Dynamic beam shaping with programmable diffractive optics

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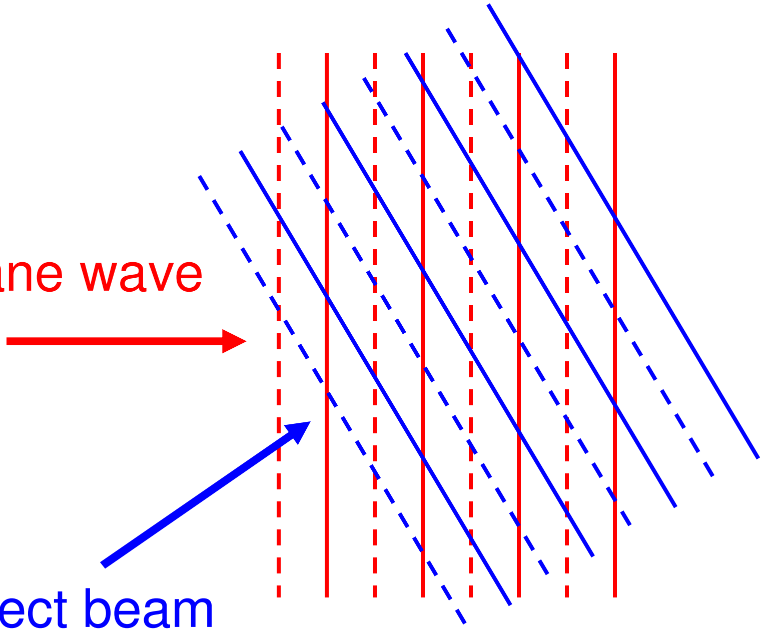
Outline of the talk

- Introduction
  - Holography
  - Programmable diffractive optics
- Laser scanning confocal microscopy (LSCM)
  - Aberration correction in LSCM
- Programmable reference phase stepping interferometry
- Conclusion

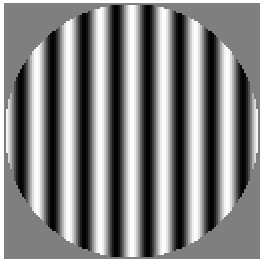
The principle of holography



Reference plane wave

Object beam

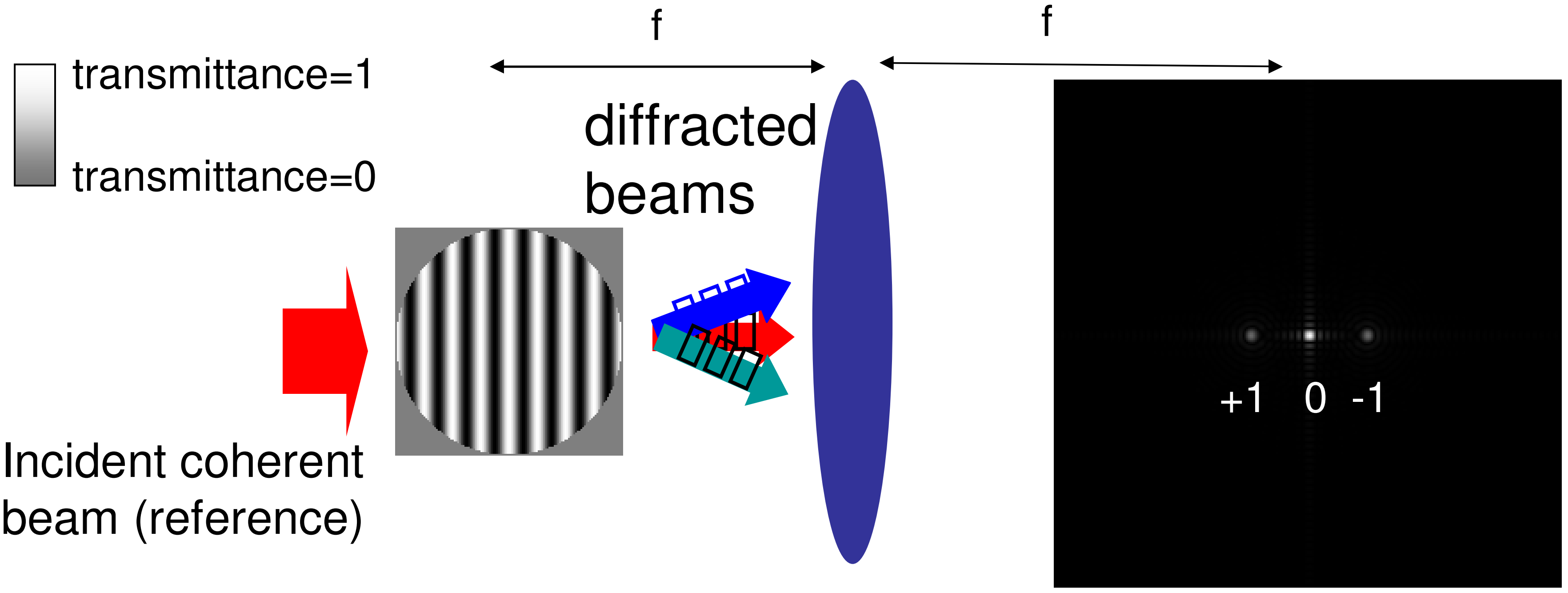
Resulting interference pattern



—— Crest

-------- Trough

The principle of holography



transmittance=1

transmittance=0

f

f

diffracted beams

+1 0 -1

Incident coherent beam (reference)

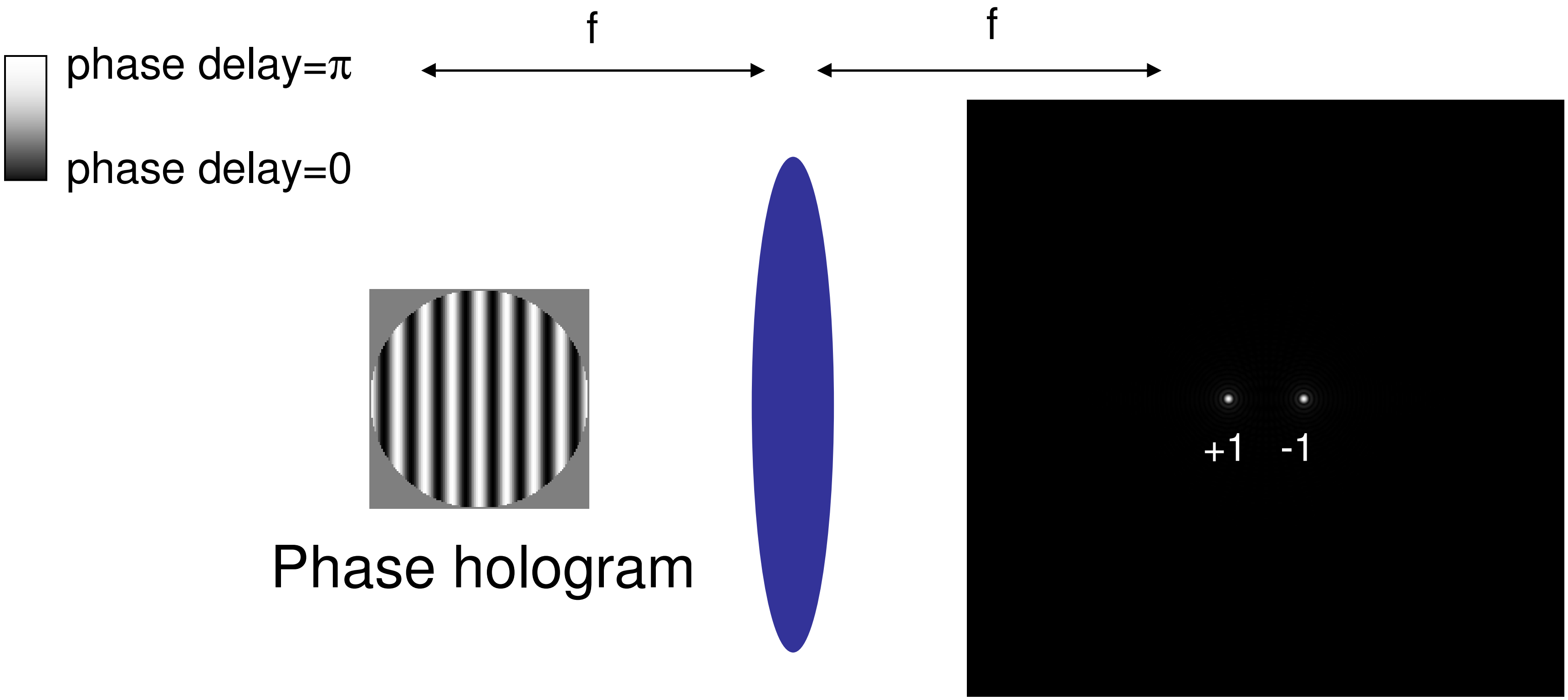
hologram

lens

diffraction pattern
(Fourier plane of the hologram)

➡ Reconstructed object beam
➡ Conjugate beam

Phase only hologram



Phase hologram

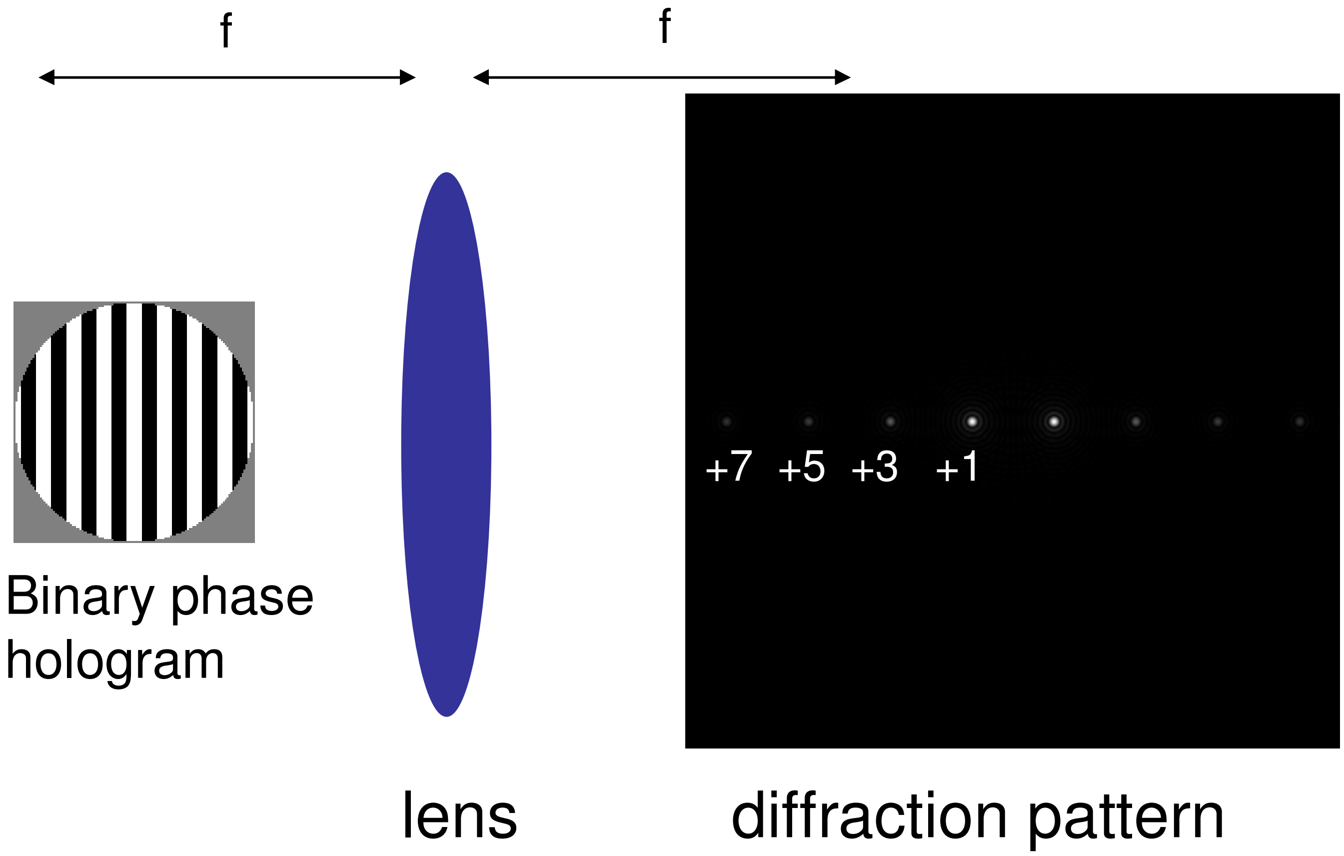
lens

diffraction pattern

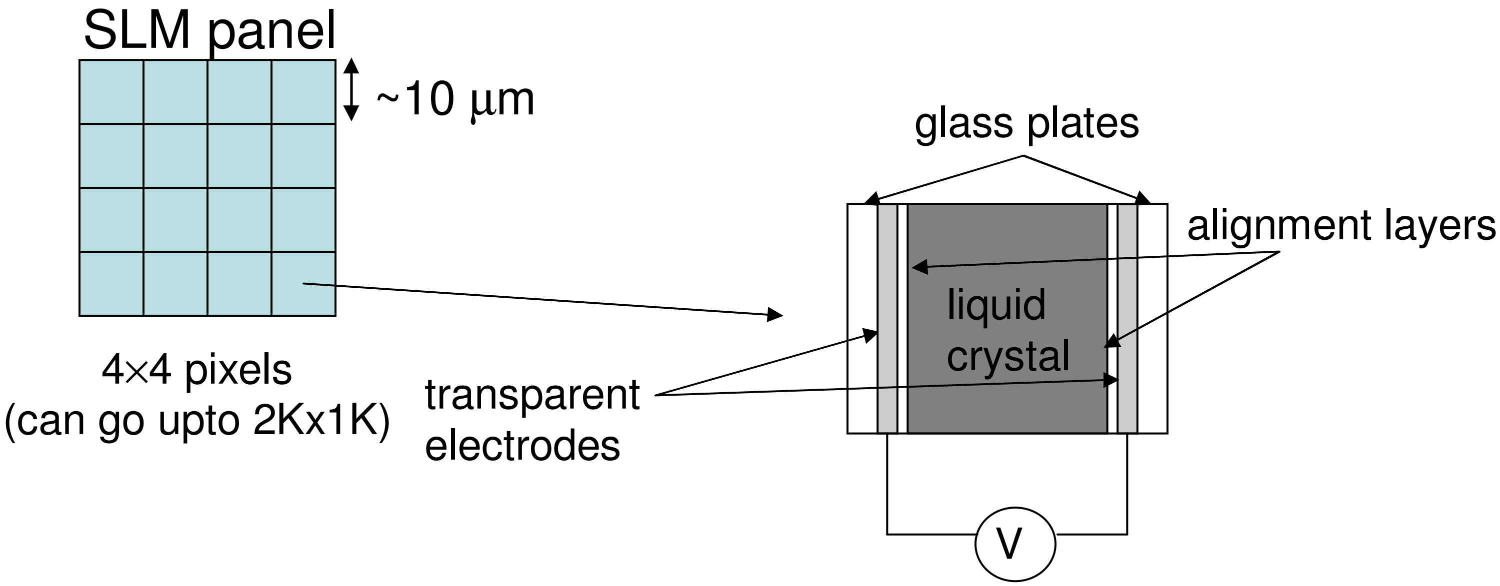
Binary phase only hologram

☐ phase delay=π

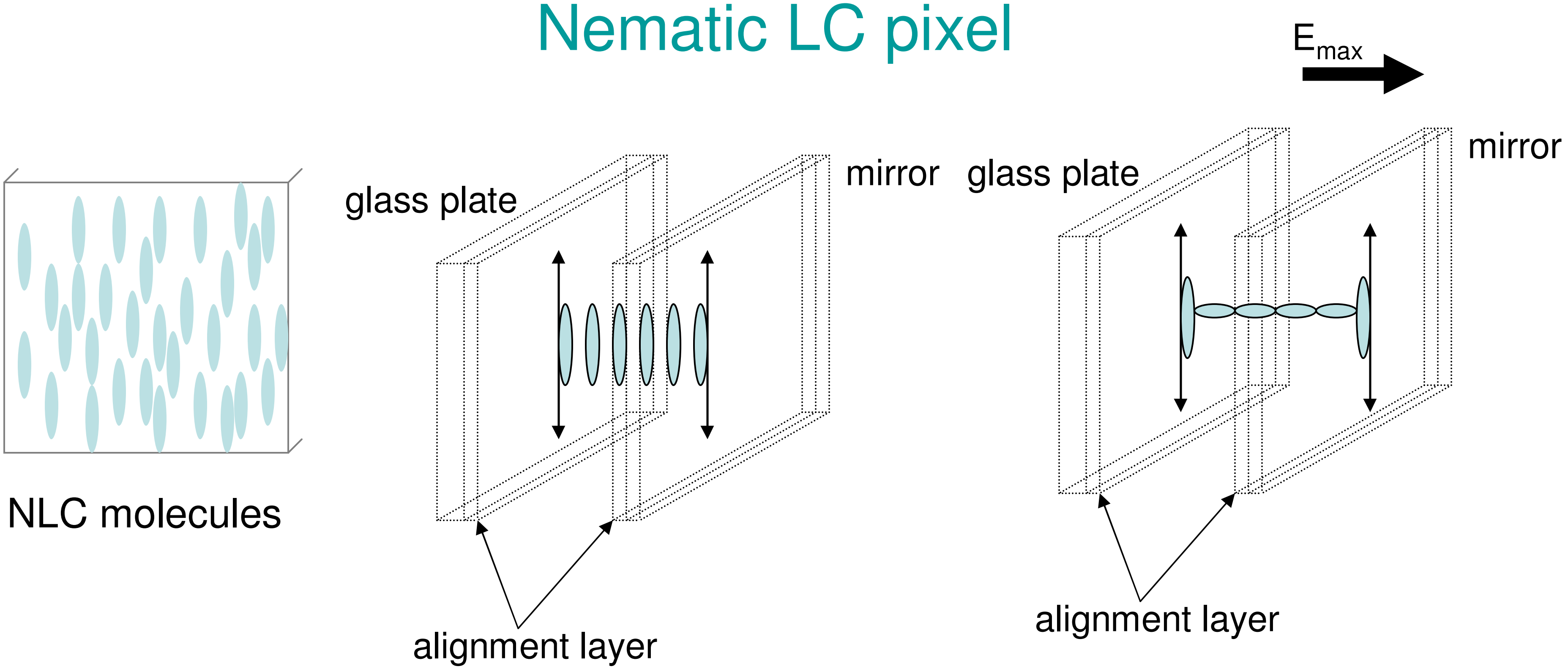
■ phase delay=0



Liquid crystal spatial light modulator (LCSLM)

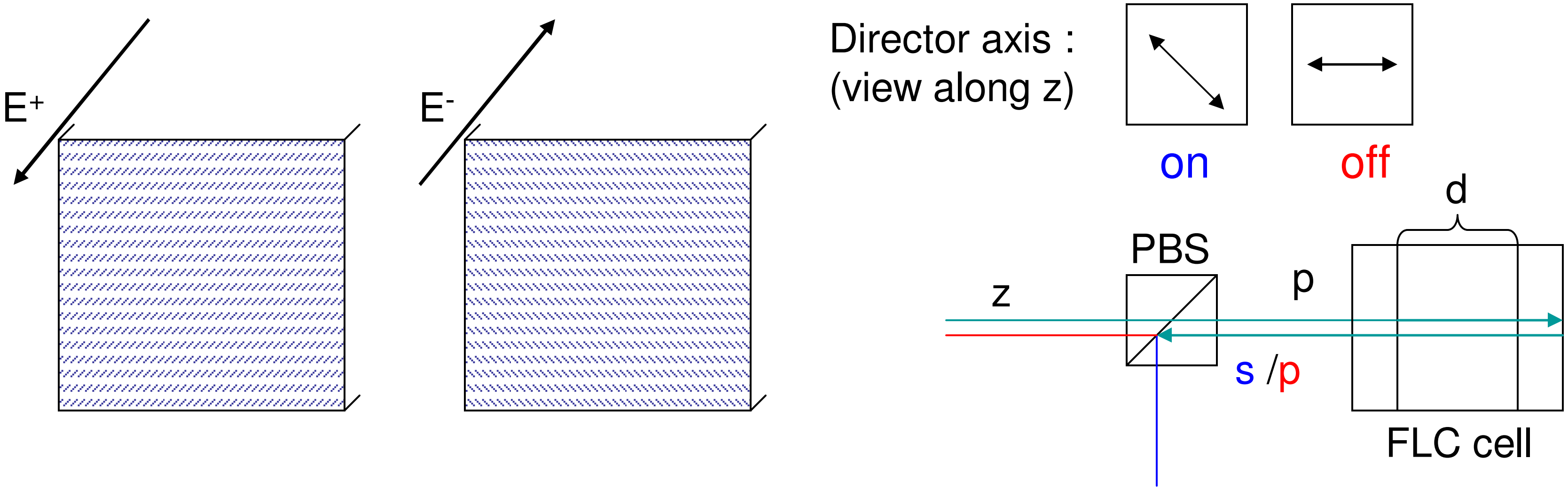


Nematic LC pixel



- Analog phase modulation
- Response time of the molecules :~ms
- Frame rate :60Hz
- Light efficiency :50%

Ferroelectric LC pixel



- Binary amplitude or phase (0 or π) modulation
- Response time of the molecules :~10µs
- Frame rate :1440 Hz
- Light efficiency (amplitude modulation) : 70%

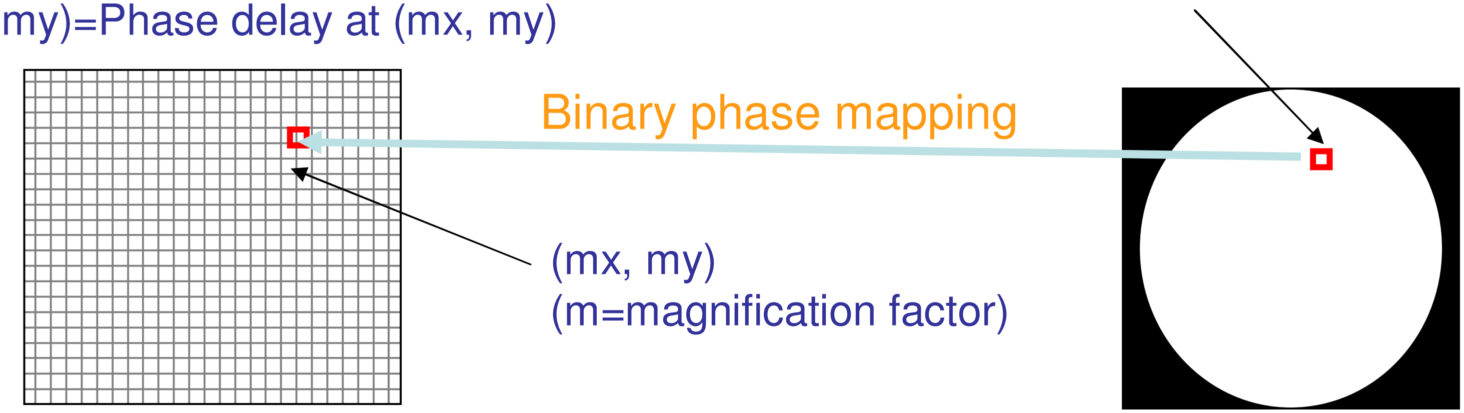
Binary Hologram Design for phase and amplitude modulation

Complex amplitude
over the pupil plane (x,y) $= a(x,y)\, e^{i\phi(x,y)} = u(x,y) + iv(x,y)$

a(x,y) = normalised amplitude= $\sqrt{u^2 + v^2}$

ϕ(x,y) = desired phase+overall tilt= $\tan^{-1} \dfrac{u}{v}$

S(mx, my)=Phase delay at (mx, my)



[u(x,y) ,v(x,y)]

Binary phase mapping

(mx, my)
(m=magnification factor)

F (ferroelectric) LCSLM plane

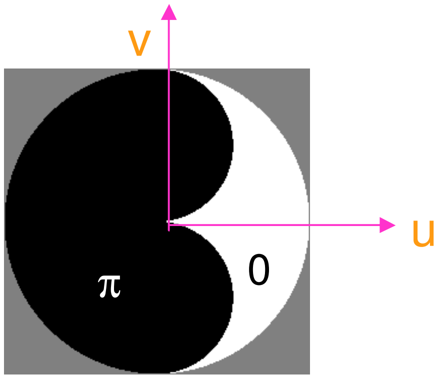
Pupil plane

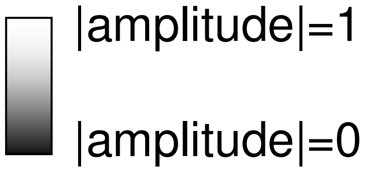
Binary phase mapping algorithm

Complex amplitude desired = [u(x,y), v(x,y)]

Binary phase map

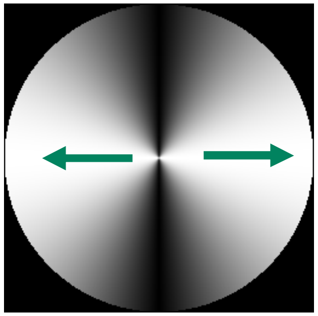
$\phi(x, y) \rightarrow S(mx,my)$





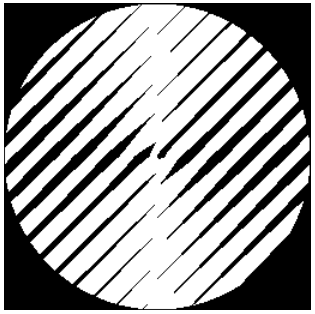
Desired amplitude profile

In the pupil plane



Off-axis hologram on

FLCSLM



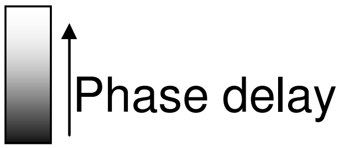
Binary phase mapping algorithm

Complex amplitude
over the pupil plane (x,y) = $e^{i\phi(x,y)}$ such that $a(x,y)=1$

$$S(mx, my) \quad \begin{cases} =0 \text{ if } \cos(\phi(x,y))>0 \\ =\pi \text{ if } \cos(\phi(x,y))<0 \end{cases}$$

Desired amplitude profile
In the pupil plane

Off-axis hologram on
FLCSLM



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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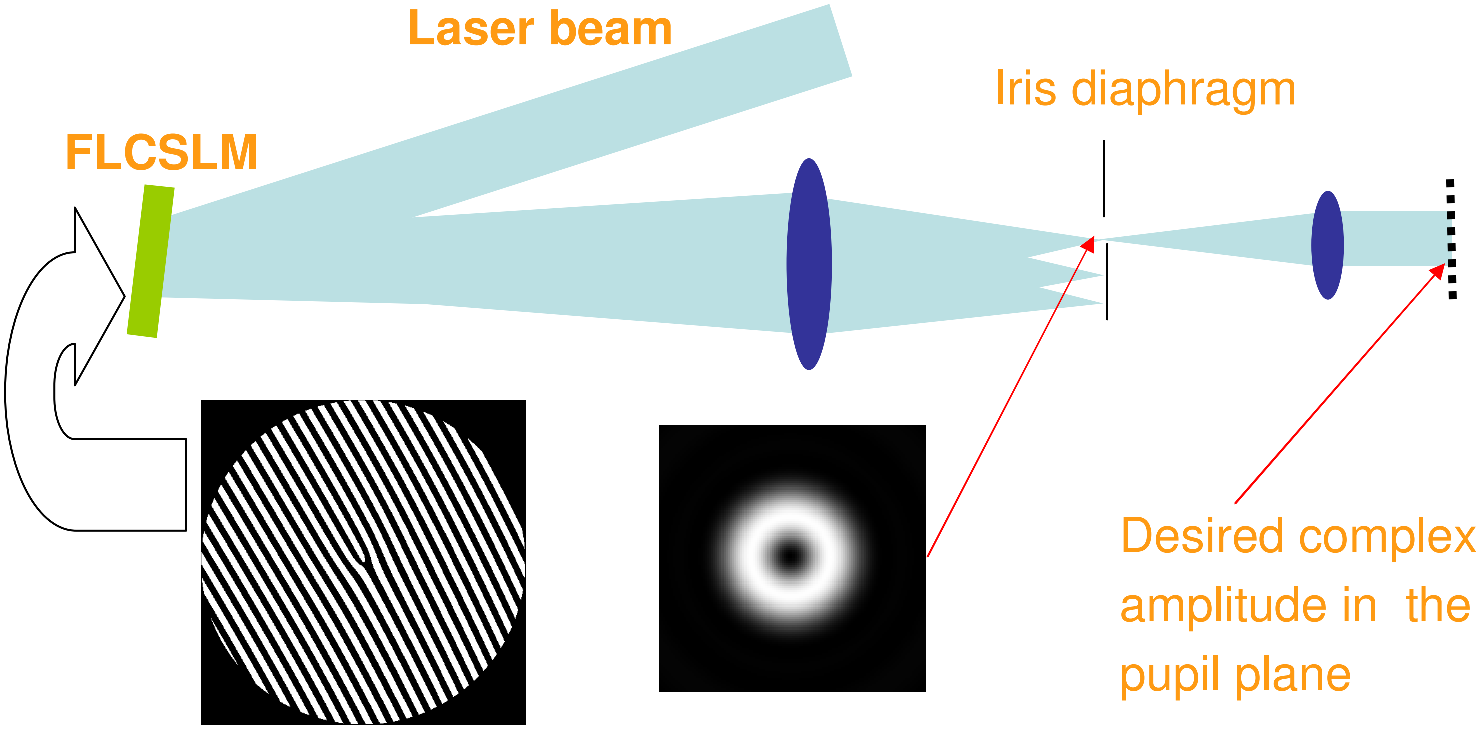
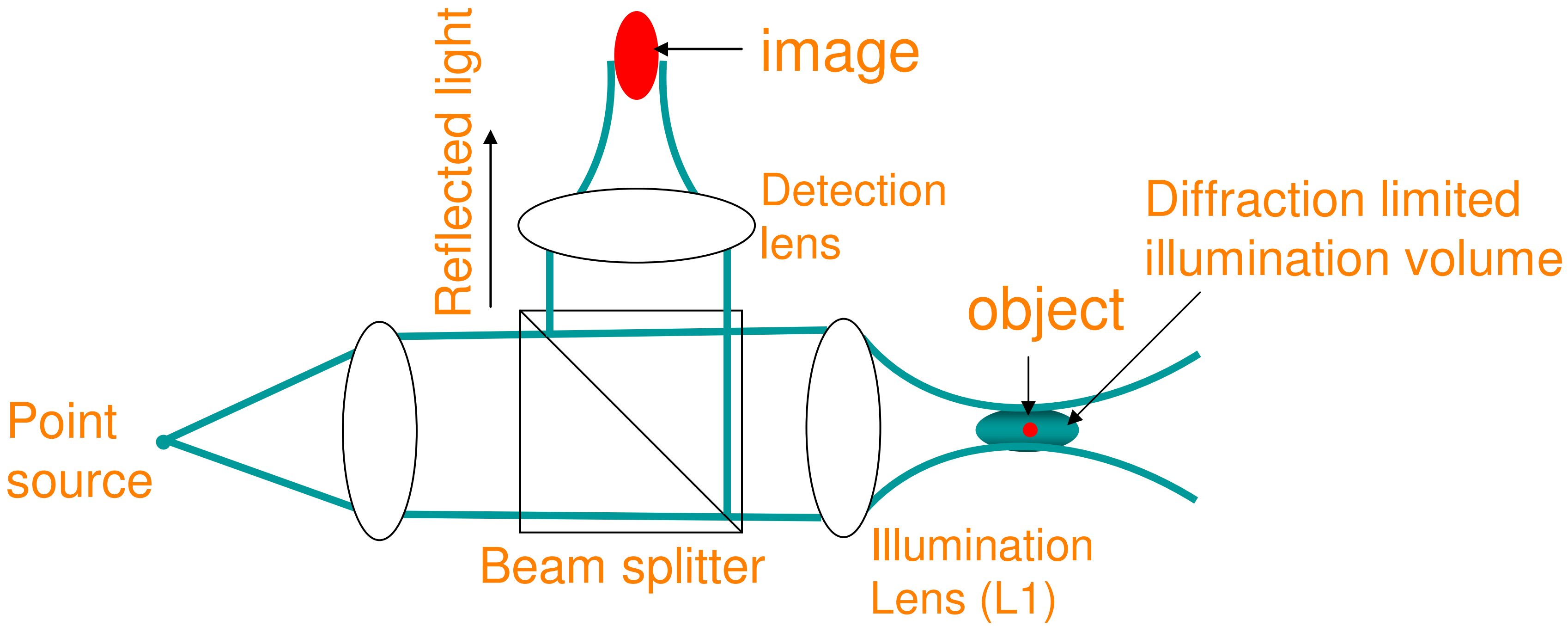
Generation of arbitrary complex amplitude profile

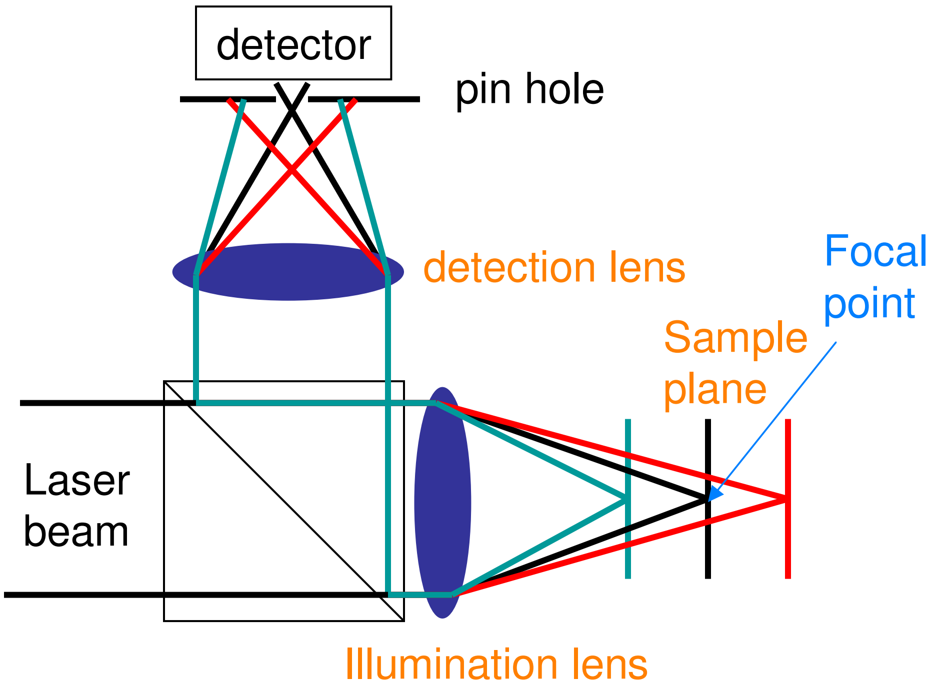


Wide field microscope



- Collimated beam of wavelength λ is focused by L1 to a diffraction limited volume
- The illumination volume depends on λ, focal length and diameter of the illumination lens
- A point object is imaged into a diffraction limited volume in the image space
- Resulting image has poor axial resolution

Optical sectioning in a confocal microscope



detector

pin hole

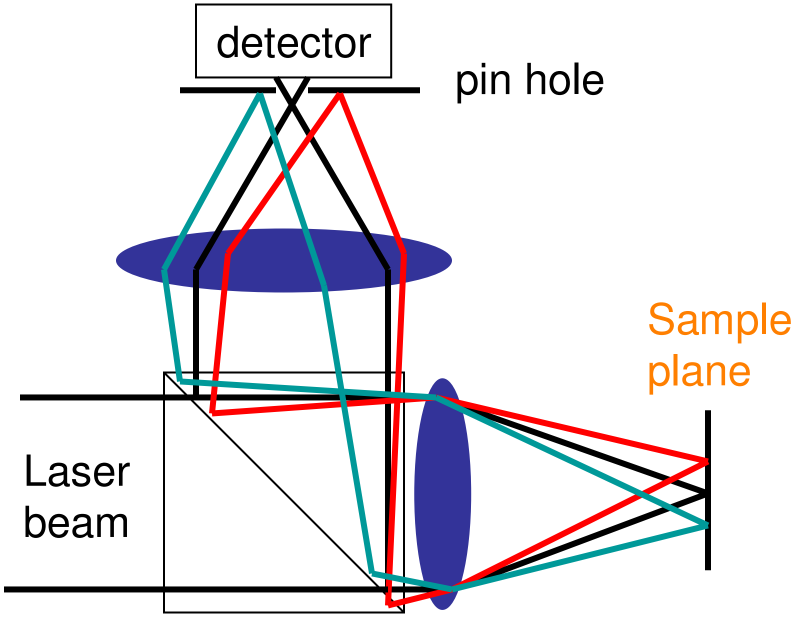
detection lens

Focal
point

Sample
plane

Laser
beam

Illumination lens



detector

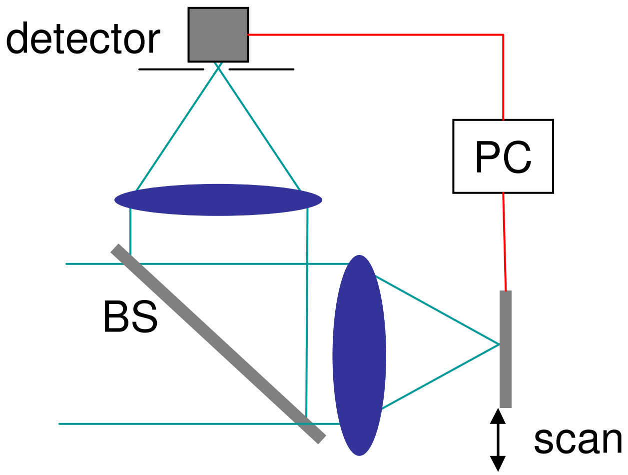
pin hole

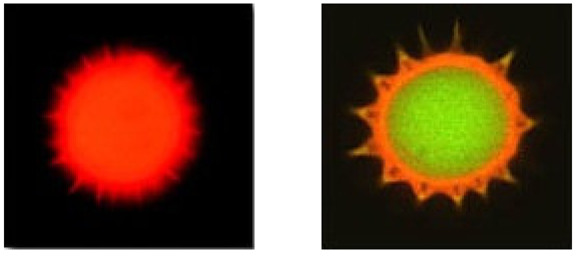
Sample
plane

Laser
beam

- Confocal arrangement of focal point and pinhole blocks light from out of focus planes or points away from the optic axis
- The detector receives light mostly from the focal point
  - Image, free of out of focus blur, of a point object located at the focal point

Optical sectioning in a confocal microscope



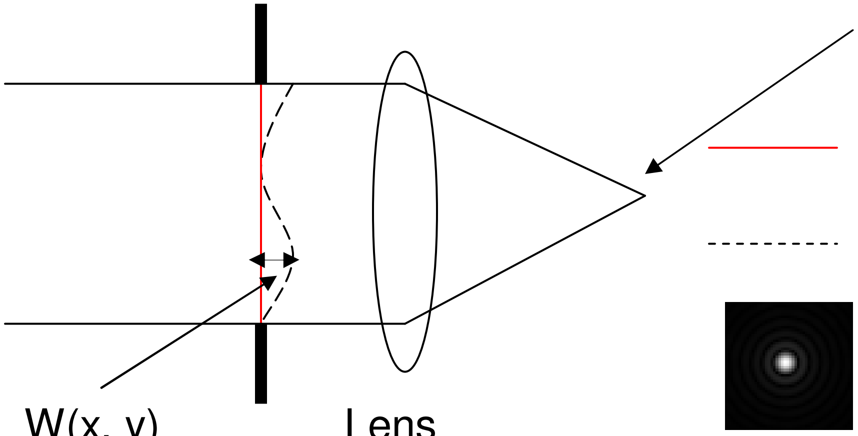


Wide field image Confocal image

(Source :www.olympusfluoview.com)

- Either the sample holding stage or the illumination spot is scanned
  - Scanning is controlled by a PC
- For each object point at the illumination spot, the detector signal is stored in the PC
- Results in an optically sectioned image (image corresponds to a sharply defined object plane, devoid of out of focus blur) of the sample
- Much better axial and marginally better lateral resolutions than a conventional (wide field) microscope

Effects of aberrations



Entrance pupil

Point spread function (PSF)

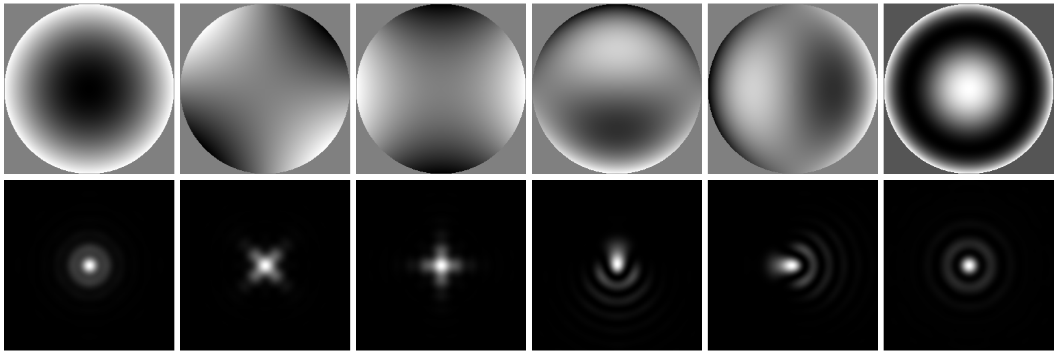
Unaberrated wavefront

Aberrated wavefront

PSF for an unaberrated Beam, Airy disc

W(x, y)

Lens

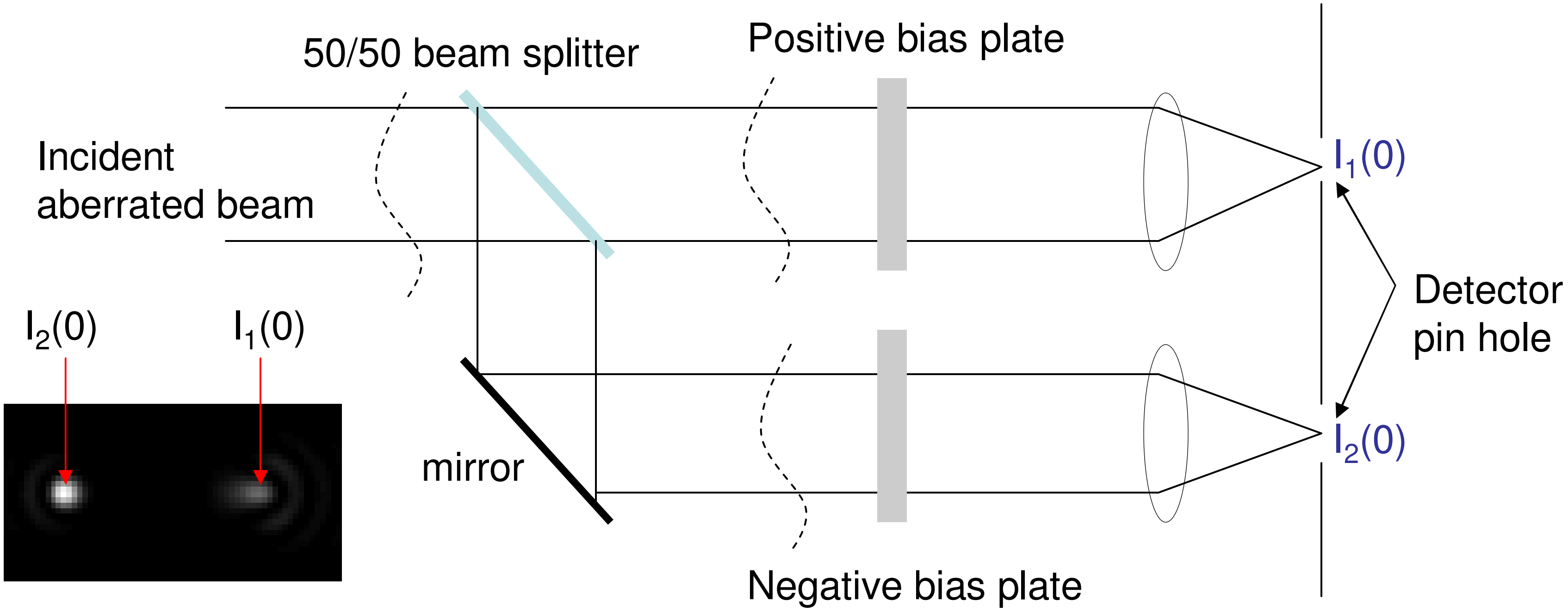


Zernike Modes

PSFs

- Presence of aberrations in the illumination beam effects the performance of the confocal microscope
- Need for aberration compensation

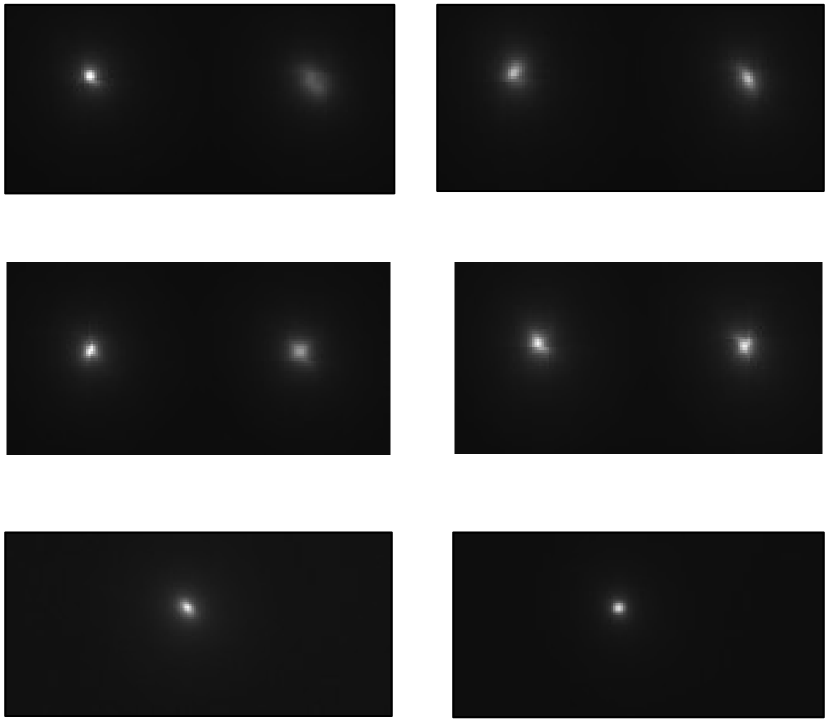
Modal wavefront sensor



Sensor signal=$I_2(0)-I_1(0)$

- Positive and the negative bias plates adds and subtracts a certain of a zernike mode aberration
- LCSLM assembly can be used to detect and correct aberrations in terms of various zernike modes

Modal wavefront sensor (results)



before correction

after correction

biased orders (Z_4)

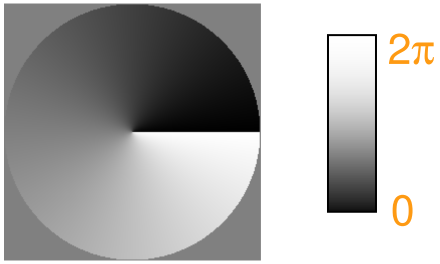
biased orders (Z_6)

PSF

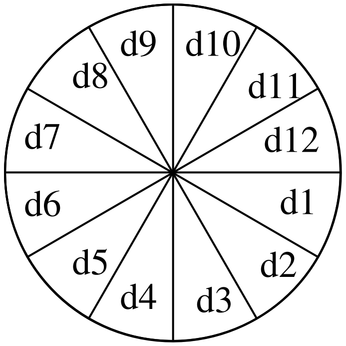
Peak intensity improves by a factor of three

Aberration sensitivity and correction using a helical beam

Helical phase profile across the pupil

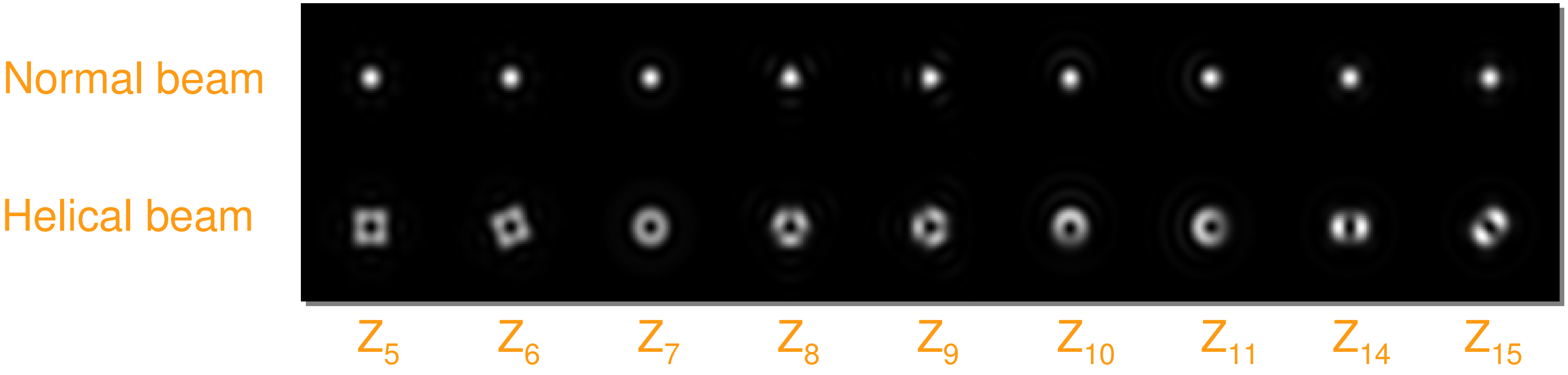


Sensor circle



- Helical type beams are highly sensitive to azimuthally dependent aberrations!

Low NA aberrated PSFs to 0.8 Strehl ratio in normal beam (normally considered well corrected)



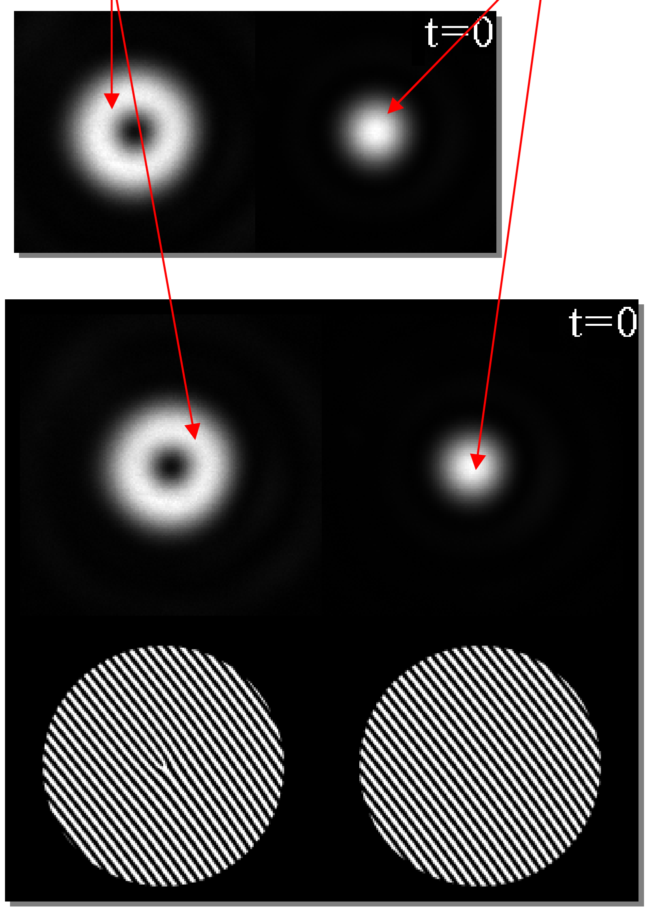
Low NA aberration correction demonstration

PSF (helical beam)

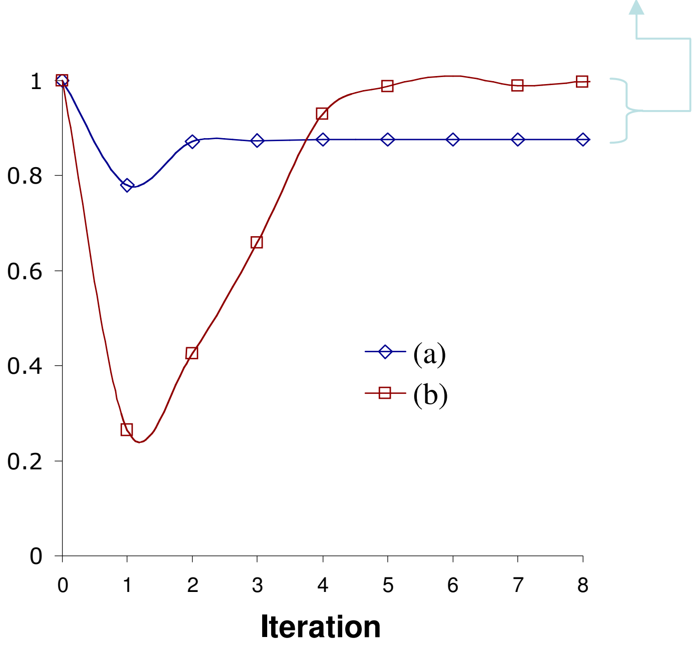
PSF (normal beam)

(a)

(b)



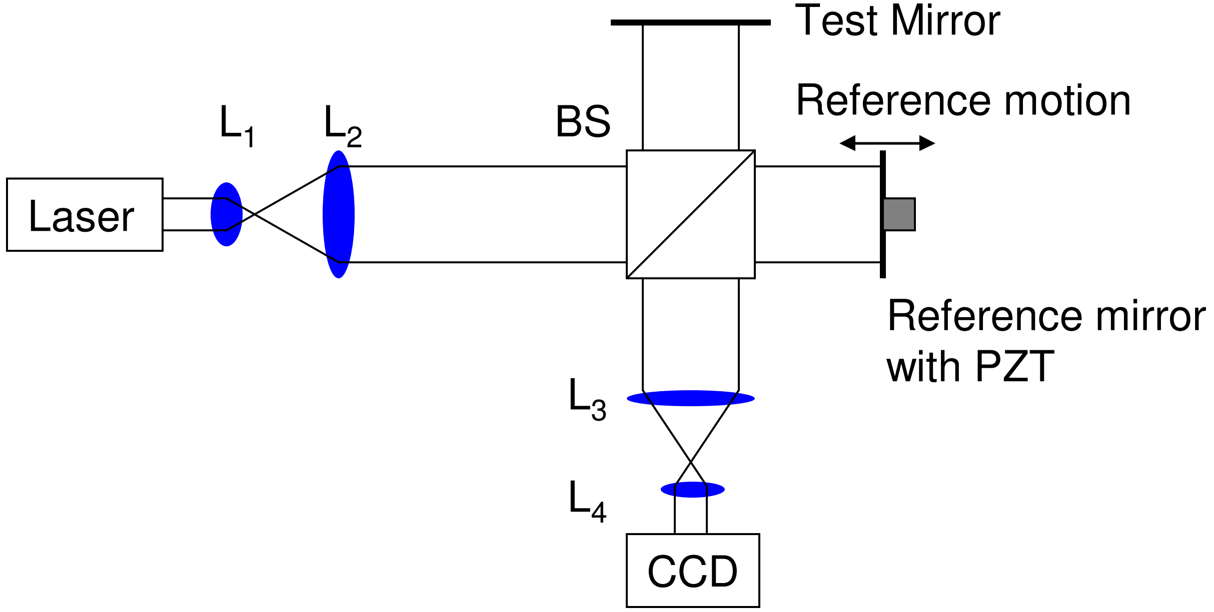
Drop due to
slide reflectivity



(a) With aberrated test slide

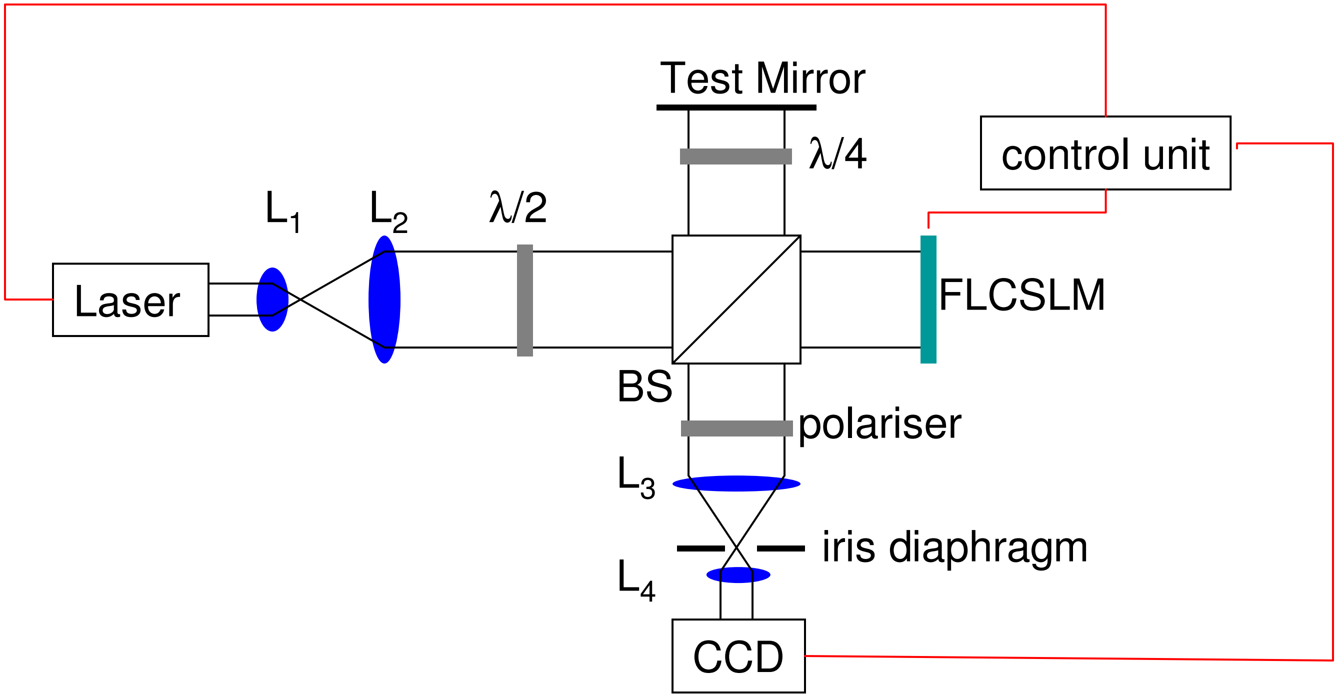
(b) With initial offset aberration (1.4 radian RMS)

Phase stepping interferometry



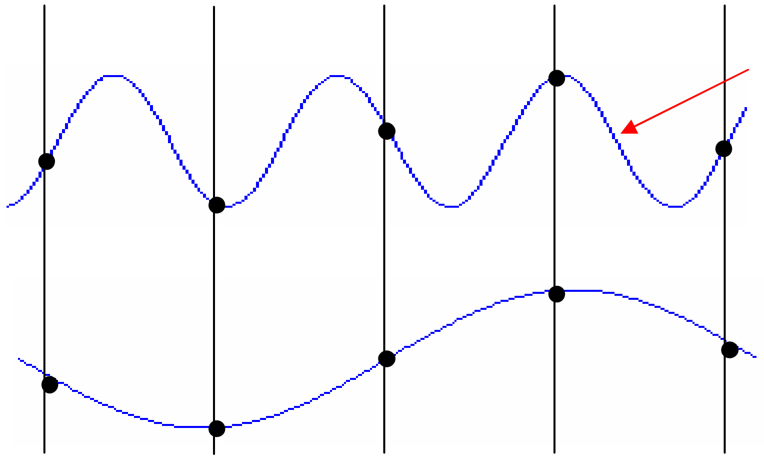
- Reference mirror stepped n times with a step size $\lambda/(2n)$
- CCD records n interference patterns, where $n>2$
- Intensity at a CCD pixel as a function of step index is a sine wave
  - Surface profile of the test mirror manifests as phase delay
- Not effected by the inhomogenity in the beam intensity profile
- No fringe centering required
- Does not depend on the number of fringes

Programmable reference PSI



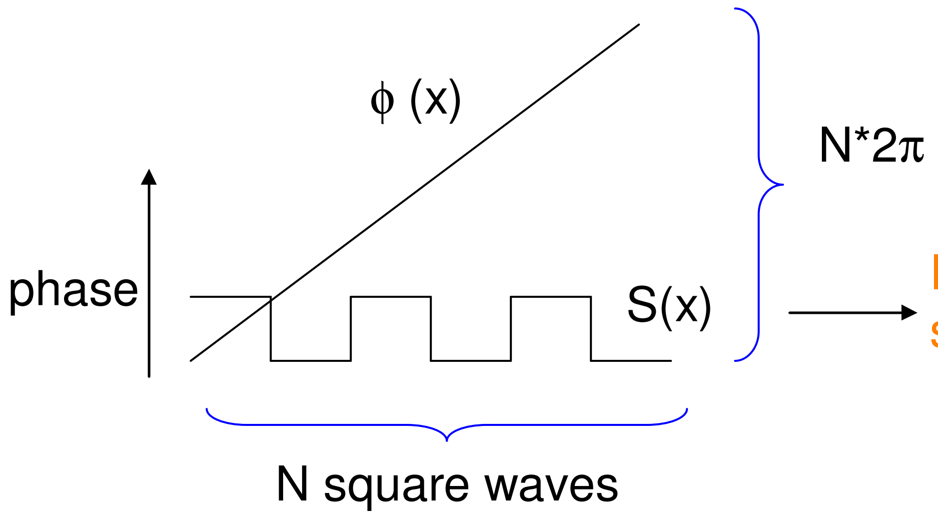
- Accurate and repeatable phase stepping
- Reference wavefront can be programmed to match the test surface
- Accuracy in phase measurements are effected by aliasing

Aliasing



Profile to be sampled

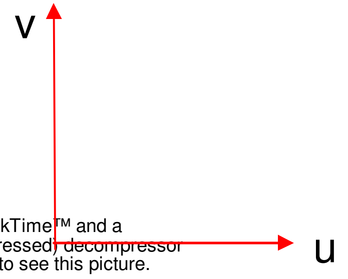
After sampling



In disguise as low frequency square wave, if no of pixels for N square waves <2N

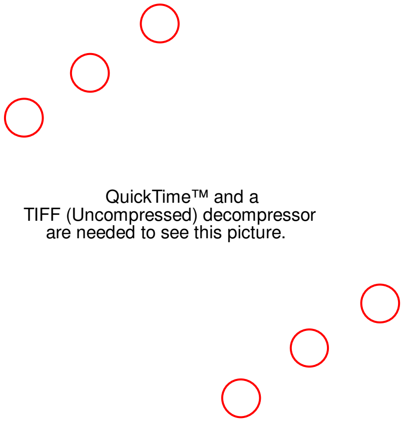
Random binarisation to remove aliased orders

$S(x, y)=[\cos(\phi(x, y)<\mathrm{Rand}(x,y)]\ \pi$



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Fourier plane of a binarised hologram



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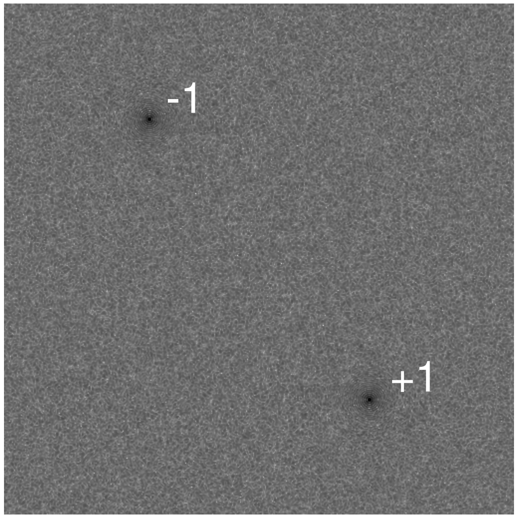
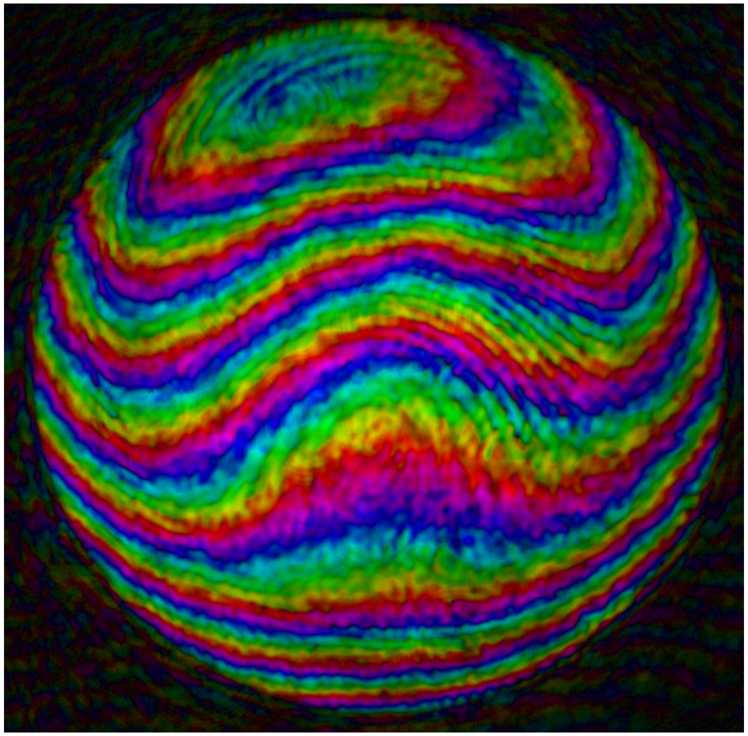
Fourier plane of a randomly Binarised hologram

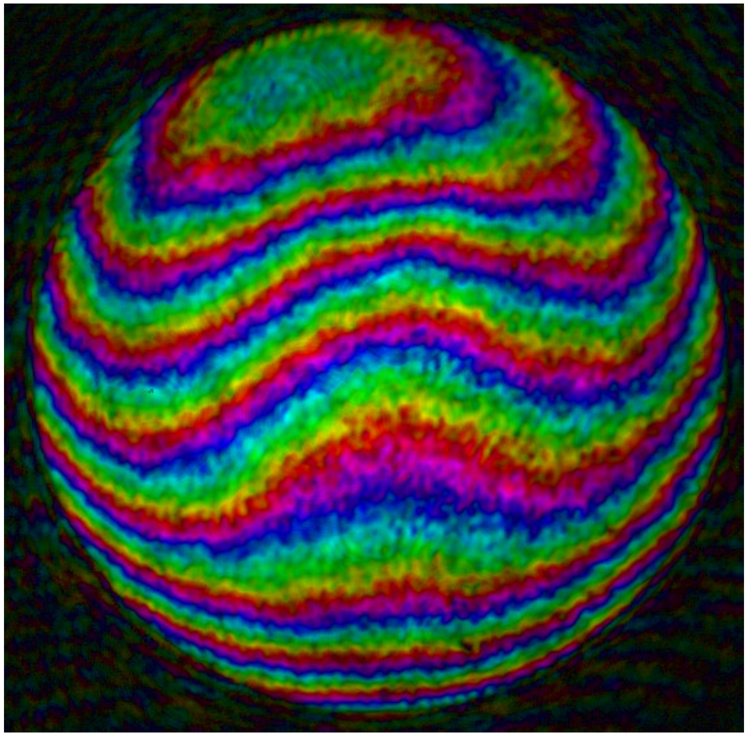


Phase profile using 24 bit random binarization

Blue → red → yellow → green → blue
Phase: $0 \rightarrow 2\pi$



Normal binarization



24 bit random binarization

Conclusion

- Generation of arbitrary wavefront using an LCSLM
  - accurate, fast and with excellent repeatability
- LCSLM can be used both for detection and correction of optical aberrations
- Can used in a phase stepping interferometer to generate the reference beam
- Poor light efficiency
  - May effect its applicability to other areas

Thank You