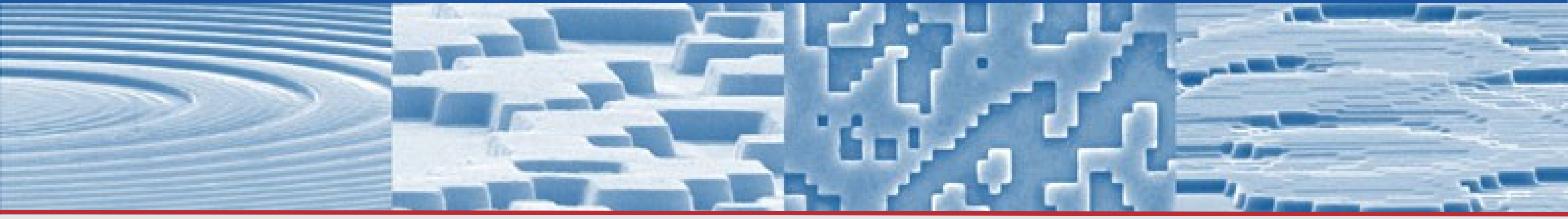
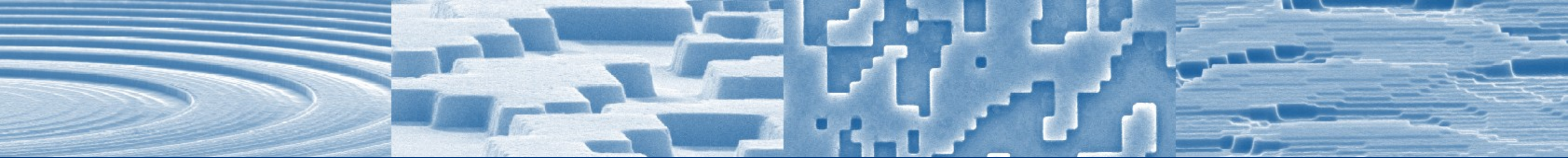


OptiXplorer – Optics experiments with an addressable Spatial Light Modulator (SLM)

Dr. Andreas Hermerschmidt
HOLOEYE Photonics AG

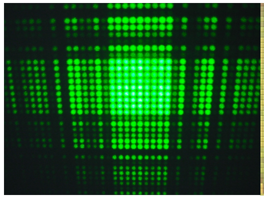
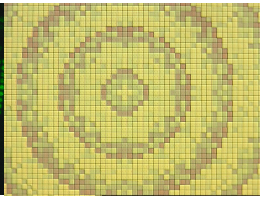
HOLOEYE Pioneers in Photonic Technology



Introduction

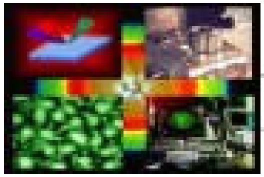
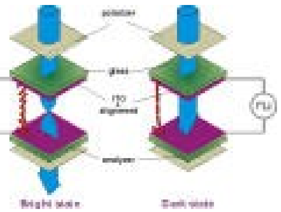

Components based on optical technologies are used in more and more applications:

- Displays
- Projection devices
- Diffractive Micro-optics (e.g. for laser modules)

The 'OptiXplorer' kit transports knowledge about:

- Liquid crystal cells and LC-displays
- Amplitude modulation and projection
- Polarisation (Jones-Formalism)
- Diffractive Optics and Fourier optics

Spatial Light Modulator 'LC2002'

Main hardware component of the kit:

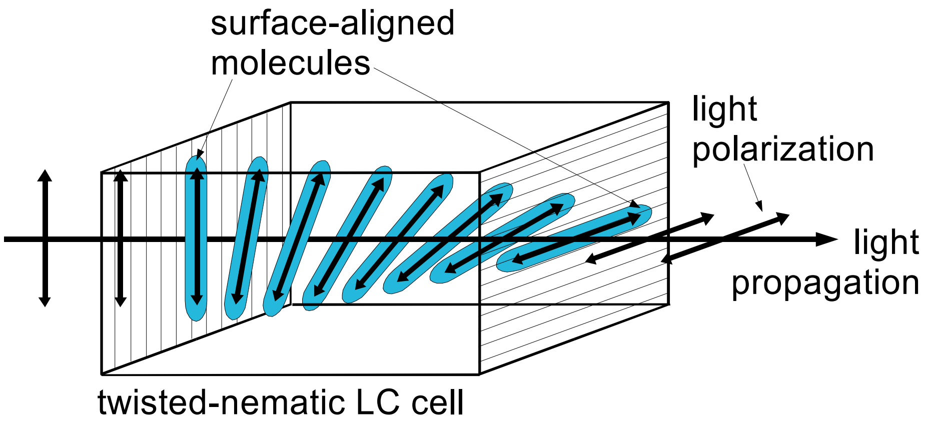
- Addressable spatial light modulator
- Transmissive LC display
- SVGA resolution (800 x 600 pixels)
- 32µm pixel size

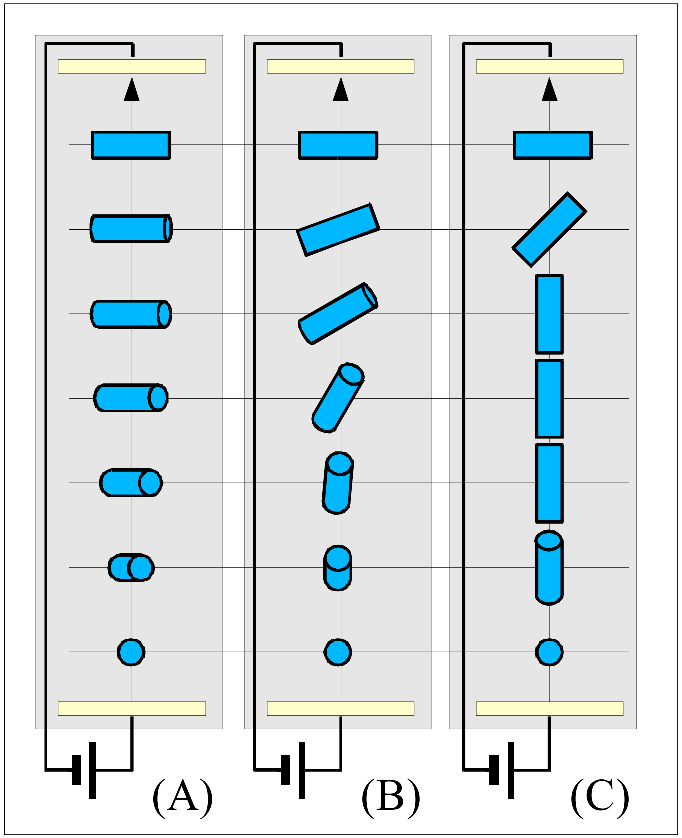
Interface for transmission of image content:

- VGA-interface of a PC
- Frame rate of 60Hz

Compact and robust housing design.

Properties of 'twisted nematic' liquid crystal cells





Tilt of twisted LC molecules with voltage increasing from (A) to (C)

Fundamental principle of operation:

- Incident light is linear polarised
- Helix of molecules forced by the 'director' surfaces of the cell covers
- Polarisation is guided by the helix → rotation
- Voltage at the cell leads to re-orientation of the molecules relative to the field → isotropy

Manual for the 'OptiXplorer' kit

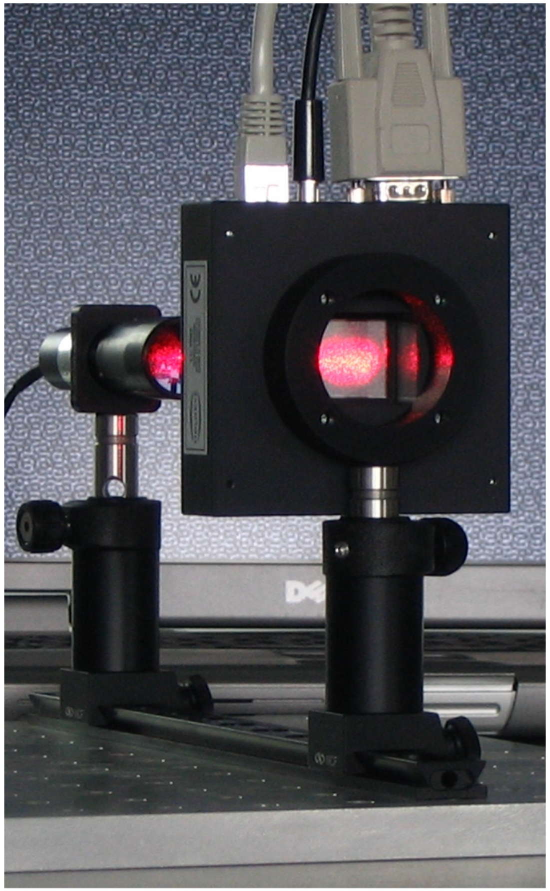
Contents of the manual

- Introduction to the theory of polarisation and liquid crystal cells
- Introduction to scalar wave theory and Fourier optics
- Tutorials for six experimental modules
- Description of and operating instructions for the hardware (SLM 'LC 2002', laser module, polarisers)
- Instructions for the provided software

OptiXplorer - Experimental modules

The experimental tutorial contains 6 modules:

- AMP: amplitude modulation and projection
- JON: Determination of the Jones matrix and the parameters of the TN-LC cells
- LIN: Linear and spatially separable binary beam-splitter gratings
- RON: Diffraction at dynamically addressed Ronchi gratings
- CGH: Computer-generated Holograms and adaptive lenses
- INT: Interferometric measurement of the phase modulation



AMP: Amplitude modulation and projection

Topics and Objectives:

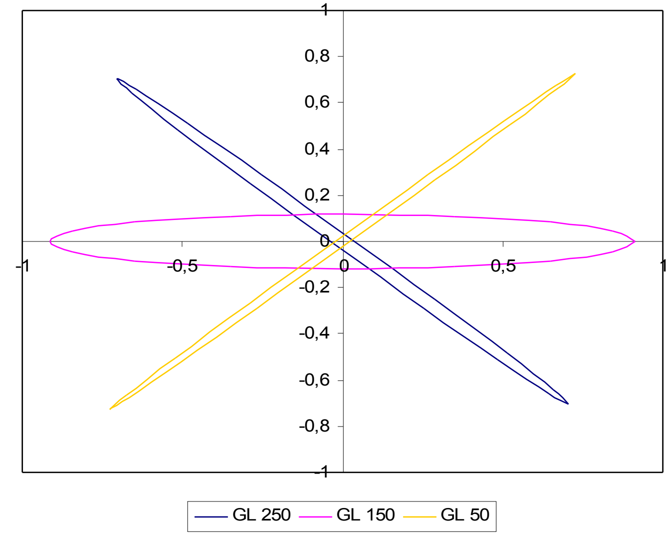
Understanding polarisation effects

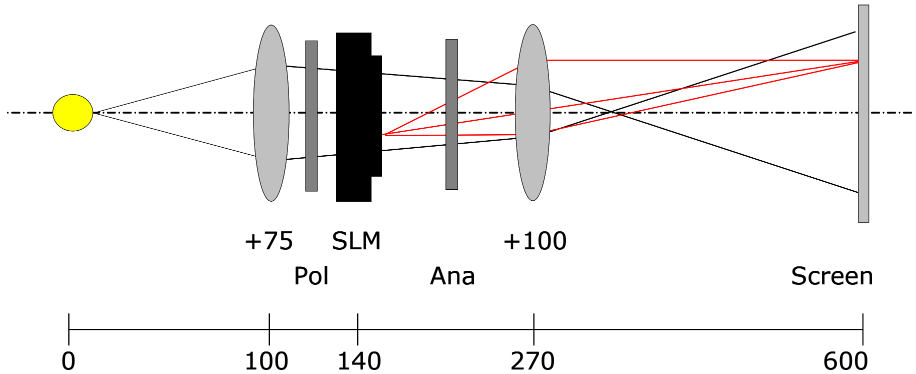
Creation of amplitude modulation

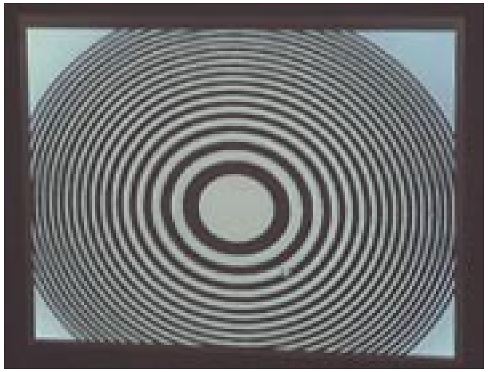
Optical set-up of a projector

Measurement of contrast

Determination of the pixel size of the modulator







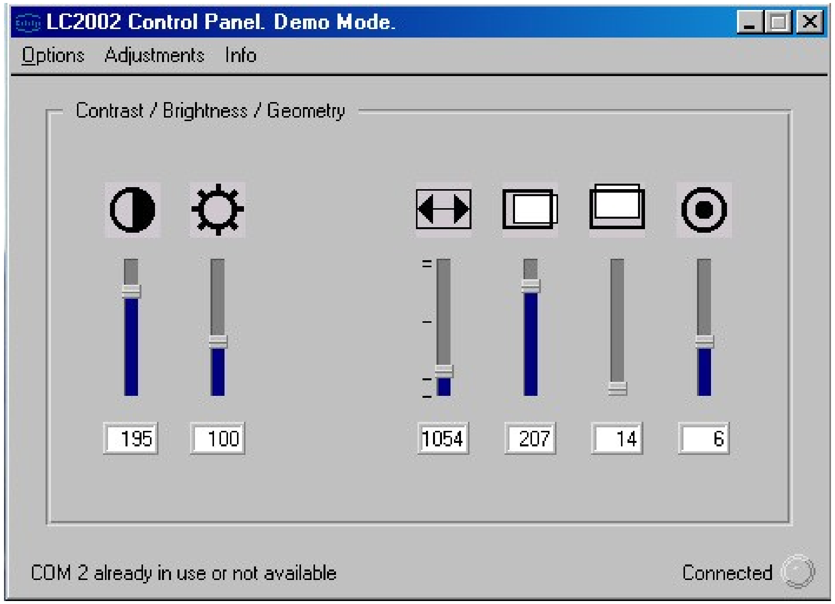
AMP: Amplitude modulation and projection

Device control software for the 'LC2002':

Optimisation of the properties

- Contrast
- Brightness
- Geometry

These parameters can also be set directly via RS232 commands – programming e.g. with LabView(TM) is possible for automated measurements



JON: Jones matrix and parameters of the TN-LC cells

Topics and Objectives:

Introduction to the Jones matrix formalism

Calculation of the transmission properties

Determination of the components of the Jones matrix

Derivation of the parameter of the LC cells:

Twist α, birefringence β, orientation ψ,

quantity $\gamma = \sqrt{\alpha^2 + \beta^2}$

$$f = \cos\gamma \cdot \cos\alpha + \frac{\alpha}{\gamma} \cdot \sin\gamma \cdot \sin\alpha$$

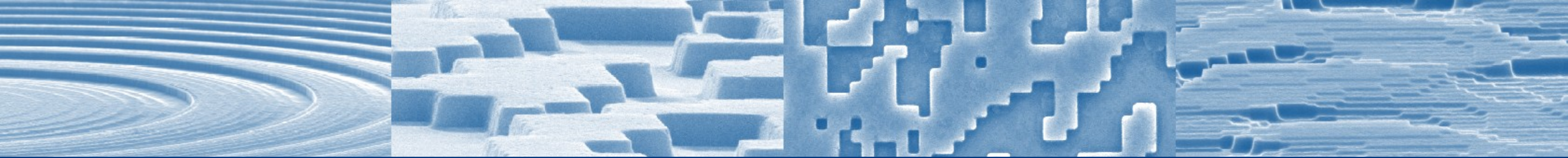
$$h = \cos\gamma \cdot \sin\alpha - \frac{\alpha}{\gamma} \cdot \sin\gamma \cdot \cos\alpha$$

$$g = \frac{\beta}{\gamma} \cdot \sin\gamma \cdot \cos(2\psi - \alpha)$$

$$j = \frac{\beta}{\gamma} \cdot \sin\gamma \cdot \sin(2\psi - \alpha)$$

Jones matrix of a 'twisted nematic' liquid crystal cell

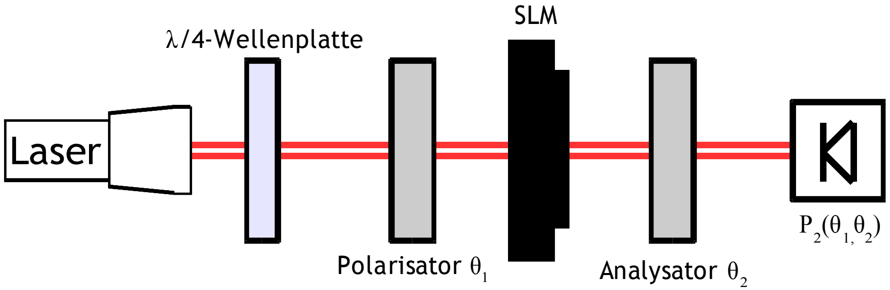
$$W_{\text{TN-LC}}^{\text{fghj}} = R(-\psi) \cdot W_{\text{TN-LC}} \cdot R(\psi) = e^{-i \cdot \beta} \cdot \begin{pmatrix} f - i \cdot g & h - i \cdot j \\ -h - i \cdot j & f + i \cdot g \end{pmatrix}$$



JON: Jones matrix and parameters of the TN-LC cells

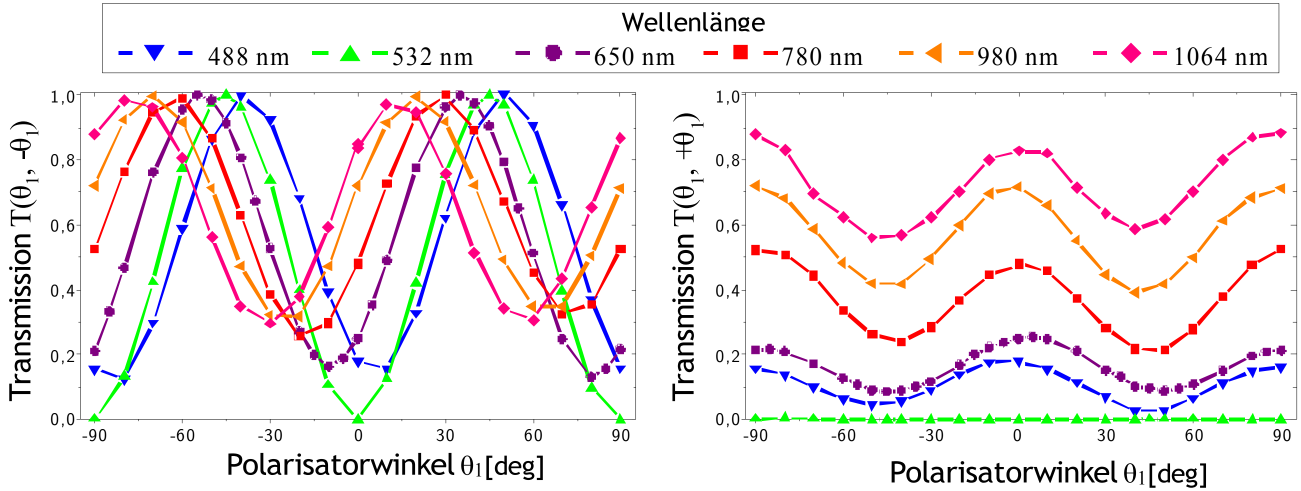
Experimental set-up:

Polarisers are rotated firstly in the same and secondly in the opposite directions

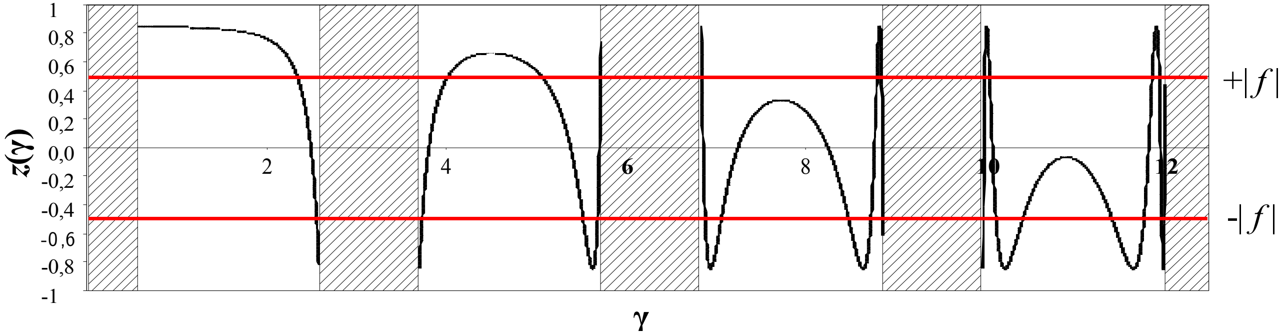


$$T^{+}(\theta_1) = T(\theta_1, +\theta_1) = f^2 + \left(g \cdot \cos(2\theta_1) + j \cdot \sin(2\theta_1)\right)^2$$

$$T^{-}(\theta_1) = T(\theta_1, -\theta_1) = g^2 + \left(f \cdot \cos(2\theta_1) + h \cdot \sin(2\theta_1)\right)^2$$



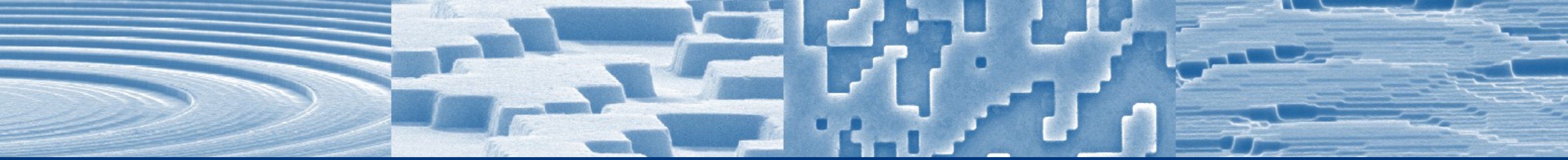
Derivation of the cell parameters: requires numerical calculations



$$z(\gamma) = \sqrt{\frac{f^2 + h^2 - \cos^2\gamma}{\sin^2\gamma}}\,\sin\gamma\,\sin\left(\gamma\sqrt{\frac{f^2 + h^2 - \cos^2\gamma}{\sin^2\gamma}}\right) + \cos\gamma\,\cos\left(\gamma\sqrt{\frac{f^2 + h^2 - \cos^2\gamma}{\sin^2\gamma}}\right)$$

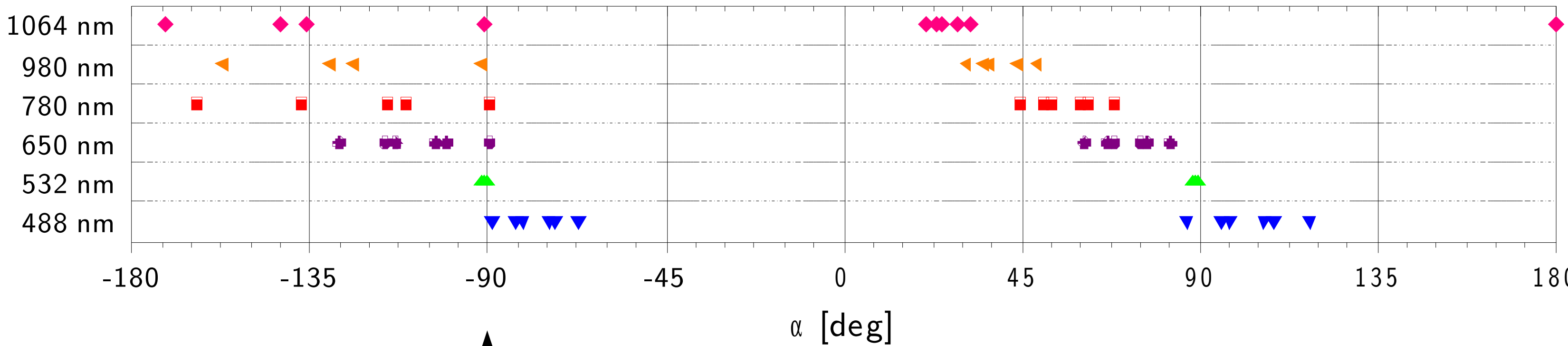
α [deg]	β[rad]
-127,50	2,91
-116,08	6,40
-113,30	9,64
-103,16	8,83
-100,43	5,59
-89,55	2,11
61,06	2,48
66,76	5,75
68,47	8,93
75,11	9,75
76,85	6,56
82,72	3,29

Determination of zeros delivers multiple solutions for a single wavelength (here, curves from measurements at 650nm wavelength



JON: Jones matrix and parameters of the TN-LC cells

Measurement with several different wavelengths:



Ambiguity can be resolved

Birefringence β as a function of the wavelength in agreement with expectation

λ[nm]	α [deg]	β [rad]	ψ [deg]
488	-88,80	3,20	-43,61
532	-90,03	2,69	N/A
650	-89,55	2,11	-41,91
780	-89,76	1,75	-42,19
980	-91,52	1,44	-44,17
1064	-90,97	1,16	-43,37

LIN: Linear and spatially separable binary beam-splitter gratings

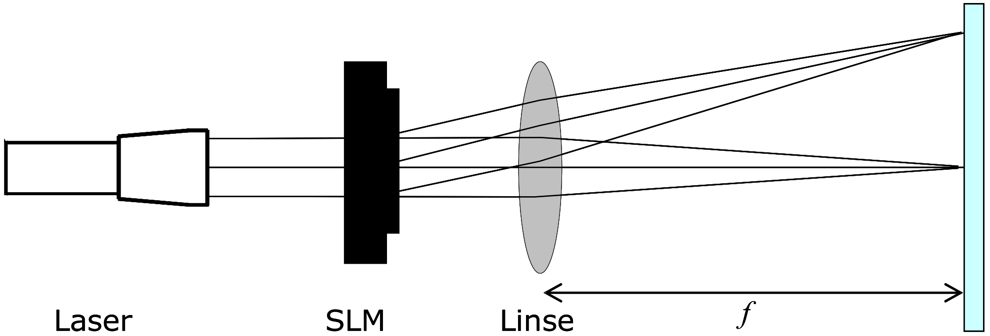
Topics and Objectives:

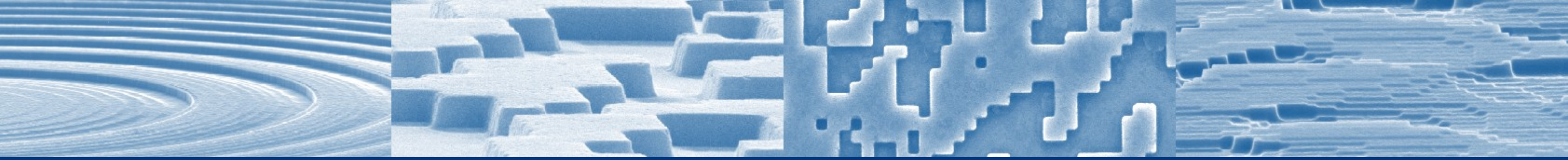
Introduction to scalar wave theory of diffraction

Focus on binary linear gratings - analytical formulas for diffraction efficiencies available

Measurement of diffraction angles and diffraction efficiencies

Determination of the geometric parameters of the LC cells (size, fill factor)

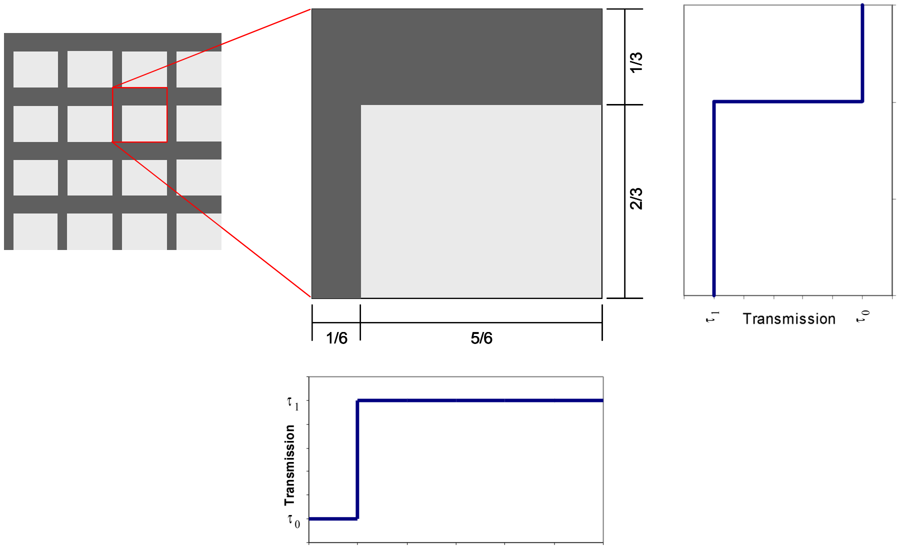




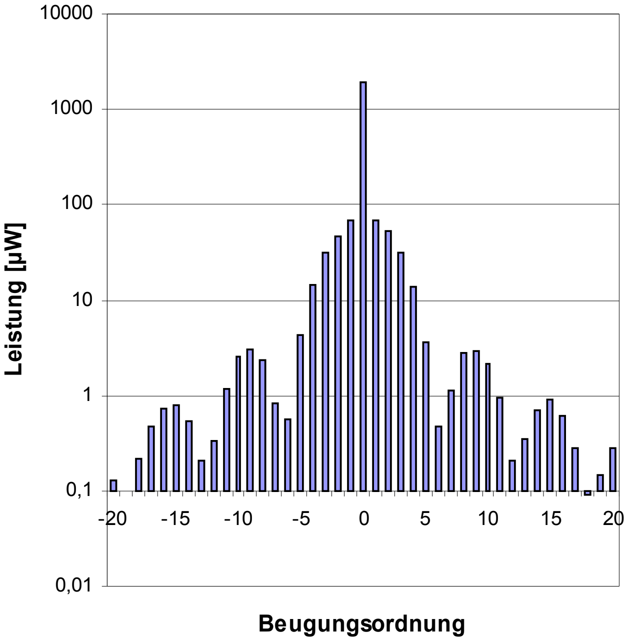
LIN: Linear and spatially separable binary beam-splitter gratings

Light modulator consists of single pixels

Approximation as two crossed linear gratings is feasible



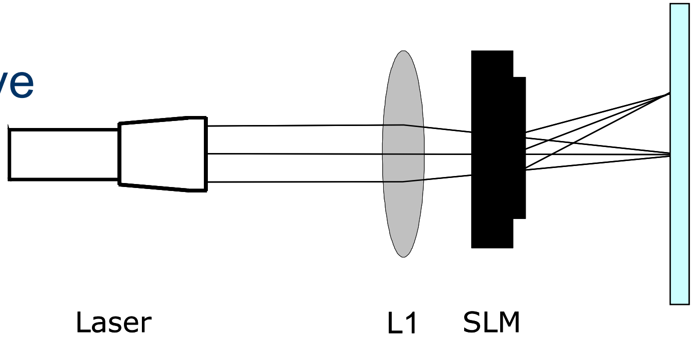
schematic drawing of the modulator's display cells



$$\eta_l = \frac{|\tau_2 - \tau_1|^2}{\pi^2 \cdot l^2} \cdot \sin^2\left(\pi l \frac{x_1}{g}\right)$$

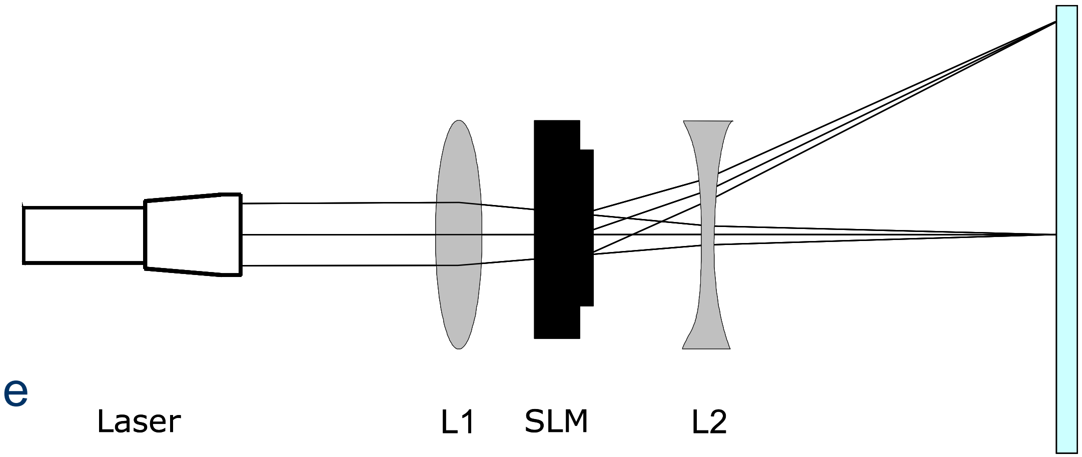
LIN: Linear and spatially separable binary beam-splitter gratings

Convergent illumination of the SLM: Fraunhofer-diffraction pattern in the focus of the convergent wave

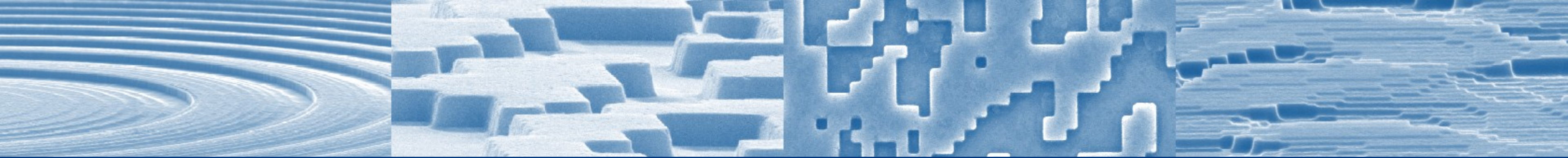


Angle magnification with a diverging lens with focal length f and distance d to the SLM

$$\alpha_2 = \alpha_1 \left(1 - \frac{d}{f} \right)$$



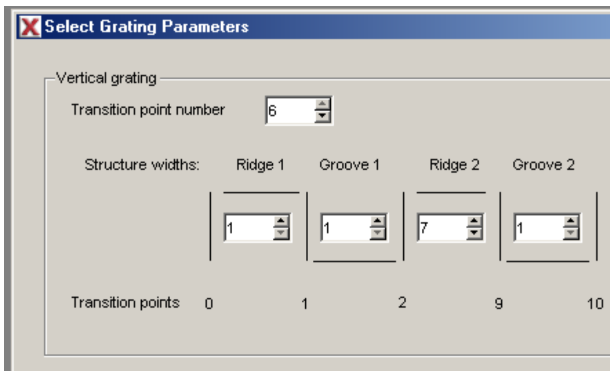
Separation of the orders is possible with a much more compact set-up



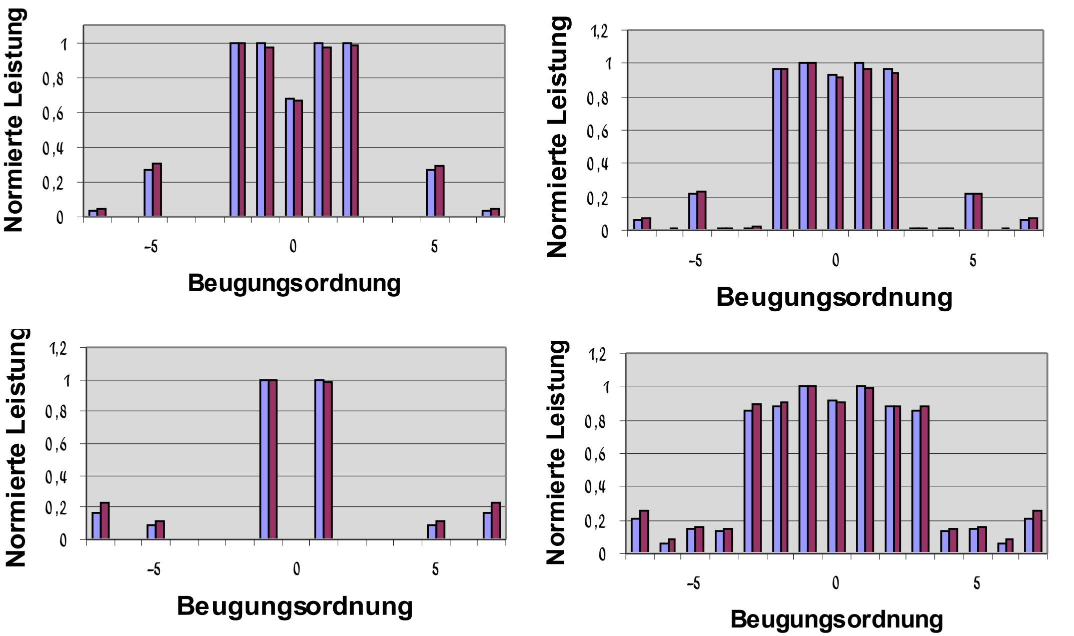
LIN: Linear and spatially separable binary beam-splitter gratings

Measurement of optical power in diffraction orders of binary linear gratings with specified designs

Analytical computation of diffraction efficiency is possible for comparison



'OptiXplorer' software: dialogue window for entering parameters



Comparison of theory (blue) and experiment (magenta)

RON: Diffraction at dynamically addressed Ronchi gratings

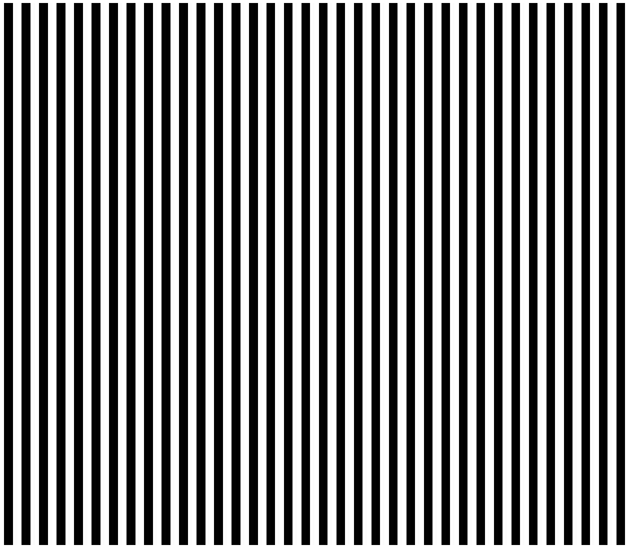
Topics and Objectives:

Introduction to scalar theory of diffraction

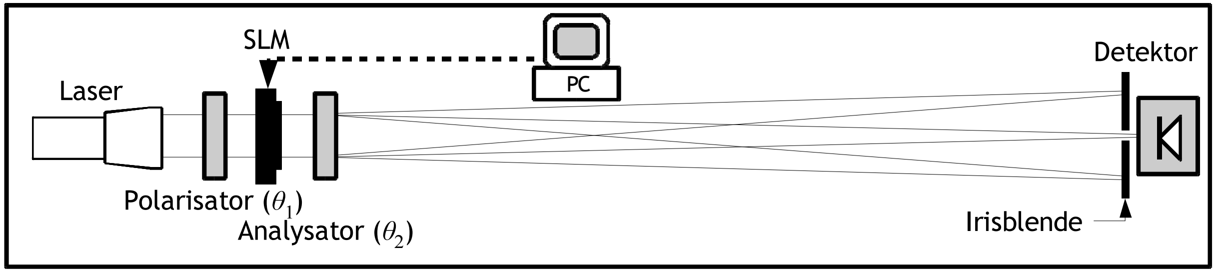
Power measurement of diffraction orders created by binary linear gratings with 1:1 duty cycle (Ronchi grating)

Derivation of the phase modulation of the spatial light modulators

Automatic Measurement with a LabVIEW(TM)-based software (can be modified for programming exercise)

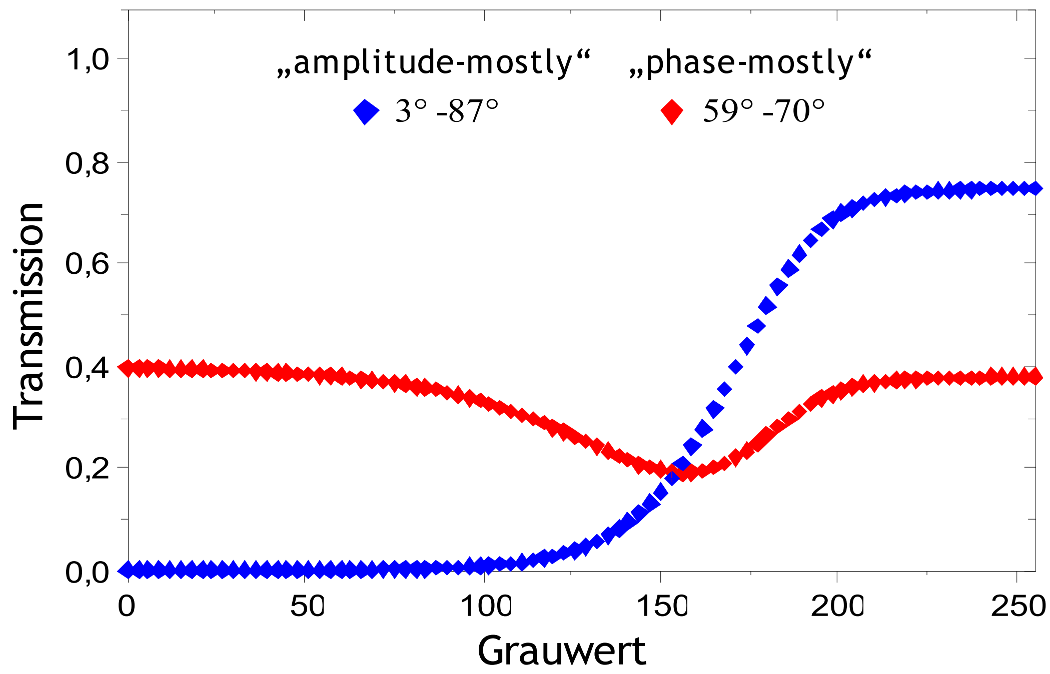


Ronchi grating



RON: Diffraction at dynamically addressed Ronchi gratings

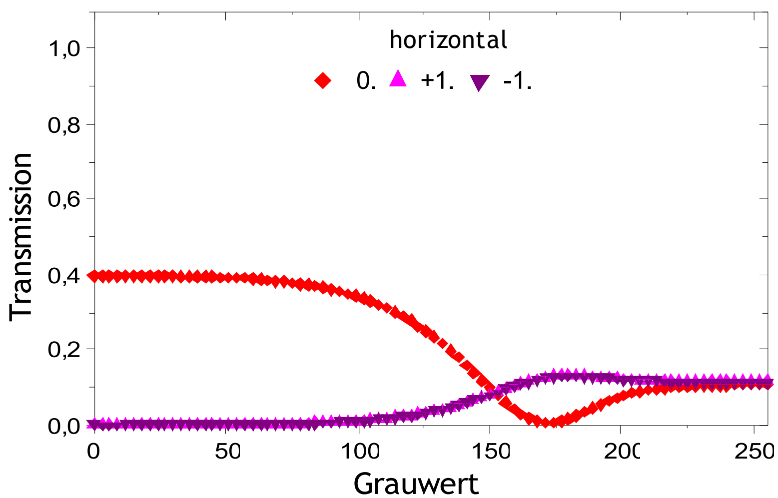
Rotational orientation of polarisers changes light modulation properties (amplitude-mostly vs. phase-mostly)

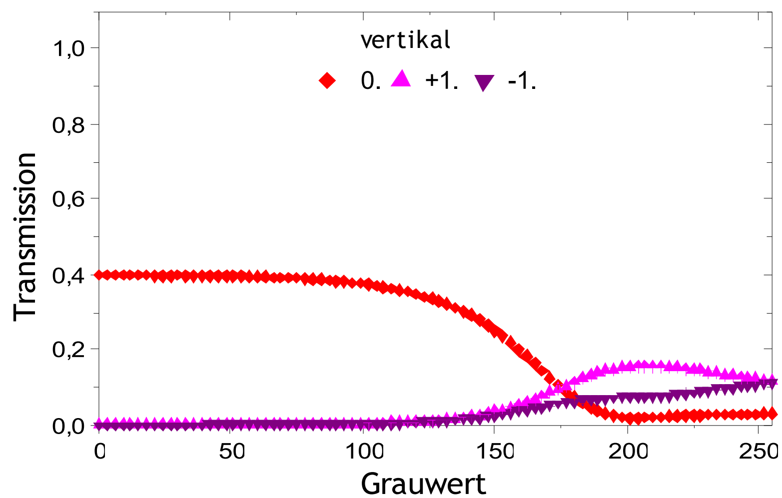


Transmission measurement

RON: Diffraction at dynamically addressed Ronchi gratings

Power in diffraction orders permits derivation of the phase modulation:



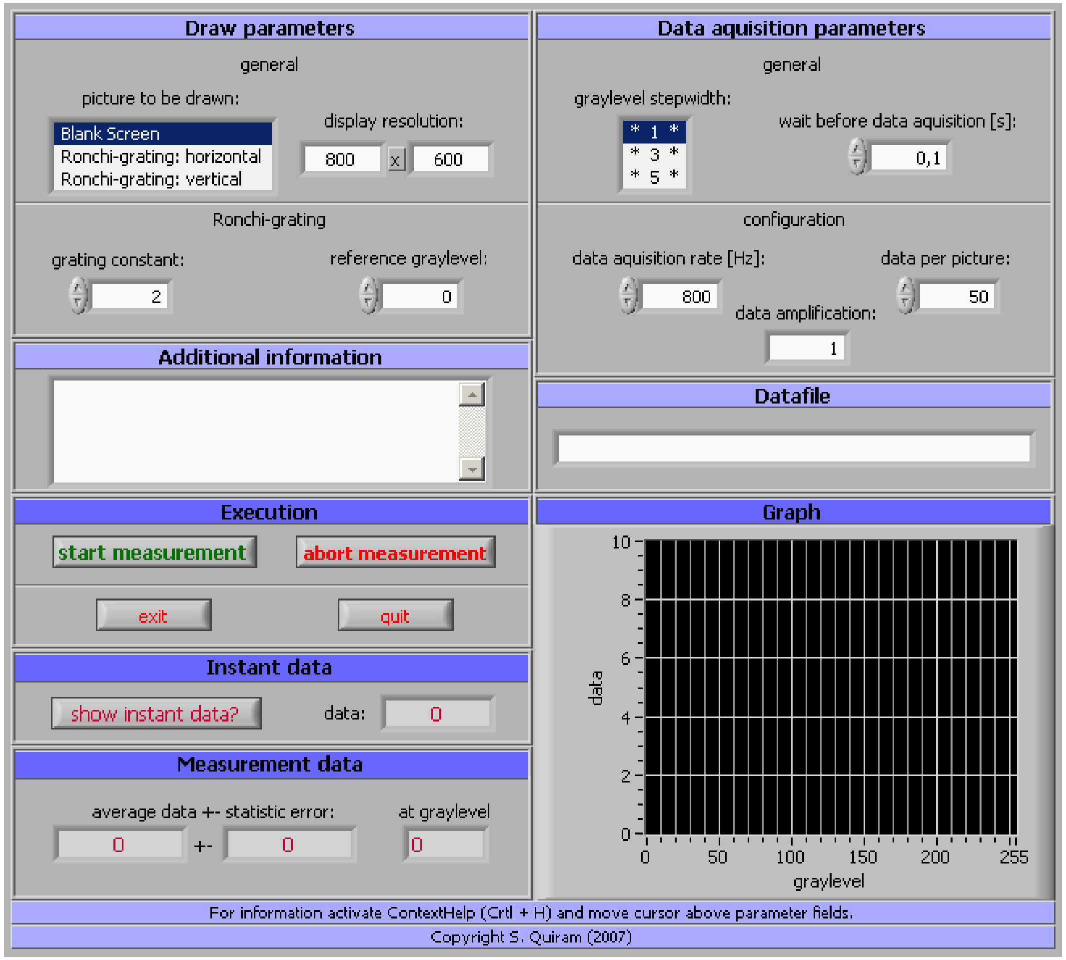


Measured powers in diffraction orders dependent on the gray-scale contrast of the displayed Ronchi grating

Phase modulation: $\Delta\Phi = \arccos\left(\frac{(\rho_1^2 + \rho_2^2)\cdot(4\cdot\eta_0 - \pi^2\cdot\eta_{\pm 1})}{\rho_1\cdot\rho_2\cdot(8\cdot\eta_0 + 2\pi^2\cdot\eta_{\pm 1})}\right)$

RON: Diffraction at dynamically addressed Ronchi gratings

LabVIEW(TM)-based software „DynRon“ draws automatically bitmaps representing Ronchi-gratings and reads the corresponding power detector value



The software can be modified to satisfy your needs !

CGH: Computer generated holograms and adaptive lenses

Topics and Objectives:

Introduction of the computational design of diffractive optical elements

Iterative Fourier Transform Algorithm (IFTA)

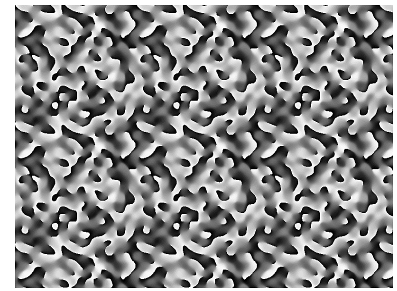
Determination of focal lengths of addressed diffractive lenses

Optical effect of superposition of analytic phase functions (linear, quadratic)

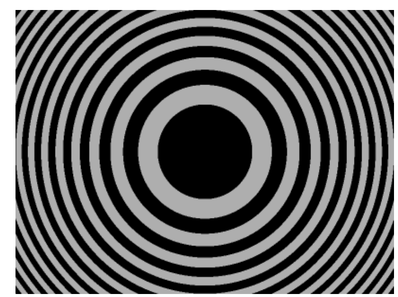
Spatial separation of the undiffracted order

Optical systems with refractive and dynamic diffractive elements

Derivation of the pixel size of the SLM

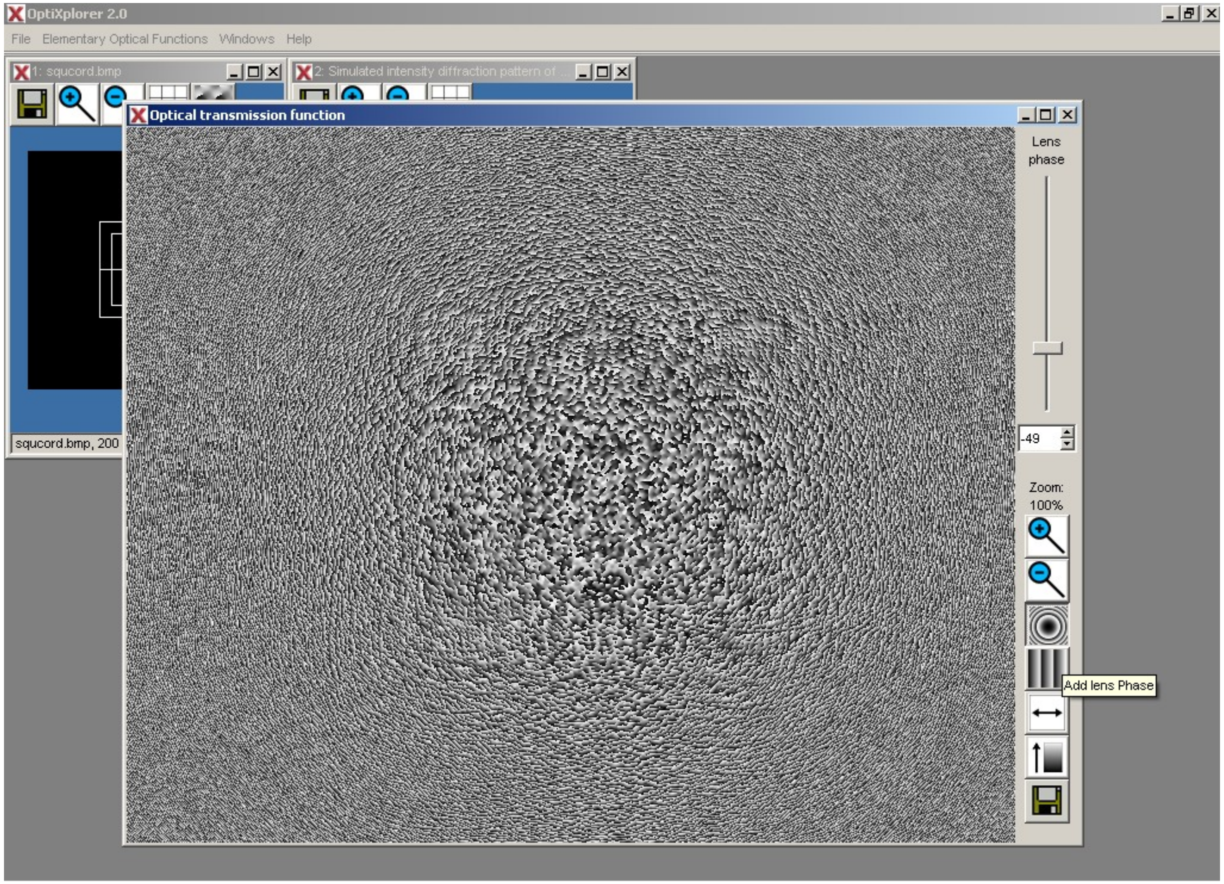


Multi-Level CGH



Binary Fresnel Zone lens

CGH: Computer generated holograms and adaptive lenses

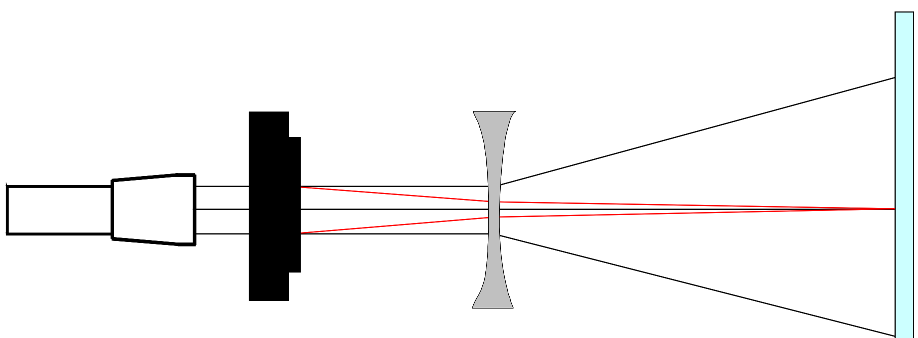


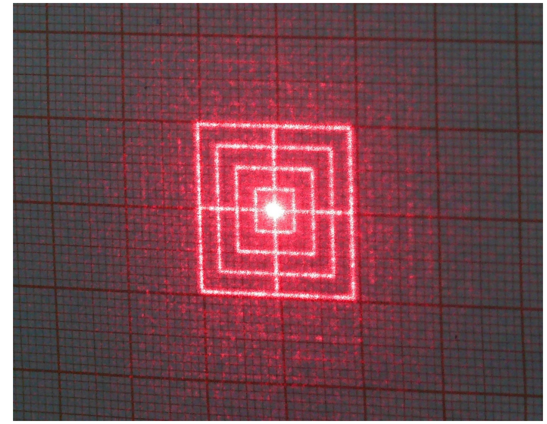
'OptiXplorer' software:

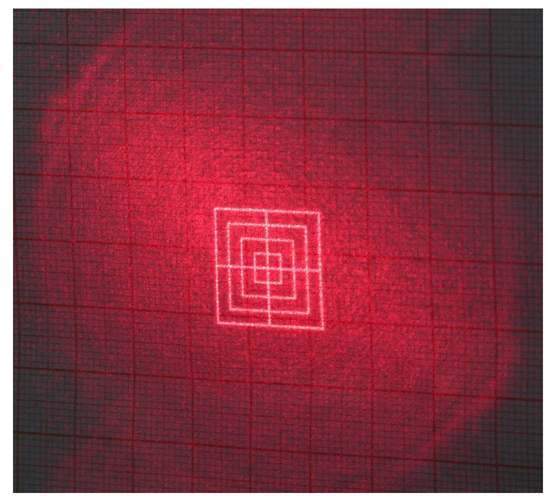
- Superposition with
  - Lens phase function
  - Prism phase function
- Zoom in/Zoom out
- Translation
- Modification of Gamma curve or contrast

CGH: Computer generated holograms and adaptive lenses

- Addressing a CGH: undiffracted order creates bright spot in the far field diffraction pattern
- Superposition of a lens phase: Fresnel-hologram, reference wave is out of focus
- Angle enlargement with a diverging lens







INT: Interferometric measurement of the phase modulation

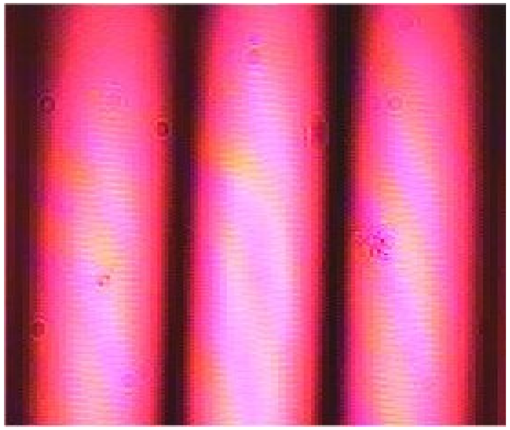
Topics and Objectives:

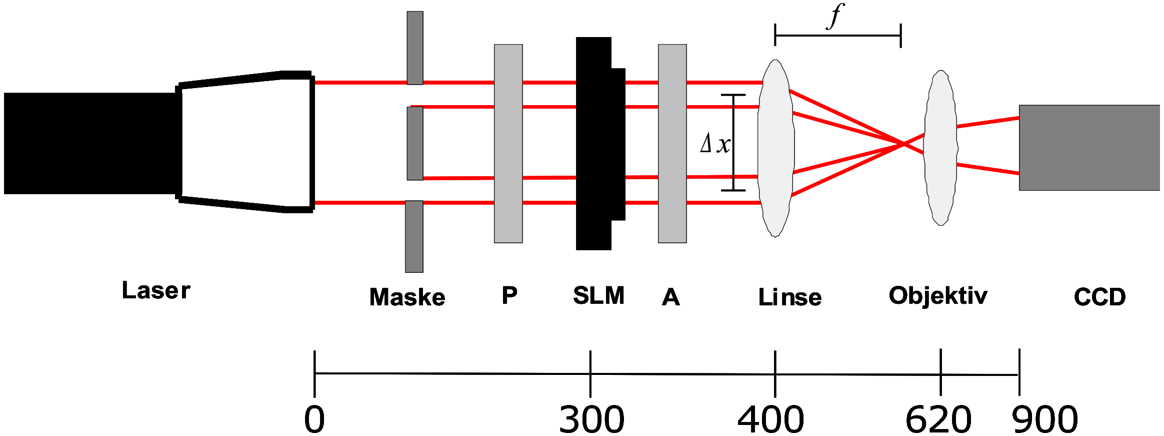
Introduction to interferometric measurements

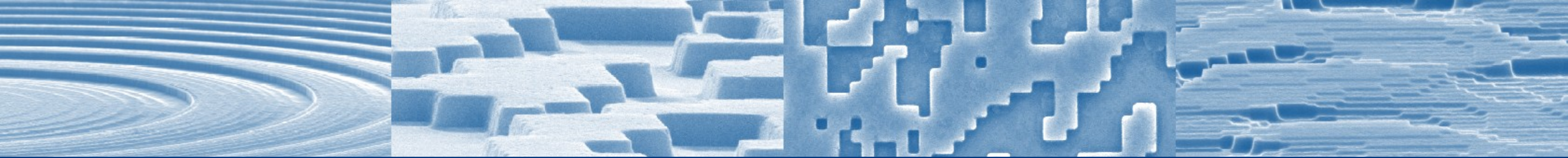
Determination of the SLM's phase modulation with a simple two-beam interferometer

Automatic Measurements using provided 'PhaseCam' software

Determination of rotational polariser orientation for the desired 'phase-mostly' modulation

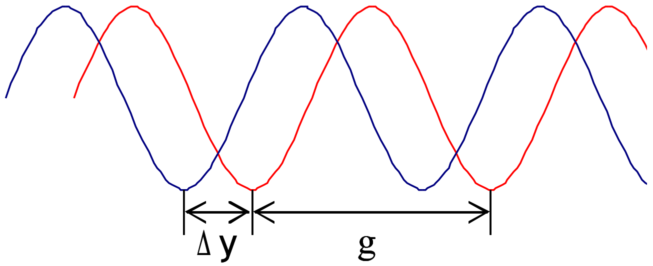






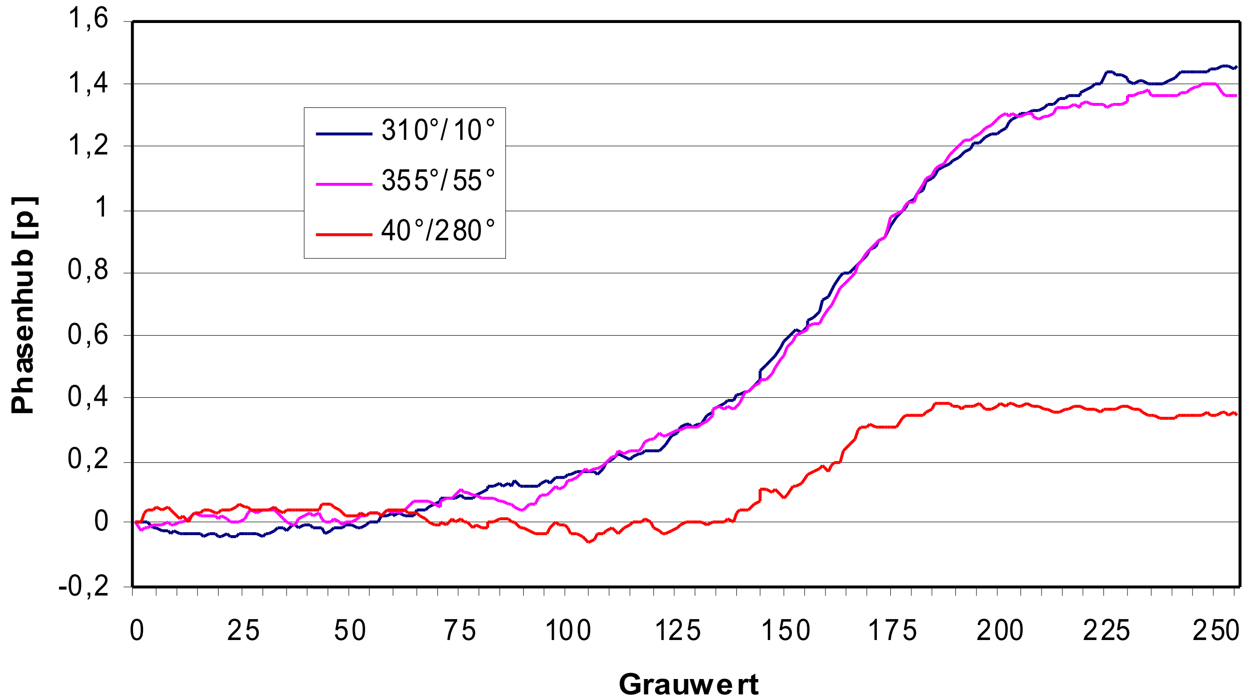
INT: Interferometric measurement of the phase modulation

- Addressing half-screen images on the SLM
- Phase modulation leads to spatial fringe shift
- Magnified image on the CCD camera sensor created with a telescope
- Simple derivation of the phase modulation from the measured movement of the interference pattern:



$$\Delta\Phi = \frac{2\pi}{g} \cdot \Delta y$$

INT: Interferometric measurement of the phase modulation



Automatic Measurement with provided 'PhaseCam' software permits a search for optimum orientations of the polariser and the analyser

Summary of the 'OptiXplorer' experimental tutorial

Relatively small number of affordable components permits experiments related to different topics in optics, among them are

- Geometric Optics and Imaging
- Polarisation
- Diffraction and interference
- Holography

The suggested experiments can be combined in many ways to create advanced experimental projects – for example: „**Characterisation of a transmissive SLM**“:

(1) Cell size and fill factor by diffraction

(2) Jones matrix and LC-related cell parameters by transmission measurements with two polarisers

(3) Amplitude modulation and contrast with a projector

(4) Phase modulation with a two-beam interferometer

Acknowledgement - Contributions from universities

We would like to thank for the contributions from universites which have helped to develop and improve the Opti**X**plorer:

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- PD Dr. Günther Wernicke,
  Labor für Kohärenzoptik, Institut für Physik,
  Humboldt-Universität zu Berlin

- Dipl.-Phys. Stephanie Quiram
  (Group of Prof. Hans Joachim Eichler),
  Technische Universität Berlin, Institut für Optik und Atomare Physik

- Dipl.-Phys. Sven Plöger
  (Group of Prof. Jürgen Eichler),
  Labor für Laseranwendungen und Optoelektronik,
  Technische Fachhochschule Berlin

Thank you for your interest in the OptiXplorer.
Questions ?
Please contact optixplorer@holoeye.com

HOLOEYE Pioneers in Photonic Technology