4B11 Photonic Systems

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Holographic Switches

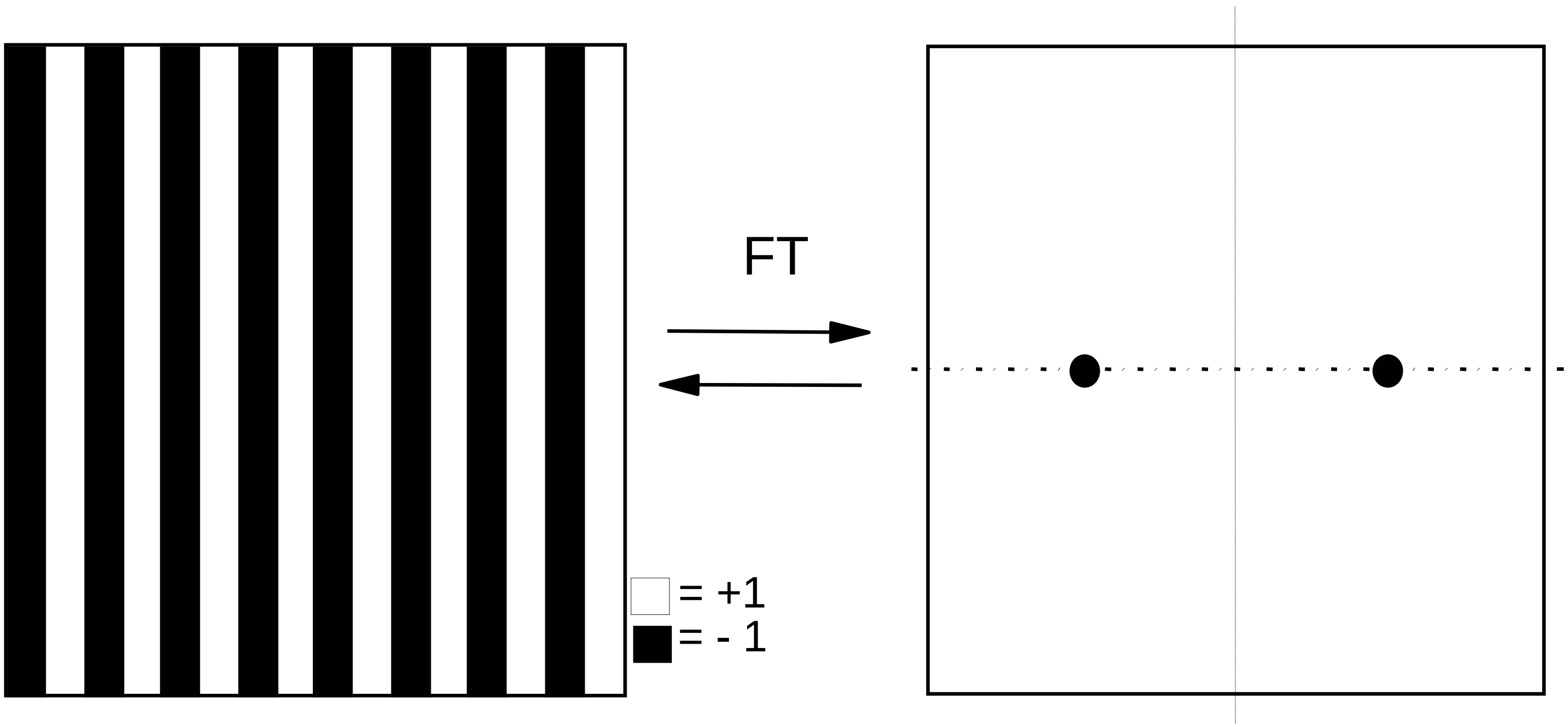

nupower

One of the most useful features of a 2-D binary phase computer generated hologram (CGH) is its ability to shift light into desired positions anywhere in the replay field.

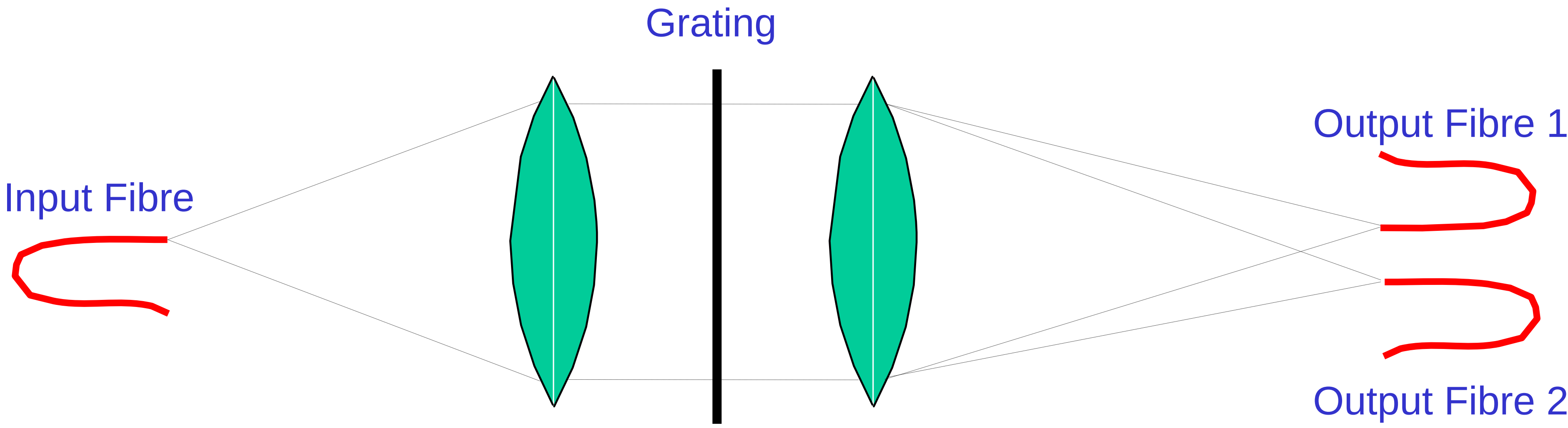
The ability to dynamically display the CGH in an optical system through the use of FLC SLMs means that we can reconfigure the replay field at a rate set by the SLM technology.

Such freedom allows us to perform optical interconnects through free space. Although SLM reconfiguration times are of the order of 100μsec, there are significant advantages in making an optically transparent interconnect.

The one to two splitter



An input fibre is collimated by a lens and illuminates the grating. The FT is performed by a second lens and the focused spots in the replay field are launched down a pair of output fibres.



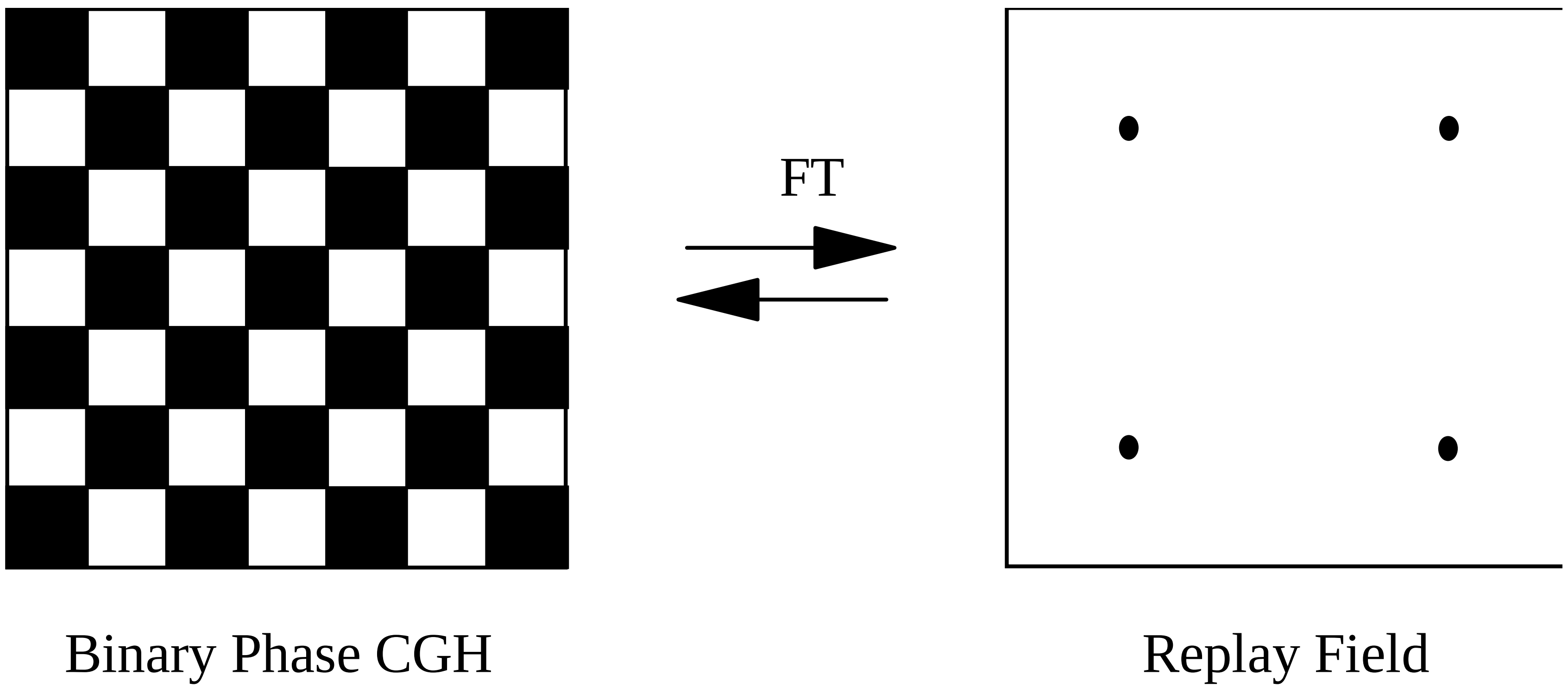
The total amount of light in the replay field (the area contained by the central lobe of the envelope sinc function) is defined as P_{in}.

The total efficiency of the splitter is not 50% as would be expected, in fact it is closer to 40%, because the grating loses power into the outer orders of the sinc function. There are also optical losses to be considered as the optical components are non-ideal.

Opto-mechanically it is complicated

Hence, the one to two splitter is not really feasible and cannot compete with current fibre couplers.

If we replace the grating in the above system with a binary phase CGH displayed on a FLC SLM, then it is possible to **dynamically** route light to several fibres in the replay field.



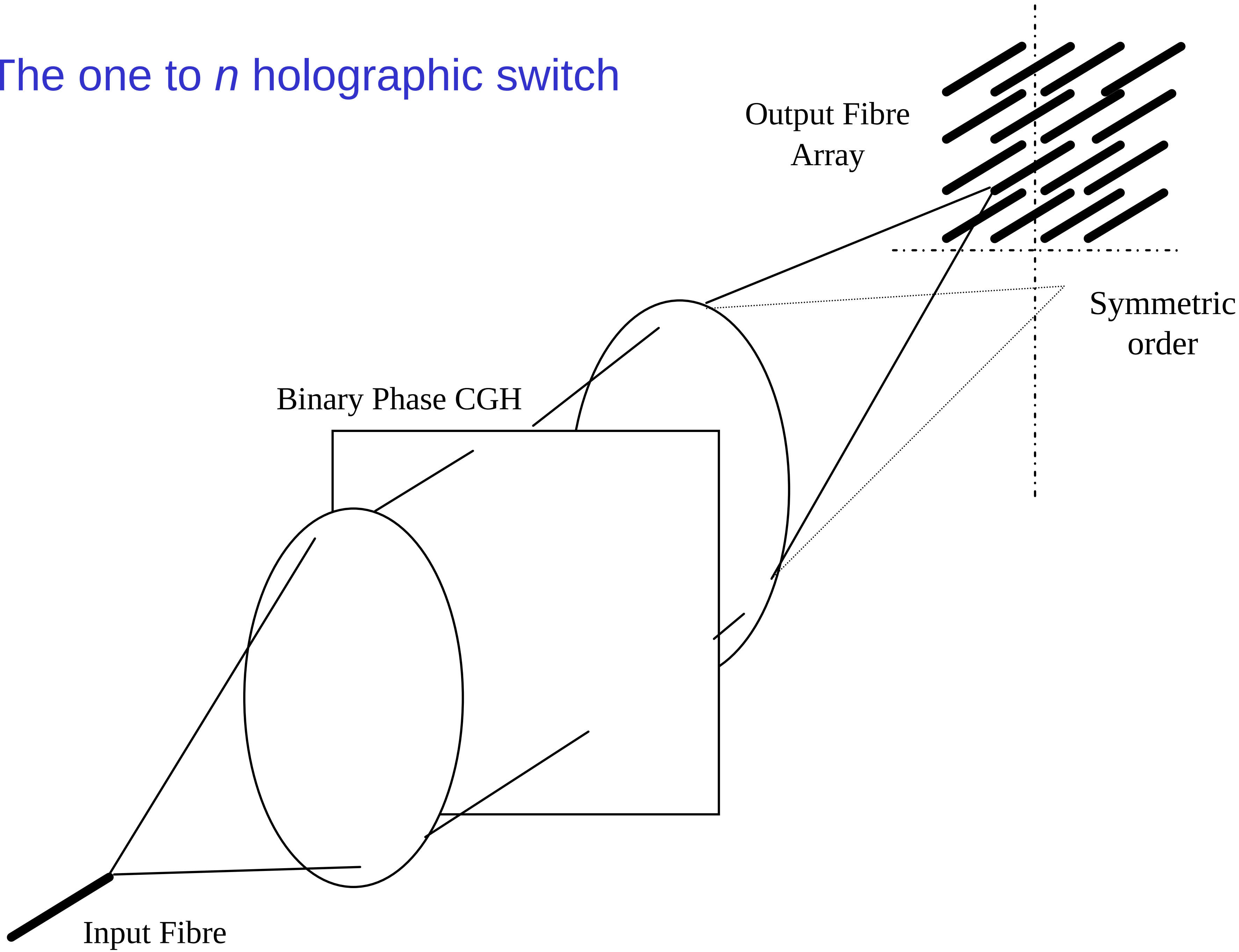
We are limited however, by the binary phase modulation of the FLC SLM which means that a symmetric copy of the desired replay field always appears rotated by 180º.

Such a property is useful if the desired replay field is 180º rotationally symmetric, but this is not the case with a one to *n* interconnect as this leads to asymmetric replay patterns.

For this reason, we have to accept a 3dB penalty in the power which can be routed from the input fibre to the output.

In the analysis of these switches, we will assume that the replay field is limited to the upper half plane and that the symmetric order is repeated in the lower half plane.

The one to *n* holographic switch



The operation of the switch is such that the CGH displayed on the SLM routes the light from the input fibre to a fibre in the output array of *n* fibres in the output plane.

If we assume an ideal situation of loss-less optics and SLM and that the CGH has zero pixel pitch and infinite number of pixels, then we can perform a simple analysis on the operation of the interconnect.

The total input power which appears in the output plane is P_{in}. The total power which is routed into a spot by the CGH is P_{sp} and the remaining power is dissipated into the whole plane as the background or noise power P_{bk}.

$$P_{in} = 2P_{sp} + P_{bk}$$

The factor of 2 is due to the symmetry of the pattern due to binary phase. We can define the CGH efficiency η as the ratio between the power in the spot, P_{sp} and the input power P_{in}.

$$\eta = \frac{P_{sp}}{P_{in}}$$

A typical value for this efficiency would be around 38% for a CGH generated by simulated annealing (the ideal maximum would be 50% due to the symmetry in the replay field).

Higher efficiencies (up to 41%) are possible, depending on the position of the spot, number of CGH pixels and the method of generation.

One of the most fundamental characteristics of an optical interconnect is the **crosstalk**.

If the switch is configured to route light to the *k*th fibre in an array of *n*, then the crosstalk is the *ratio of light launched down the desired fibre to the light launched down one of the other fibres which are not being routed to*.

For *n* fibres in the output array of a 1 to *n* switch, the power into a single fibre will be ηP_{in}.

If the CGH has *N*x*N* pixels, then the replay field can also be assumed to contain *N*x*N* 'spatial frequency pixels'.

If we assume that the background power is uniformly distributed over the N^2 spatial frequency pixels in the replay field then the background power at each spatial frequency pixel will be.

$$P_{bpix} = \frac{(1-2\eta)P_{in}}{N^2}$$

Hence the crosstalk is the ratio of the light routed to P_{bpix}.

$$C = \frac{\eta}{1-2\eta} N^2$$

This is a ‘best case’ crosstalk estimate. The actual crosstalk is more complex than this as there are several factors, which have been overlooked.

1. Due to the binary phase modulation, the distribution of the background power is not uniform and there tends to be small peaks of intensity which may occur at fibre positions. This becomes less of a problem with large numbers of CGH pixels and careful CGH design.

2. The number of CGH pixels is finite and forms an overall aperture which leads to sinc or Bessel sidelobes on the individual spots. There is also Gaussian illumination. These effects lose power into the sidelobes and cause the spot to be broader than the original source fibre, leading to poor fibre launch efficiency. (Apodisation)

3. The pixel pitch is finite which leads to an overall sinc envelope which reduces the power into spots that occur further away from the centre of the replay field. The sinc envelope also leads to power being lost in the outer orders due to replication of the replay field.

4. The SLM used to display the CGH inevitably has deadspace (optically inactive areas) between the pixels. This space limits the performance of the CGH as it alters the envelope of the replay field and increases the power replicated into the unwanted higher orders.

5. The physical alignment of the fibres in the output array is not perfect, so there are position errors in the spot locations which leads to poor interconnections. This can be corrected if *N* is large by slightly shifting the positions of the spots to match the fibre array.

6. So far we have assumed perfect optics with no limitations or distortions. In reality, it is optically more difficult to route light into the outer corners leading to fan-in loss. This loss is usually modelled as a *1/n*. We can reduce this by placing the outputs close to the zero order and limiting *n*. But this increases crosstalk!!

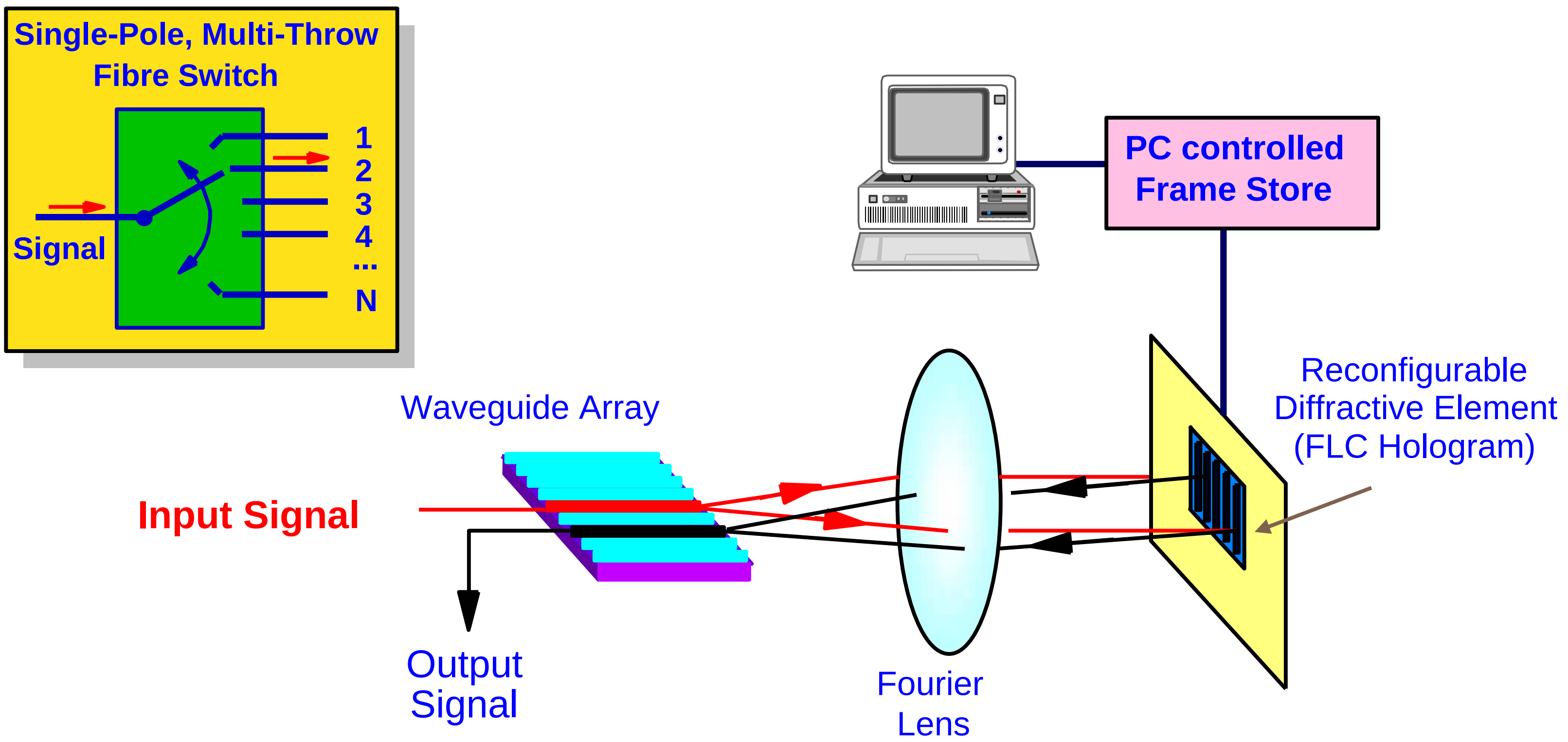
It is assumed that the light can be efficiently launched into a fibre without significant loss. For a 100% efficient launch, it is assumed that the distribution of the light focused into the fibre is exactly the same as when it was radiated from the input fibre.

In the case of a single mode fibre, the distribution is almost Gaussian which means that the FT will be Gaussian, aiding launch efficiency.

It is difficult to match this distribution when there are several distortions due to apertures, SLM imperfections, polarisors and optical aberrations.

This can be relieved by launching into multimode fibre, but a single mode to single mode fibre switch is far more desirable.

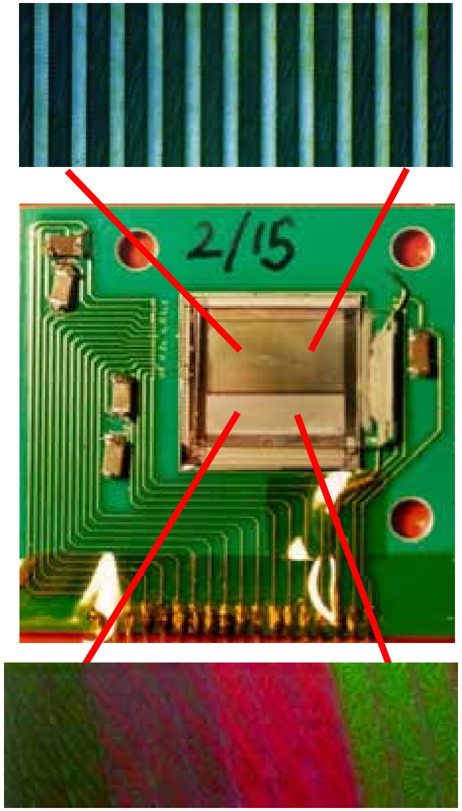
The ROSES Switch Design



Data signal routed to different output ports by varying hologram period.

Spatial Light Modulator Design

Binary Array

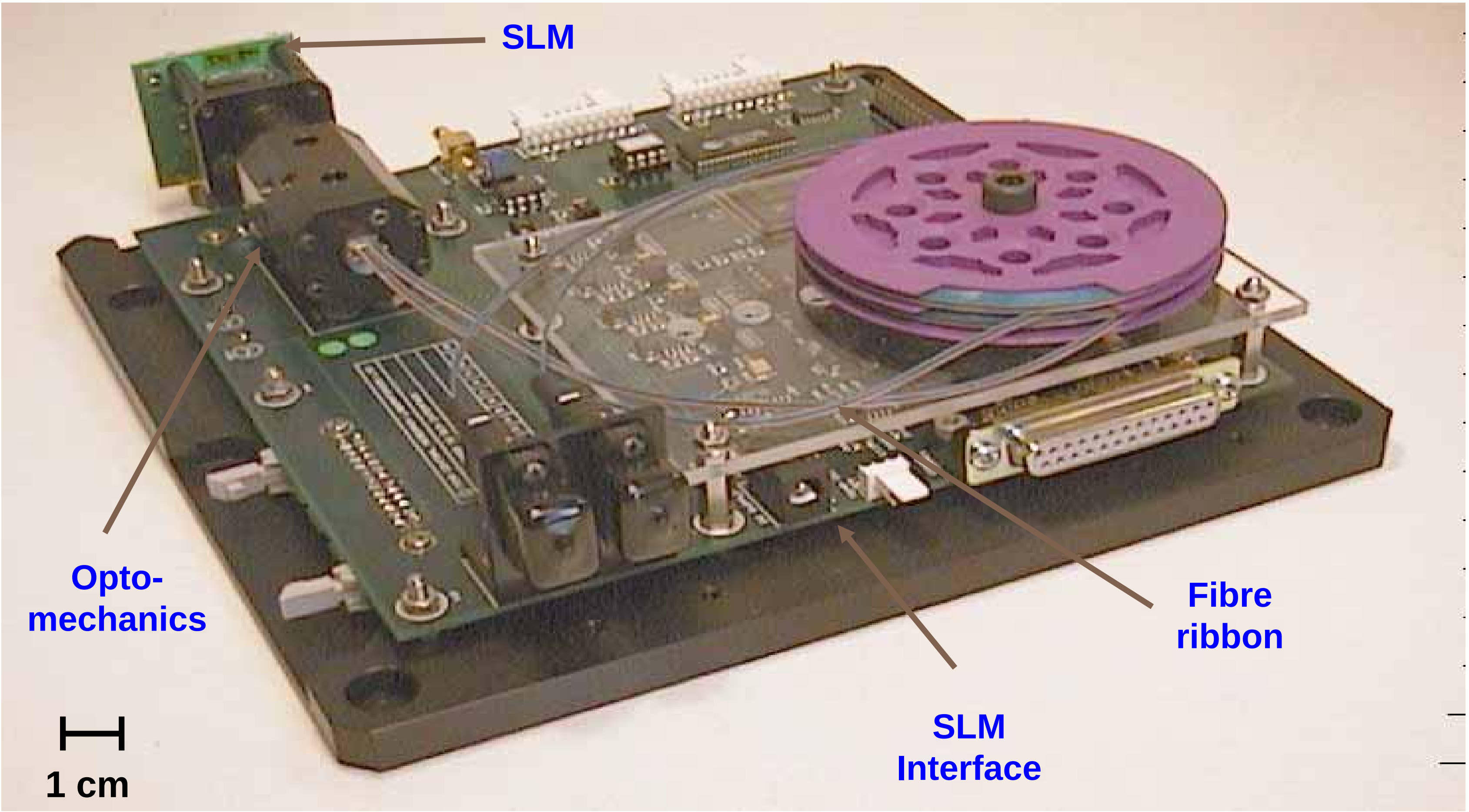


Quad Array

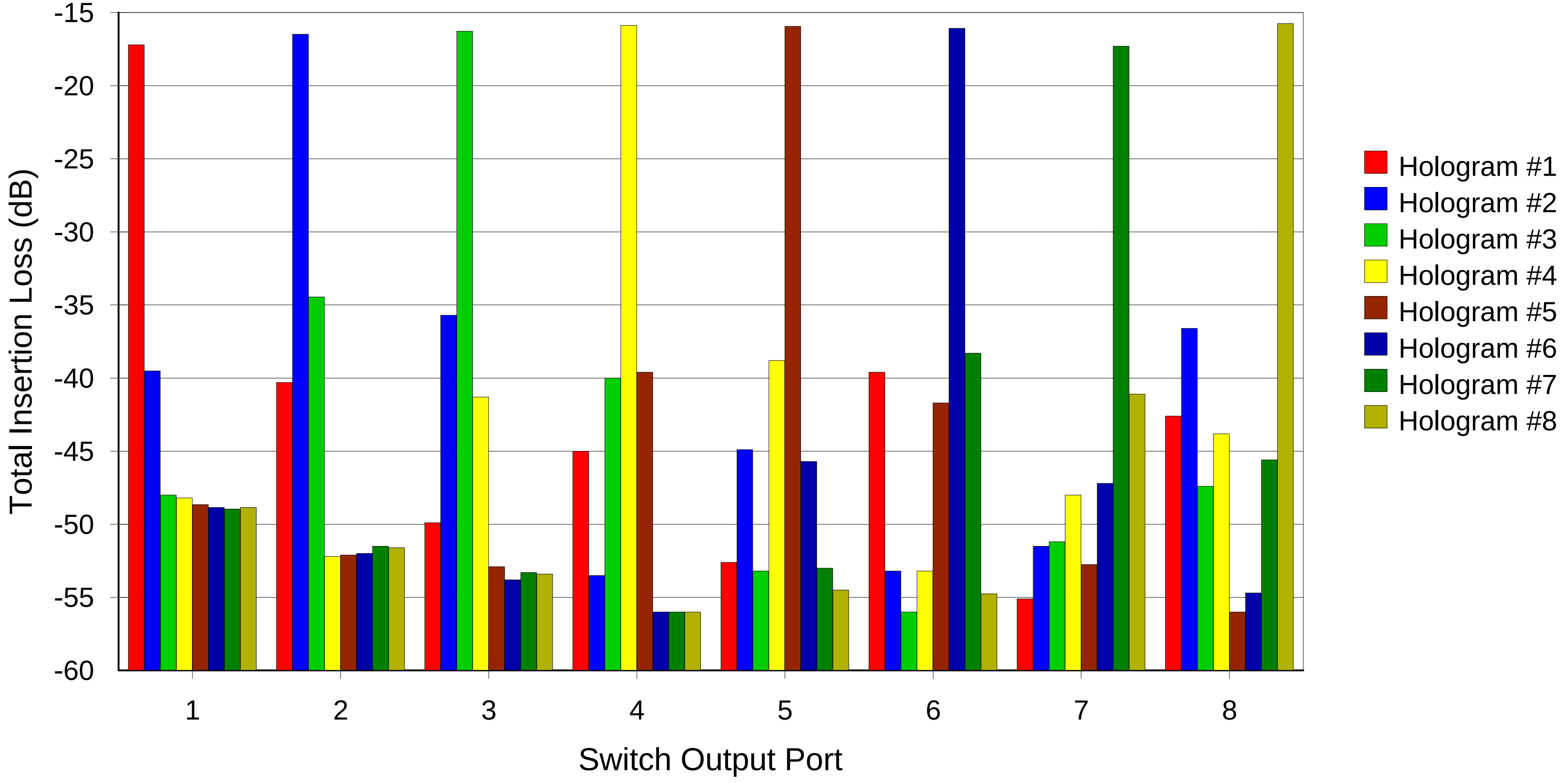
Device Performance

- 540x1 pixels 18μm x 6mm long
- 2μm pixel deadspace
- Partial Planarisation
- ~3.5μm FLC layer, CDRR8
- Rubbed nylon 6-6 alignment
- Up to 50μsec reconfiguration speed
- SRAM pixel design, 11V drive
- Experimental quaternary drive

The ROSES 1x8 Switch Demonstrator



Demonstrator Performance



- Worst case crosstalk ratio = 18.0dB (Target = 20dB).

Demonstrator Power Budget

Current Performance

Component	Loss
Connector Loss	0.4dB
Input/Output Fiber Array	1.5dB
Optical Component Loss	0.7dB
Hologram/SLM Losses	11dB
Accounted Losses	**13.6dB**

Component	Loss
ITO Loss (two pass)	3dB
Cell Gap Error	2.4dB
Deadspace	0.9dB
Non-Ideal FLC	0.7dB
Hologram Efficiency	4dB
Hologram/SLM Losses	**11.0dB**

Total Measured Loss	**16.5±0.8dB**

- Measured loss from input connector to output connector.
- DFB laser operating at -6.0±0.1dBm, central wavelength = 1547.2nm.
- Excess loss of 2.9dB due to aberrations and alignment errors.

Demonstrator Power Budget

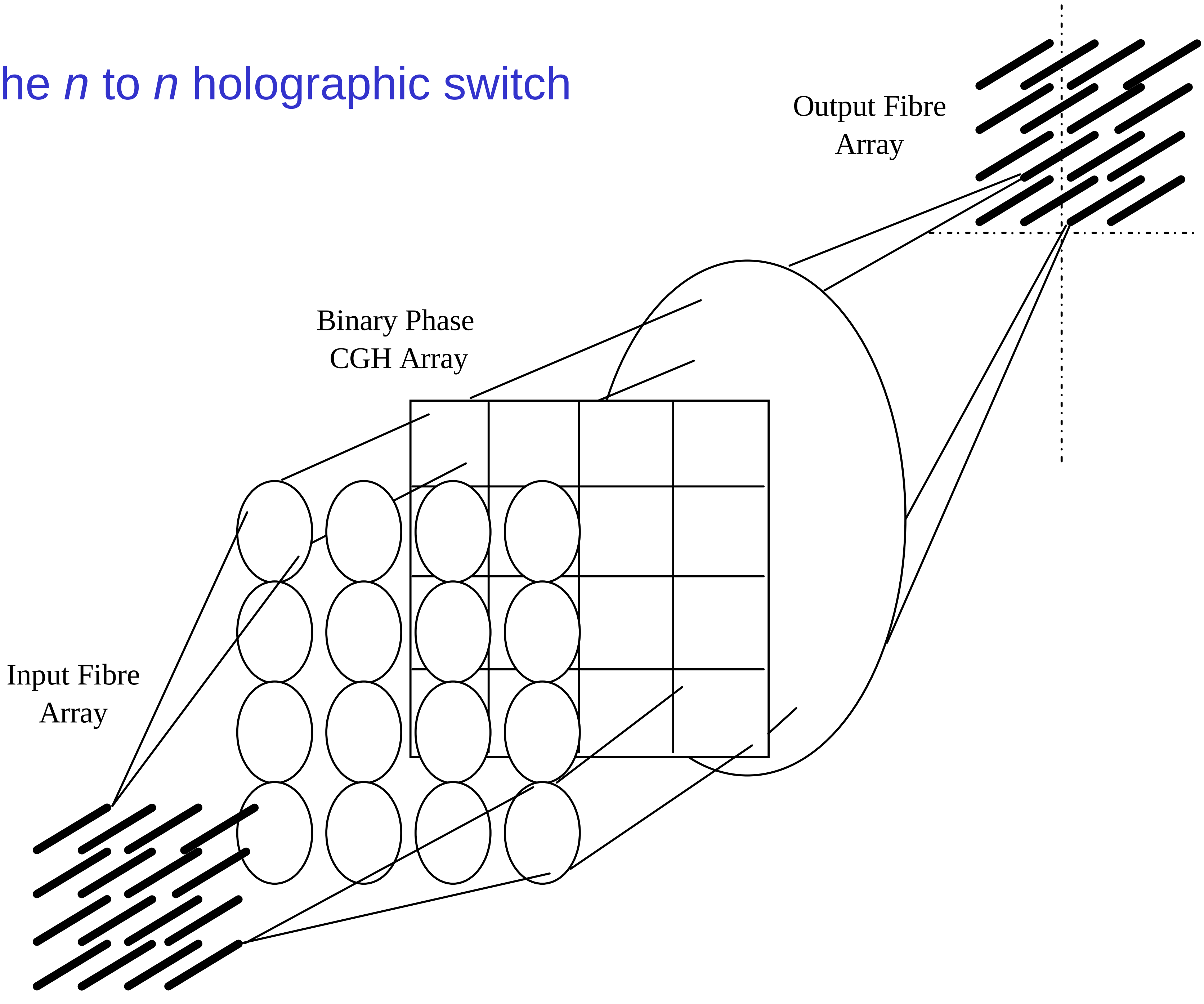
Optimal Performance

Component	Loss
Connector Loss	0.4dB
Input/Output Fiber Array	1.5dB
Optical Component Loss	0.30dB
Hologram Efficiency	6.0dB

Estimated Loss	**8.2dB**

Targeted Loss	**<10dB**

The *n* to *n* holographic switch



The loss factors of this switch are similar to those of the one to *n* switch, but fan-in loss becomes more dominant.

We can apply the same idealistic approach to the analysis as for the one to *n* switch, assuming uniform distribution of the non-routed light in the background of the replay field.

We also assume that the efficiency η of each CGH will be the same. The analysis for the crosstalk is the same except that we now have the background noise from each of the other $n - 1$ input fibres appearing at the each output fibre along with the ηP_{in} from the routed input. Hence the crosstalk bound will be.

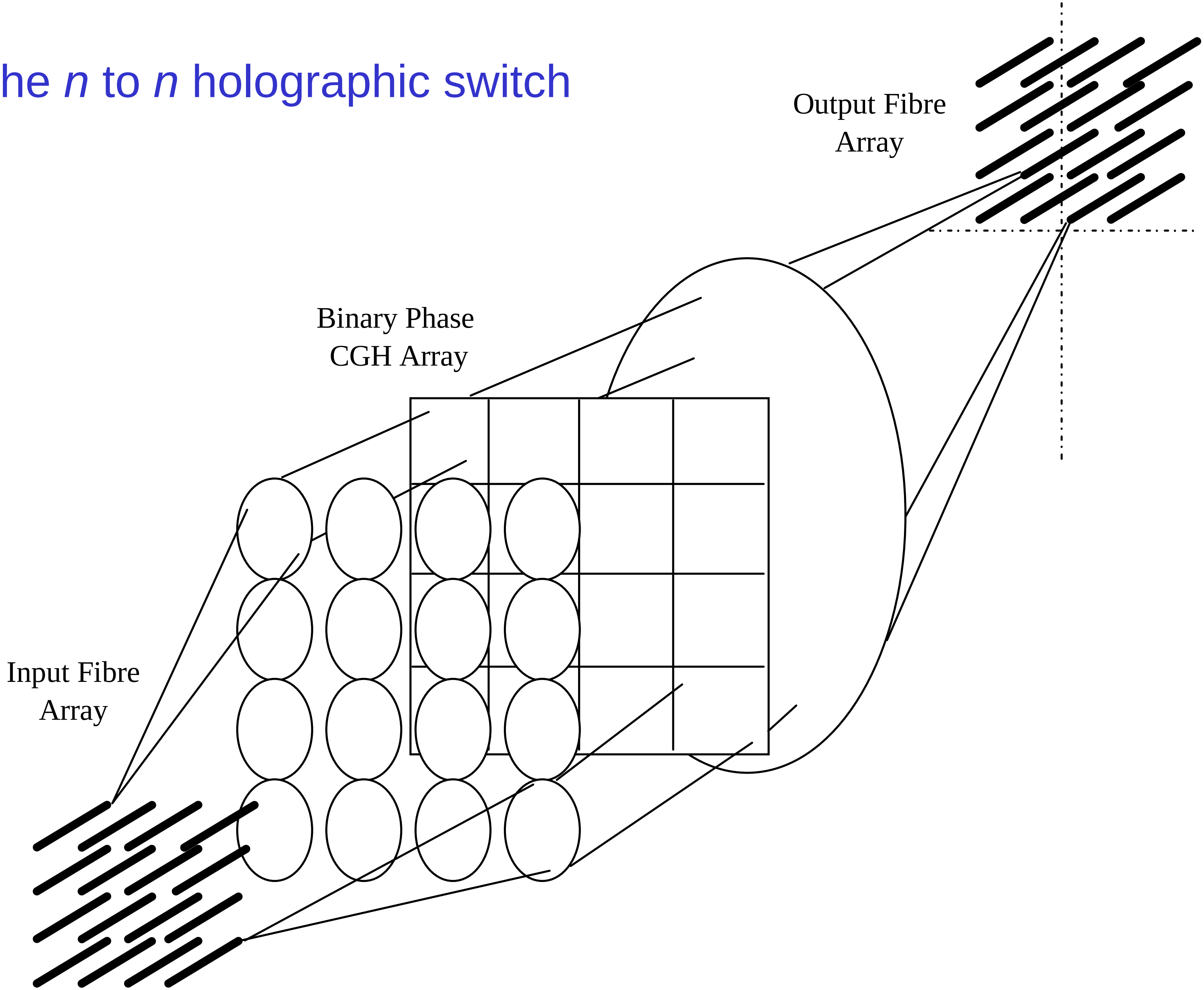
$$C = \frac{\eta}{1-2\eta}\frac{N^2}{(n-1)}$$

A main limitation of the *n* x *n* switch is the fan in loss problem as it is difficult to group all of the fibres near the zero order, hence the outer fibres will see a steep angle.

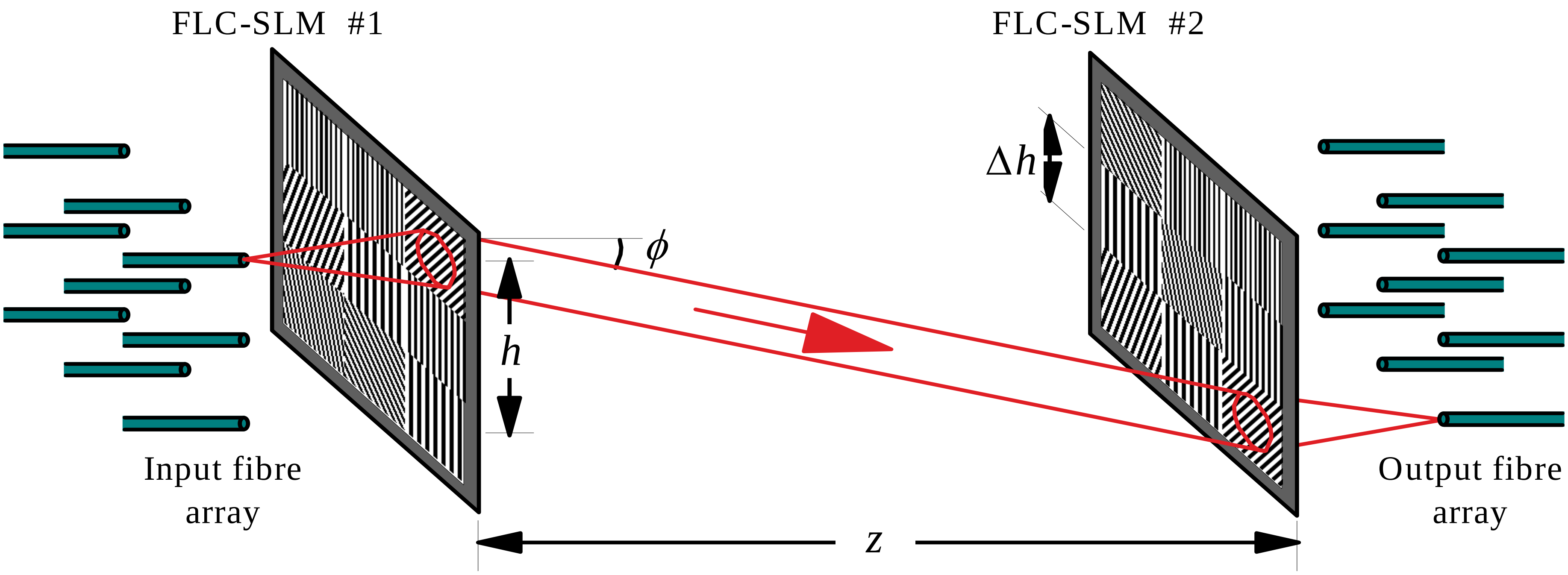
This can be removed by having a pair of complementary holograms to form the switch.

The first steer the light away from the input, whilst the second steers the light towards the output.

The *n* to *n* holographic switch



The two hologram *n* x *n* holographic switch



The first hologram steers light into the switch, whilst the second steers light out of the switch back onto the output fibre's axis. The most efficient combination for routing is if the second hologram is the complex conjugate of the first routing hologram.

The two hologram switch can be scaled to any size of *n* and the loss through the switch does not scale with the number of input and output ports. The loss does double however as there are now two binary phase holograms routing the same beam.

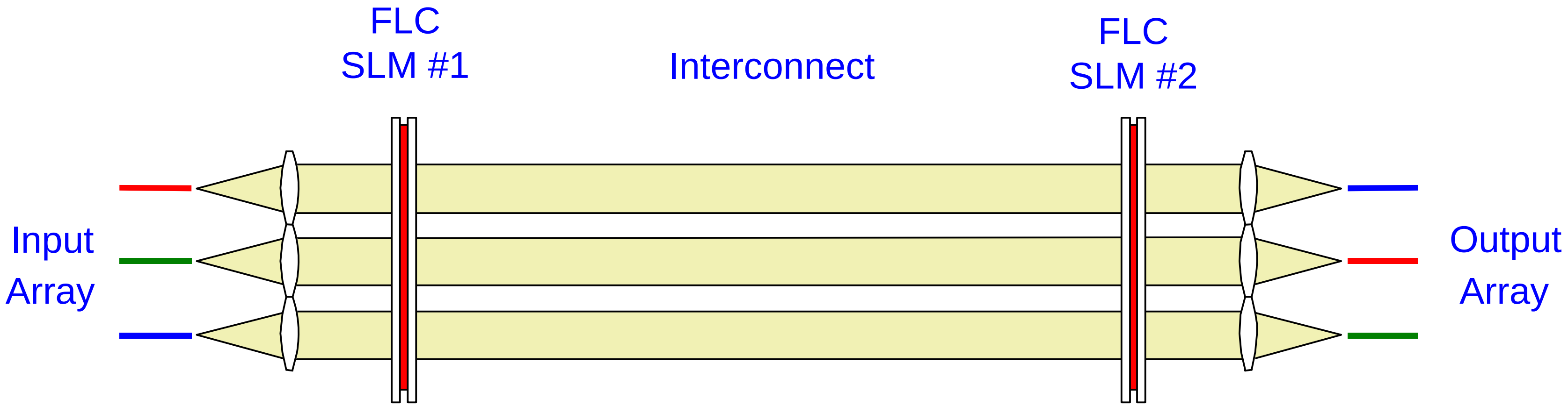
For this reason, it is better to use multi-phase holograms with better efficiencies (~95%), than binary phase holograms.

The only parameters which scale with the number of ports are the crosstalk and the physical length *z*.

The crosstalk of the two hologram switch is greatly improved as the crosstalk of the first hologram is multiplied by the cross talk of the second hologram.

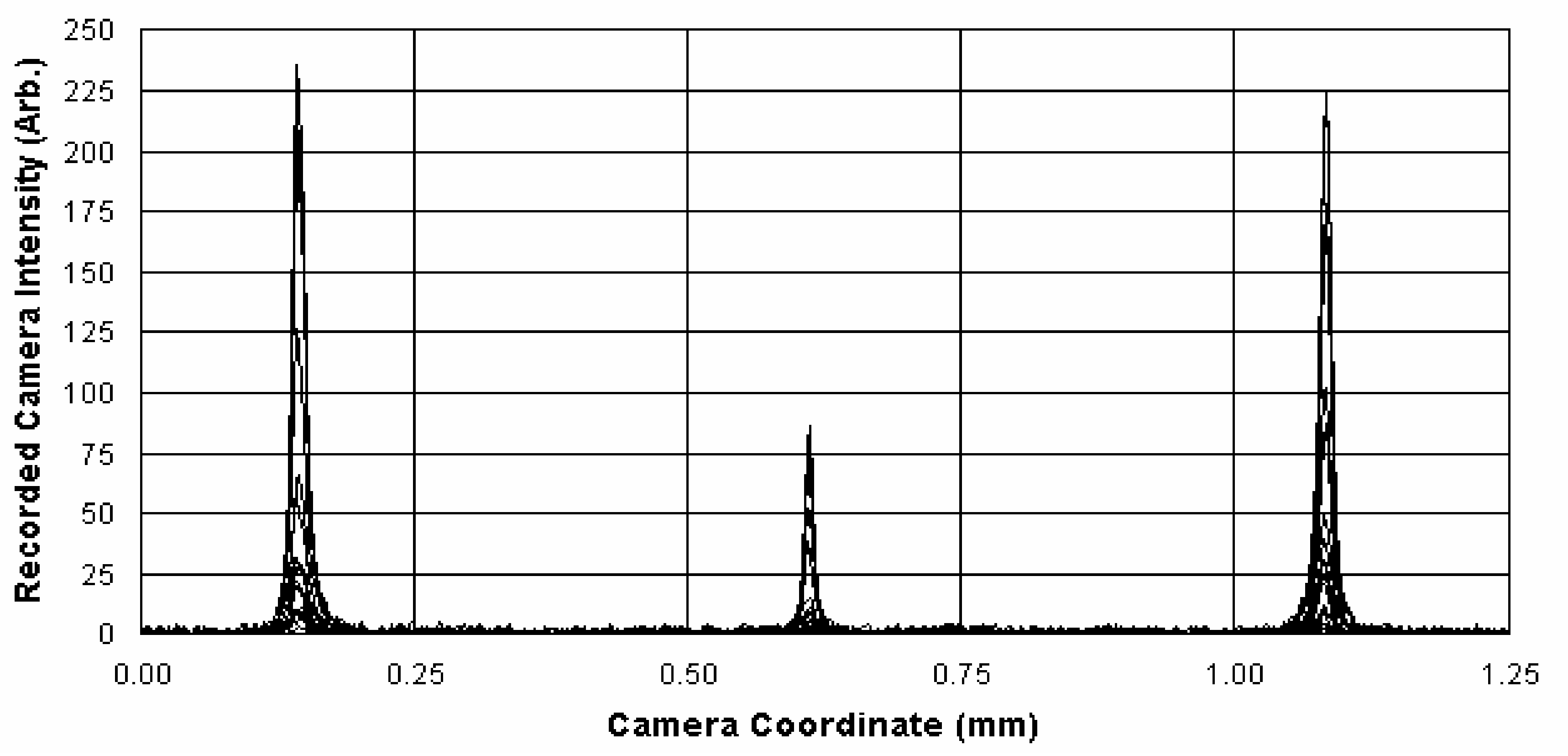
$$C = \left(\frac{\eta}{1-2\eta} \frac{N^2}{(n-1)} \right)^2$$

ROSES 3x3 Switch Using 1D SLMs



- 3 input and 3 output fibres on the ROSES waveguide array
- Catalogue lens optics (acromatic doublets)
- Opto-mechanical stages from Elliot Scientific

Far Field of the Grating Without Polarisors



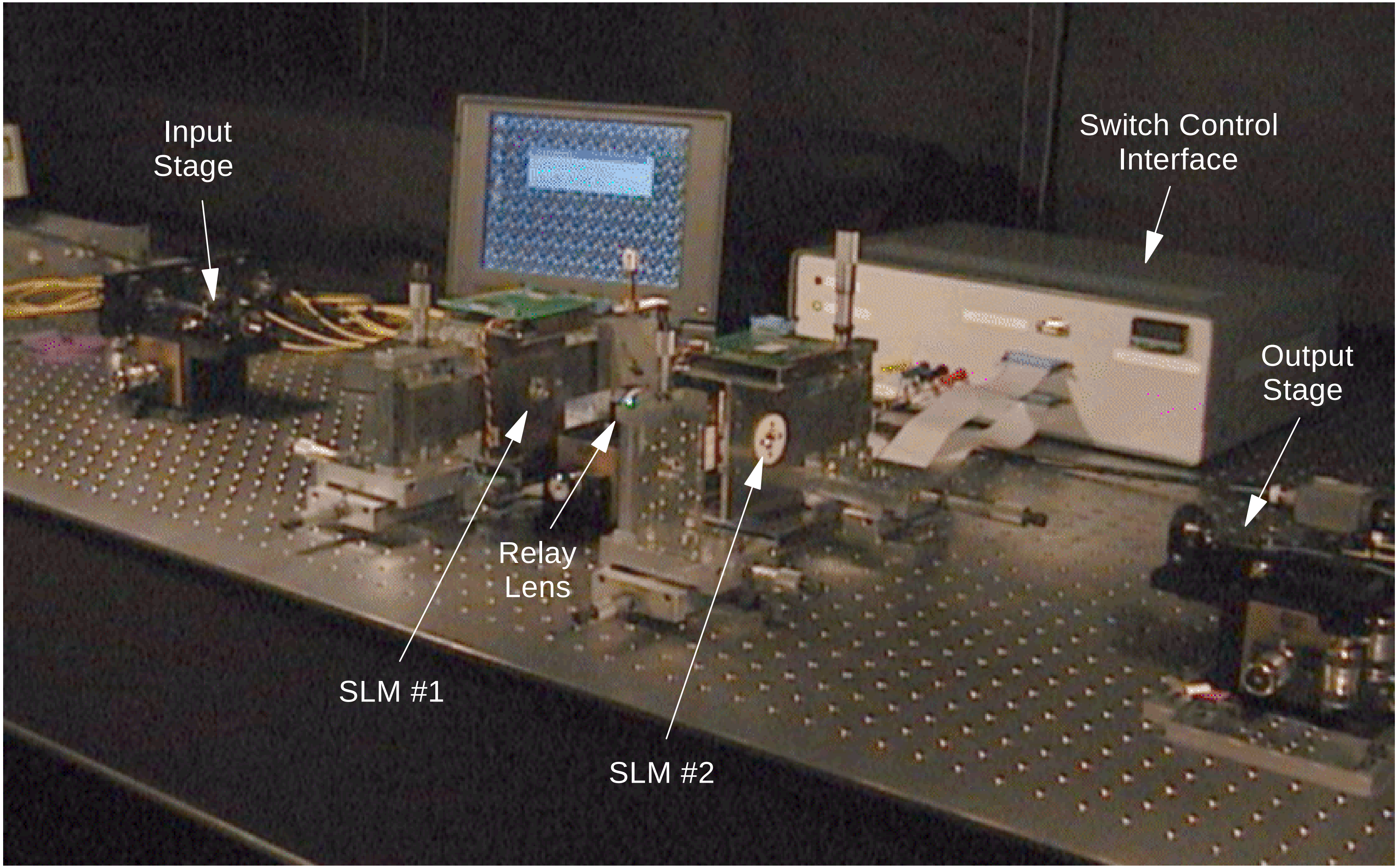
- DFB input source (λ=1554.2nm),
- ZnS photo-electric infrared camera.

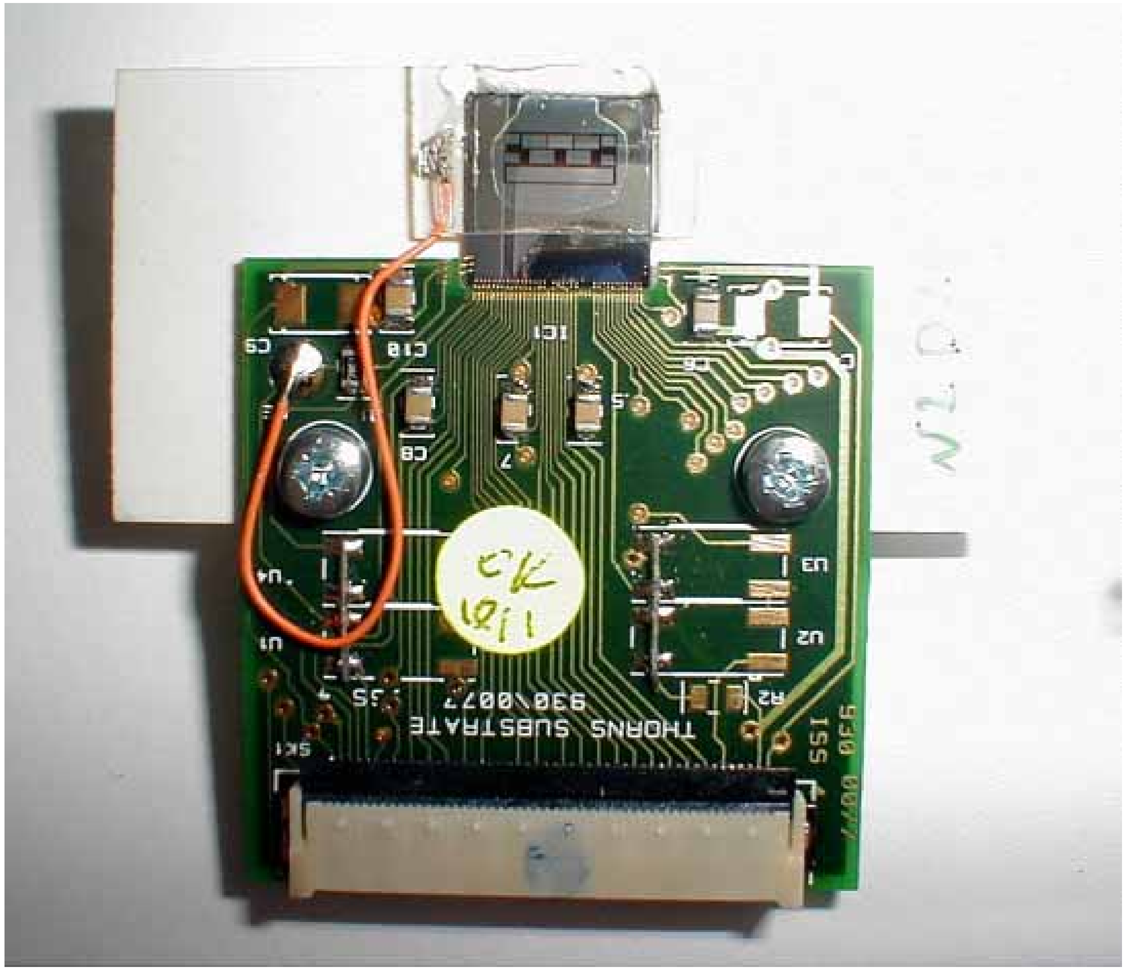
CS2005

t = 6.3μm　　λ = 1550nm

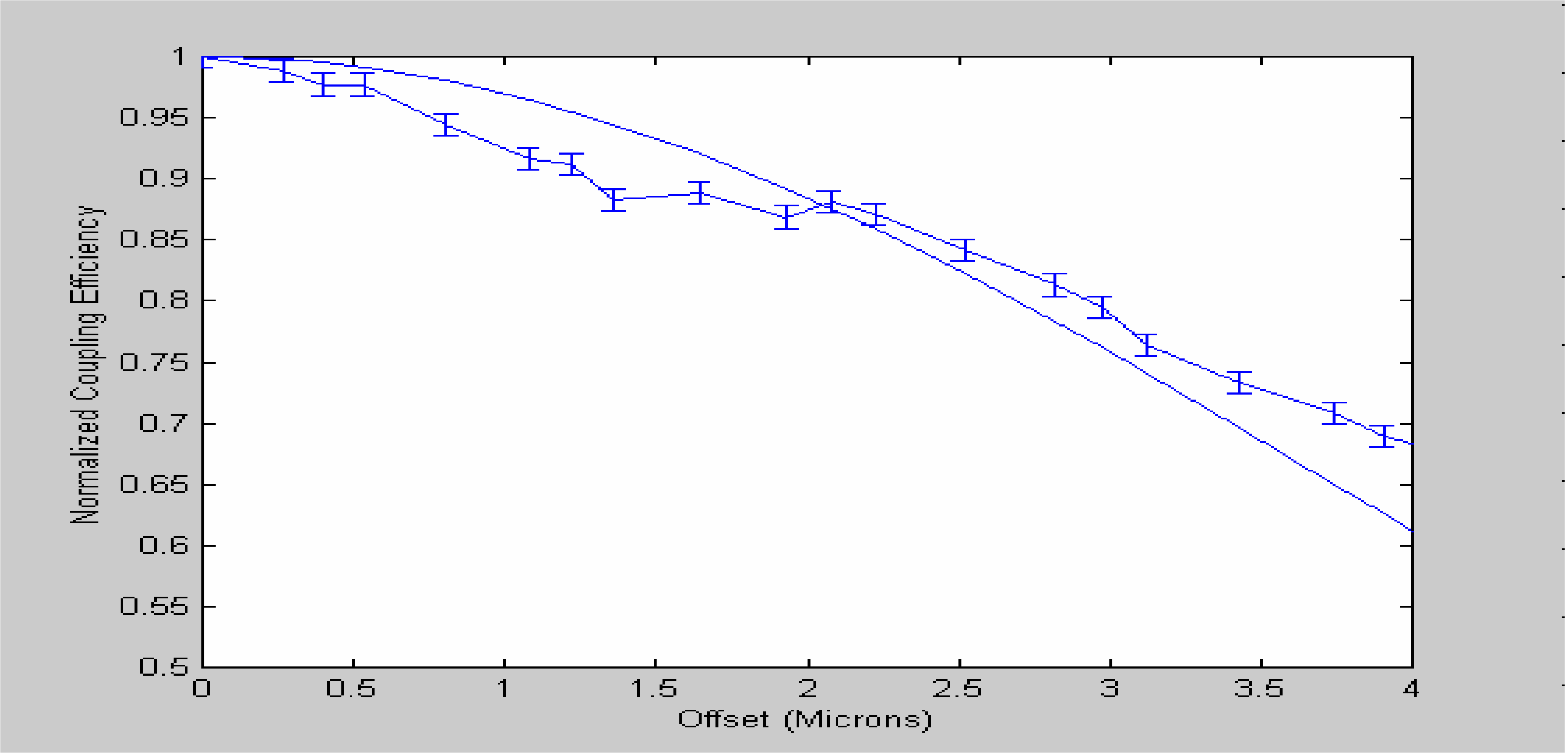
Δn = 0.12　　Field = 8V/μm

ROSES 3x3 Switch Using 1D SLMs




THORNS SUBSTRATE

Adaptive Alignment



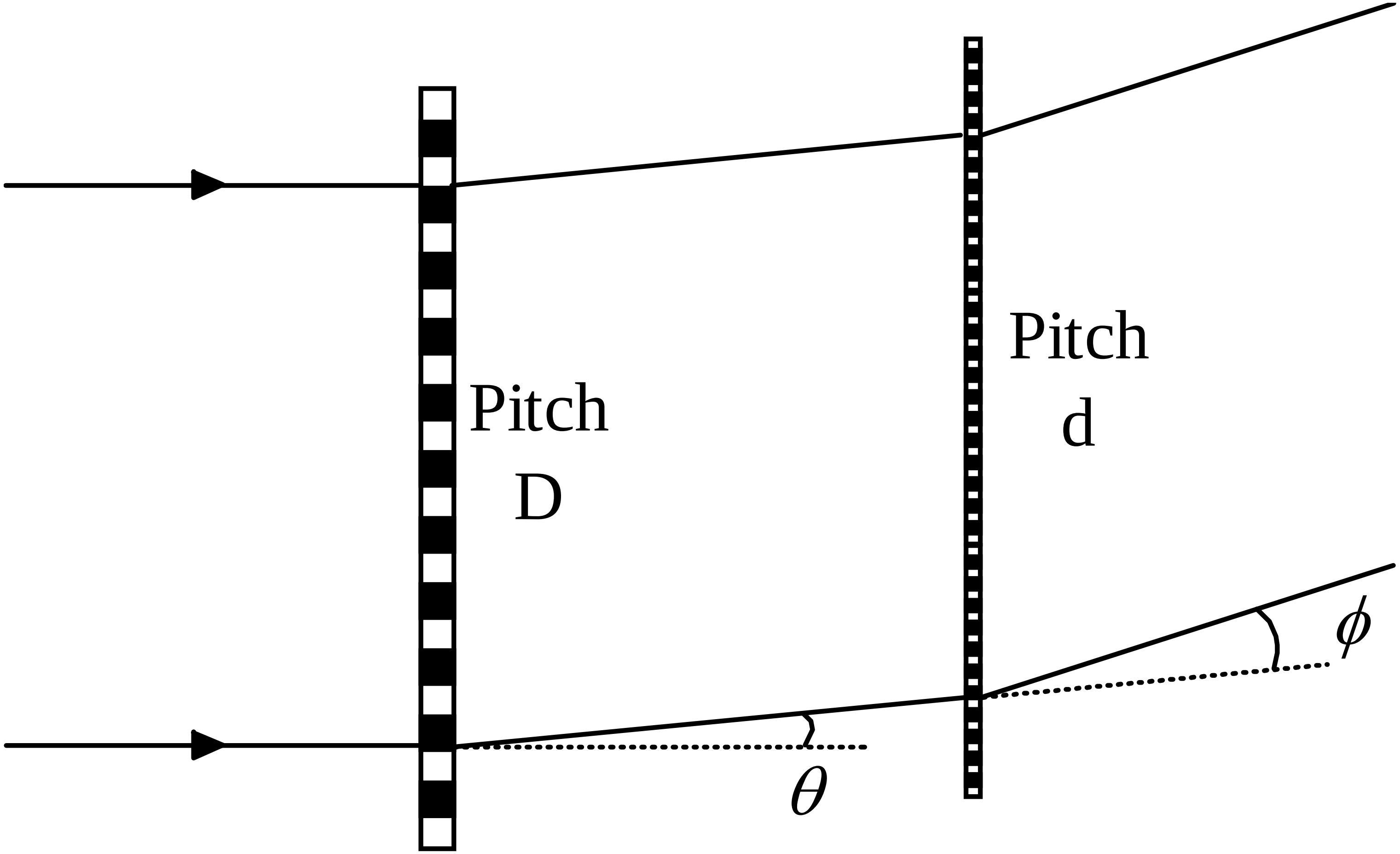
- Alter hologram pattern to optimize position of output beam - correct for any fabrication or alignment errors in situ.
- Simultaneous dynamic control of crosstalk and insertion loss.
- Experimental verification - stepped signal beam in 0.2μm steps across output waveguide.

A simple grating can be used as a wavelength filter as different wavelengths are diffracted at different angles as the light passes through the grating.

By using one dimensional holograms, we can select any point in the output plane along the single axis and hence any wavelength.

WDM systems require channels separated by 0.8nm centred at a wavelength of 1550nm which requires a 1-D SLM with a pixel pitch of about 5um.

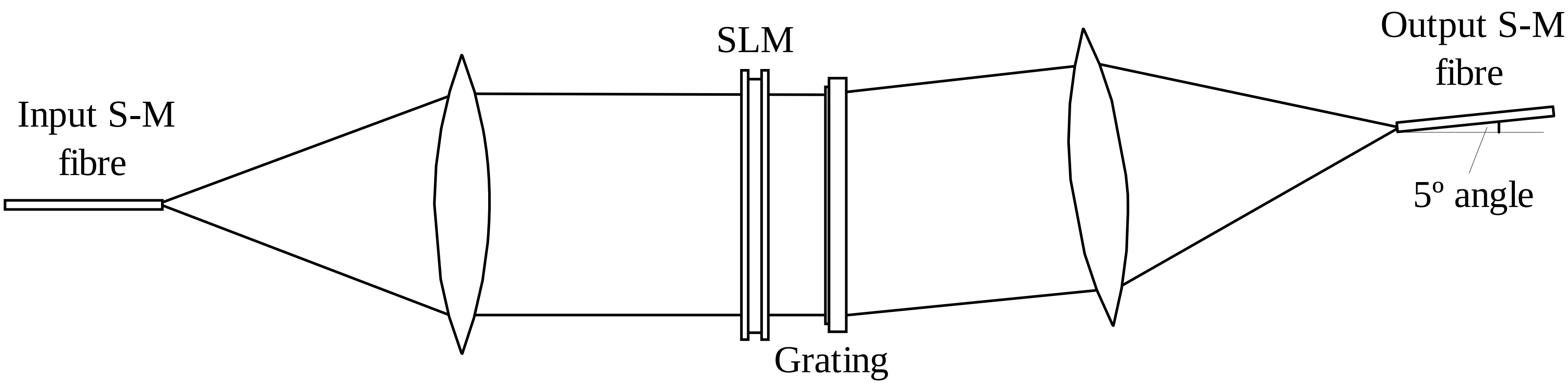
This is unlikely to be built in the near future and may never work properly due to the properties of the LC domains.



$$\sin\theta = \frac{\lambda}{D} \qquad \sin\phi = \frac{\lambda}{d}$$

From this system we can define the two angles of diffraction, where *D* and *d* are the respective grating pitches.

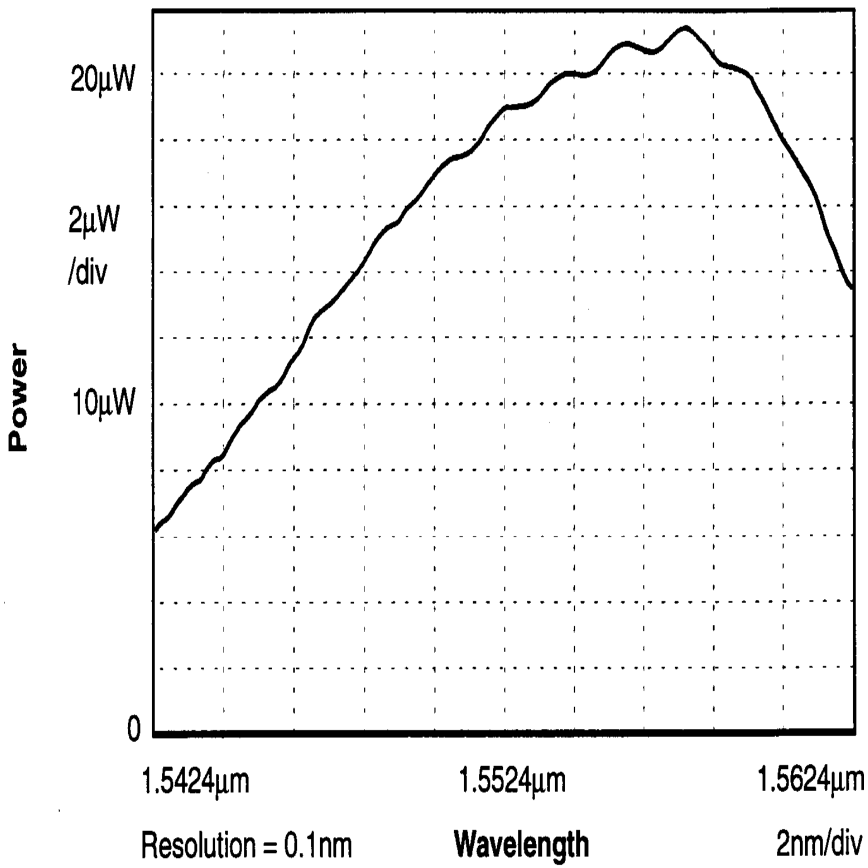
Hence, for an SLM with pixel pitch *D* we can choose the second grating pitch *d* based on the desired centre wavelength and tuning range.



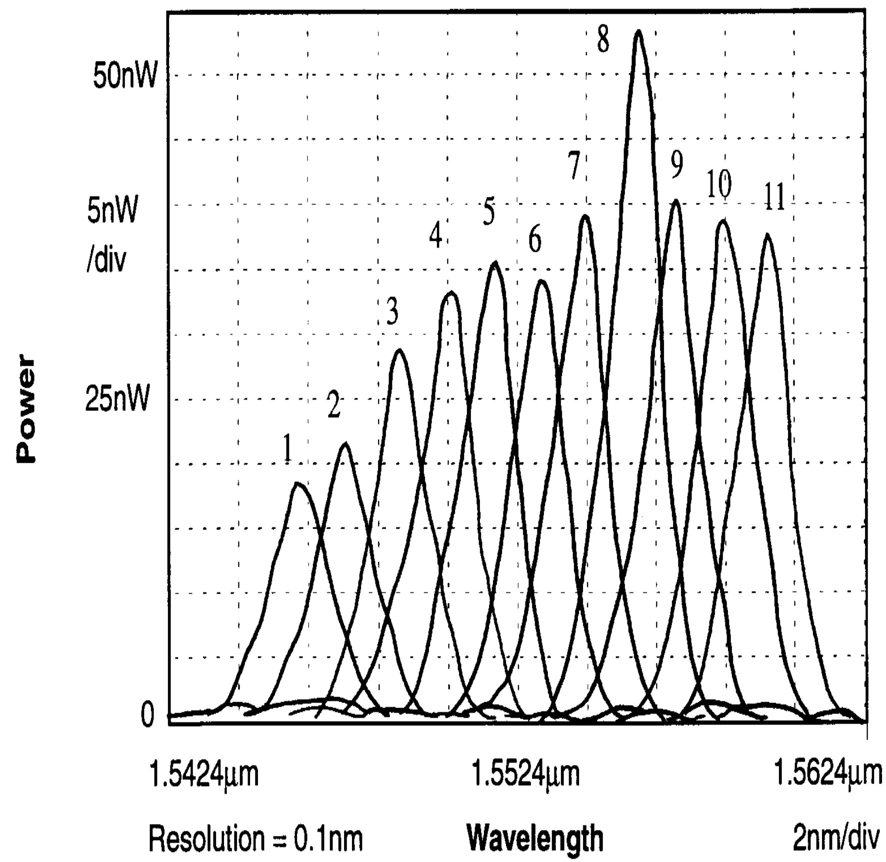
The SLM has N pixels at a pixel pitch D and the fixed grating has a pitch d. We also have a lens of focal length f to form the far field pattern and we are using a single mode fibre at a spatial position x to collect the tuned wavelength.

$$\lambda \approx \frac{x}{f\left(\frac{n}{ND} + \frac{1}{d}\right)}$$

Practical the parameters could be set at f = 96.1mm, N = 128, D = 165μm, d = 18μm, x = 8.3mm and n is an integer laying between 0 and $N/2$ which gives a tuning range of $\lambda_{n=0}$ = 1592.1nm to $\lambda_{n=64}$ = 1509.7nm in 64 steps of resolution 1.29nm.


Power
20μW
2μW
/div
10μW
0
1.5424μm
1.5524μm
1.5624μm
Resolution = 0.1nm
Wavelength
2nm/div

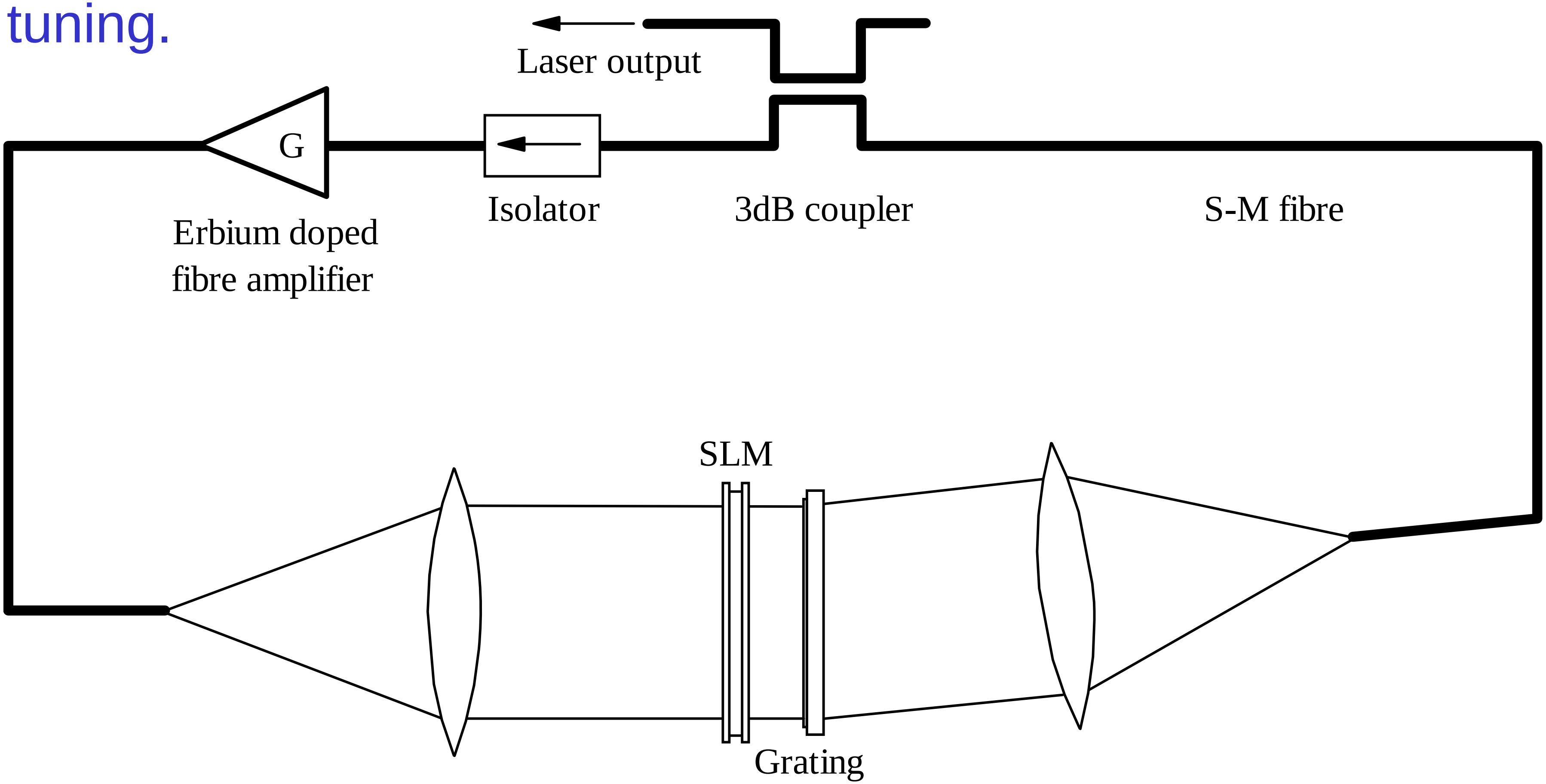
(a)

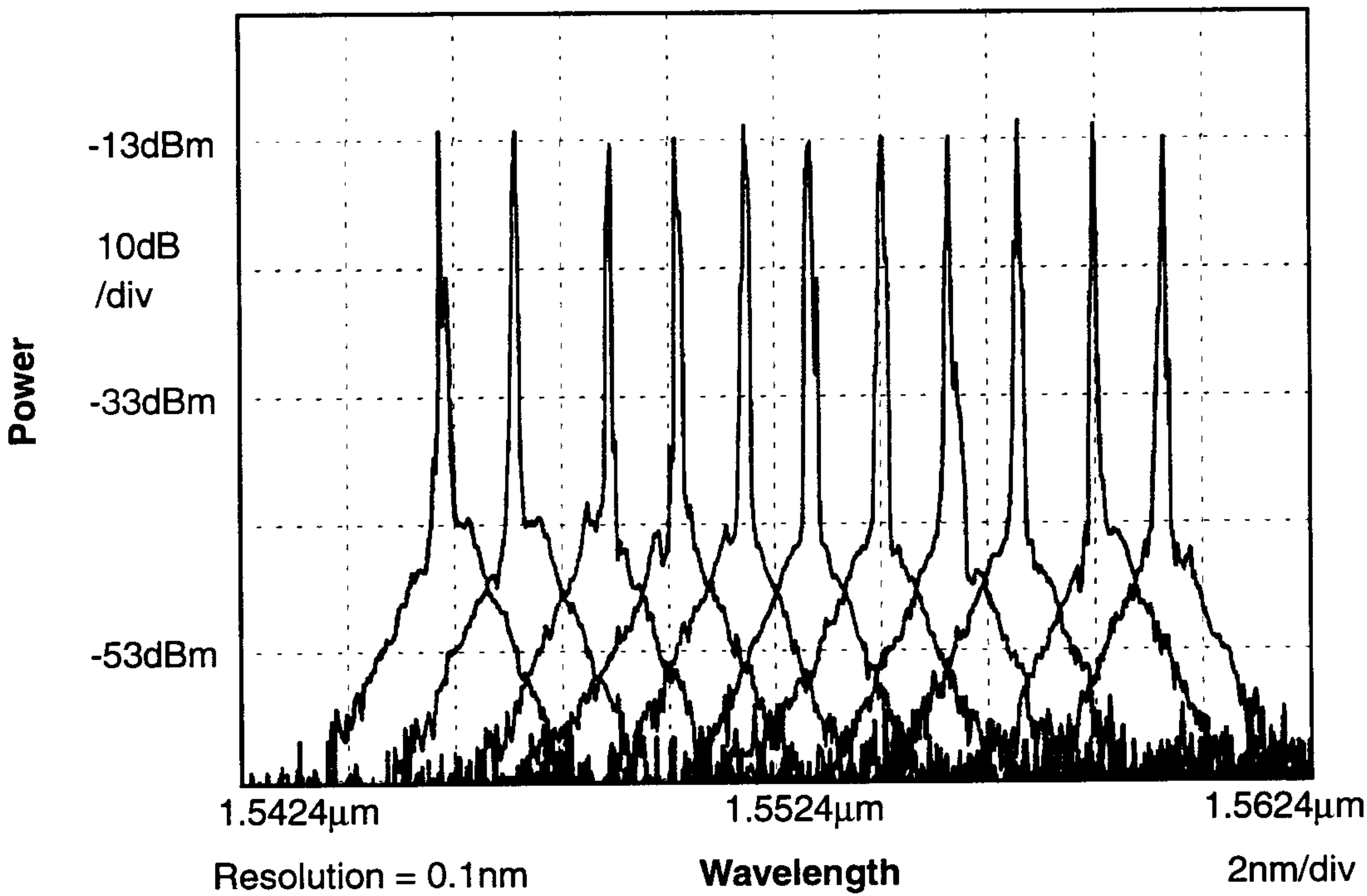

Power
50nW
5nW
/div
25nW
0
1
2
3
4
5
6
7
8
9
10
11
1.5424μm
1.5524μm
1.5624μm
Resolution = 0.1nm
Wavelength
2nm/div

(b)

The next step from the wavelength tuneable filter is to use this filter as a tuning element to create a digitally tuneable laser.

The relatively long cavity lengths of fibre lasers (from metres to a few centimetres) results in very narrow linewidths and closely spaced longitudinal modes, enabling almost continuous tuning.




-13dBm
10dB
/div
-33dBm
-53dBm
Power
1.5424μm
1.5524μm
1.5624μm
Resolution = 0.1nm
Wavelength
2nm/div