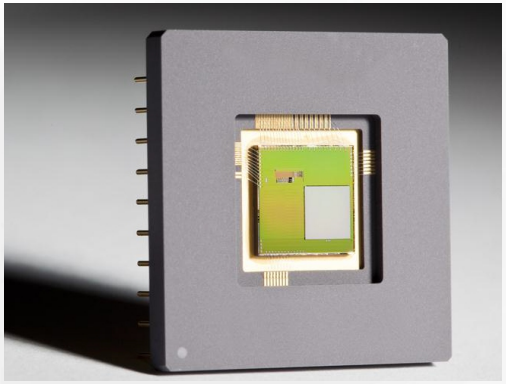
OKO Mirror, courtesy of Flexible Optical (OKO-Tech)



GLV, courtesy of Silicon Light Machines

TFT LCD microdisplay, courtesy of Kopin

HOLOEYE LCOS SLM, LETO series



CMOS-based 240x200 piston-type MEMS, courtesy of Fraunhofer IPMS

LCOS Structure and Function

Nematic Liquid Crystals

Director distribution (**n**):

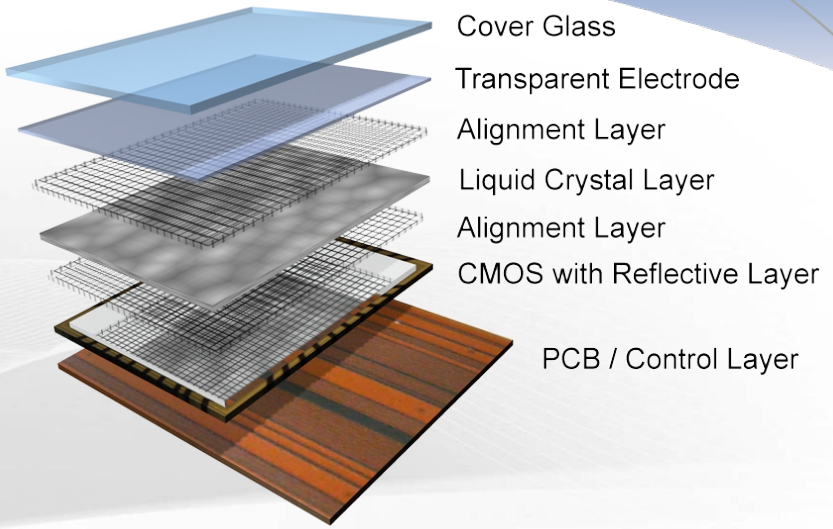
No Voltage → boundary conditions

→ minimization of Frank's free energy density

$$F = \frac{1}{2} K_{11} (\nabla \cdot n)^2 + \frac{1}{2} K_{22} (n \cdot \nabla \times n)^2 + \frac{1}{2} K_{33} |n \times \nabla \times n|^2$$

$K_{11} - splay$, $K_{22} - twist$, $K_{33} - bend$

→ similar to elastic energy (spring)



Most used modes:

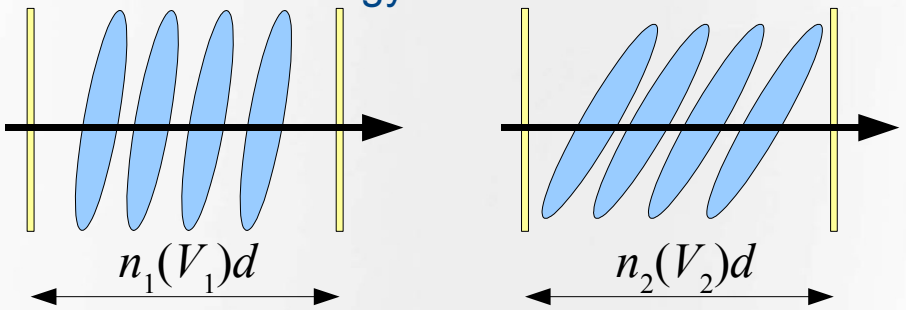
→ homogenous (parallel aligned, PA, ~splay)

→ homeotropic (vertically aligned, VA, ~bend)

→ twisted (chirally aligned, TN, ~twist)

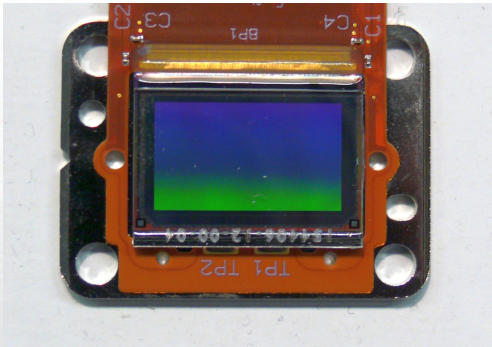
Applied Voltage → dielectric anisotropy → Electrostatic free energy

$$u = \frac{1}{2} \frac{D^2}{\epsilon_{\parallel} - \Delta\epsilon \sin^2 \theta(z)}$$



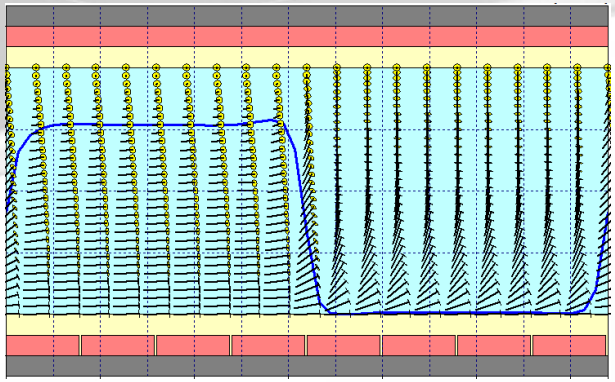
LCOS Structure and Function

- Intrinsic polarization modulation / phase modulation for p- and/or s-polarizations
  - Phase-only modulation: light linear polarized parallel to director alignment for both homogenous and homeotropic alignment
  - Intensity modulation: light linear polarized under 45° to director alignment crossed or parallel polarizers scheme; for homeotropic and twisted alignment, also for homogenous
  - Various approaches for complex modulation (e.g. multiple panels)

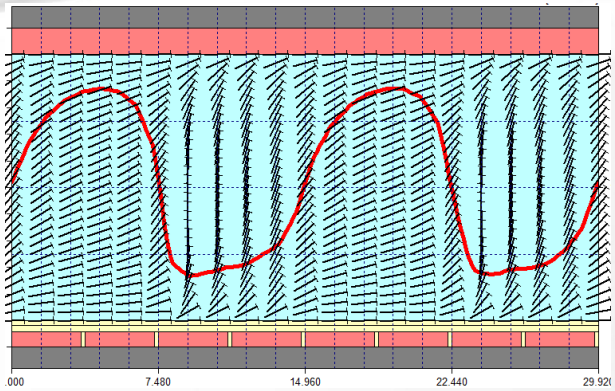


LCOS microdisplay

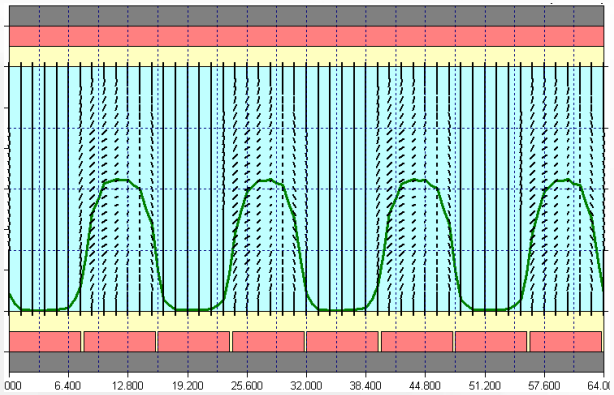
Simulated director distribution and reflectance for TN (intensity modulation) SLM



Simulated director distribution and retardance for homogenous (phase modulation) SLM



Simulated director distribution and retardance for homeotropic (phase modulation) SLM



LCOS SLMs: CMOS Backplane

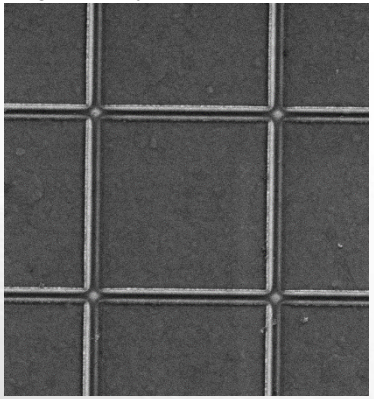
— CMOS process with top-metall layer
— High quality Aluminium pixel mirror and passivation layer (at a broader wavelength range) → R~70-80%

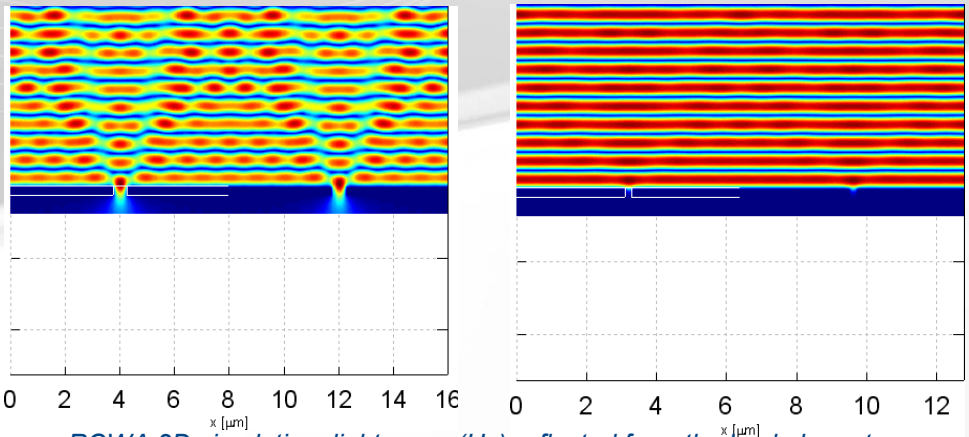
— Integration of dielectric coatings in wafer manufacturing process → R~99%

— Processes for smaller pixel structures (2-8um) and interpixel gap (200-500 nm)

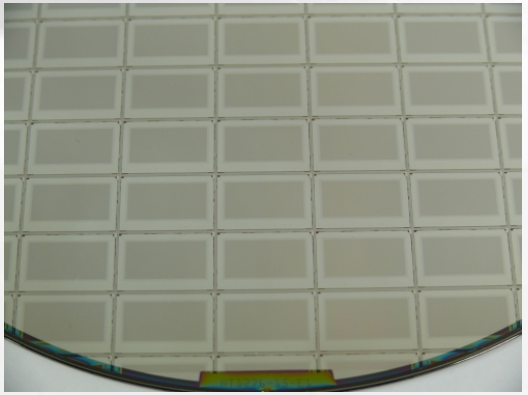
—Pixel arrays up to 4160x2464 (10Mpix)

Image courtesy Fraunhofer IZM/Gollhardt



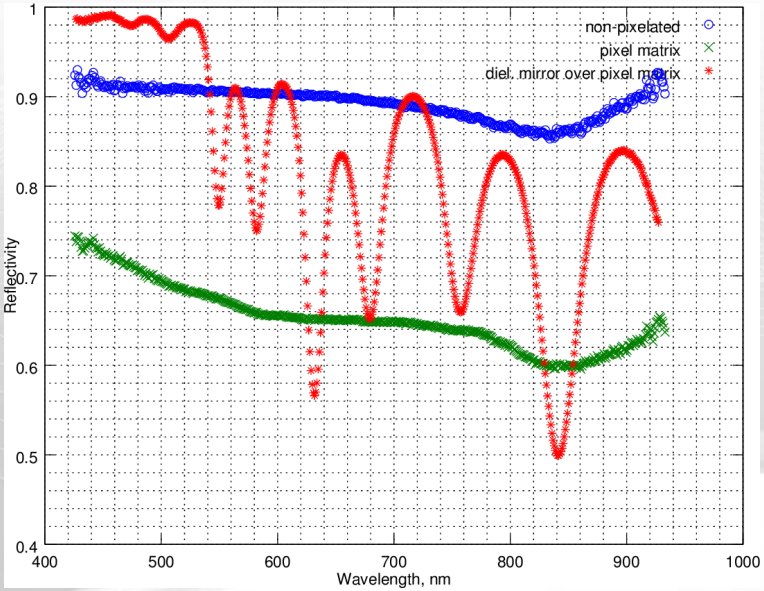


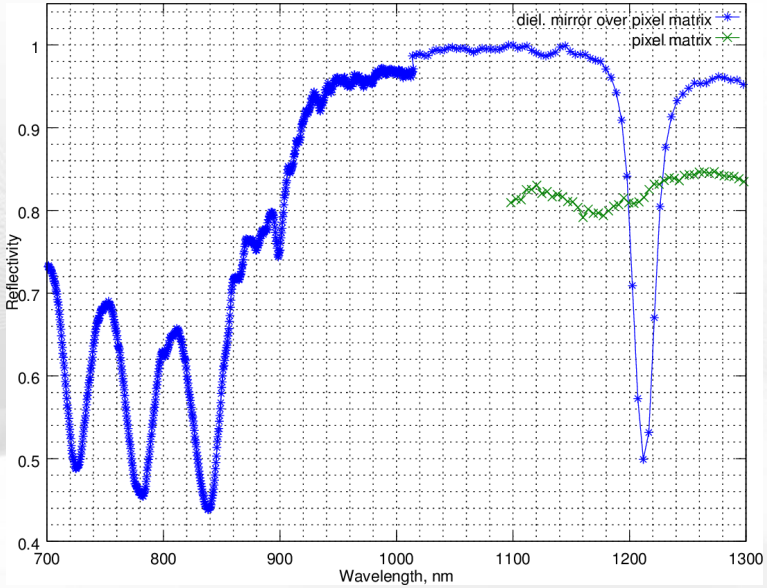
RCWA 2D simulation, light wave (Hx) reflected from the backplane, two different interpixel gaps



0.25 micron process 8“ CMOS wafer - 0.7“ HD LCOS

CMOS Backplane: reflectivity improvement





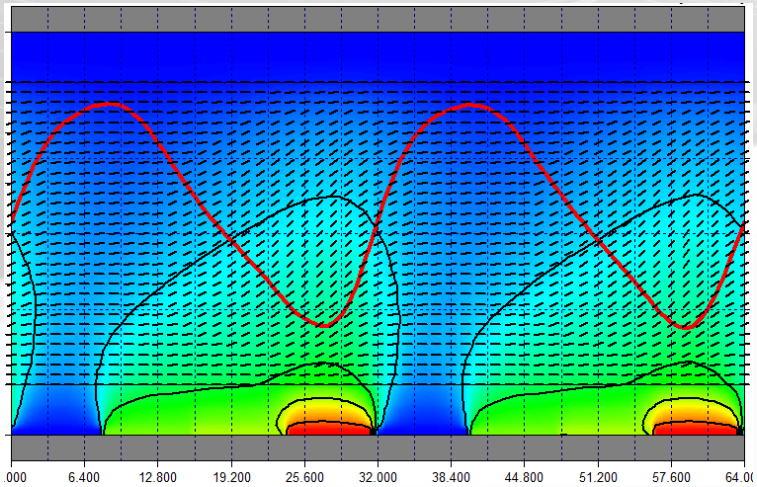
Optimization of the LCOS technology for laser microprocessing applications. G Lazarev. Elsevier Phys.Procedia 83 (2016)

Power handling note: PLUTO C-49 withstands long-time test with almost 200W cw 1070 nm laser (Intensity >450W/cm^2)

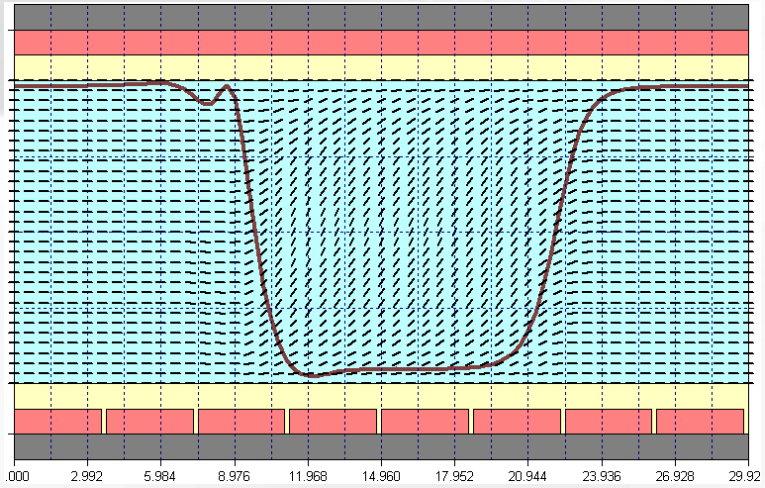
LCOS Cell

- Spectral bands: UV, SWIR, MWIR..(LCs can work even in THz!)
- UV: Absorption ITO and cover glass materials, UV sensitivity of the (organic) alignment, LC-damage
- Phase shift > 1 wavelength (>2pi)

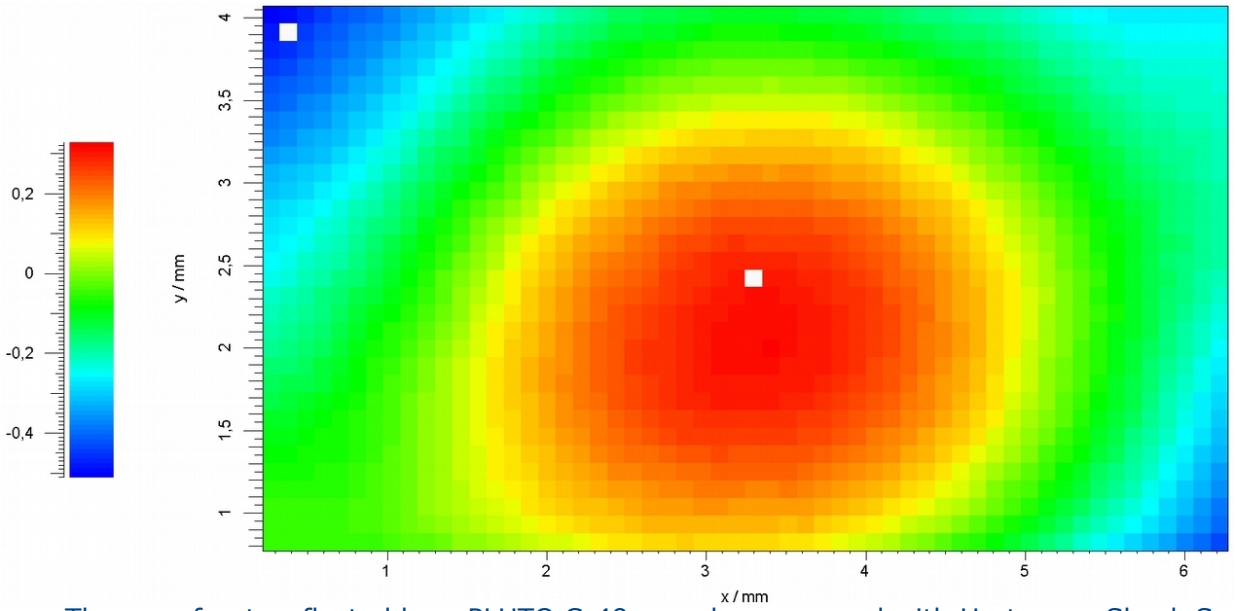
Simulation of director distribution (2D) and electrostatic field for 4 pixel blazed grating



Simulation of director distribution (2D) for 8 pixel binary grating

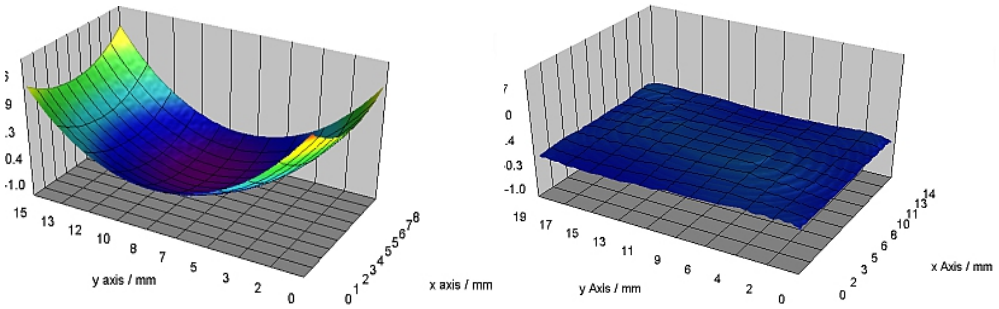


Optical Flatness



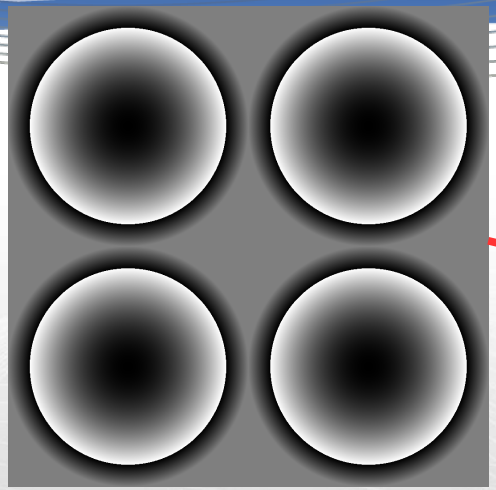
RMS 0.18um
(0.07um)
P-V=0.84um
(0.52um)

The wavefront, reflected by a PLUTO C-49 sample, measured with Hartmann-Shack Sensor

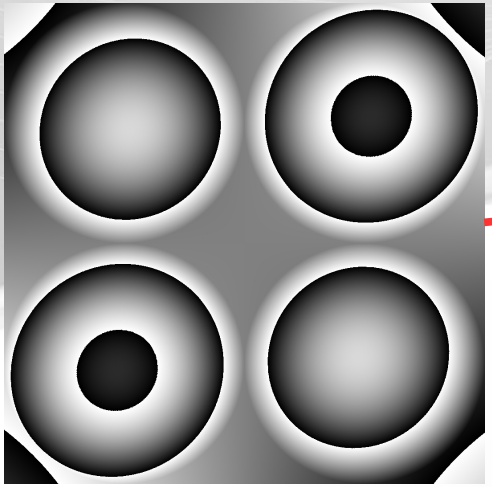


The uncorrected (left) and corrected (right) wavefront, reflected by a PLUTO sample, measured with interferometer

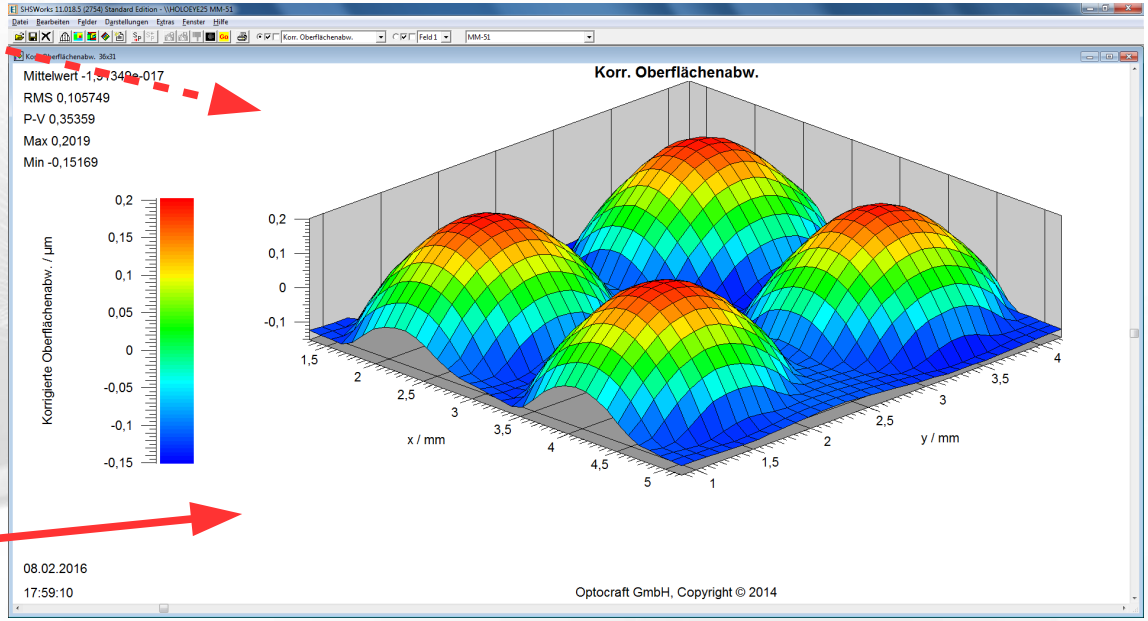
Correction of the SLM wavefront in application



No correction



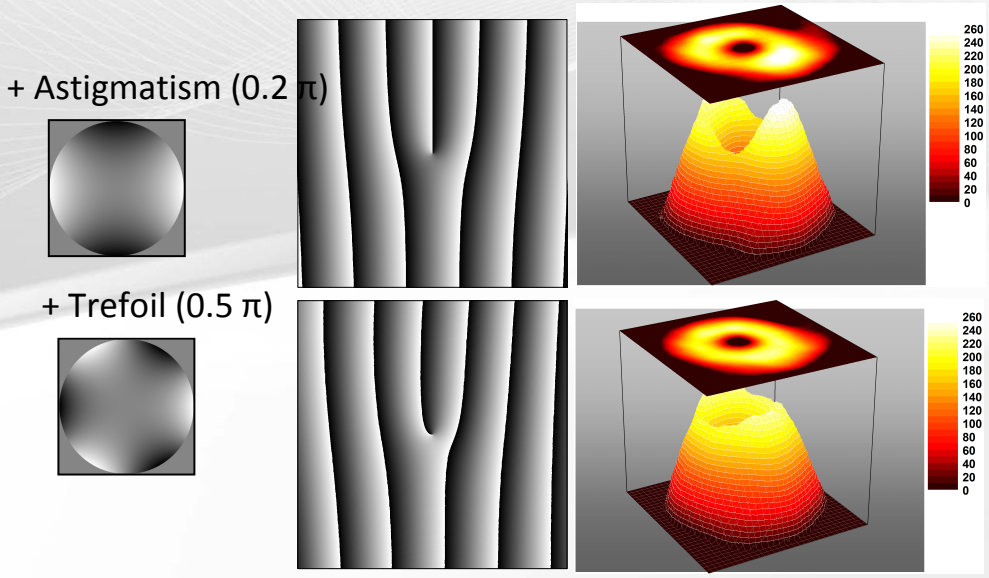
Corrected pattern



The wavefront, reflected by a PLUTO C-49 sample, measured with Hartmann-Shack Sensor, where 2x2 lens array is addressed onto SLM

Correction of the SLM wavefront in application

Example: quality of the doughnut spot is very sensitive to aberrations

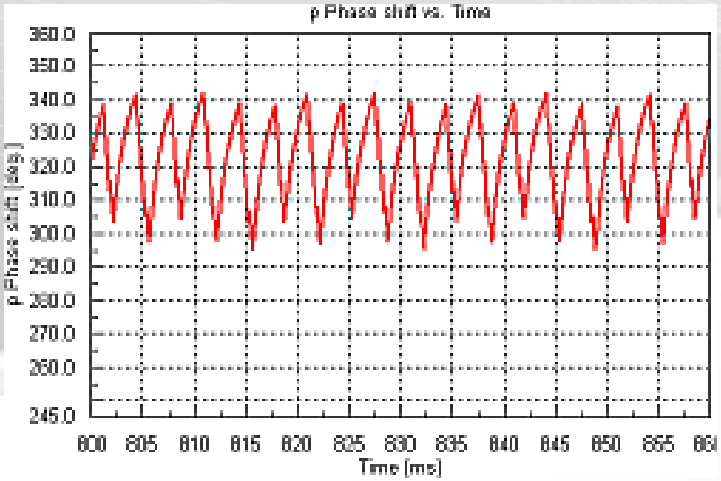


Courtesy University of Potsdam

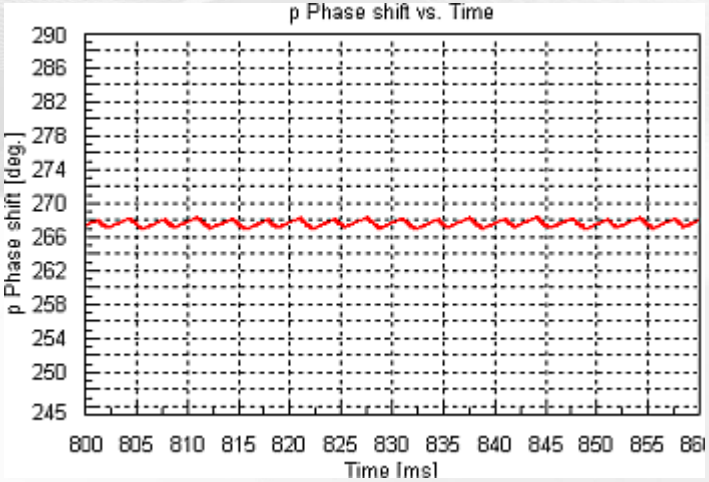
Driving schemes for LCOS SLMs

- Analogue modulation is theoretically ideal
- Pulse-width modulation is poor for phase applications
- Pulse code modulation with high-bandwidth and custom sequences was adapted for phase and intensity applications

Typical voltage PCM sequence, applied to digital pixel (field inversion ignored for simplicity)



Simulation of the dynamic response for certain design and addressed phase level

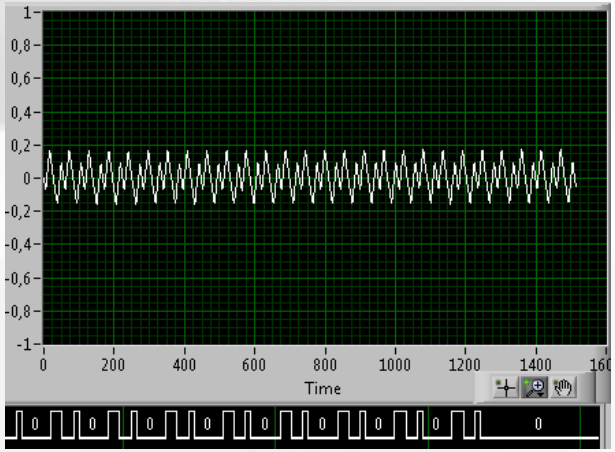


Simulation of the dynamic response for optimized design

Driving schemes: PCM

Example of pixel voltage using PCM (field inversion omitted)

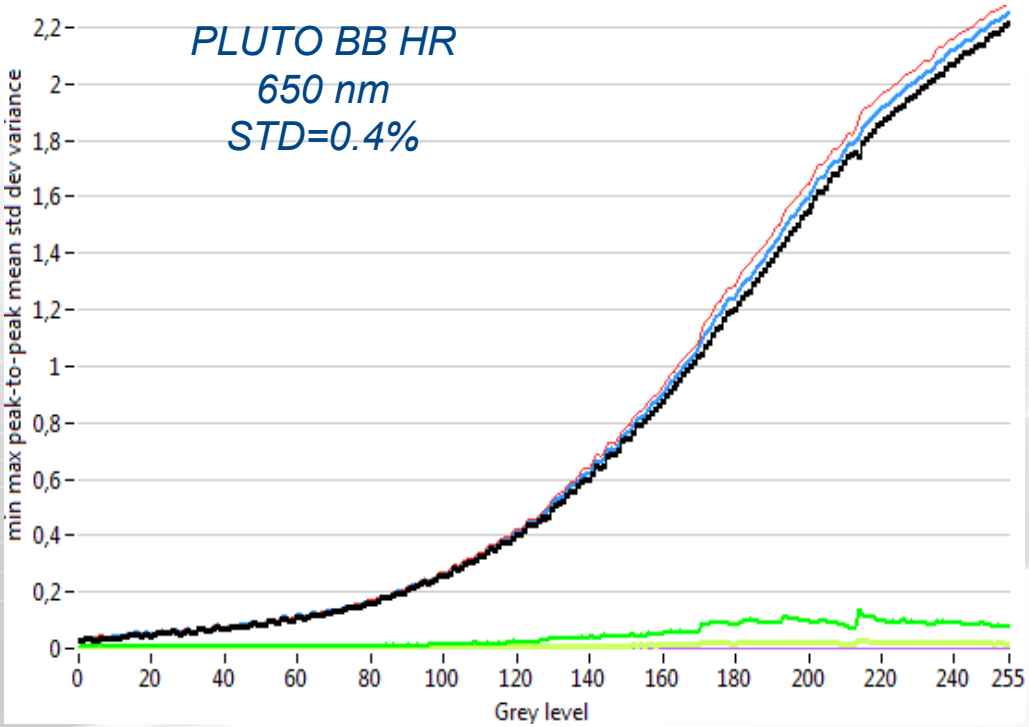
- ASIC or FPGA-driven
- High bandwidth (140-266MHz)
- Microdisplay data bus 32-128 bit
  (for arrays up to 4160x2464 pix)
- Bitplanes (e.g. 1920x1080) with freq. upto 16kHz[1]
- 50-250 bitplanes per 60Hz frame



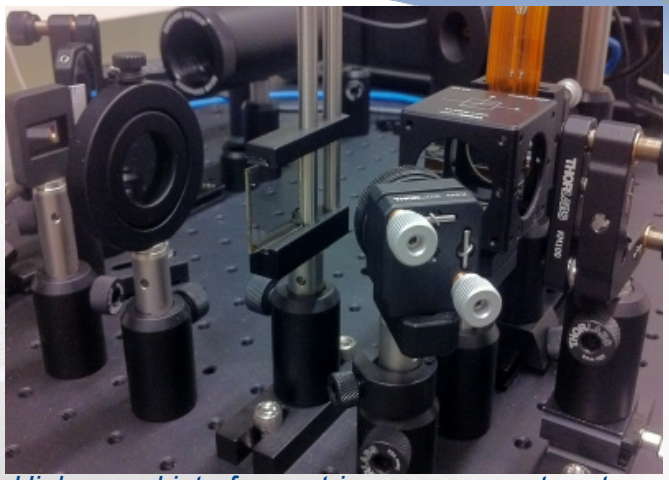
Interferometrically measured dynamic response for certain design and addressed phase level

[1] *High-resolution LCOS microdisplay with sub-kHz frame rate for high performance, high precision 3D sensor. G Lazarev, S Bonifer, P Engel, D Höhne, G Notni. Proc. SPIE 10335(2017)*

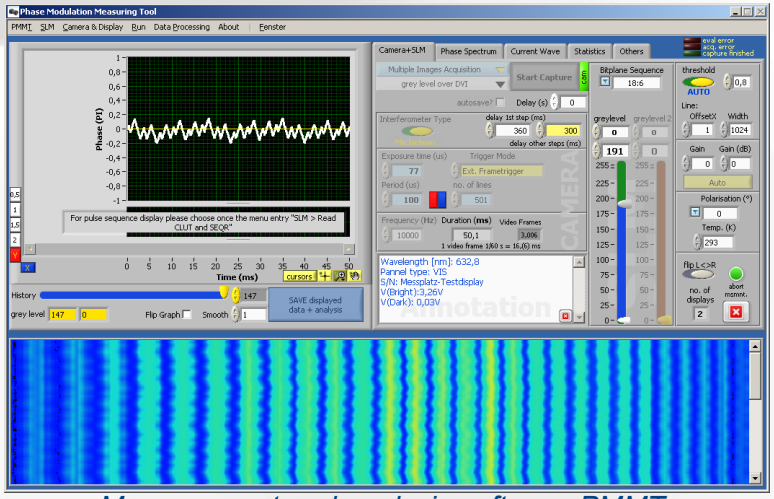
Phase response and noises



Signal/Modulation properties vs. adressed „grey level“, measured with interferometric system. Red - max. phase, black – min. phase, blue – mean phase, green – standard deviation, yellow - variance

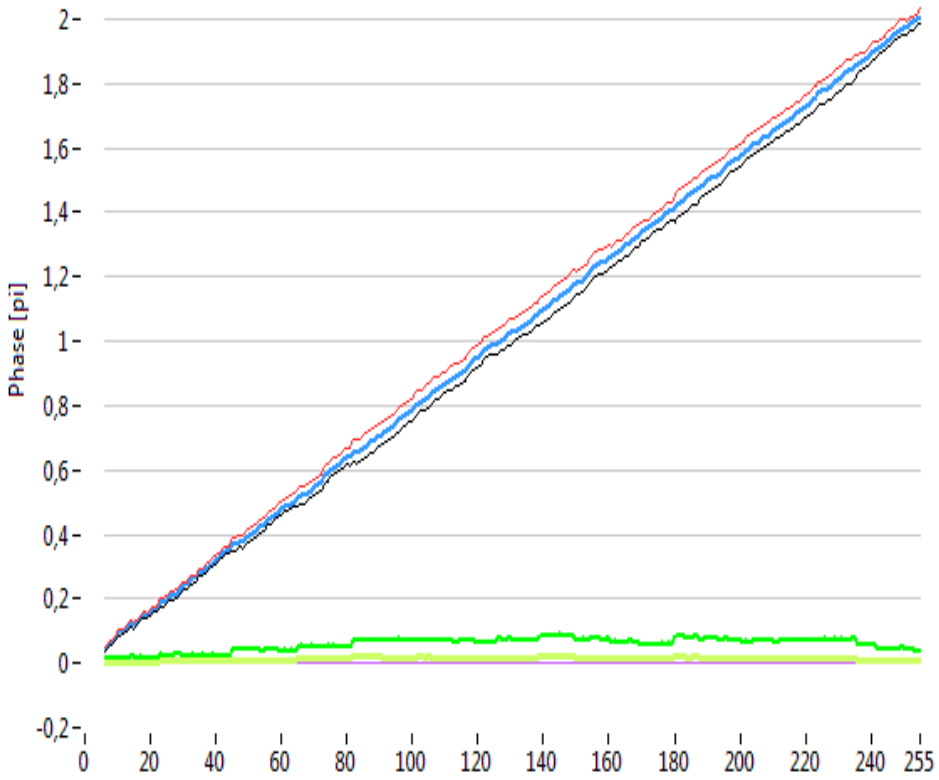


High-speed interferometric measurement system



Measurement and analysis software PMMT, developed at HOLOEYE

Linearized phase response



Linearized phase response and noise statistics for a PLUTO C-49 sample measured at 1064 nm, 30°C, STD=0.4%, max phase shift 2pi

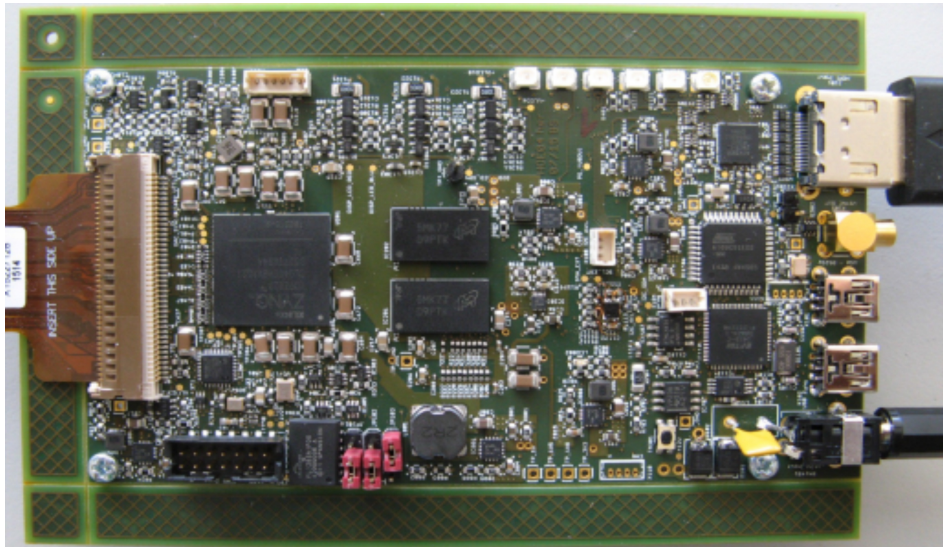
STD=0.4%
~30°C

Diff. Efficiences:
8 pix 74%
16 pix 86%
24 pix 92%

High-resolution high-reflective LCOS spatial light modulator for beam manipulation beyond visible spectrum G Lazarev, F Kerbstadt, J Luberek. Proc. SPIE 10090 (2017)

Driver Electronics

- Large amount of input data
- Input data per high-bandwidth video interfaces as HDMI, DisplayPort, Thunderbolt
- Diverse Interfaces for industrial applications (USB, CAN, …)
- FPGA or ASIC-based
- SoC: FPGA+ARM
- On-board pattern-generator in FPGA or ARM
- Sync/Trigger output



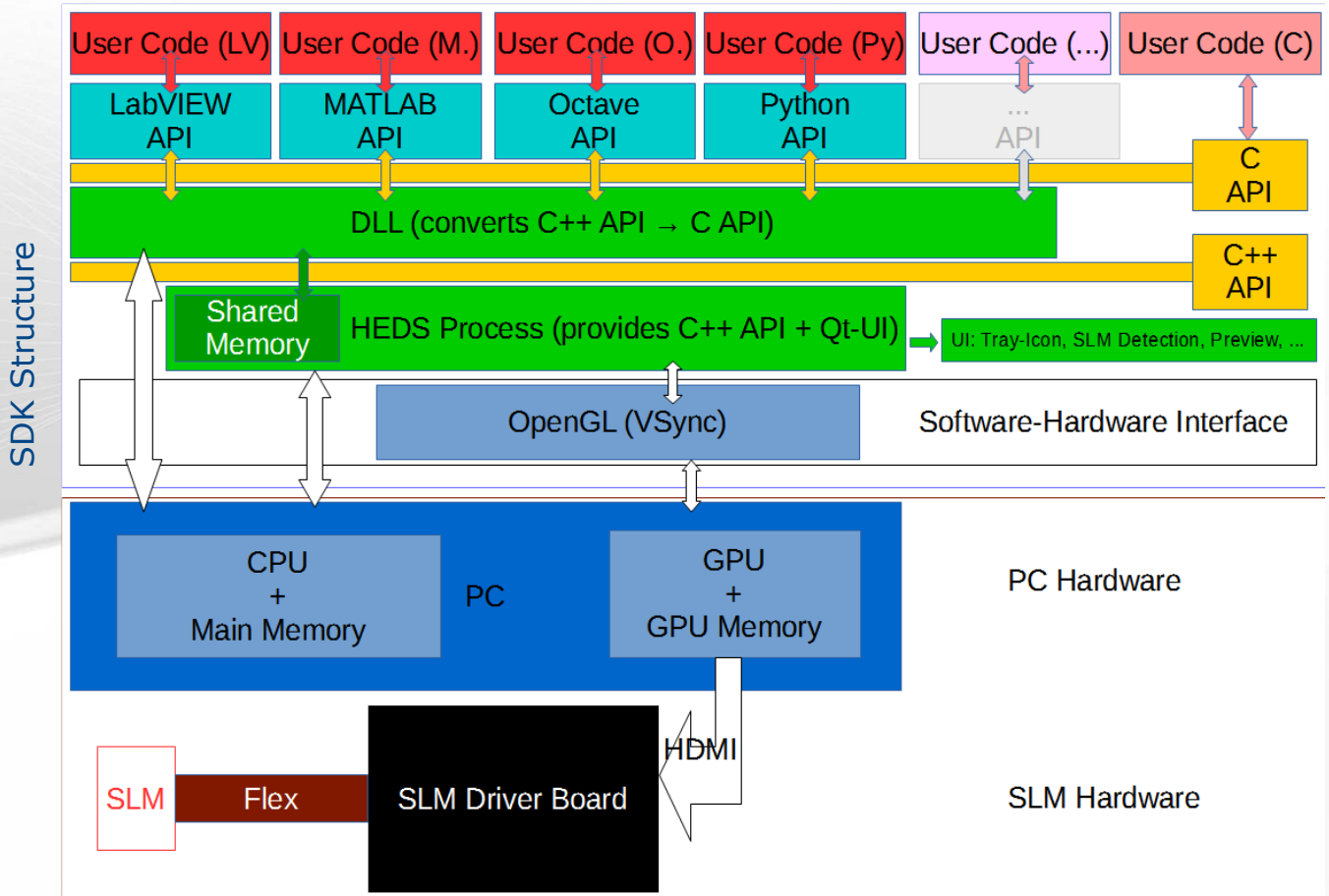
Drive board with FPGA

Board in housing with passive cooling

LCOS SLM for scientific applications and prototyping: HOLOEYE SLM Display SDK (HEDS)

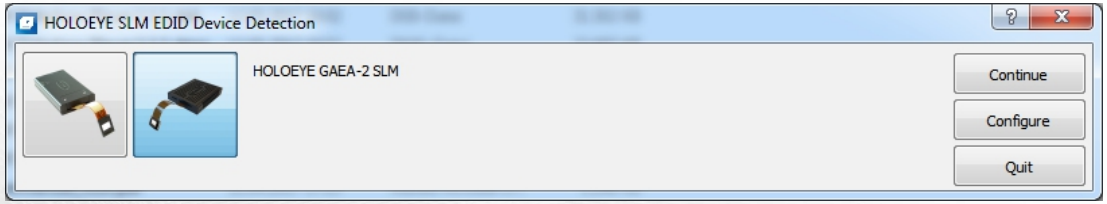
—SDK provides APIs for different programming languages, e. g.

- — C++
- — C
- — LabVIEW
- — MATLAB
- — Octave
- — Python



General Features

General API:



- Device detection (heds_init_slm())
- Automatic display configuration

- Access to SLM properties, like:
  - Pixel size (heds_slm_pixelsize_um())
  - Width / Height [px, mm] (heds_slm_width_px())
  - Refresh Rate (heds_refreshrate_hz())

- OpenGL with frame sync (Vsync)
  - Precise timing control
  - Timing statistics after playback

Content-based Features

Basic API:

Easy show functions to start right away:

- Show data arrays (float, int, double)
- Show phase-data-arrays (float, double)
- Show data from image files (*.png, *.bmp, …)
- Show built-in functions, like:
  - Gratings (Binary / Blaze)
  - Phasefunctions (Lens, Axicon, Vortex)
  - Devided screen

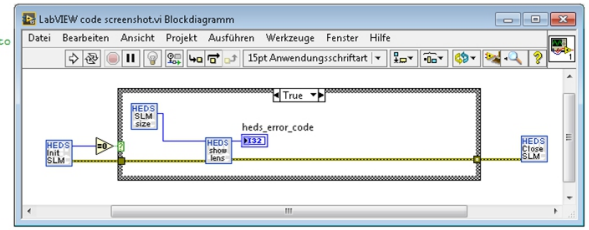
Advanced API:

Load functions to upload data to the GPU memory:

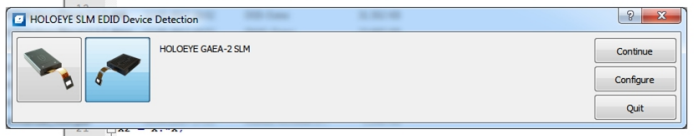
- Load phase-data-arrays (float, double)
- Load data arrays (float, int, double)
- Load data from image files (*.png, *.bmp, …)

- Fast accurate „slideshow"-playback
- Access playback timing statistics for detection of latencies

```python
# Calculates an axicon and shows it on the SLM.

import os, sys, time, math

# Import the SLM display SDK:
sys.path.append(os.getenv("HEDS_PYTHON_MODULES", ""))
import holoeye
import numpy as np

# make some enumerations available locally to
ErrorCode = holoeye.SLMDisplay.ErrorCode
ShowFlags = holoeye.SLMDisplay.ShowFlags

# open the SLM window
slm = holoeye.SLMDisplay()

# calculate the axicon
axiconDataWidth = slm.width_px / 2
axiconDataHeight = slm.height_px / 2

center_x = 0
center_y = 0

x = np.linspace(1, axiconDataWidth*2, axiconDataWidth*2, float) - float(axiconDataWidth) - float(center_x)
y = np.linspace(1, axiconDataHeight*2, axiconDataHeight*2, float) - float(axiconDataHeight) - float(center_y)

x2 = x*x
y2 = y*y

axiconData = sqrt(np.polymul()/inner_radius)

# Show data on the slm:
heds_error_code = slm.showPhasevalues(axiconData)

assert heds_error_code == ErrorCode.NoError, slm.errorString(error)

# Wait a few seconds:
time.sleep(4)

# Unload the SDK
slm.release()
```




```
% Calculates an axicon and shows it on the SLM.

% Import SDK:
add_heds_path;

% Open the SLM window:
heds_init_slm;

% Calculate the axicon:
axiconDataWidth = heds_slm_width_px
axiconDataHeight = heds_slm_height_px
axiconData = zeros(axiconDataHeight, axiconDataWidth, 'single');

y = (1:size(axiconData,1)) - size(axiconData,1)/2 + center_y;
y2 = y.*y;
y2 = y2';

axiconData = sqrt(ones(axiconDataHeight, 1, 'single')*x2 + y2*ones(1, axiconDataWidth, 'single'));

% Show data on the SLM:
heds_show_phasevalues(axiconData, 'auto', innerRadius)
```



Applications

PSF engineering (spot optimization, aberration correction)

Beam shaping (gauss to top-hat etc.)

Multibeam generation (beam splitting function)

Beam steering

Pulse shaping

Beam shaping

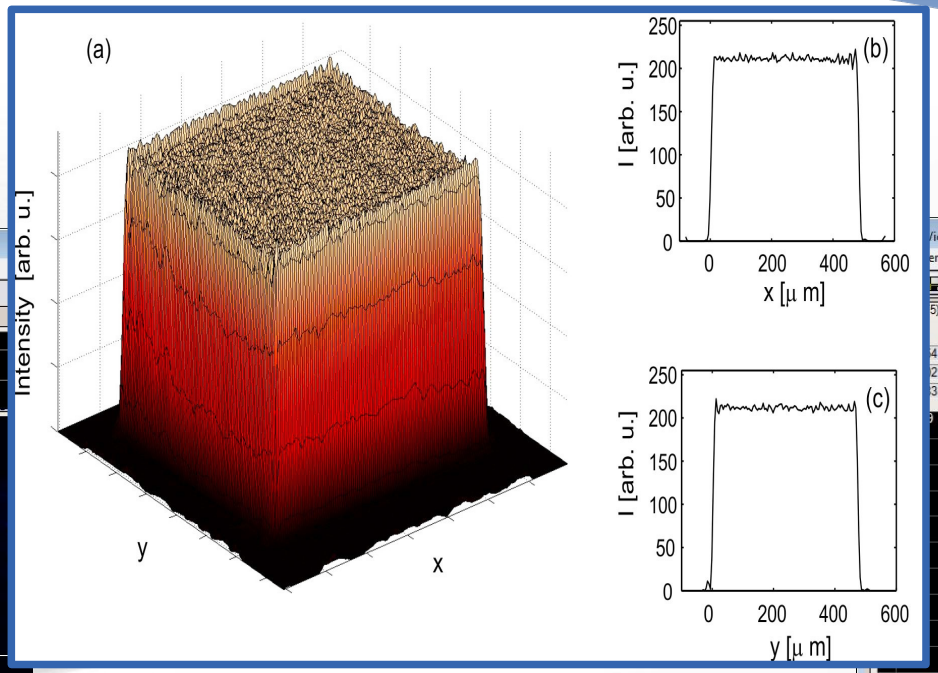
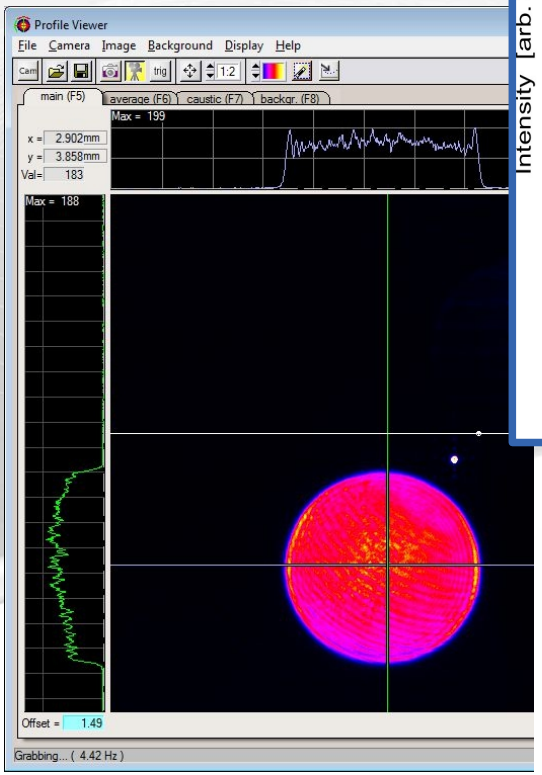
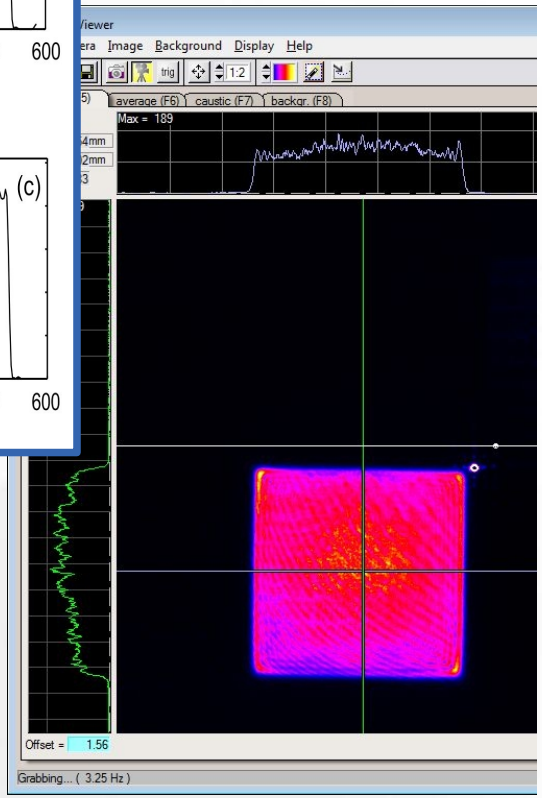
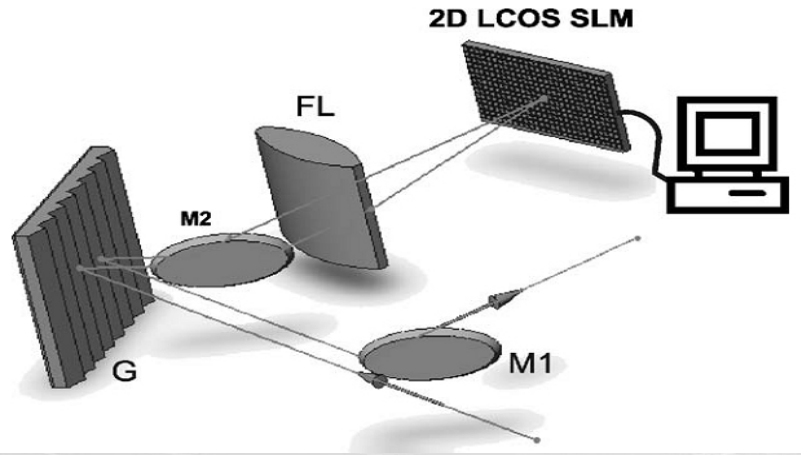


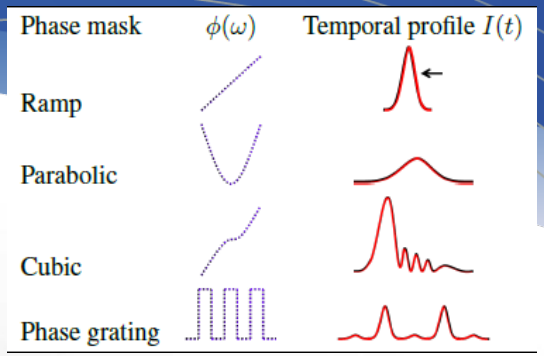
Image courtesy TU Eindhoven. Rick van Bijnen. Quantum engineering with ultracold atoms.PhD Thesis, TU Eindhoven (2013)



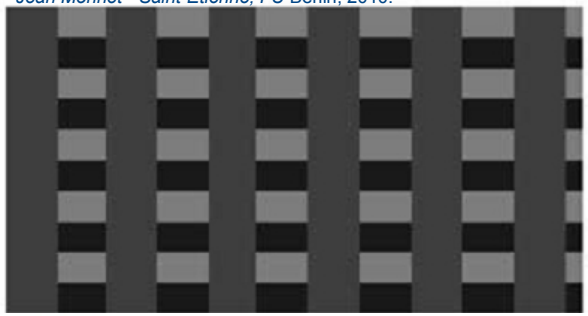


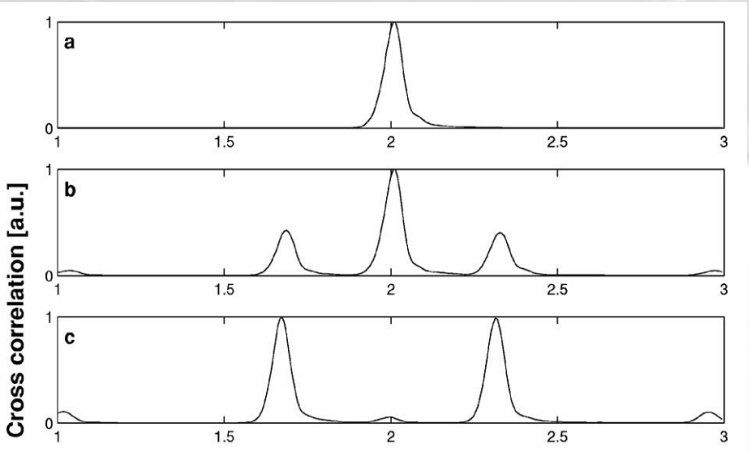
Spectral shaping – pulse shaping

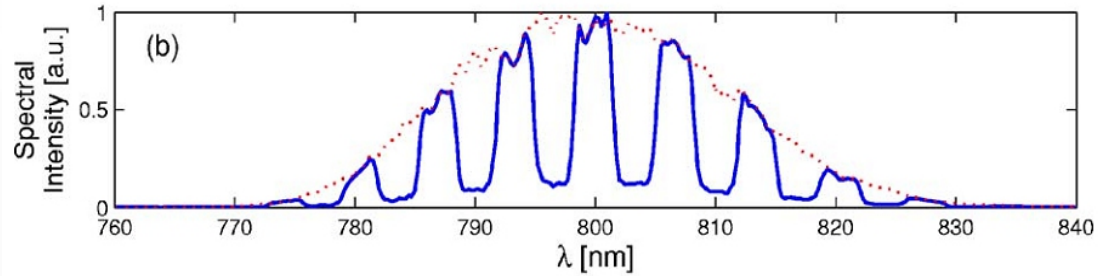




Cyril Mauclair. Spatio-Temporal Ultrafast Laser Tailoring for Bulk Functionalization of Transparent Materials. PhD Thesis, Universite Jean Monnet - Saint-Etienne; FU Berlin, 2010.







Phase and amplitude pulse shaping with two-dimensional phase-only spatial light modulators. E. Frumker, Y. Silberberg. J. OSA B, V.24, 12 (2007)

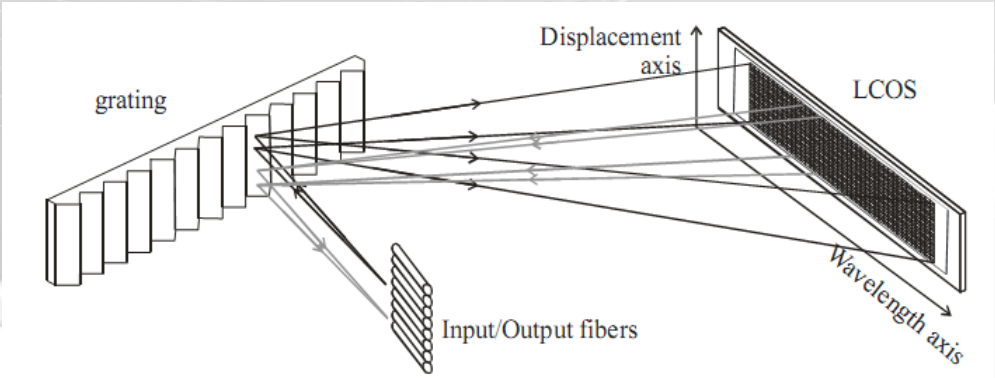
Images courtesy of Weizmann Institute

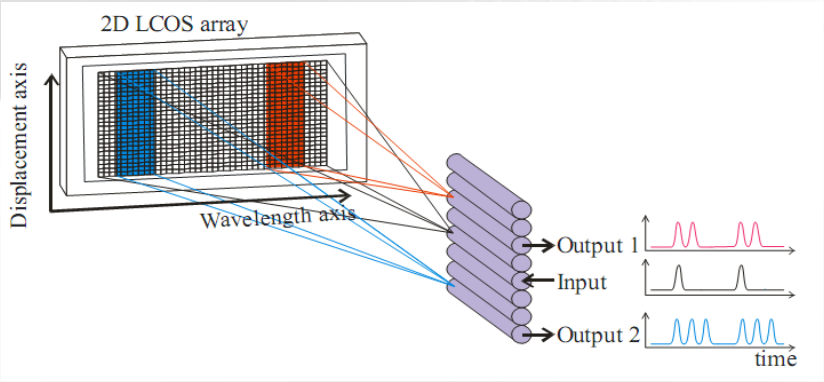
Applications

Phase modulating LCOS: adaptive optics, holography, metrology, telecommunications, microscopy, biophotonics, additive manufacturing and laser material processing, quantum physics..

— HOLOEYE made a variety of designs fitted for certain applications.
— an SLM, based on HD LCOS backplane was developed to be integrated into telecom product by one of the market leaders and got qualified for using in telecom equipment. The product is in volume production.

Images courtesy of University of Sydney





Multi-wavelength synchronous pulse burst generation with a wavelength selective switch. M. Roelens, J. Bolger, D. Williams and B.J. Eggleton. OPT. EXP., V.16, No. 14, (2008)

A bit of Marketing as a Summary

HOLOEYE LCOS
SLM, PLUTO 2 series

Resolution	1920 x 1080 - 4160x2464
Pixel Pitch	3.74µm– 8µm
Fill Factor	87% - 94% (0.2-0.5µm interp. gap)
Active Area	0.3“ - 0.7“ diagonal
LC Type	PAN, VAN, TN
Modulation Range	Phase 2pi – 8pi / Intensity
Addressing Rate	60Hz – 180Hz (R&D up to 800 Hz)
Spectral Band	350-450nm, 400-700 nm, 600-1200 nm, 1200-1450 nm, 1450-1700 nm

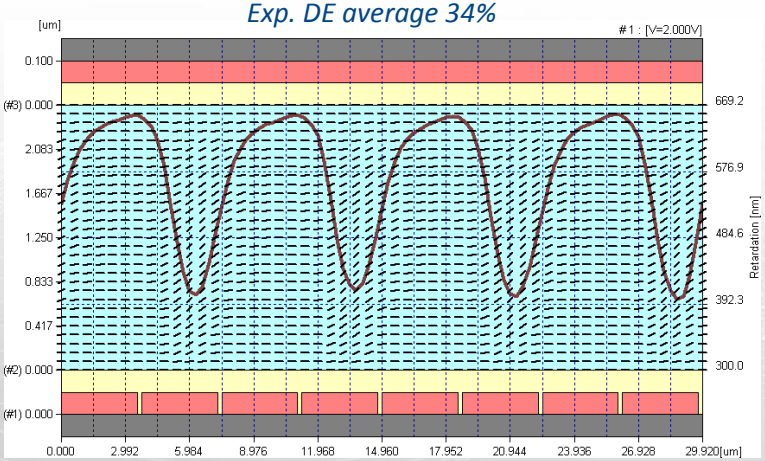
HOLOEYE LCOS SLM, GAEA 2 series

Thank you for your attention!

Questions? *lazarev@holoeye.de*

Effective Resolution

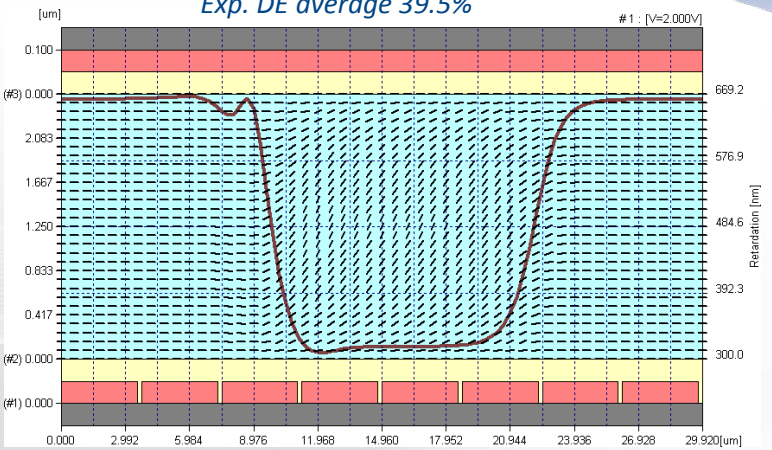
Max DE for binary grating, +1st: ~40.5%
Max DE for sine grating, +1st: ~33.8%
Exp. DE average 34%



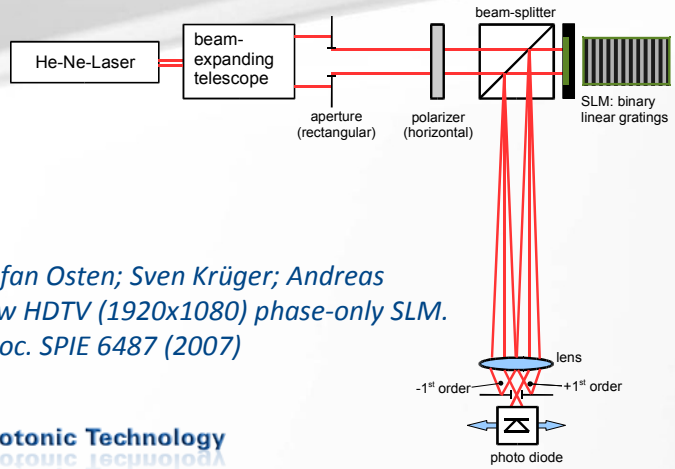
Retardation and director distribution for 1-1 binary grating

Optimized (C14) DE: 1-1 40.5% 4-4 40.0%

Exp. DE average 39.5%



Retardation and director distribution for 4-4 binary grating



Reference: Stefan Osten; Sven Krüger; Andreas Hermerschmidt. New HDTV (1920x1080) phase-only SLM. Proc. SPIE 6487 (2007)