Spatial Light Modulators in Laser Microprocessing

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Workshop: APPOLO

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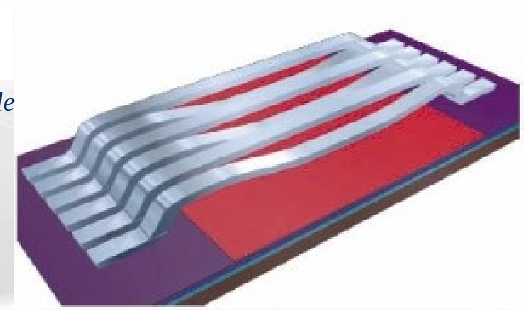
SLMs Variety Today

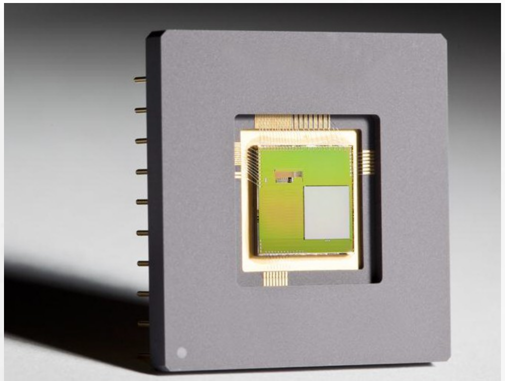
- MEMS (one- or two dimensional)
  - Piston-like (e.g. GLV)
  - DMD
  - Membrane
- LCD (one- or two dimensional)
  - Trasmissive LCD
  - LCOS
  - OASLM
- Other

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



GLV, courtesy of Silicon Light Machines

HOLOEYE LCOS SLM, LETO series



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

LCOS Structure, Design and Materials

Nematic Liquid Crystals

Director distribution (**n**):

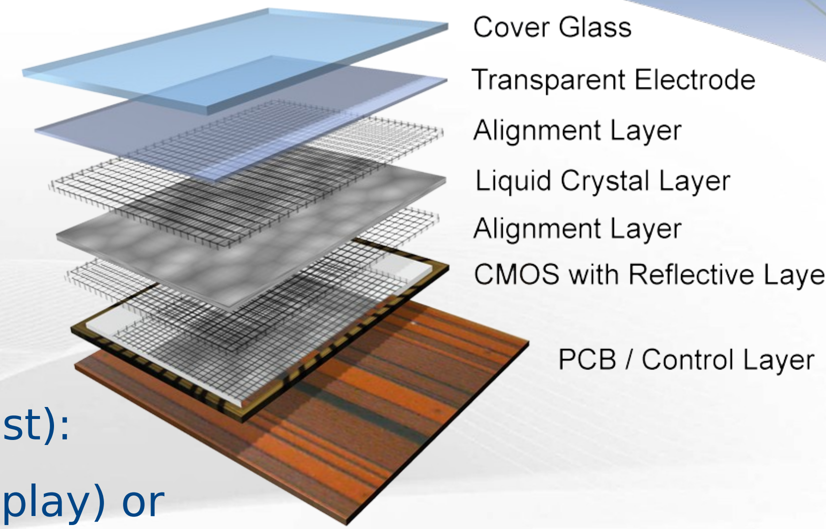
No Voltage → boundary conditions

→ 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 phase only modes (ECB - zero twist):

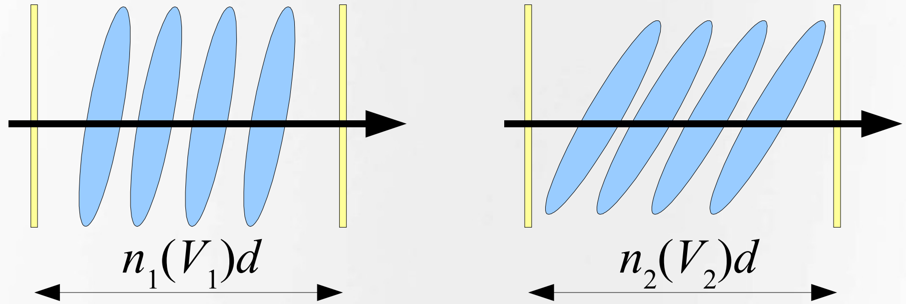
→ homogenous (parallel aligned, PA, ~splay) or

→ homeotropic (vertically aligned, VA, ~bend)

Applied Voltage → dielectric anisotropy → Electrostatic free energy

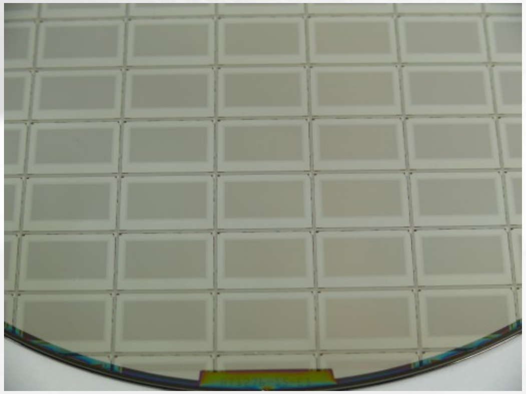
$$u=\frac{1}{2}\frac{D^2}{\epsilon_{\parallel}-\Delta\epsilon\sin^2\theta(z)}$$

Polarization in director plane → ECB mode



Quick facts about LCOS SLMs: CMOS Backplane

- High quality Aluminium pixel mirror and passivation layer (at a broader and/or specific wavelength range) → R~90%
- Integration of dielectric coatings in wafer manufacturing process → R~99%
- Processes for smaller pixel structures (2-8um) and interpixel gap (200-500 nm), spacer structures
- Higher requirements on process control and optical testing



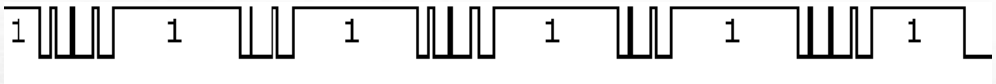
0.25 micron process 8“ CMOS wafer - 0.7“ HD LCOS

Quick facts about LCOS SLMs: LCOS Cell

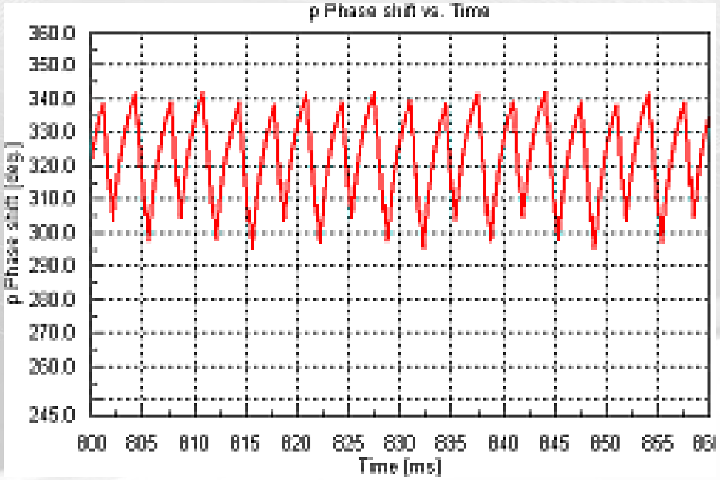
- High birefringence materials >0.25 Δn
- Slow materials – high rotational viscosity
- Fast materials – low rotational viscosity
- Spectral bands: UV, SWIR, MWIR..(LCs can work even in THz-GHz!)
- UV: Absorption ITO and cover glass materials, UV sensitivity of the (organic) alignment, LC-stability
- Characterization of materials on damage threshold, temperature range, absorption bands,..
- Availability of the characterization/measurement equipment (light sources, detectors) for the band
- Simulation possibilities

Digital Modulation - Dynamic Simulations

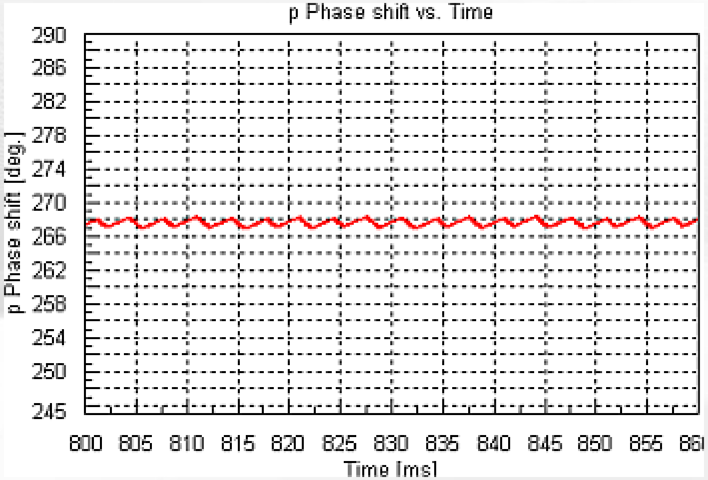
— Pulse-width modulation is poor for phase applications
— Pulse code modulation, with custom sequences for phase applications
— High bandwidth, special sequences and LC-design reduce supermodulation



Typical voltage sequence, applied to digital pixel



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

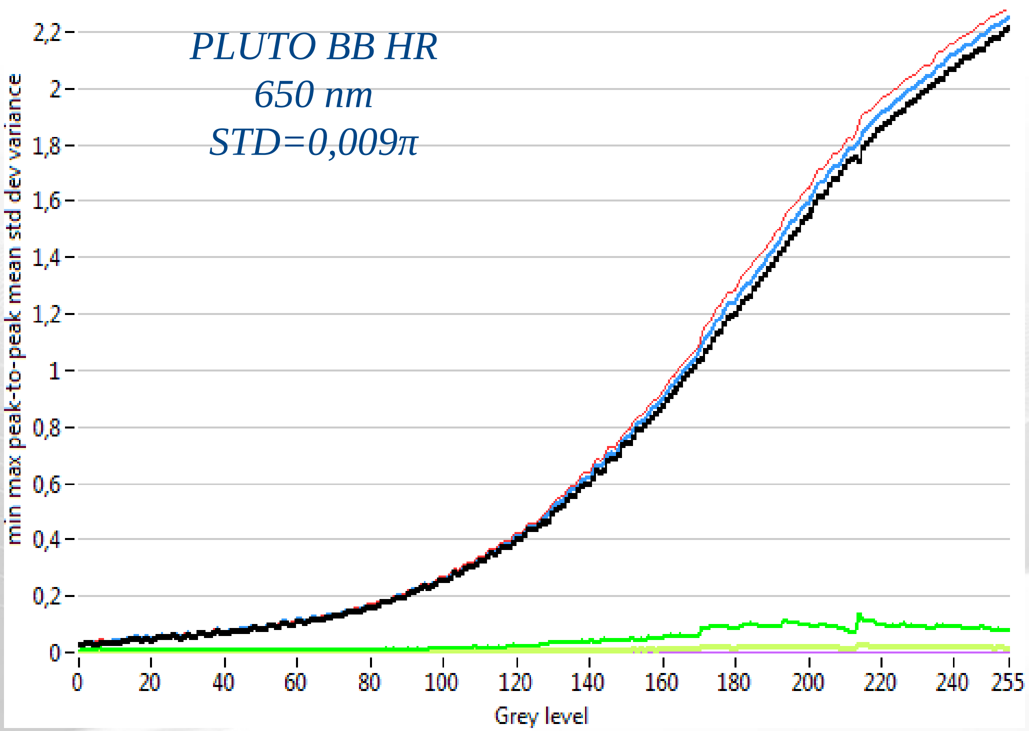


Simulation of the dynamic response for optimized design

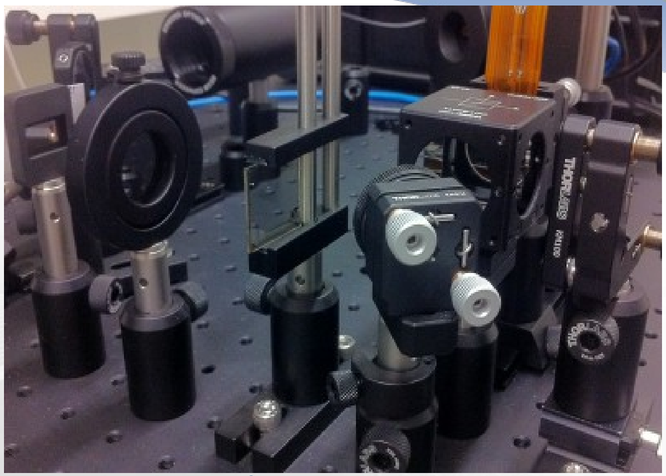
—Properties of LC-material
—Parameters of the LC-cell
—Parameters of the driving sequence/voltages

HOLOEYE Pioneers in Photonic Technology

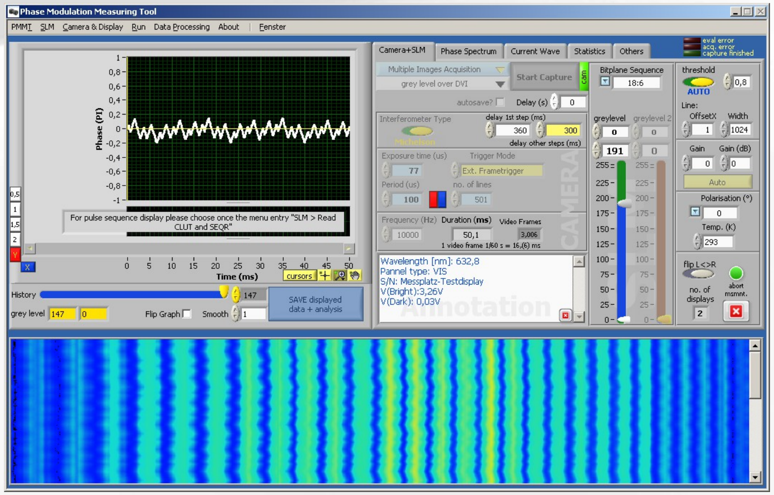
Optimizing for minimal flicker/noise



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

Typical functions of the phase-only SLM, related to laser microprocessing

PSF engineering (spot optimization, aberration correction)

Beam shaping (gauss to top-hat etc.)

- Usually calculation with phase gradients (geometrical)
- Can be combined with IFTA
-

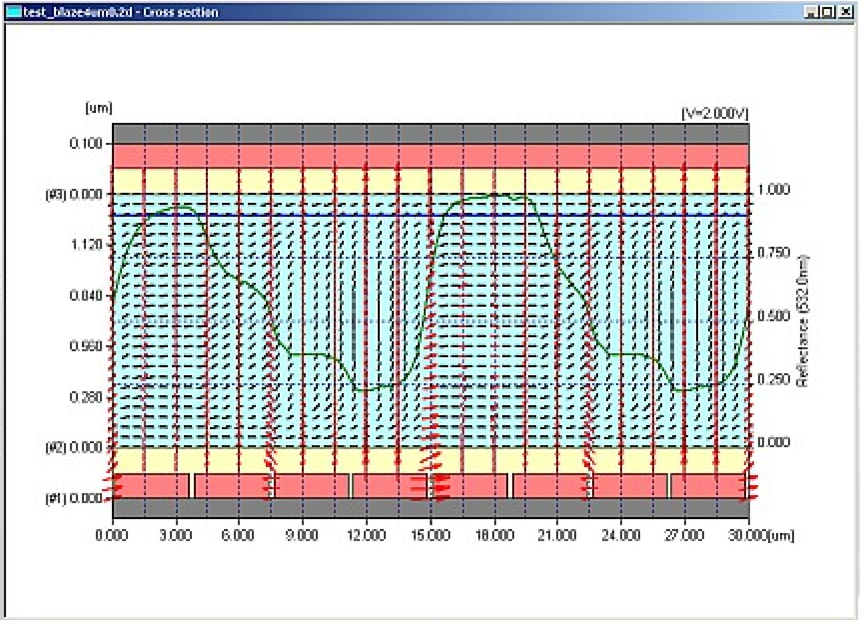
Multibeam generation (beam splitting function)

- In some cases analytical
- Usually IFTA

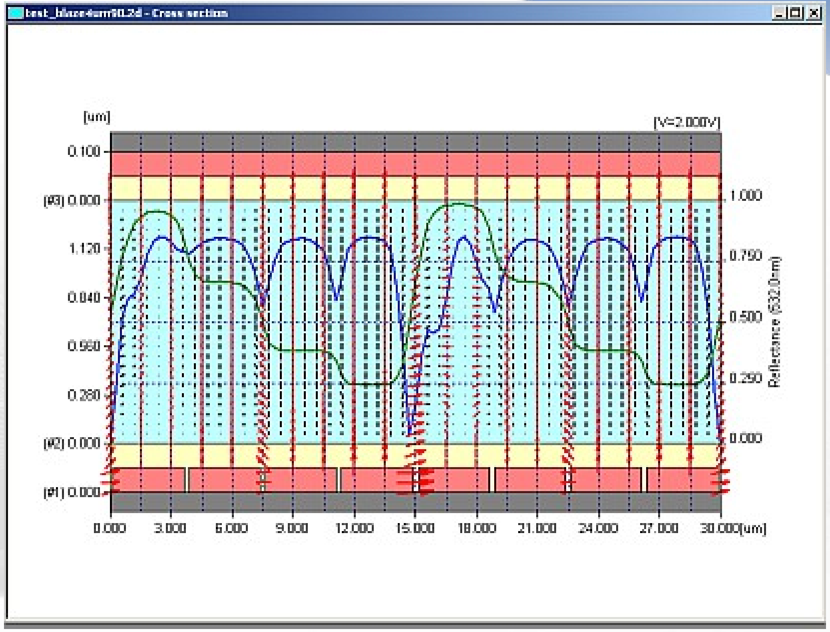
Beam steering

Pulse shaping

Beam steering / blazed gratings



Field gradient and director distribution for a blaze grating, director is parallel to field gradient
No overlapped amplitude modulation



Director is orthogonal to field gradient. Amplitude modulation is superimposed (twist K_{22}), but higher resolution, shorter fly-back

- Cross-talk → resolution, „fly-back“
- Polarization/Amplitude/Complex cross-modulation
- Limited temporal performance typ. 1Hz-1000Hz if using NLC

Beam Steering with extended modulation range

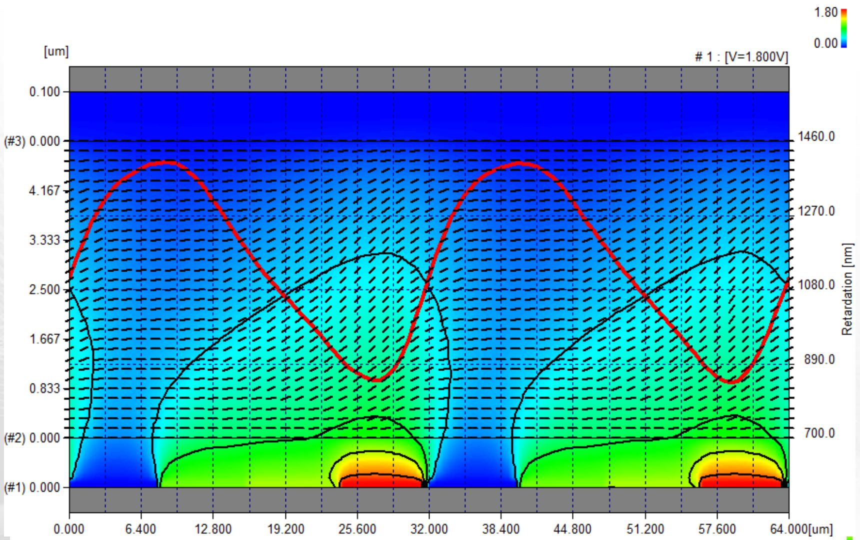
Modulation over 2pi range

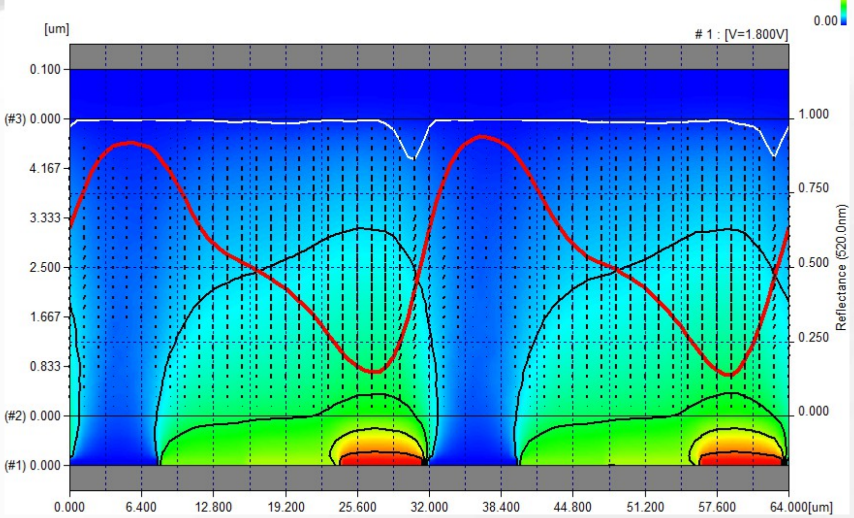
Blaze gratings instead of binary

Period	2pi	4pi	6pi
2pix	30% *		
4pix		45%	
6pix			46%

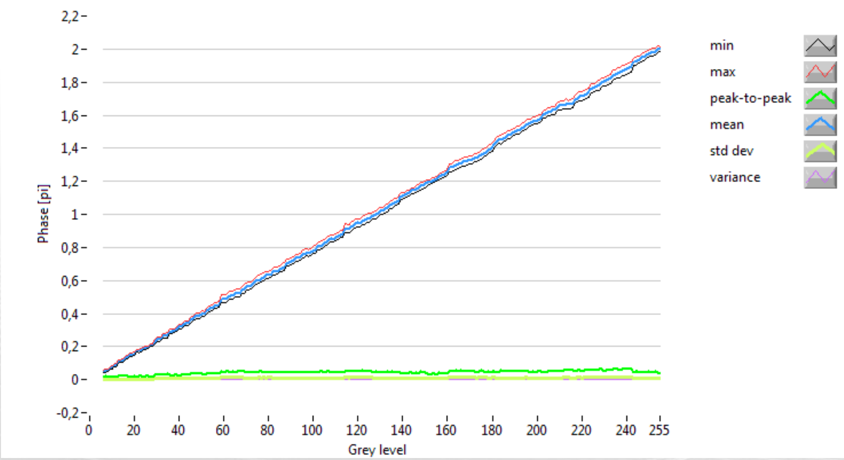
* optimized average +/-1

Director distribution and retardation for 532 nm, max. retardation corresponds to 4pi

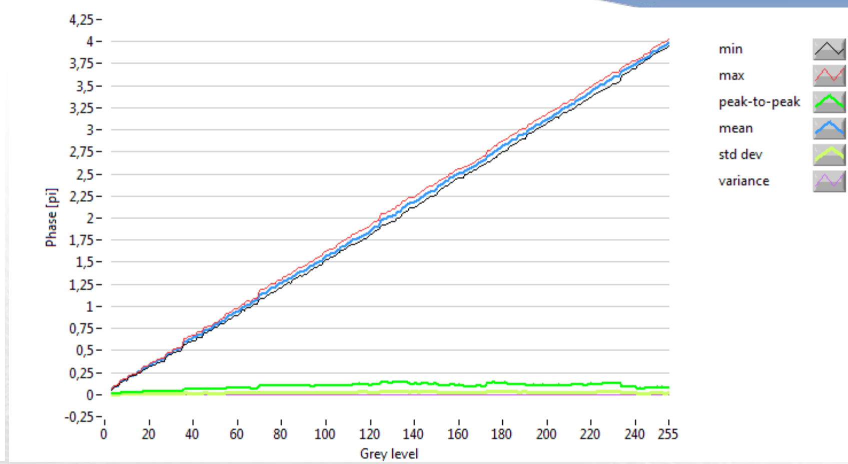




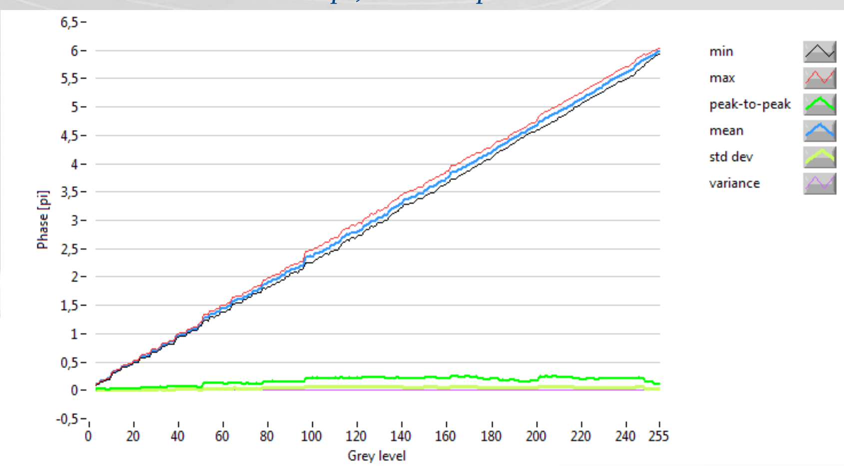
Temporal noise vs. modulation range



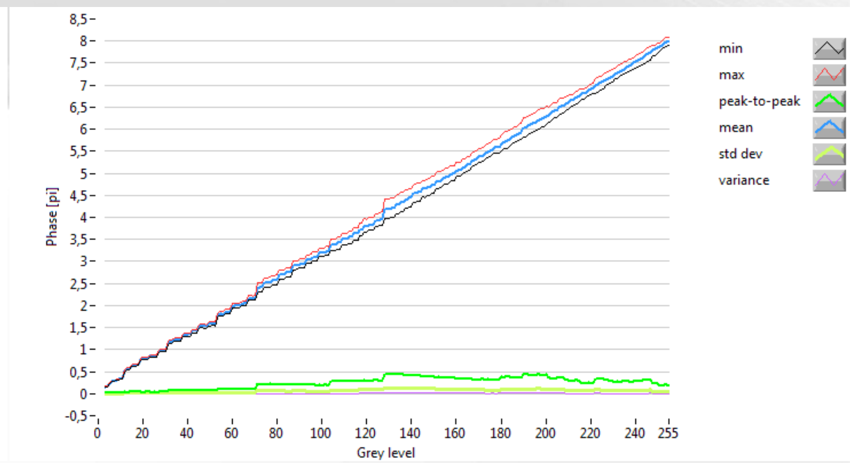
2pi, std 0.009pi



4pi, std 0.023pi

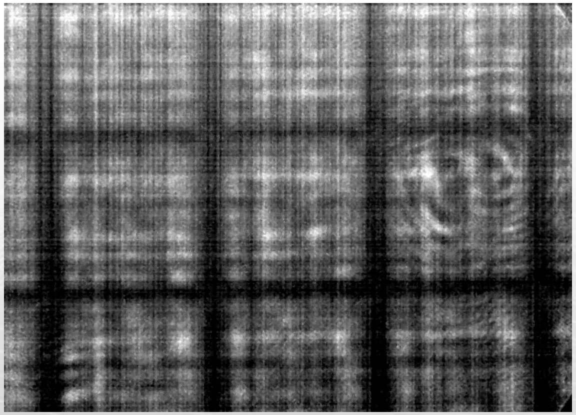


6pi, std 0.043pi



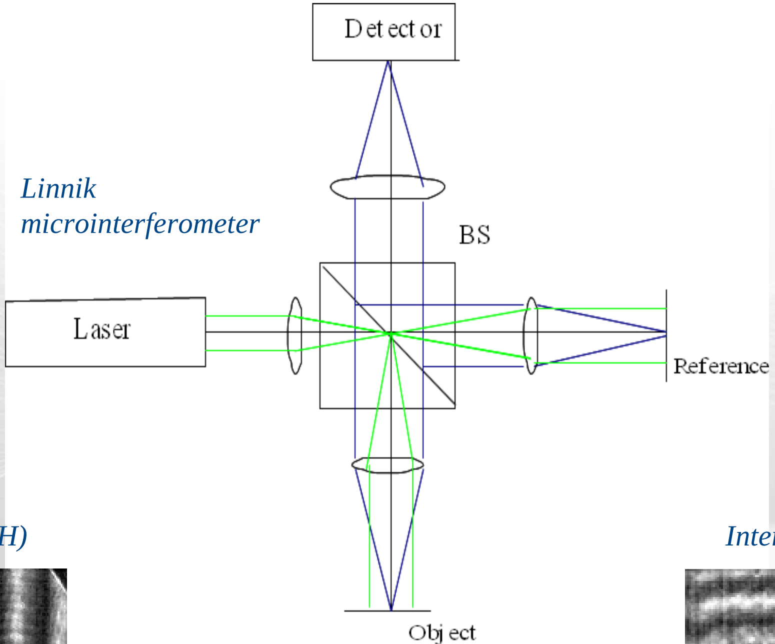
8pi, std 0.065pi

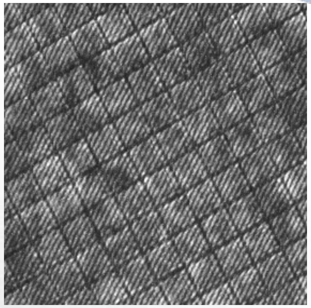
Direct Measurement of the phase distribution



Intensity image of the object beam in coherent light

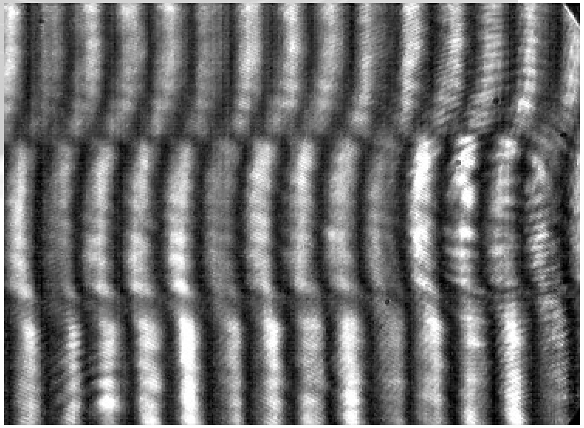
Linnik microinterferometer

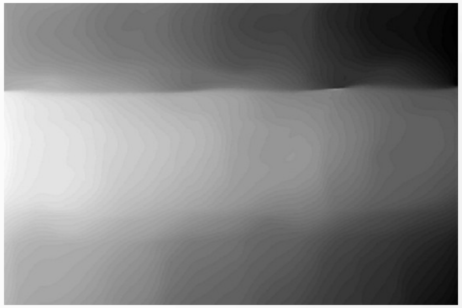




Microinterferometric image

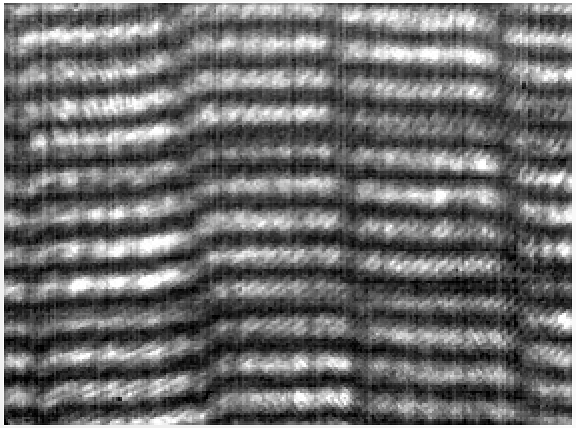
Interference pattern for binary grating (H)



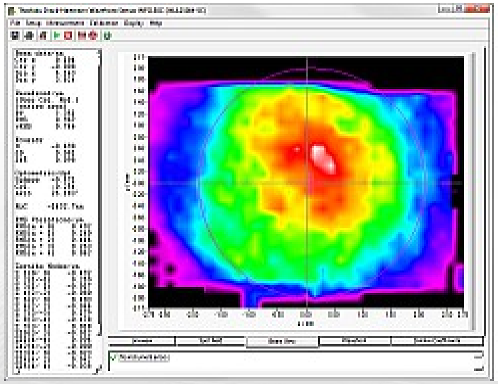


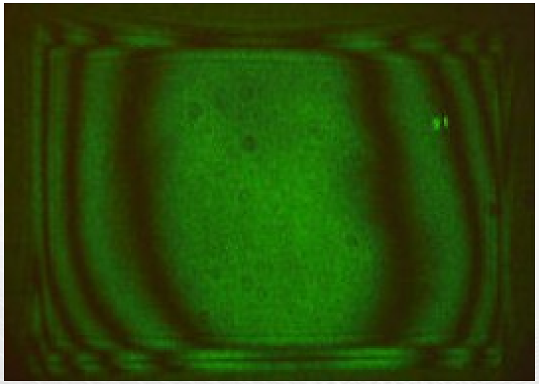
Reconstructed phase distribution

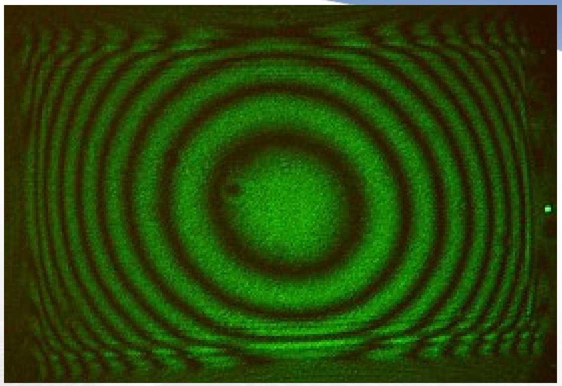
Interference pattern for binary grating (V)



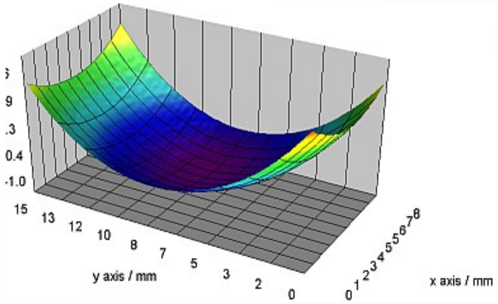
PSF quality: Flatness and Homogenity of the Display

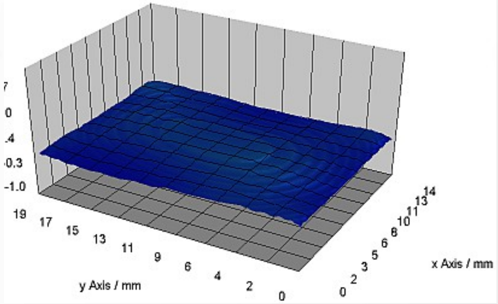






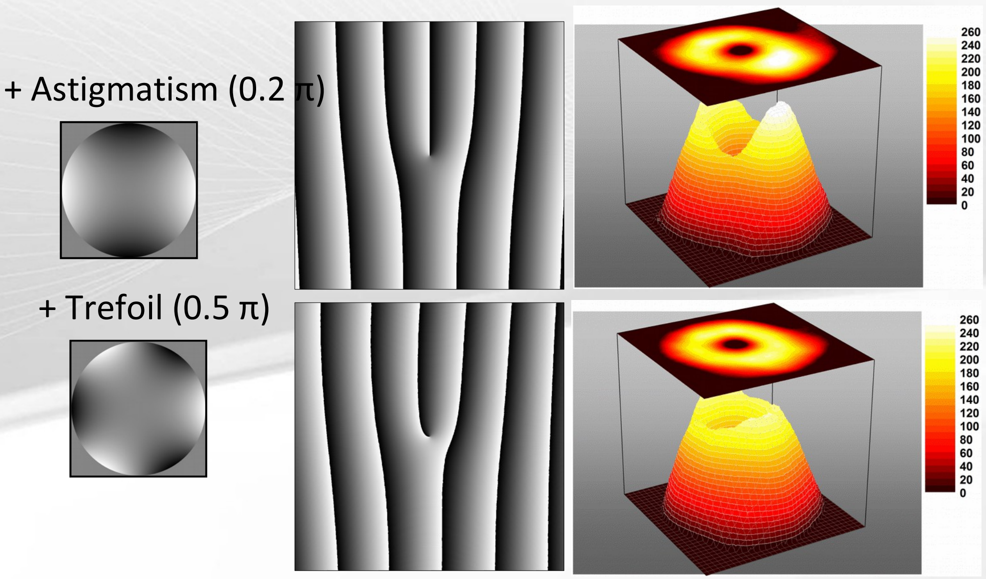
- Interferometer or Schack-Hartmann measurements
- Feedback on process and design parameters
- Software compensation possible
- Curvature depends on mechanical and thermal stress
- 0.25um wavefront PV within 8 mm circle





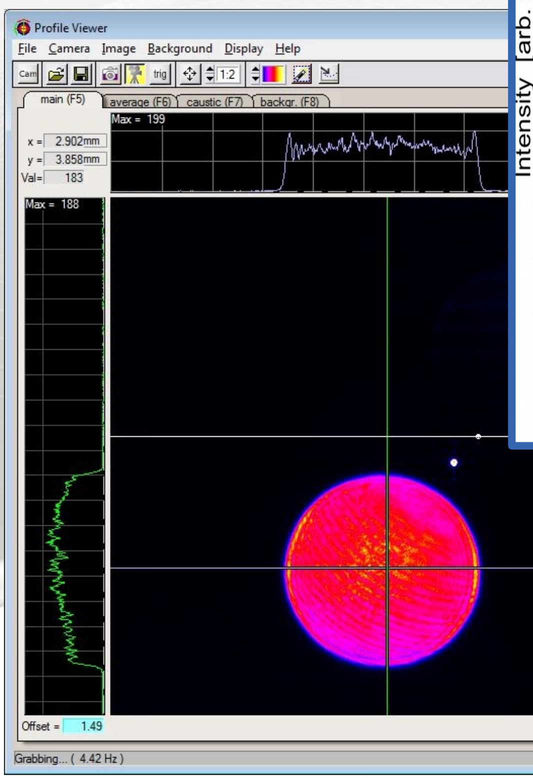
Spot generation / Aberration Correction

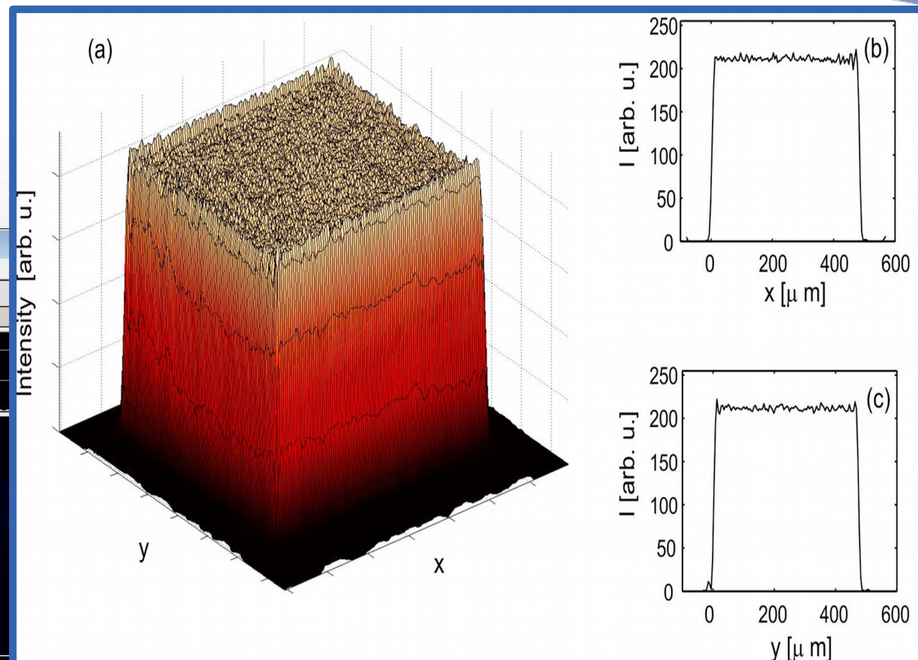
Example: quality of the doughnut spot is very sensitive to aberrations



Courtesy University of Potsdam

Beam shaping





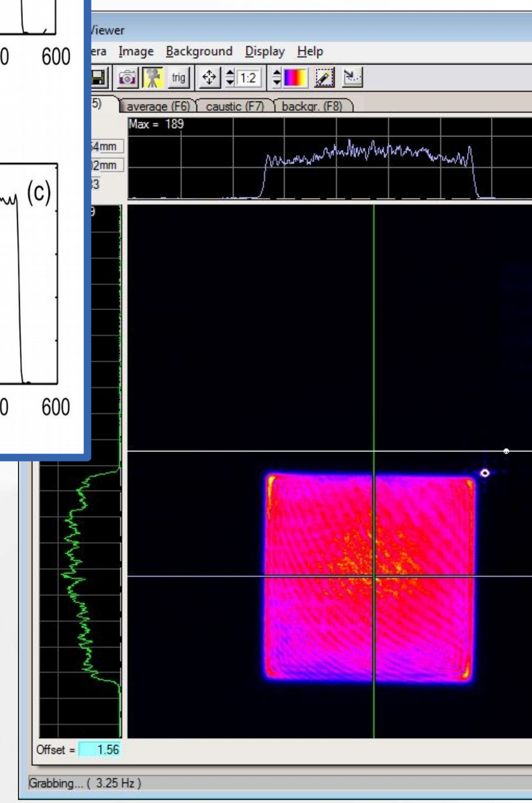
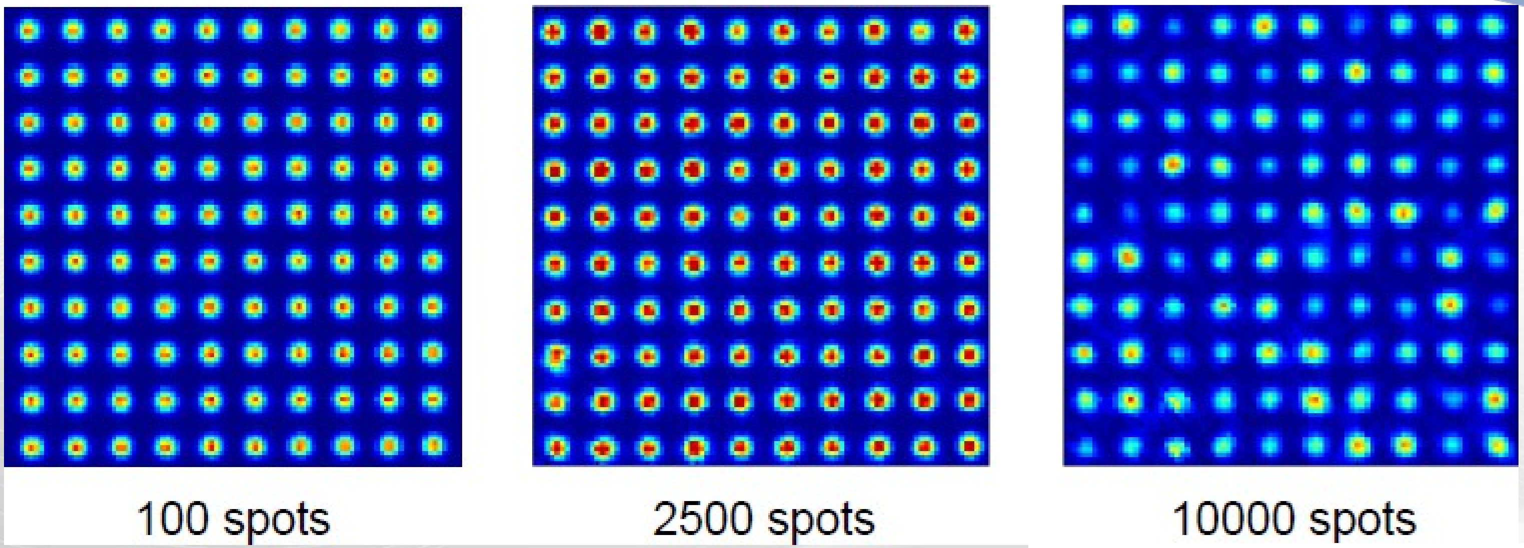


Image courtesy TU Eindhoven. Rick van Bijnen. Quantum engineering with ultracold atoms.PhD Thesis, TU Eindhoven (2013)

Multibeam Generation (SLM as beamsplitting DOE)



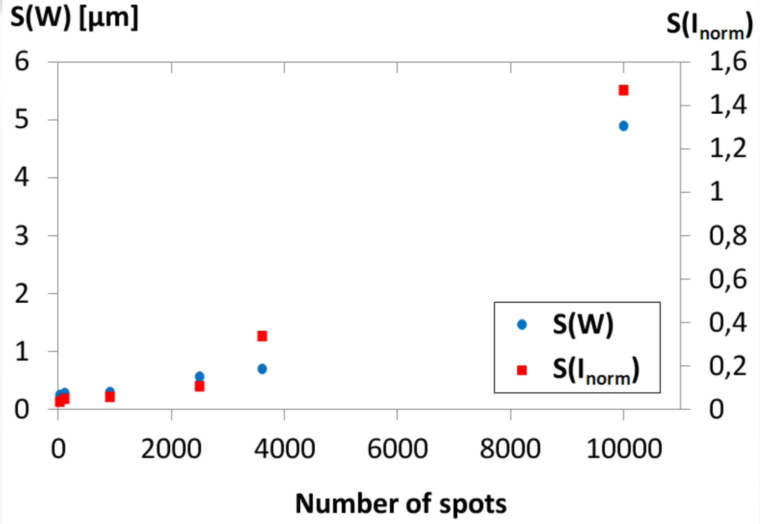
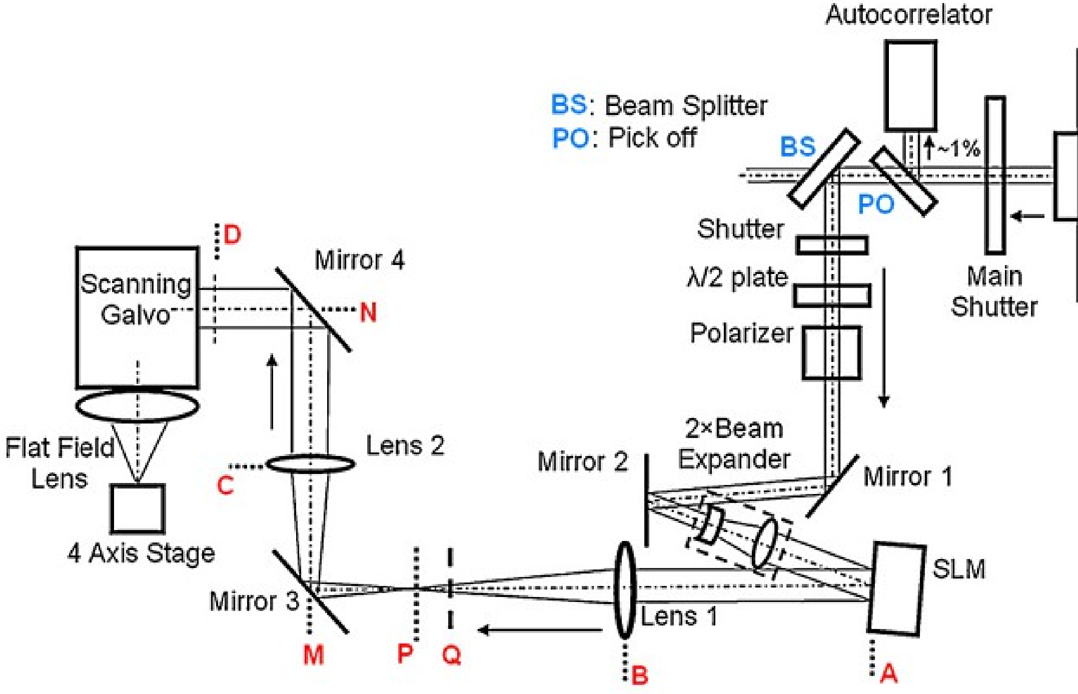
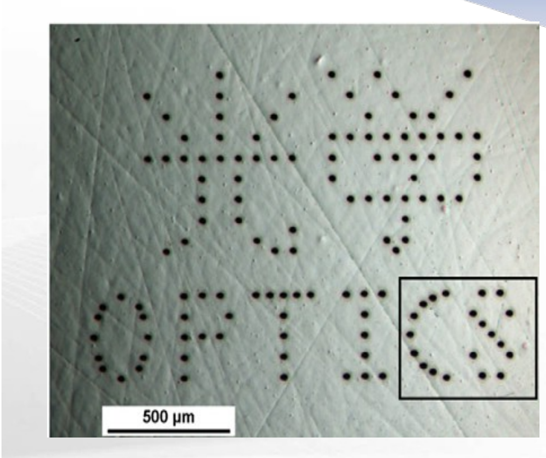
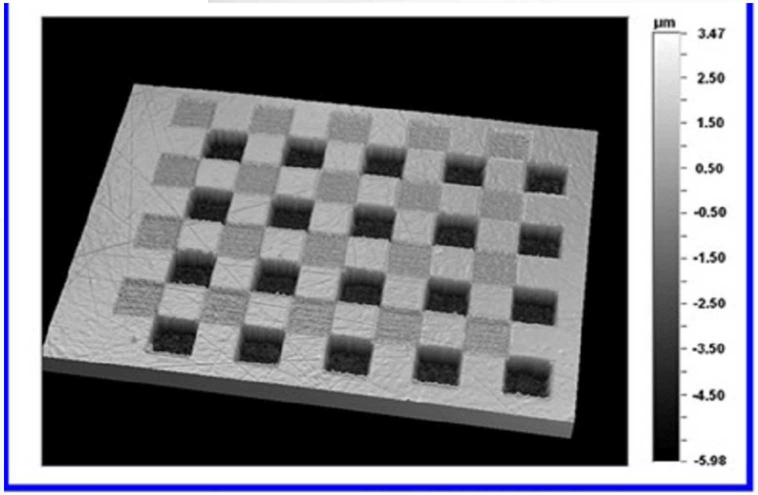


Image courtesy of TU Eindhoven. Gerwin Dijk. Intensity patterns generated with a spatial light modulator. Master thesis, TU Eindhoven (2012)

Multibeam microstructuring (laser ablation)

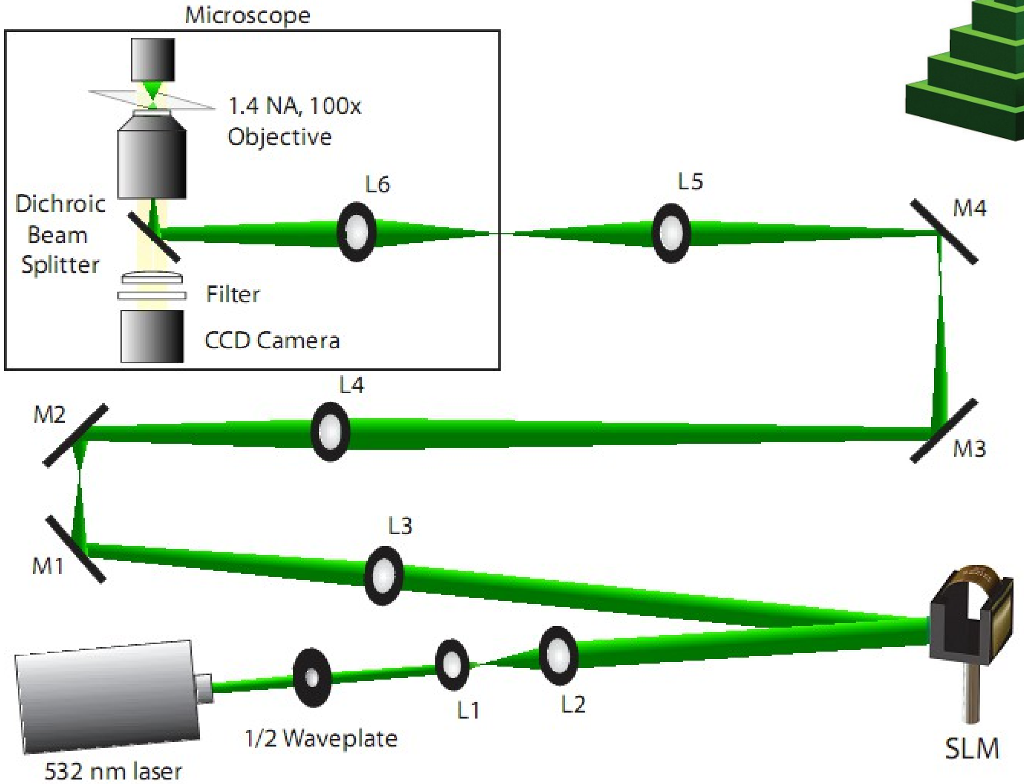




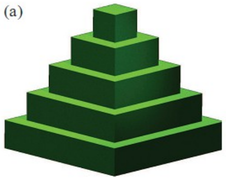


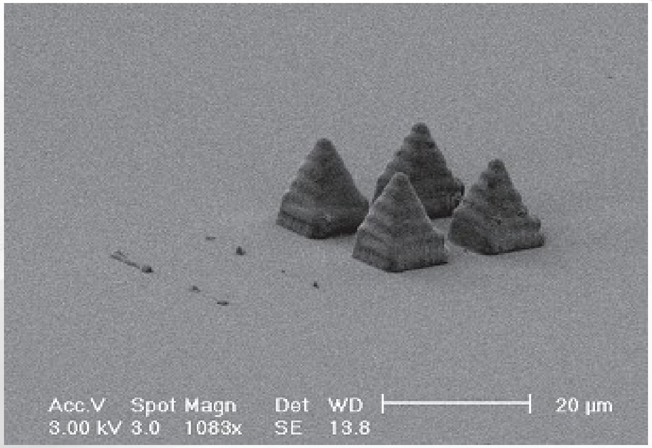
Images courtesy University of Liverpool. Z. Kuang, et al., Fast parallel diffractive multi-beam femtosecond laser surface micro-structuring, Applied Surface Science (2009)

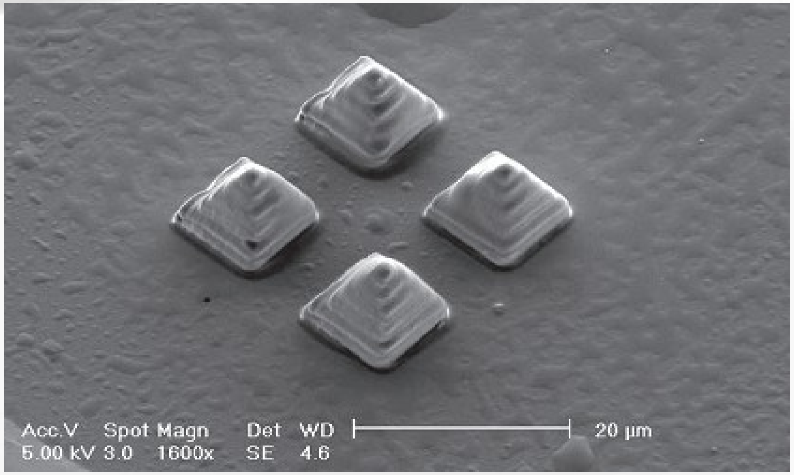
Holographic Lithography



(a)

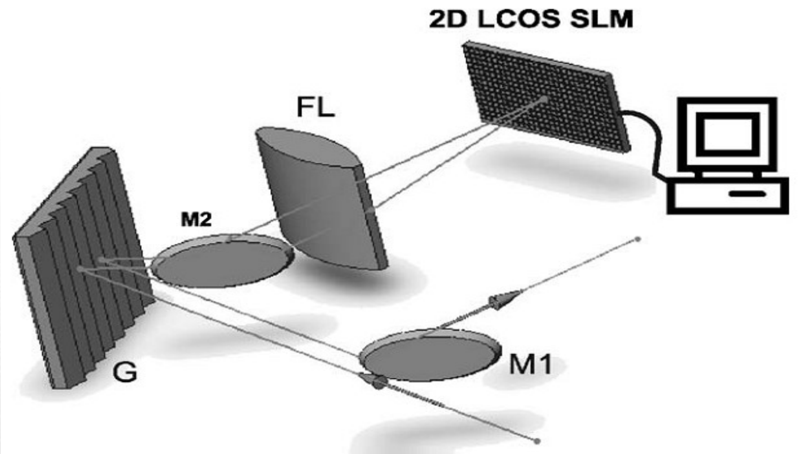


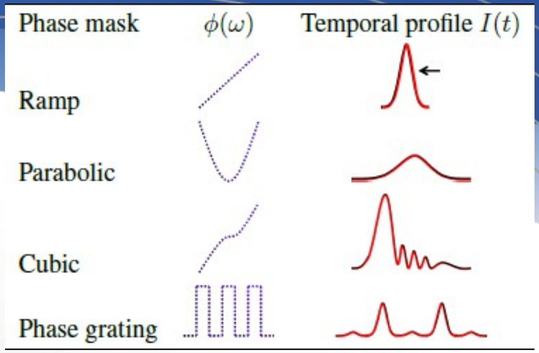




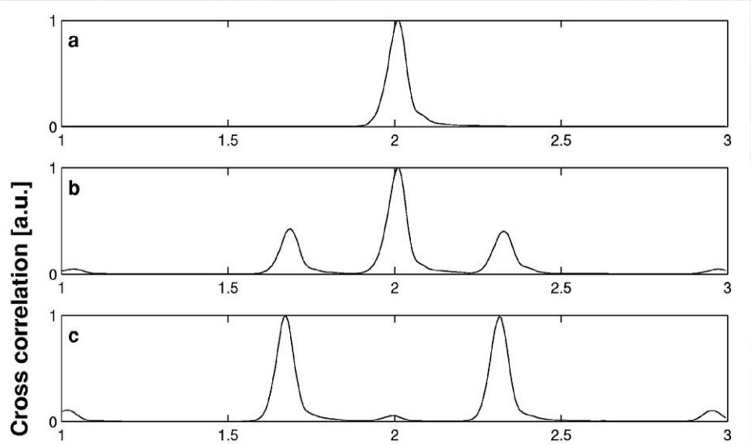
Images courtesy of Duke University. N. J. Jenness et al. Three-dimensional parallel holographic micropatterning using a spatial light modulator. Optics Express, 16(20), 2008.

Spectral shaping – pulse shaping – burst generation

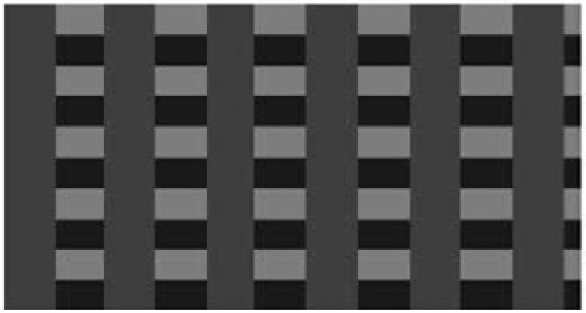


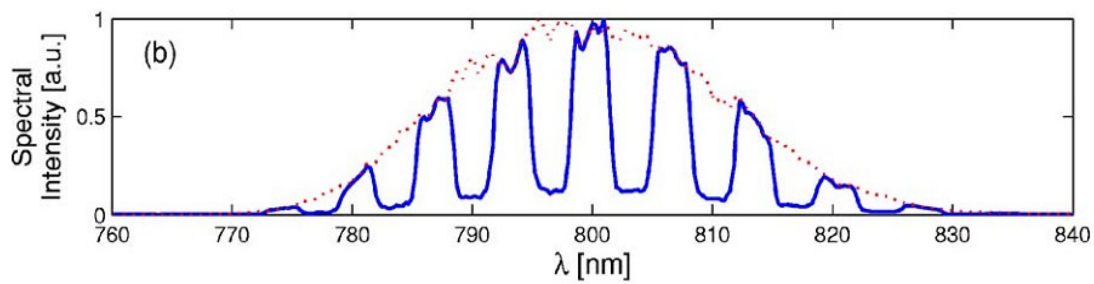


C. Mauclair. Spatio-Temp. Ultraf. Laser Tailoring for Bulk Functionalization of Transp. Materials. PhD Thesis, Uni.J.Monnet S.-Etienne; FU Berlin, 2010



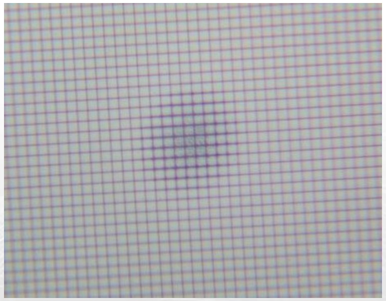
Phase and amplitude pulse shaping with two-dimensional phase-only spatial light modulators. E. Frumker, Y. Silberberg. J. OSA B, V.24, 12 (2007)



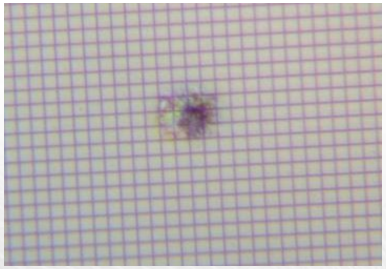


Images courtesy of Weizmann Institute

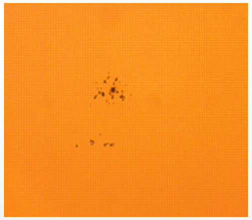
Guide on LIDT Levels (PLUTO Series)



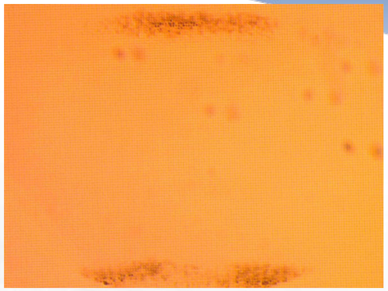
0.82 J/cm2 , 7ns 532 nm, 100Hz



0.064 J/cm2, 300fs 515 nm, 5kHz



0.036 J/cm2, 2ps 760 nm, 120Hz,
45K pulses



0.010 J/cm2, 2ps 380 nm, 120Hz

LIDT ns-laser 532 nm ~0.5J/cm2 (measured with 200um spot)
LIDT fs-laser 515 nm ~ 0.05J/cm2 (measured with 80um spot)

-> Way to improve LIDT: HR mirror on the backplane (running developements)

Summary

Resolution	1920 x 1080 (HD) *4096x2400 on the way*
Pixel Pitch	6.4 – 8µm *3.74µm on the way*
Fill Factor	87% - 94% (0.2-0.5µm interp. Gap) *Diel. Mirror („100% fill factor“) on the way*
Active Area	0.5“ - 0.7“ diagonal
LC Type	PAN, VAN
Modulation Range	2pi - 8pi
Addressing Rate	60Hz – 180Hz (options up to 800 Hz)
Spectral Band	400-700 nm, 600-1200 nm, 1200-1450 nm, 1450-1700 nm *350-450 nm under development*

Thank you for your attention!