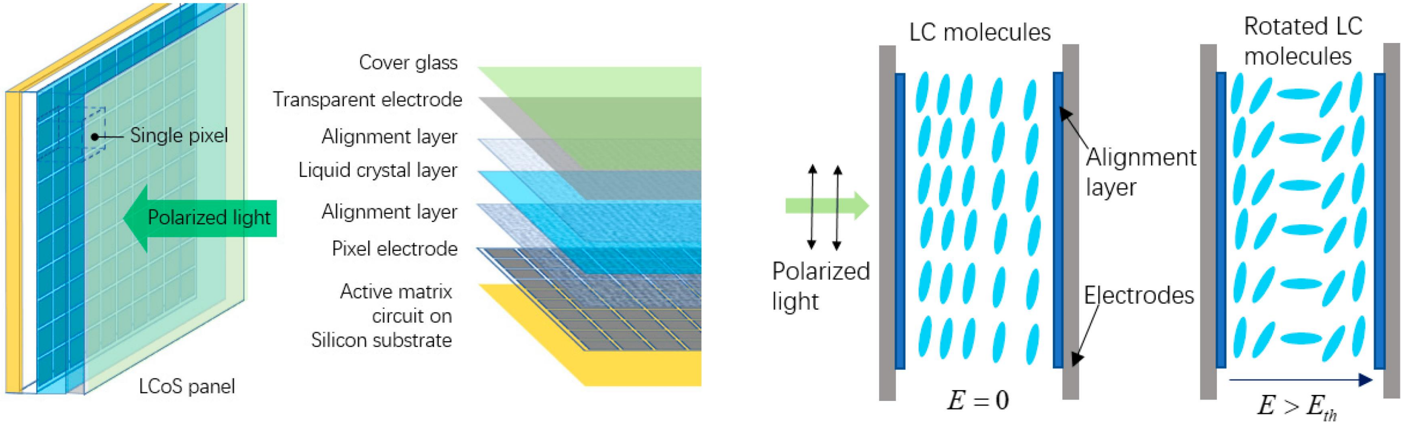
Amplitude and phase modulation with spatial light modulator

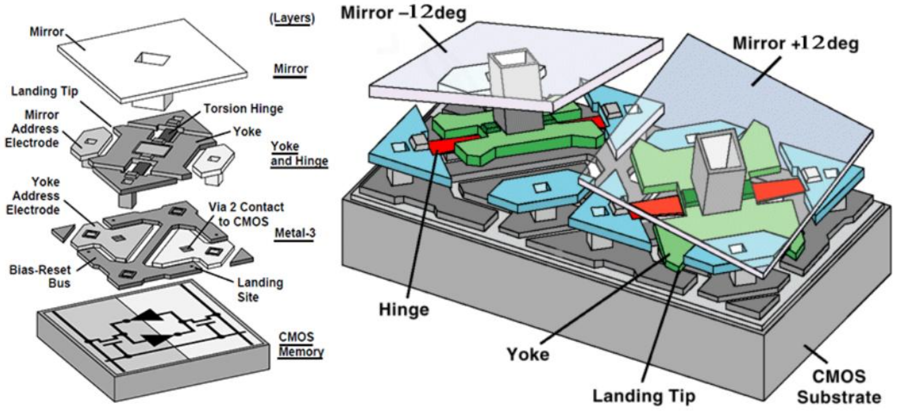
Chengjie Ding
06.05.2024

Different types of spatial light modulator

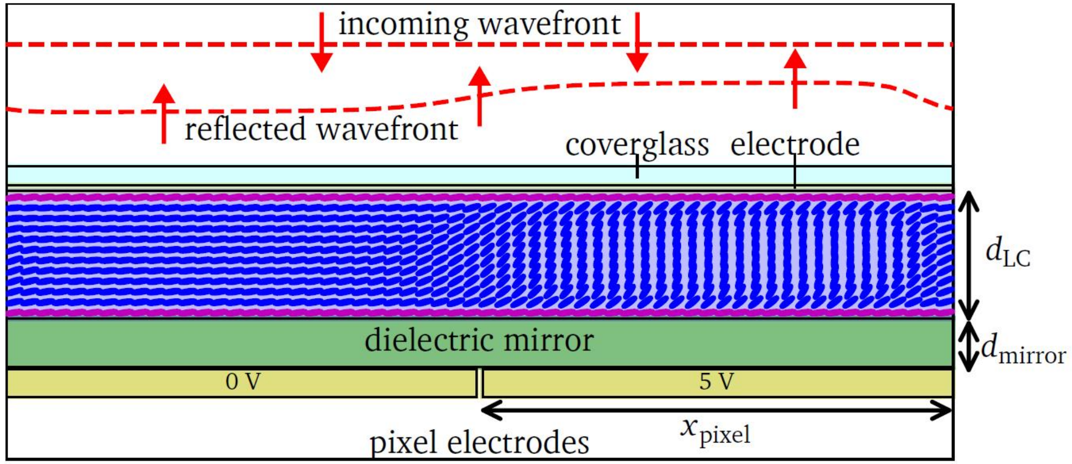
- Optically-addressed SLM
  - LCoS
- Electrically-addressed SLM
  - Digital micromirror devices (DMD)



(a) (b)



Schematic cross section of a liquid crystal on silicon SLM



The birefringence of the molecules in LC layer could be modulated by the electric field.

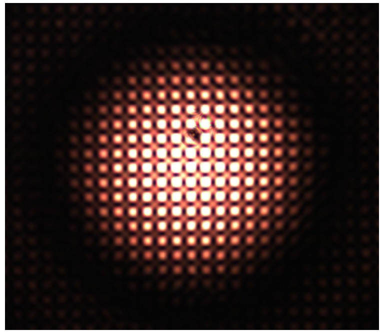
Appl. Sci. 9(10), 2012 (2019)

Amplitude and phase modulation with LCoS slm

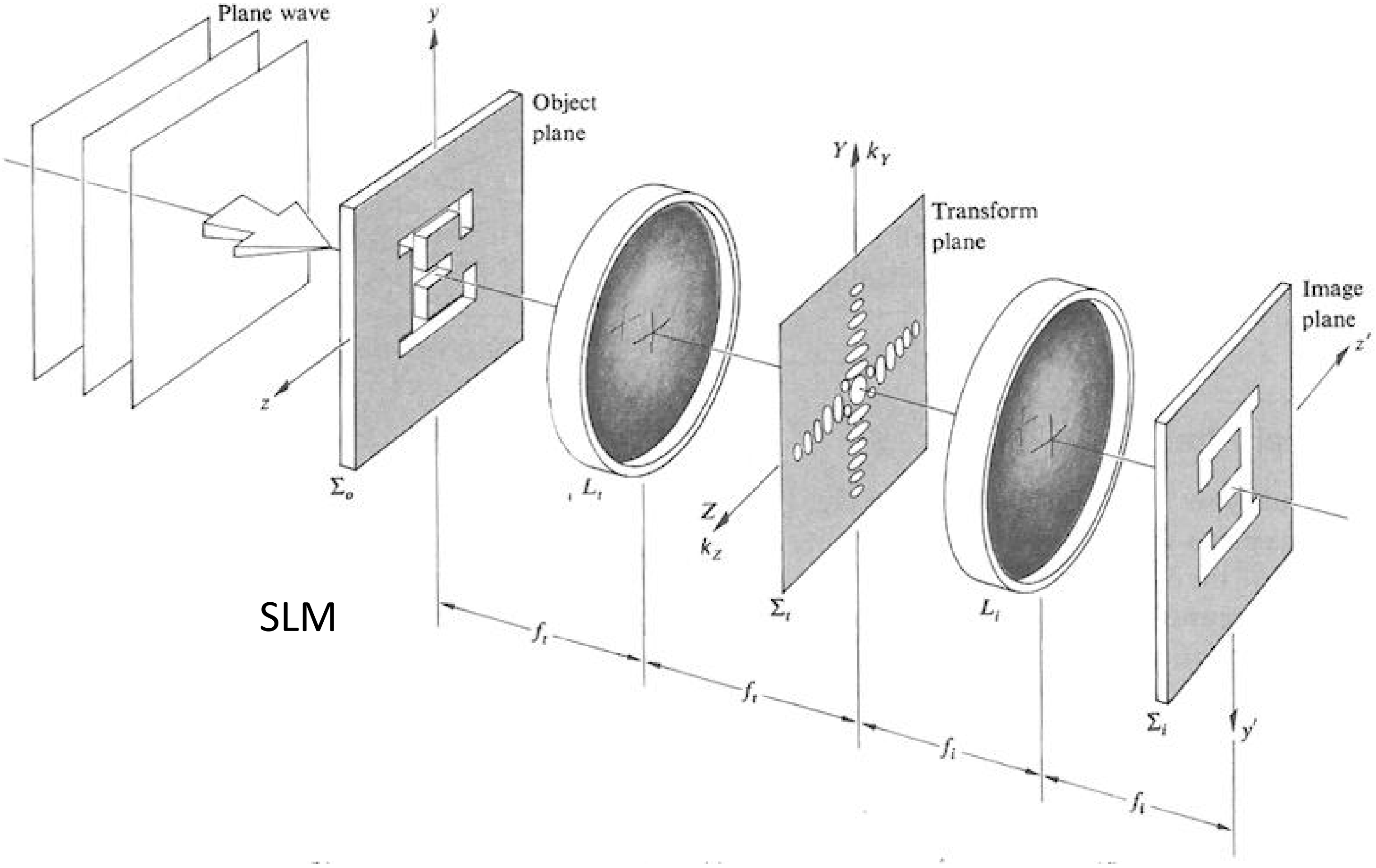
- Modulate 2D amplitude and phase with LCoS slm
    - 1D blazed grating
    - hologram with conjugate Gradient Minimisation
- Modulate 1D amplitude and phase with LCoS slm

Modulate 2D amplitude and phase with LCoS slm

Fourier plane



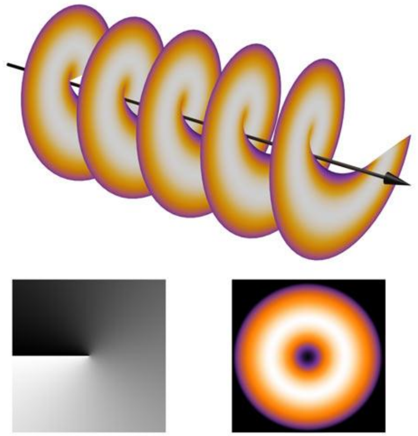
spacial frequency filtering



SLM

input plane of Rb cell

Modulate 2D amplitude and phase with LCoS slm with 1D blazed diffraction grating

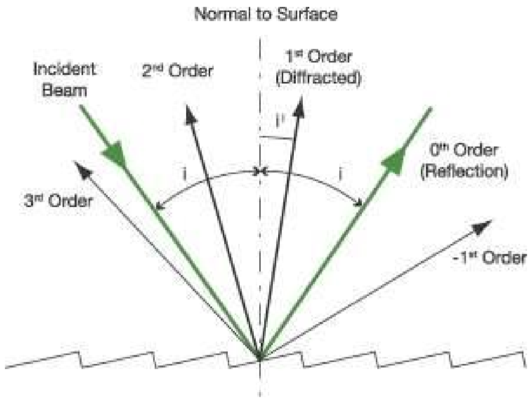


Encode phase and amplitude simultaneously

$$T(m,n) = e^{i\mathcal{M}(m,n)\mathrm{Mod}(\mathcal{F}(m,n)+2\pi m/\Lambda, 2\pi)}$$

$$\mathcal{M} = 1 + \frac{1}{\pi}\,\mathrm{sinc}^{-1}(A)$$

$$\mathcal{F} = \Phi - \pi\mathcal{M},$$



$$n\lambda = d(\sin\theta_i + \sin\theta_d)$$

OPTICS LETTERS / Vol. 38, No. 18 / September 15, 2013

Imperfections of modulate 2D amplitude and phase with LCoS slm

- Induced by the optical path
  - spacial frequency cutoff
  - dark noise
  - Gaussian beam shape
  - alignment
  - dust on the optics
  - interference pattern due to back reflection

- Induced by the LCoS slm itself
  - crosstalk
  - curved screen
  - phase as a function of applied voltage is not linear
  - inhomogeneous
  - updating speed < 10Hz

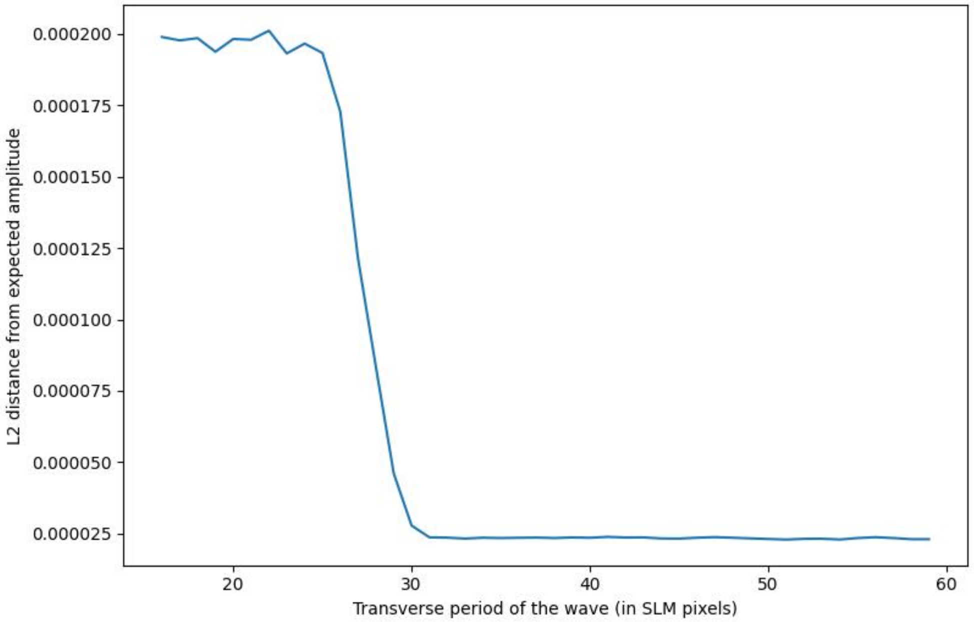
6% noise ?

When use SLM for feedback loop, all the imperfections are amplified.

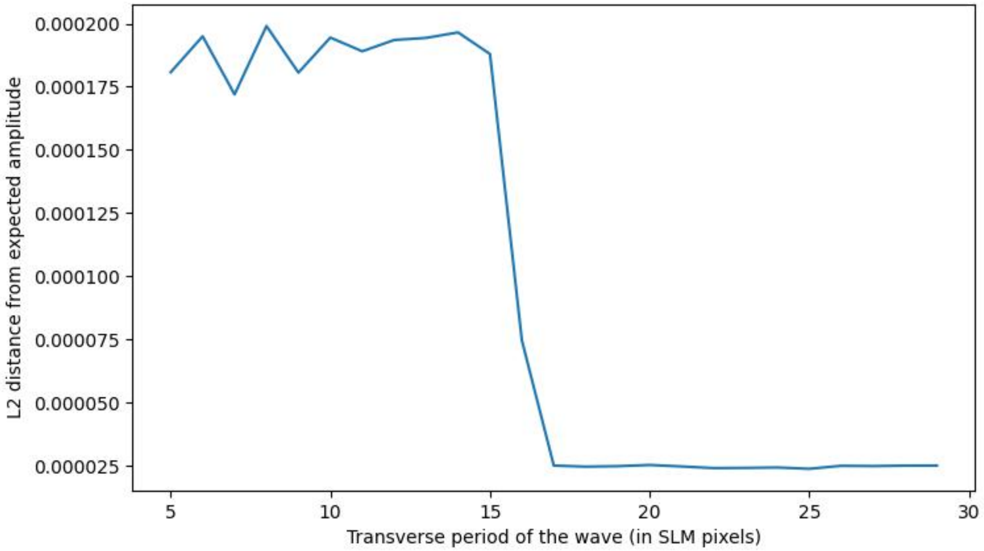
Limited resolution - Spacial frequency cutoff

$$n\lambda = d(\sin\theta_i + \sin\theta_d)$$

grating pitch = 16 pixels



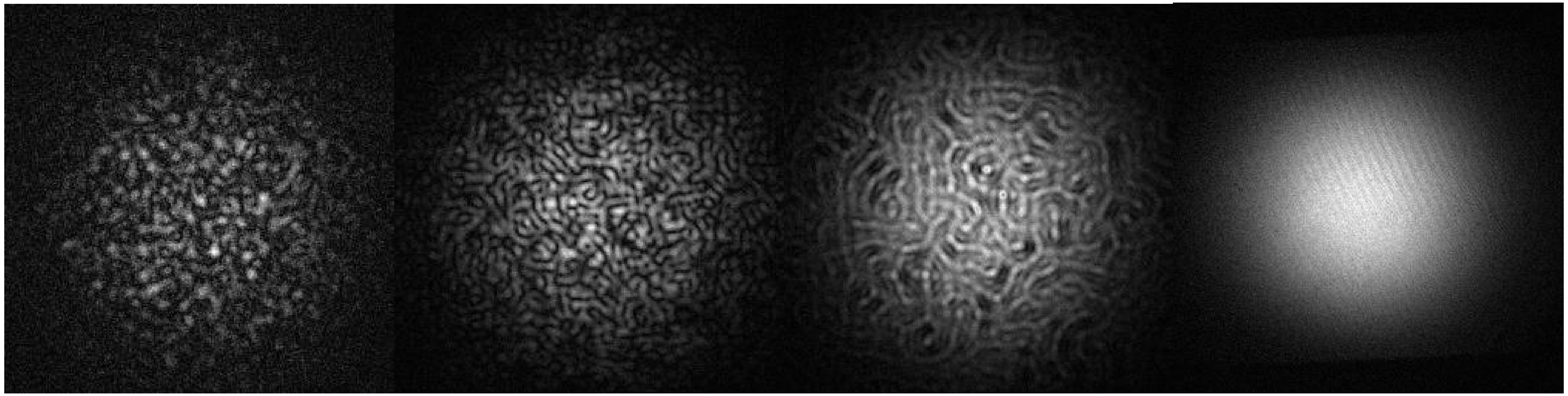
grating pitch = 8 pixels



2 * grating pitch

Limited resolution - Spacial frequency cutoff

We print Perlin Noise with different periods as phase pattern while print homogeneous amplitude on the SLM .
Detected first order diffraction amplitude pattern on the camera with increasing period:



We lost information at high spatial frequency to reconstruct the applied amplitude pattern, the more information we have in high frequency, the more error we get.

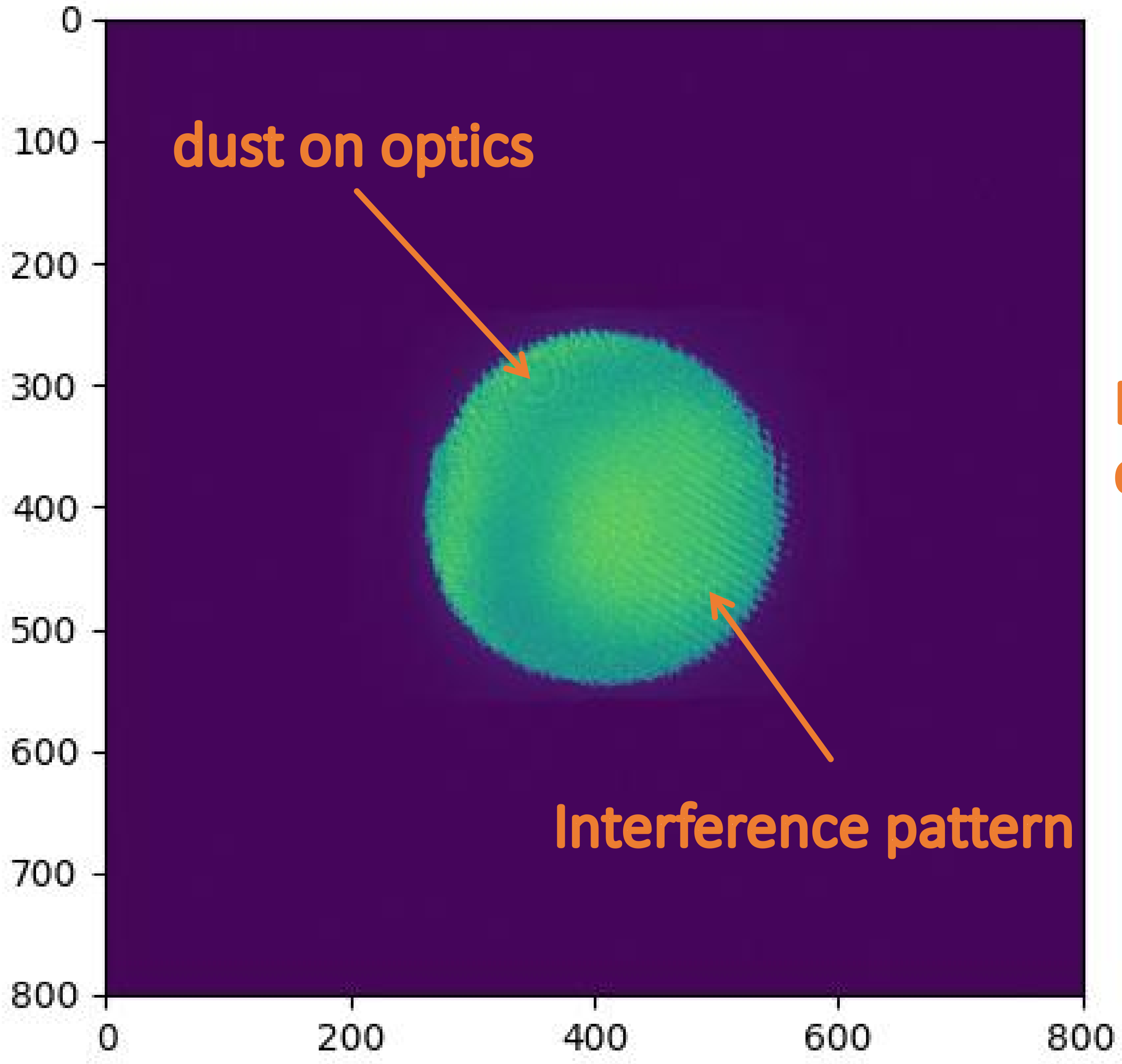
Amplitude distribution of Gaussian beam & dark noise

$$E(x,y) = A(x,y)\exp(i\varphi(x,y))$$

measured field on camera with amplitude distribution of laser beam

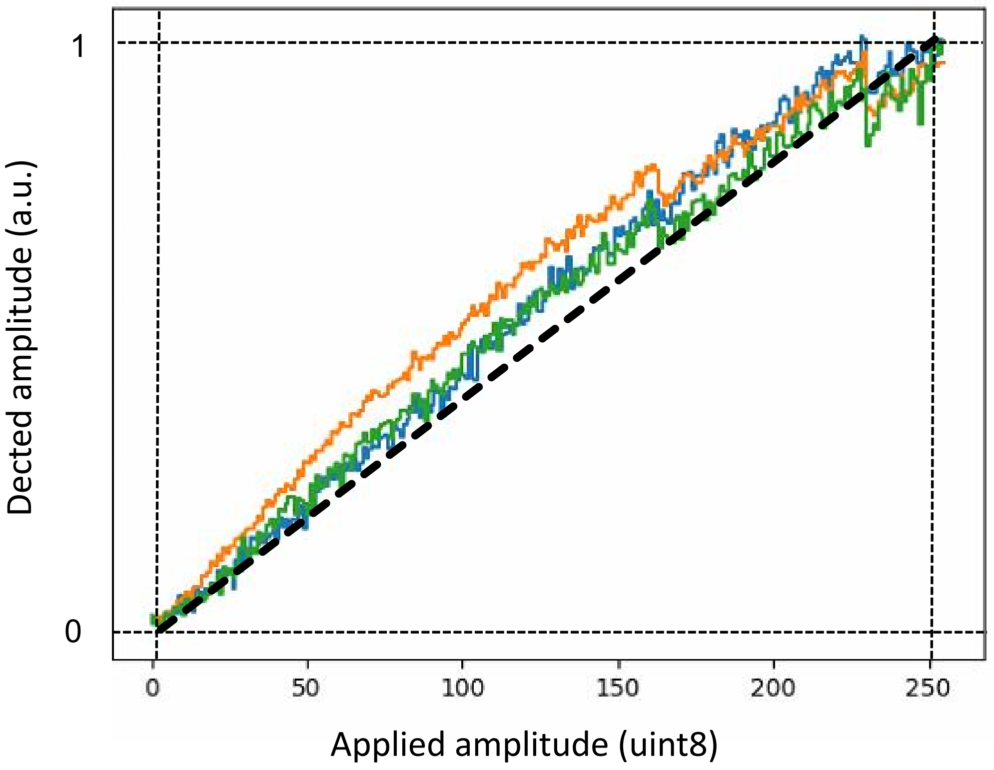
$$A(x,y) = A_{beam}(x,y) + A_{dark}(x,y)$$

When apply a homogeneous amplitude on SLM

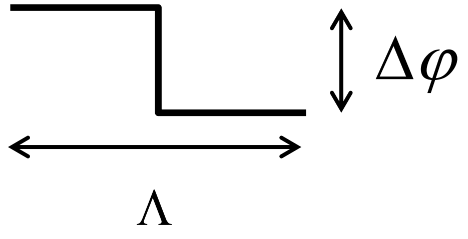


Inhomogeneous image detected by camera

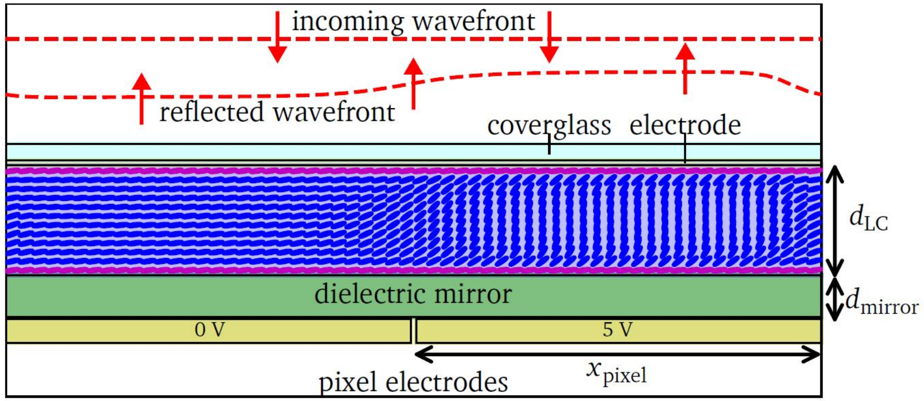
Amplitude of the generated beam, after selection of the first order of diffraction, as a function of the normalized desired amplitude

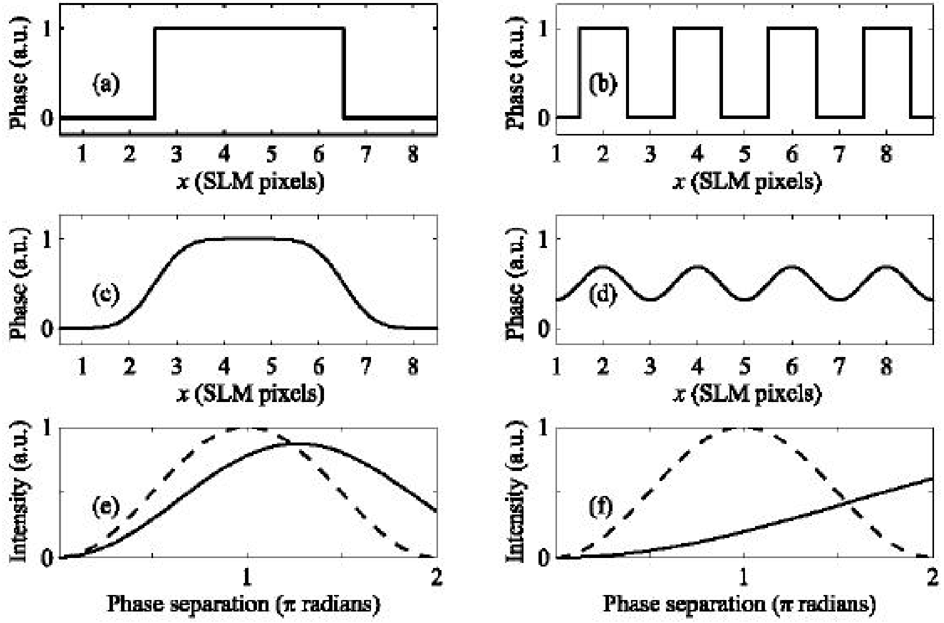


Crosstalk of SLM - Point spread function (PSF) calibration

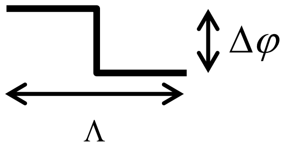


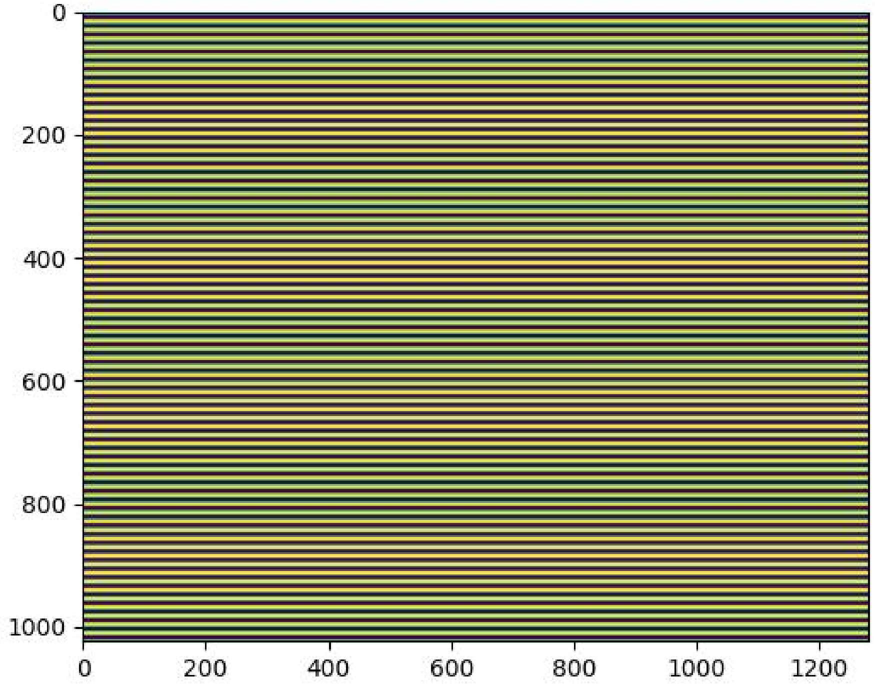
- First order diffraction intensity with binary grating
  - without crosstalk : $I(\Delta\varphi) = 0.405 \sin^2\left(\frac{\Delta\varphi}{2}\right),$
  - with crosstalk :

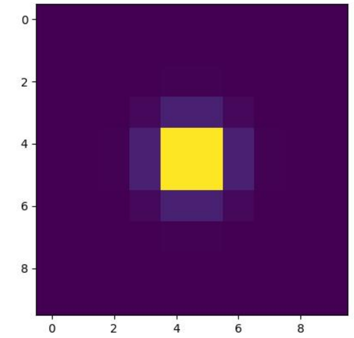




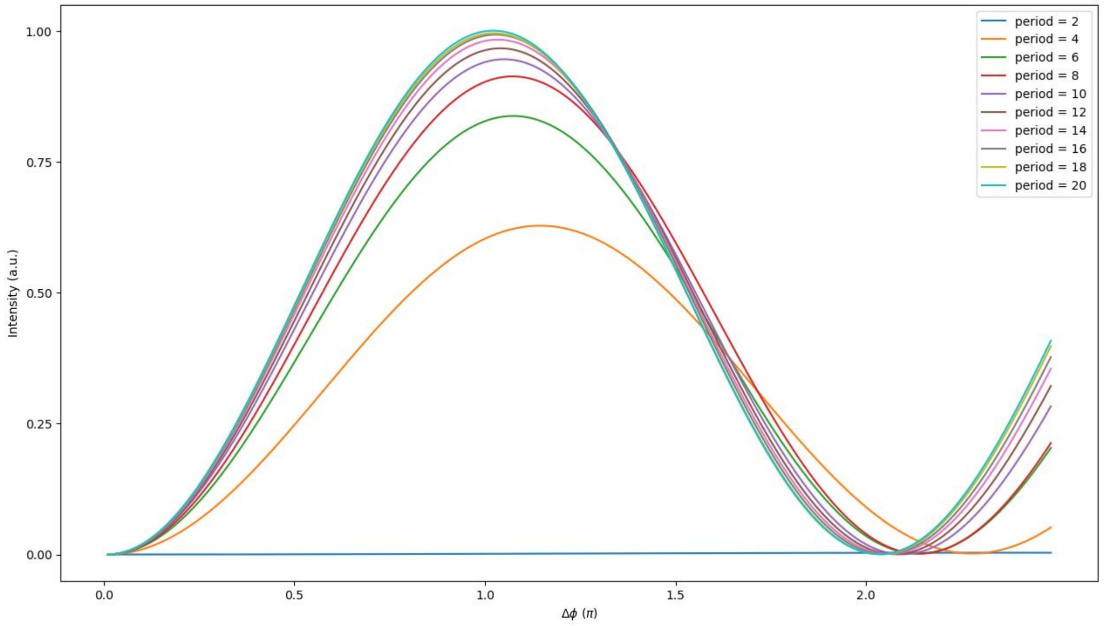
Binary grating phase pattern







$$\varphi(x^i, y^i) \otimes \mathrm{a}(x^i, y^i) = \mathrm{FFT}^{-1}\Big(\mathrm{FFT}\big(\varphi(x^i, y^i)\big)\mathrm{FFT}\big(\mathrm{a}(x^i, y^i)\big)\Big).$$



Measure the first order diffraction intensity $I^{m}_{\Lambda,\Delta\varphi}$

Simulate the first order diffraction intensity $I^{s}_{\Lambda,\Delta\varphi}$

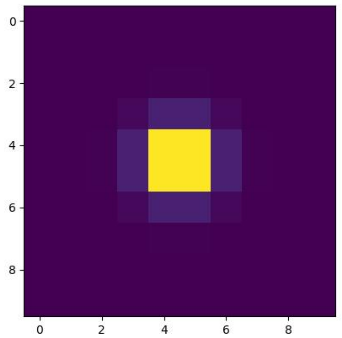
PSF calibration

First order diffraction intensity as a function of $\Delta\varphi$ can quantify the crosstalk of the SLM

Here we assume the PSF of SLM is $a_{r_x,r_y,\gamma}(x,y) = \exp\left(-\left(\frac{x^2}{2r_x^2}+\frac{y^2}{2r_y^2}\right)^{\gamma}\right),$

Optimize r_x, r_y, γ to minimize the difference between measured $I_{\Delta\varphi}$ to simulated $I_{\Delta\varphi}$ with the PSF.

$$RMSE = \sqrt{\frac{\sum_{\Lambda,\Delta\phi}\left(I^{mx}_{\Lambda,\Delta\phi} - I^{sx}_{\Lambda,\Delta\phi}\right)^2 + \sum_{\Lambda,\Delta\phi}\left(I^{my}_{\Lambda,\Delta\phi} - I^{sy}_{\Lambda,\Delta\phi}\right)^2}{N_{tot}}},$$

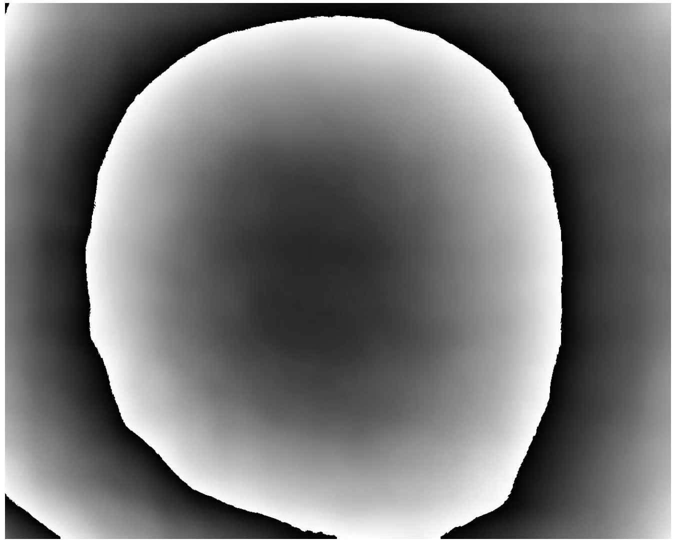


$$r_x = 0.51, r_y = 0.48, \gamma = 0.47$$

To further increase the accuracy : Nearest neighbor interpolation or change model

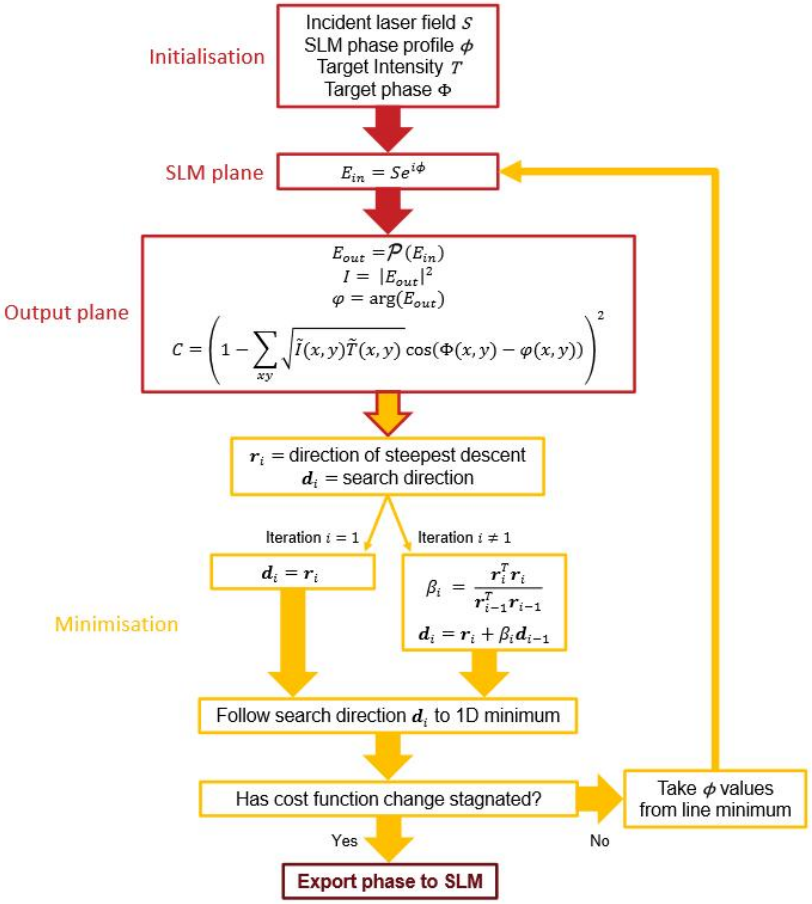
Refer to : M. Persson, OE Vol. 20, Issue 20, pp. 22334-22343

Error induced by the curved screen



correction pattern

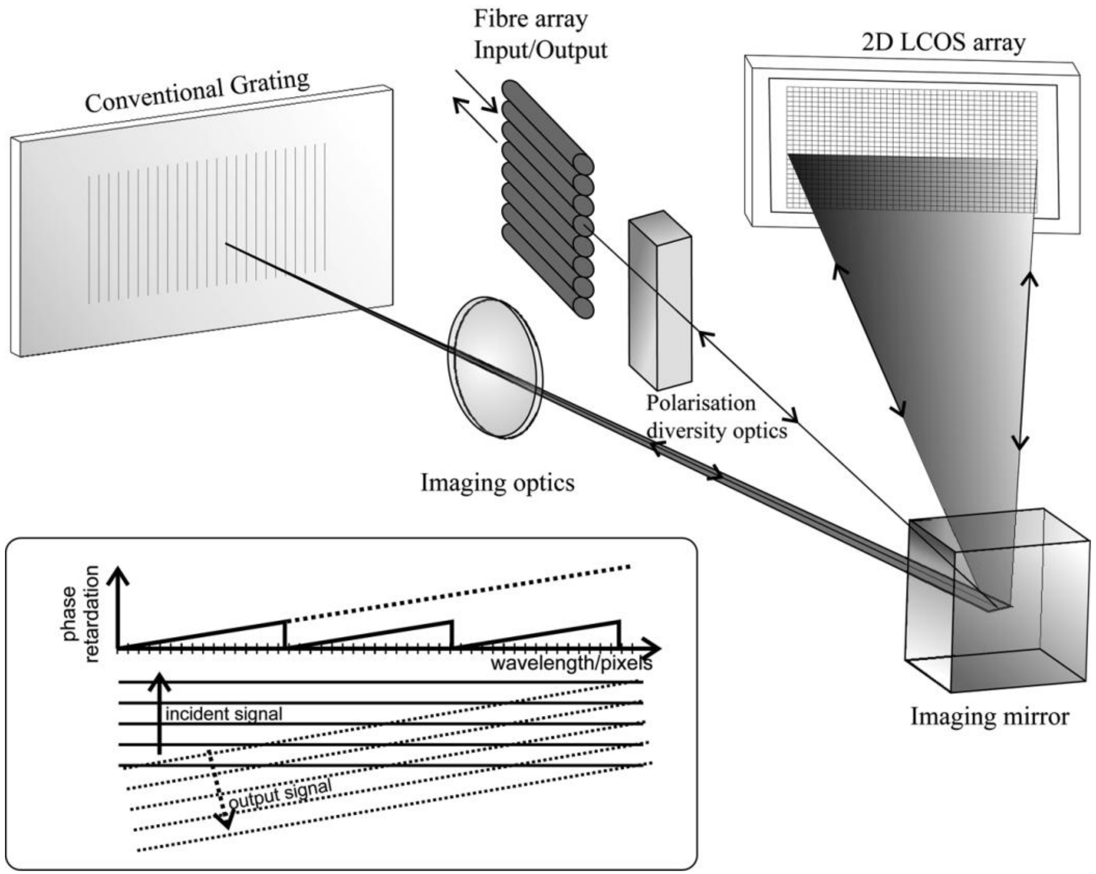
Modulate 2D amplitude and phase with LCoS slm - Hologram calculated with the conjugate Gradient Minimisation



Thesis of David Bowman

- High diffraction efficiency
- High resolution

Modulate 1D amplitude and phase with LCoS SLM

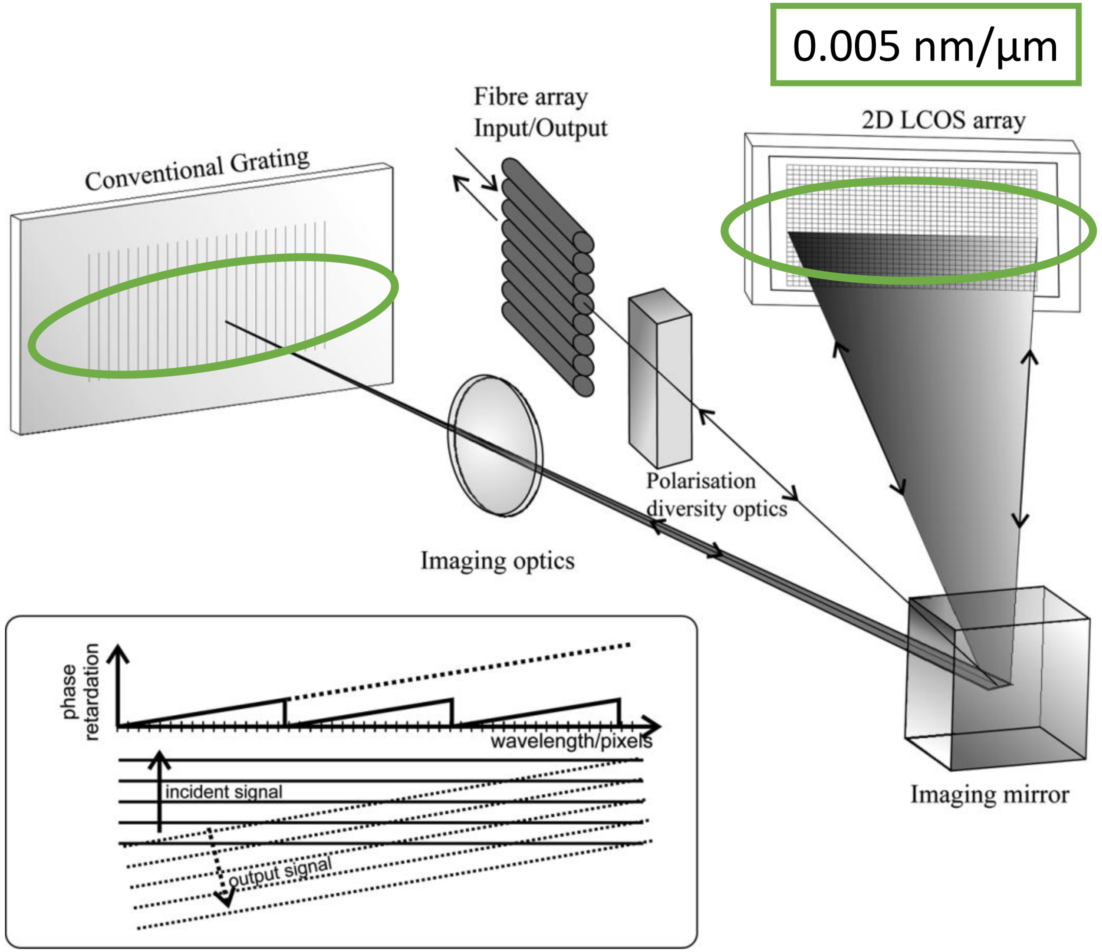


Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
  - Adding offset in time domain
  - Dispersion generation or compensation

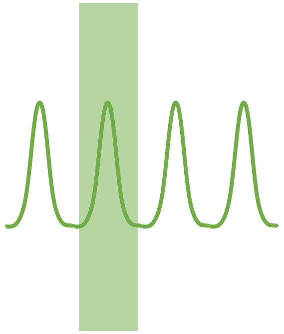
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Programmable optical processor



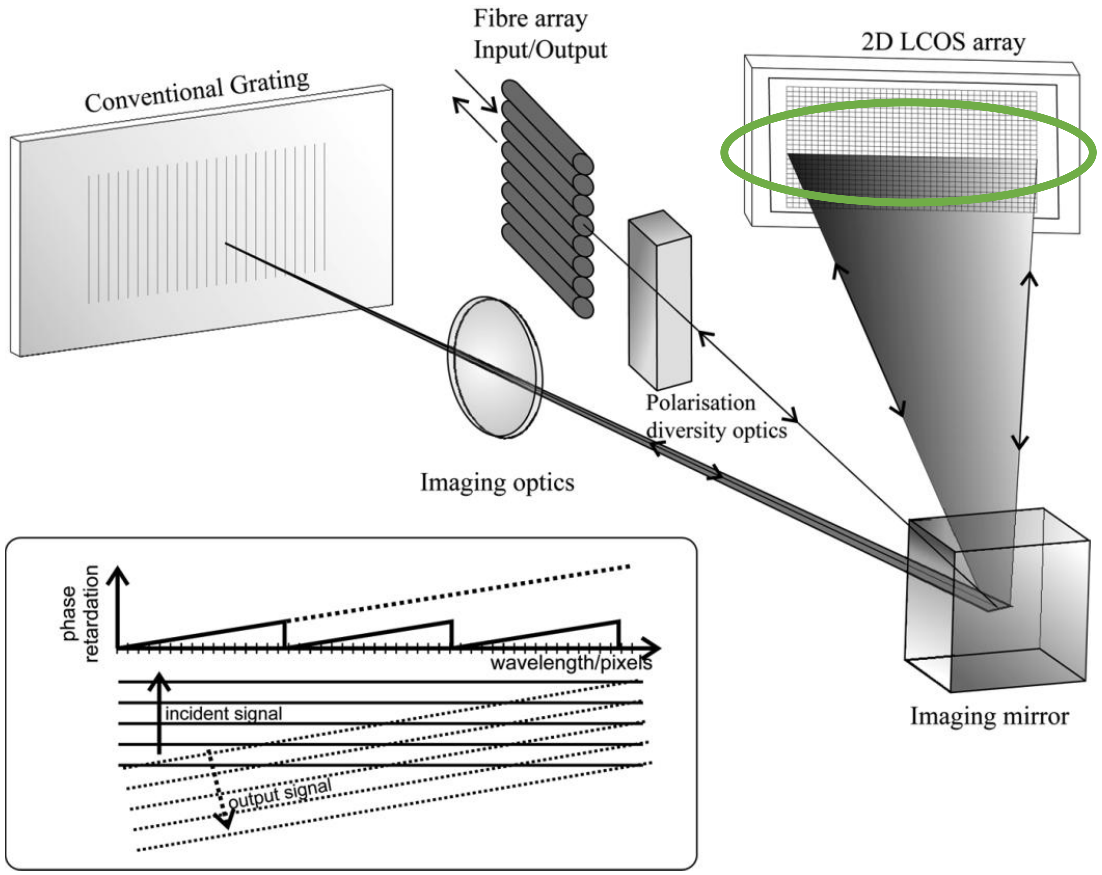
Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
  - Adding offset in time domain
  - Dispersion generation or compensation



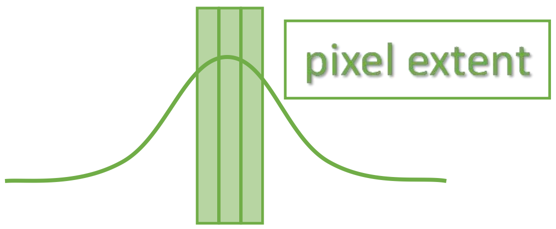
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Programmable optical processor



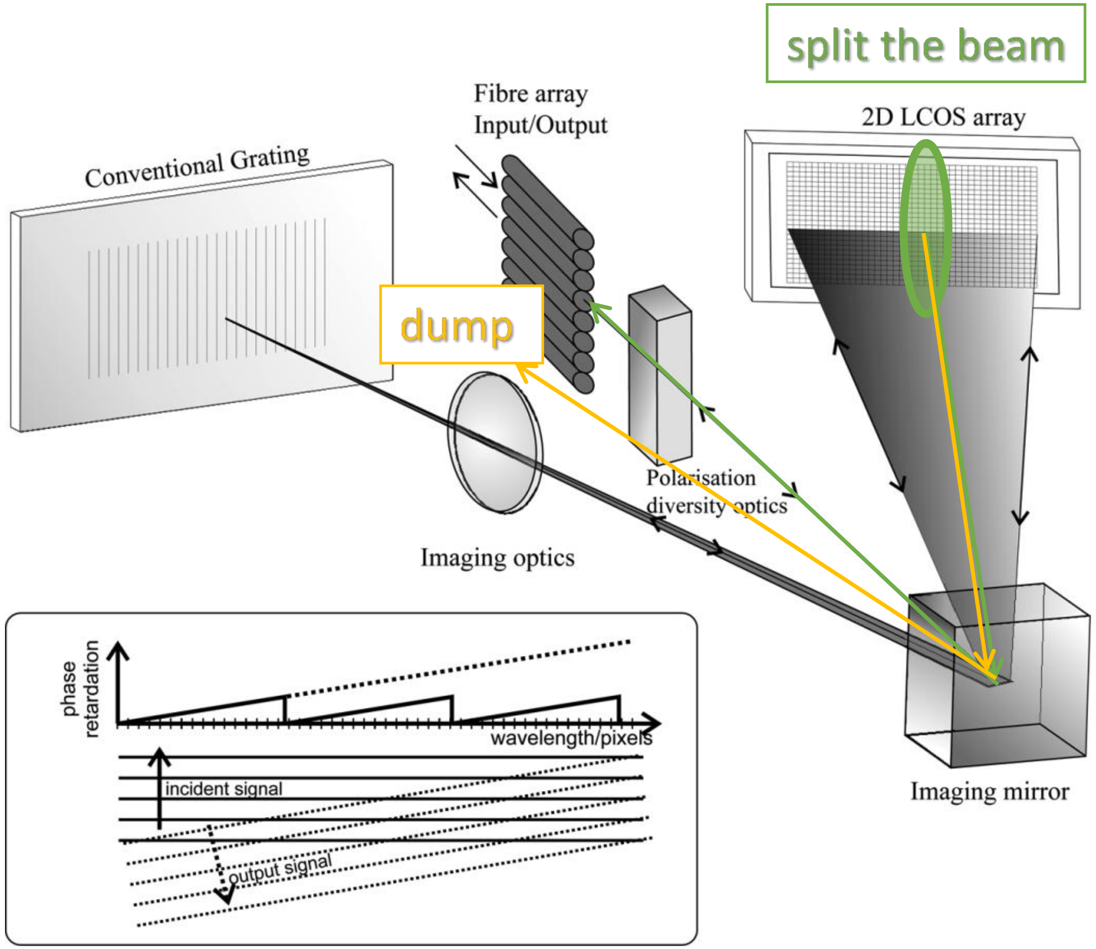
Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
  - Adding offset in time domain
  - Dispersion generation or compensation



JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Programmable optical processor

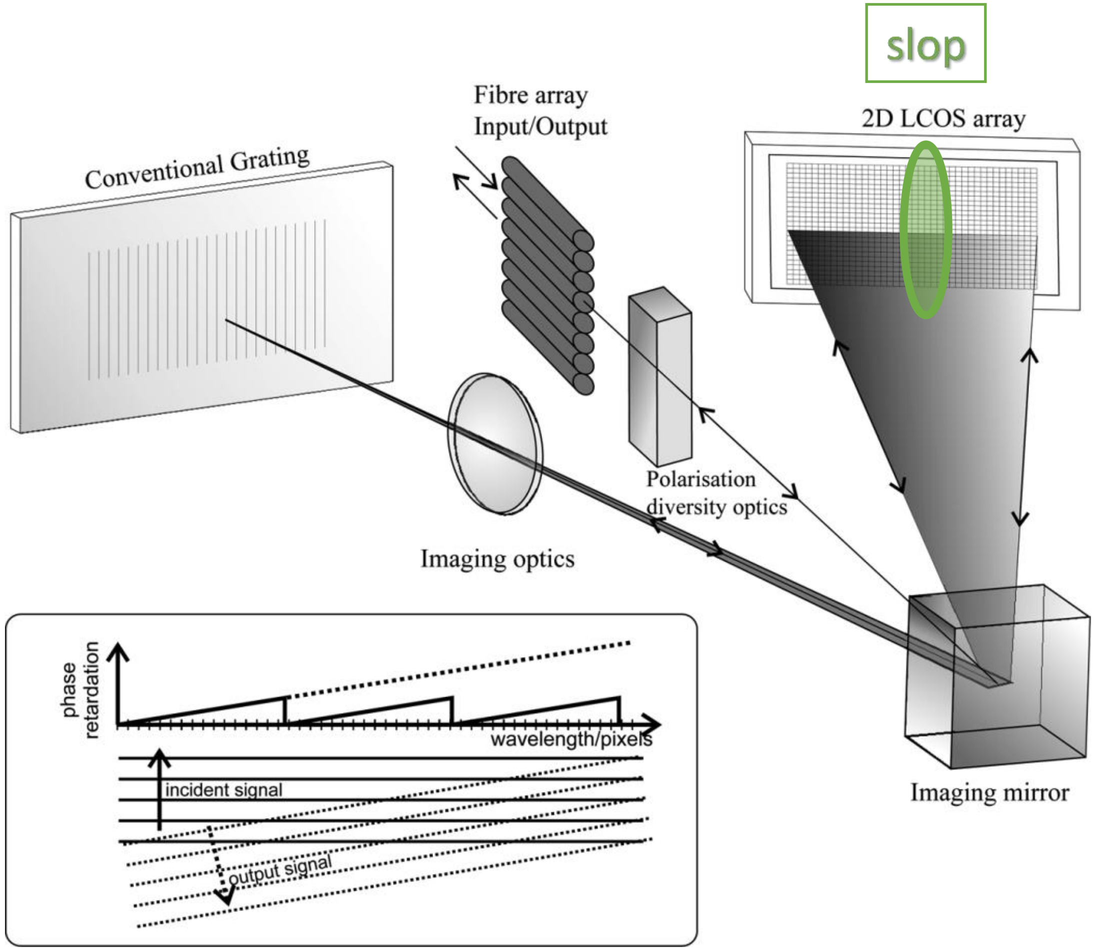


Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
  - Adding offset in time domain
  - Dispersion generation or compensation

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Programmable optical processor



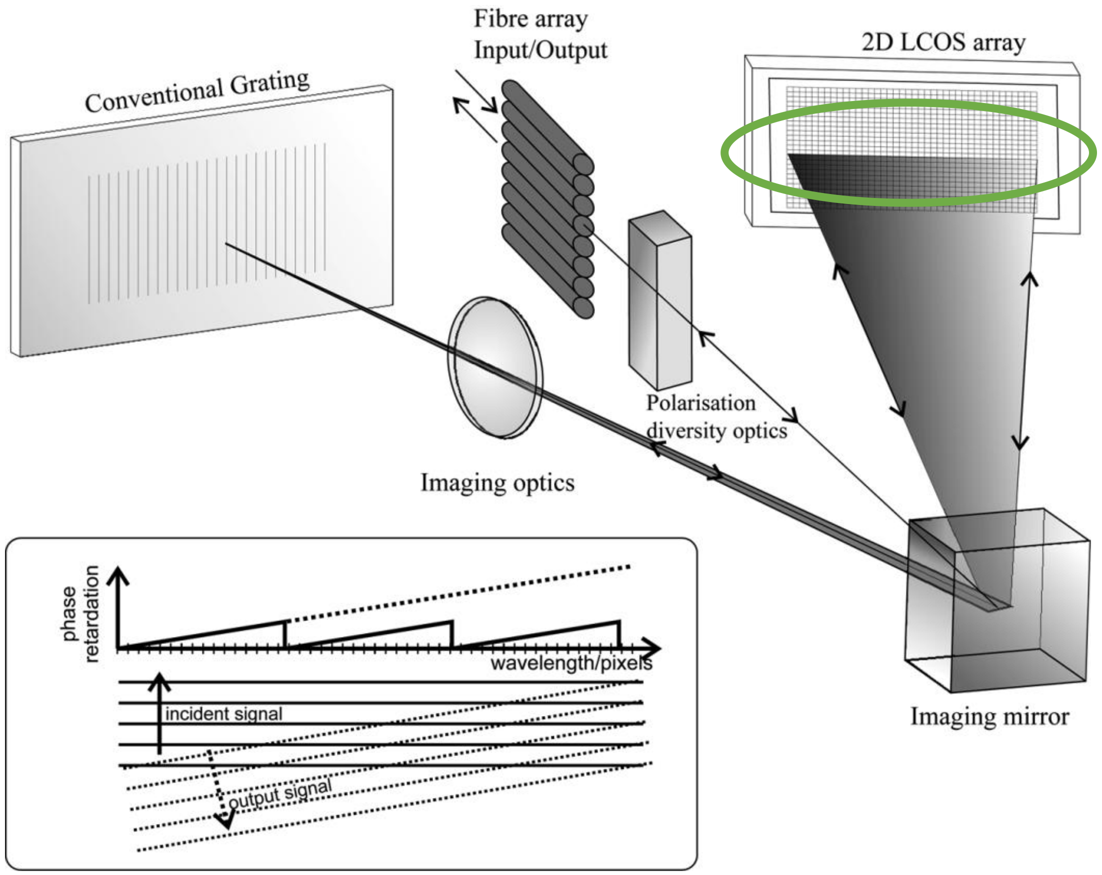
Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
    - Adding offset in time domain
    - Dispersion generation or compensation

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Programmable optical processor

linearly varying phase along spectral axis



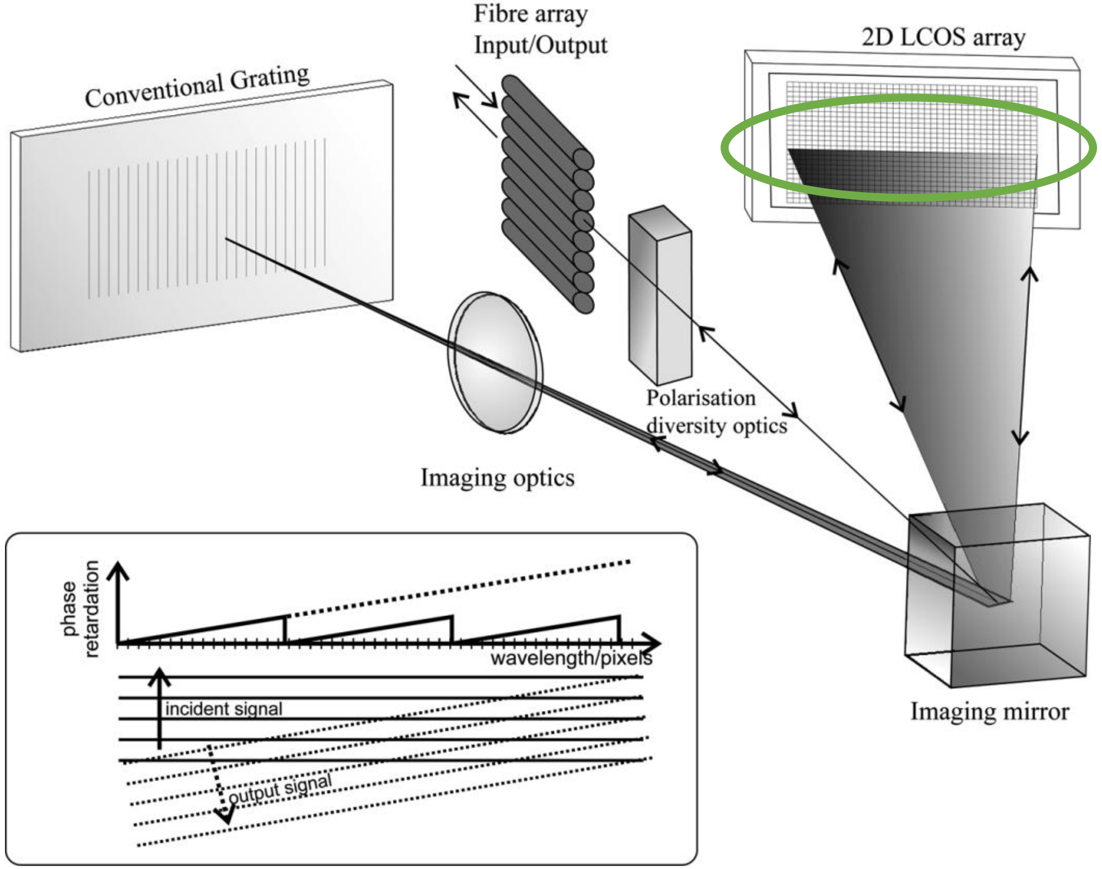
Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
- Adding offset in time domain
- Dispersion generation or compensation

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Programmable optical processor

parabolically varying phase along spectral axis

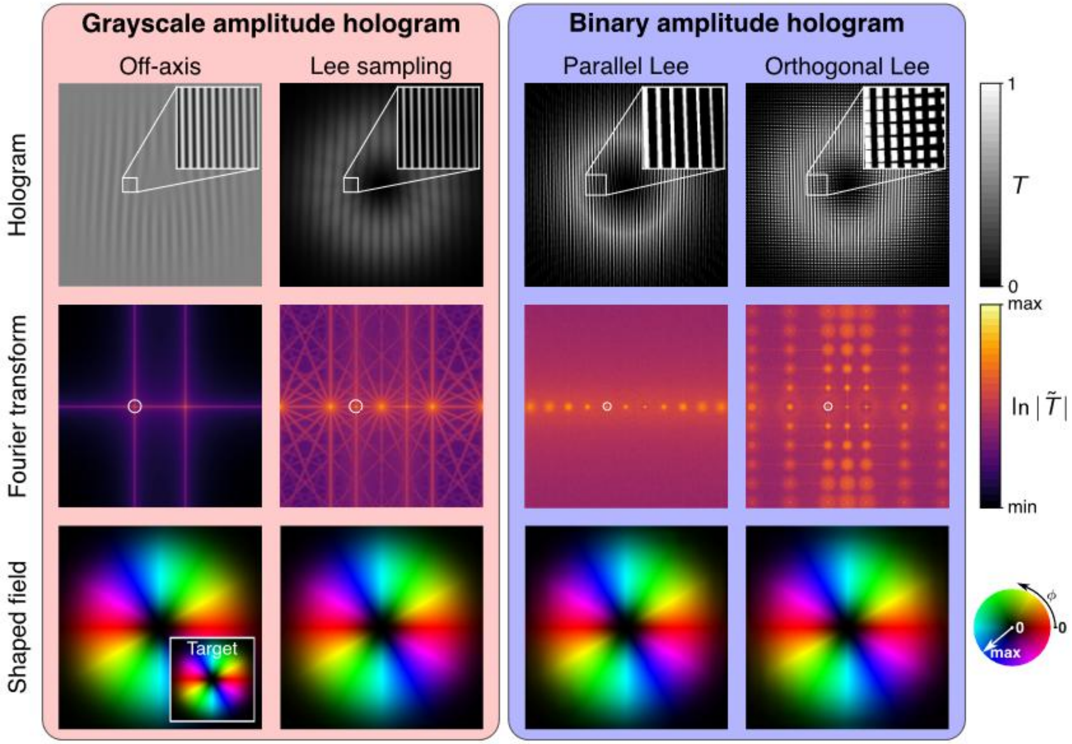


Parameters that can be modified :

- Wavelength
- Bandwidth
- Intensity
- Port
- Phase
- Adding offset in time domain (linearly varying phase along spectral axis)
- Dispersion generation or compensation

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 1, 2008

Modulate 2D amplitude and phase with DMD



Parallel Lee

Transmittance function

$$T(\mathbf{r}) = \sum_{m=-\infty}^{\infty} \frac{\sin(\pi m q)}{\pi m} e^{-\mathrm{i}m\phi} e^{2\pi \mathrm{i} m \boldsymbol{\nu}\cdot\mathbf{r}}.$$

$$T_{-1} = \frac{A}{\pi} e^{\mathrm{i}\phi}, \qquad \text{with} \qquad A = \sin \pi q,$$

Orthogonal Lee

$$T = \sum_{m_1=-\infty}^{\infty} \sum_{m_2=-\infty}^{\infty} \frac{\sin(\pi m_1/2)}{\pi m_1} \frac{\sin(\pi m_2 A)}{\pi m_2} e^{-\mathrm{i}m_1\phi} e^{\mathrm{i}2\pi(m_1\boldsymbol{\nu}+m_2\boldsymbol{\nu}_\perp)\cdot\mathbf{r}}.$$

$$T_{-1,0} = \frac{A}{\pi} e^{\mathrm{i}\phi},$$

R. Guti´errez-Cuevas

Thank you for your attention