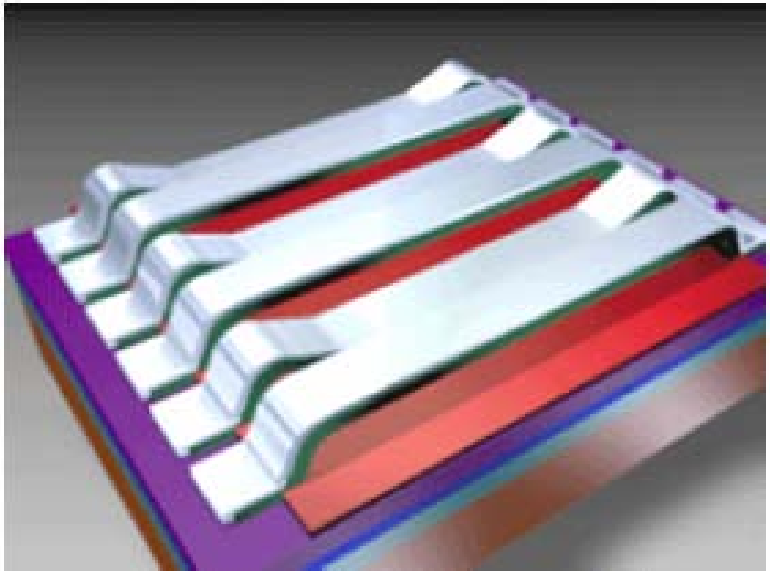
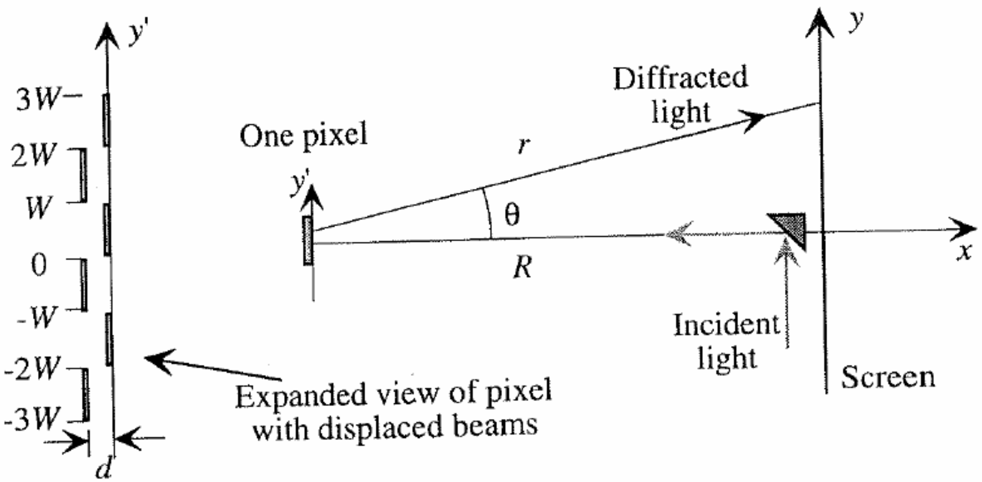
# The Optics of Grating Light Valves

FYS4230

Håkon Sagberg, SINTEF



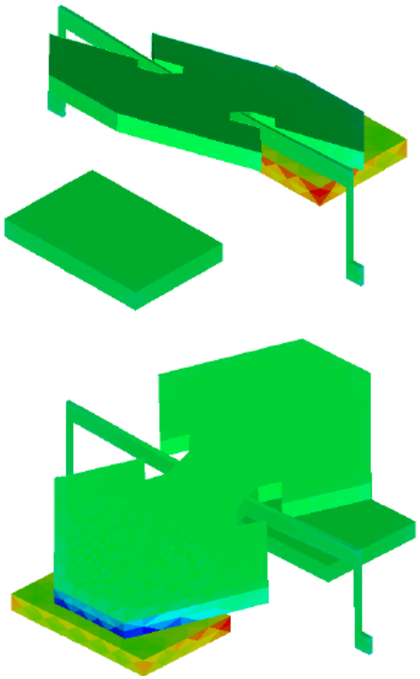


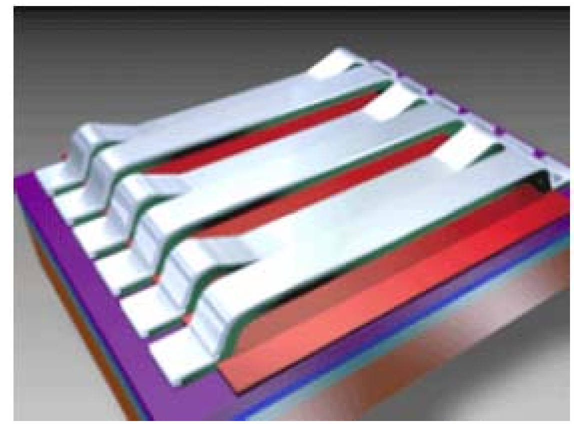
# The Optics of Grating Light Valves

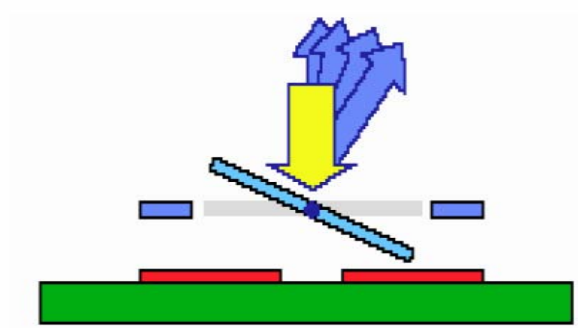
- Introduction to ”Grating Light Valves”
- Crash course in optical diffraction theory
- The grating light valve (GLV) display
- Grating light valves for other applications
  - Spectroscopy
  - Displacement sensing

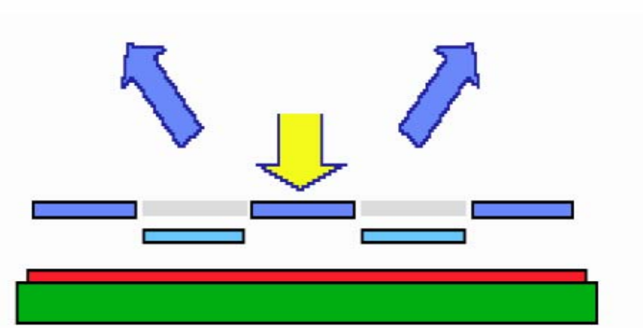
## Deformable Mirror Device (DMD)

## Grating light valves (GLV)

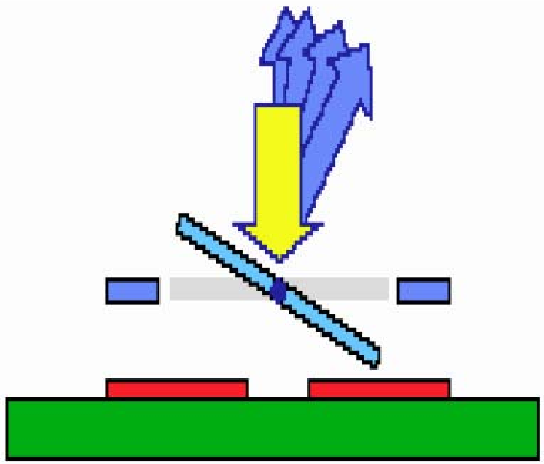




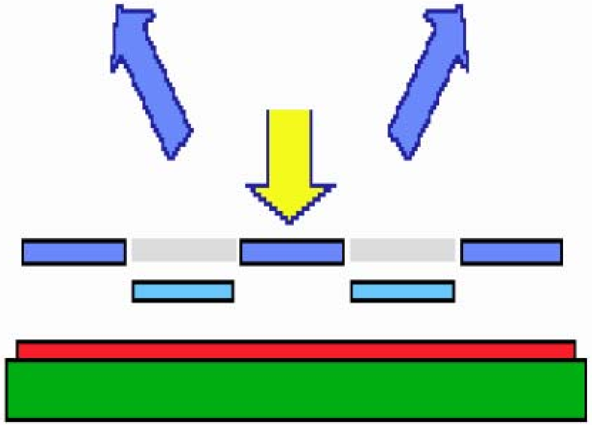




# Two methods for steering light



Deflection



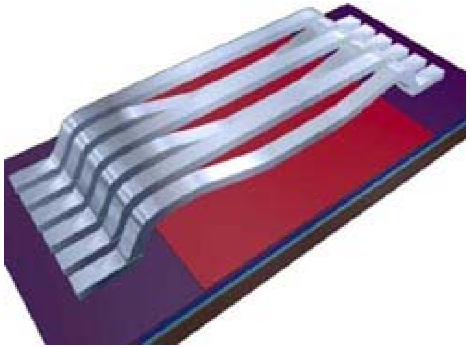
Diffraction

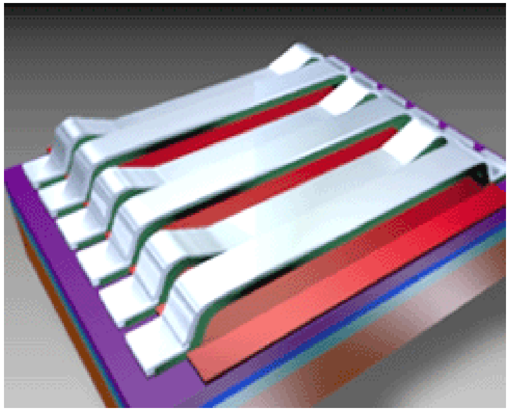
# The grating light valve (GLV)

- Grating Light Valve

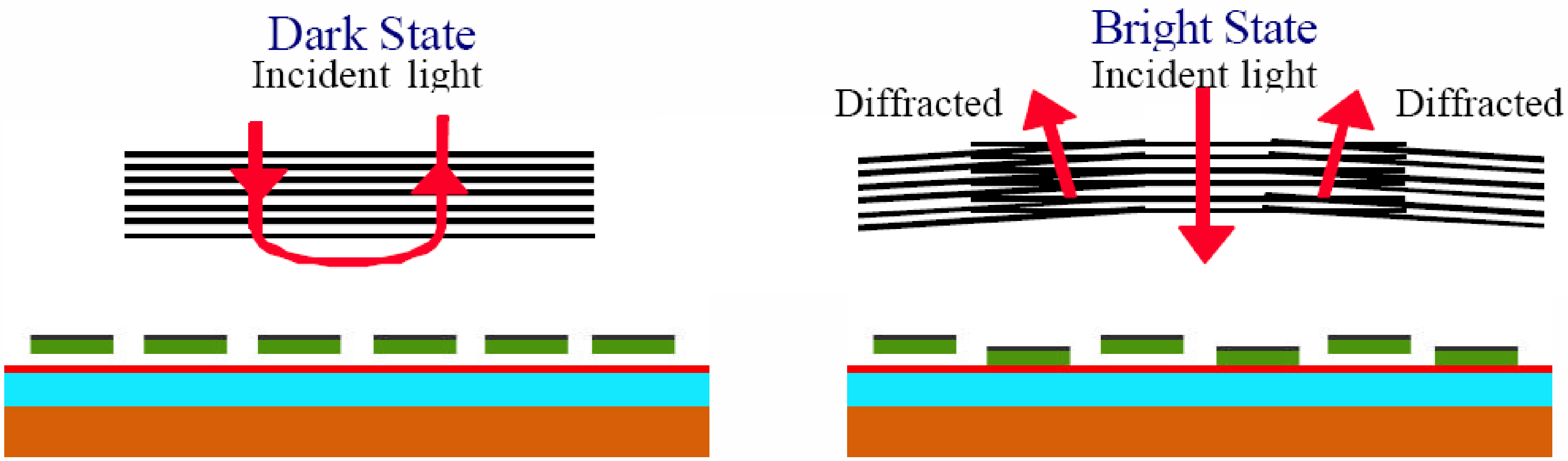
- Electrostatically deflect ribbons
- Distance to wafer $\lambda/4$
- Light is reflected or diffracted
- Diffracted light is projected to screen

- Possible to use pull-in or pull-control
- Possible to have one row of ribbon pixels only

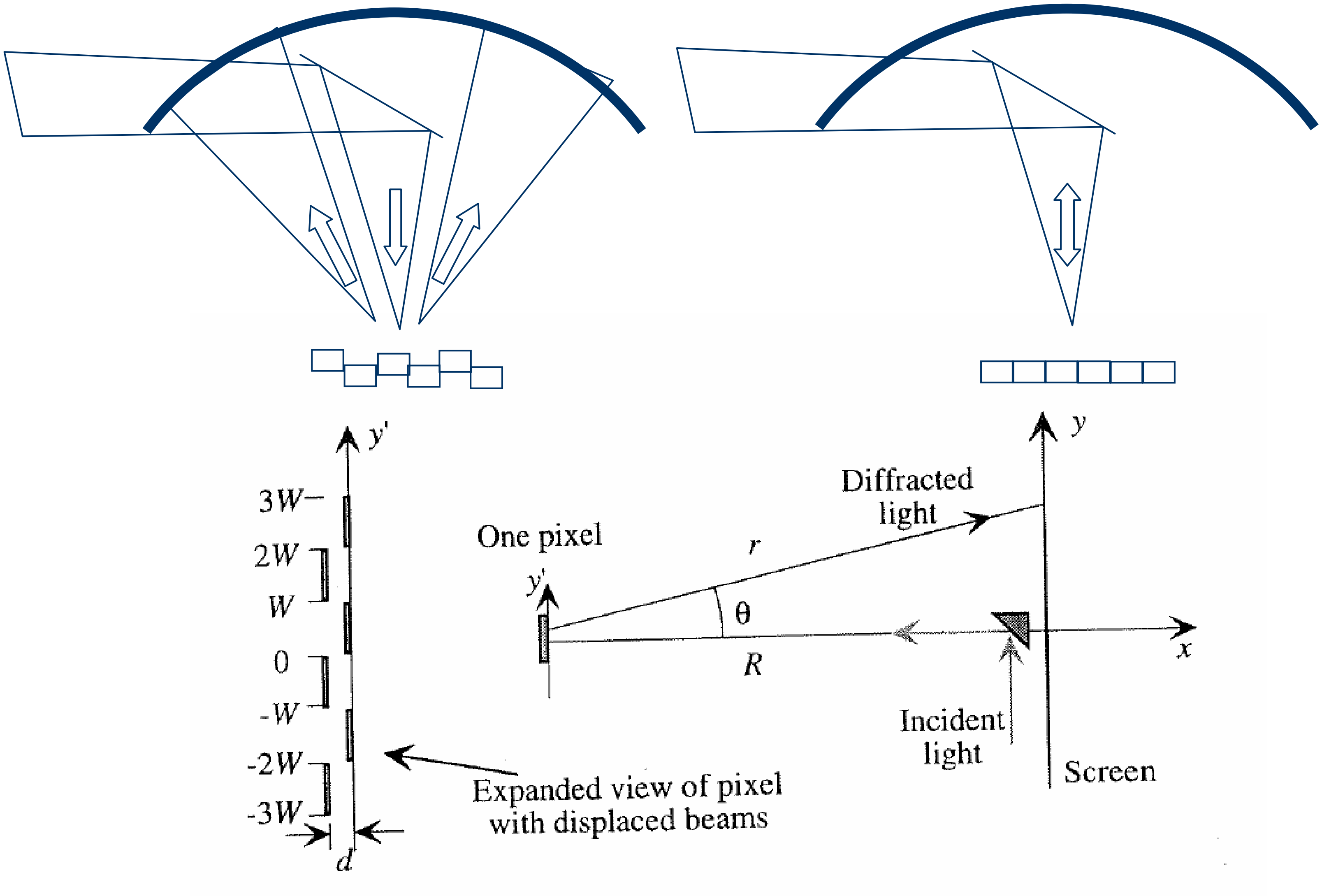




# Diffraction from a grating light valve



# GLV used in a display device



# Diffraction of Light

Maxwell's equations may be reduced to the scalar wave equation.

$$\begin{aligned}
\nabla \times \vec{H} &= \epsilon \frac{\partial \vec{E}}{\partial t} \\
\nabla \times \vec{E} &= -\mu_0 \frac{\partial \vec{H}}{\partial t} \\
\nabla \cdot \vec{E} &= 0 \\
\nabla \cdot \vec{H} &= 0,
\end{aligned}$$

$$\Rightarrow \quad \nabla^2 U = \frac{n^2}{c^2} \frac{\partial^2 U}{\partial t^2}$$

$U$ may be any component of vectors $H$ and $E$

Assumptions: *Linear*, *isotropic*, homegeneous and non-dispersive

# Diffraction of light

$$\nabla^2 U = \frac{1}{c^2}\frac{\partial^2 U}{\partial t^2}$$

Example solutions of the wave equation are the plane wave and spherical wave:

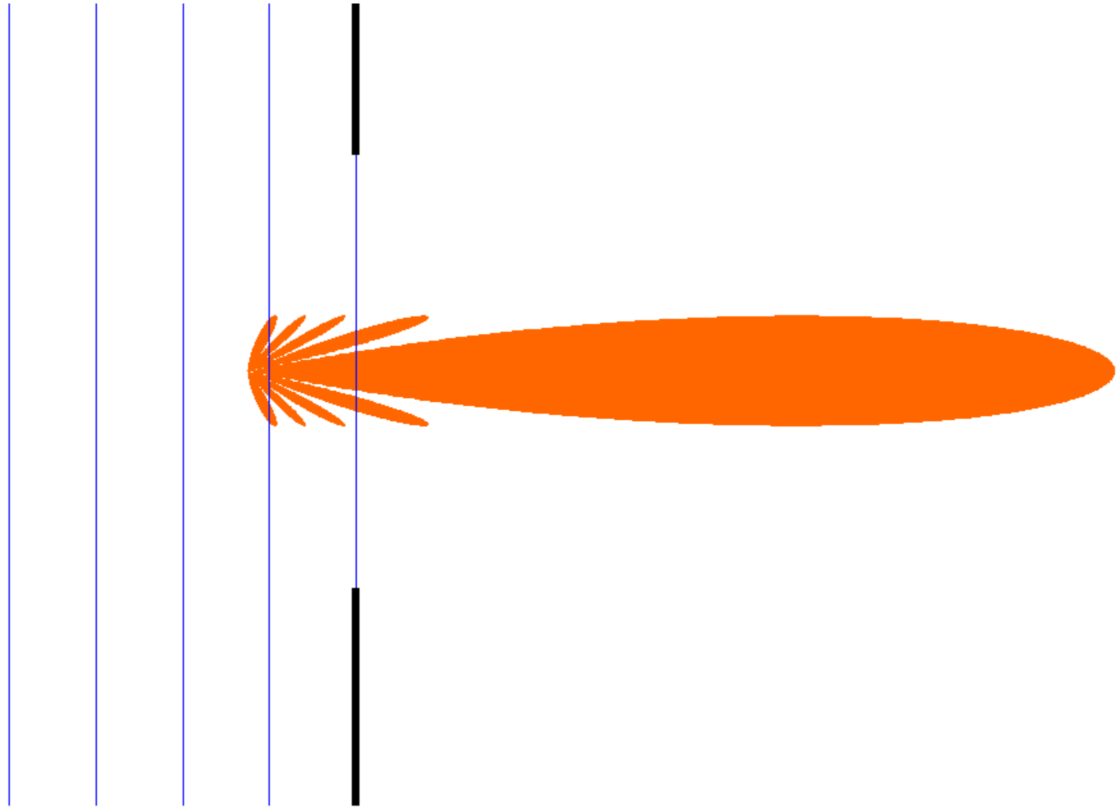
$$U = U_0 \exp(i\vec{k}\vec{r} - \omega t - \phi)$$

$$|\vec{k}| = k = \omega / c$$

$$U = \frac{U_0}{r} \exp(ikr - \omega t - \phi)$$

# Diffraction of light

Light bends or diffracts around edges. Small apertures give large diffraction angles



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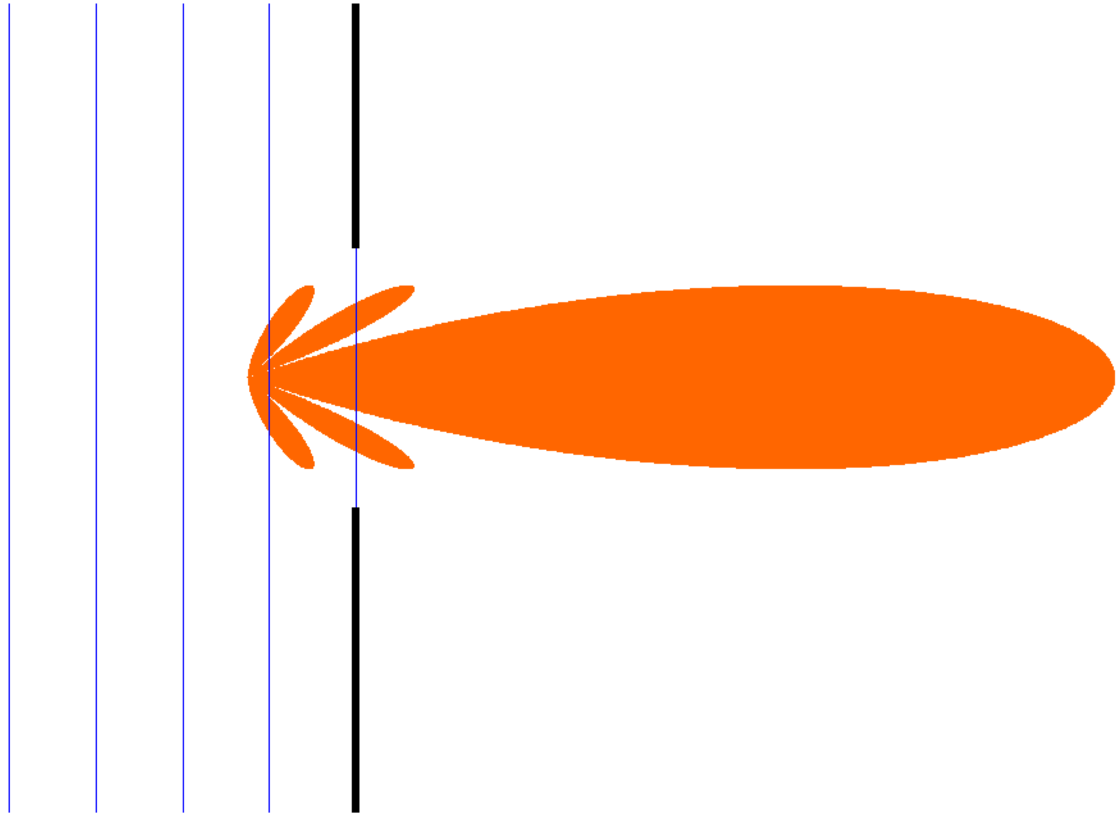

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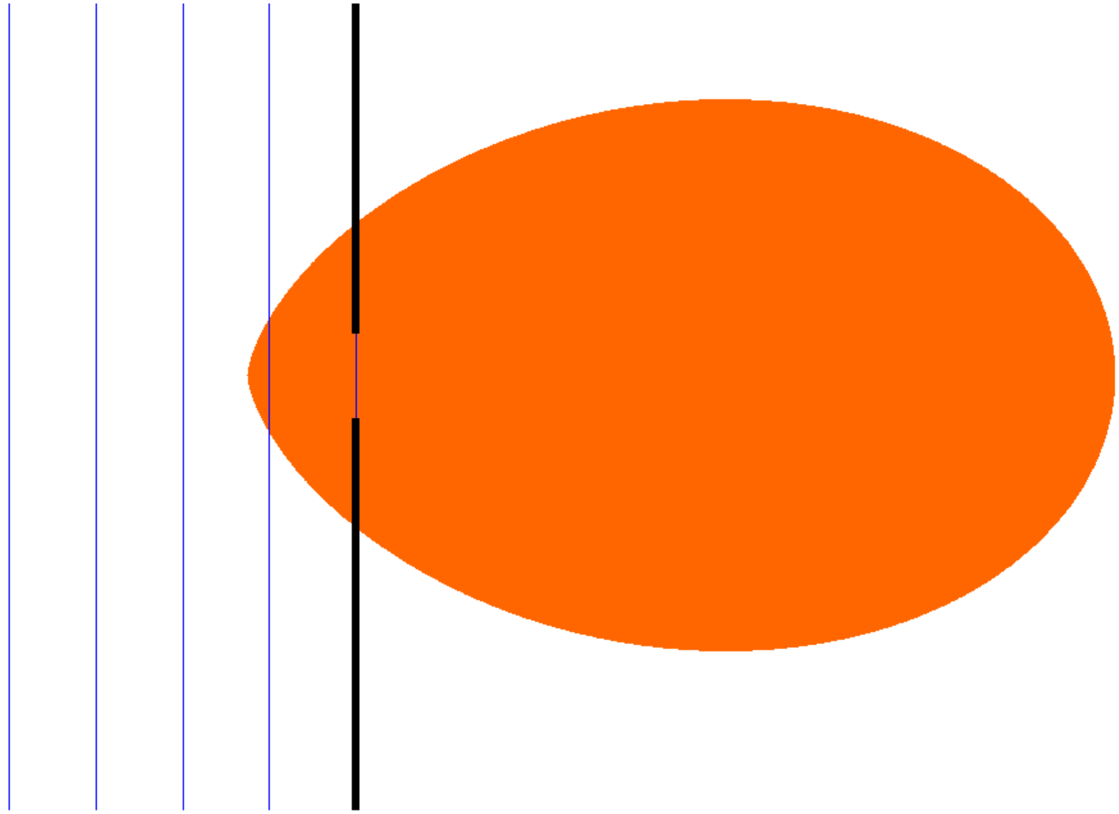
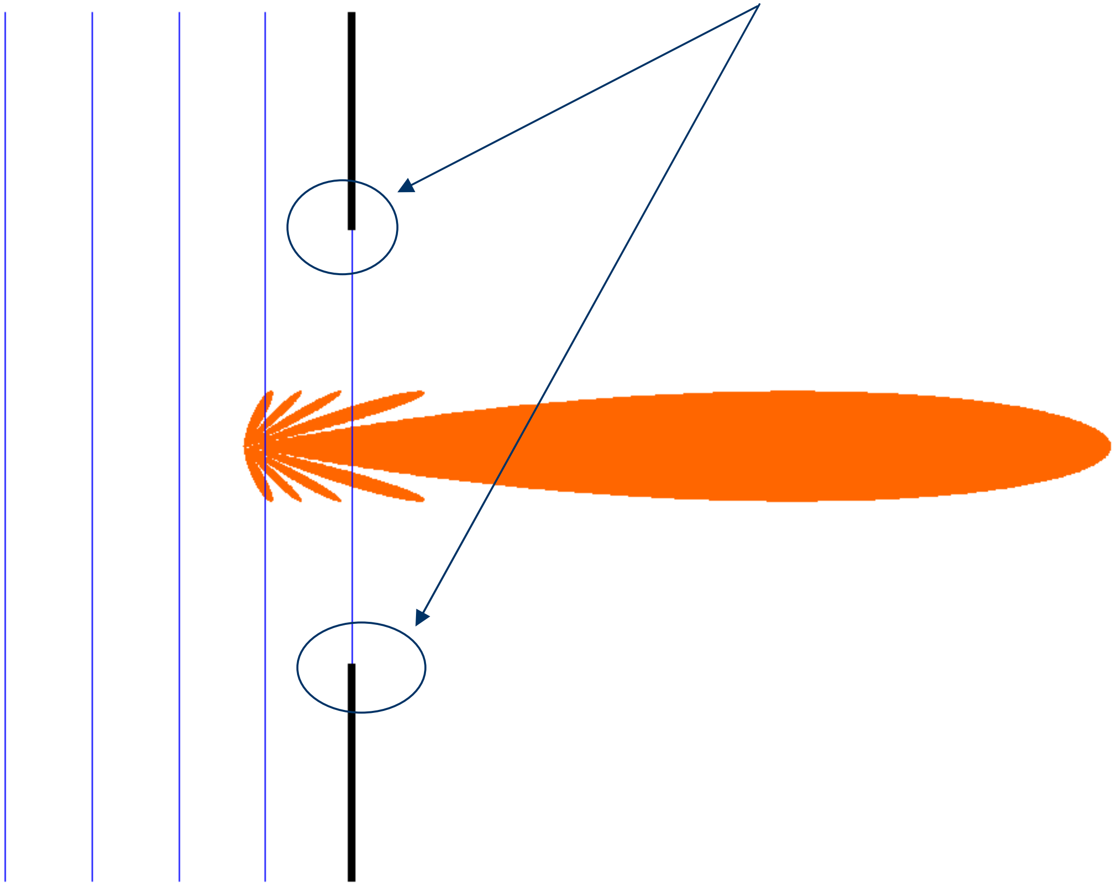


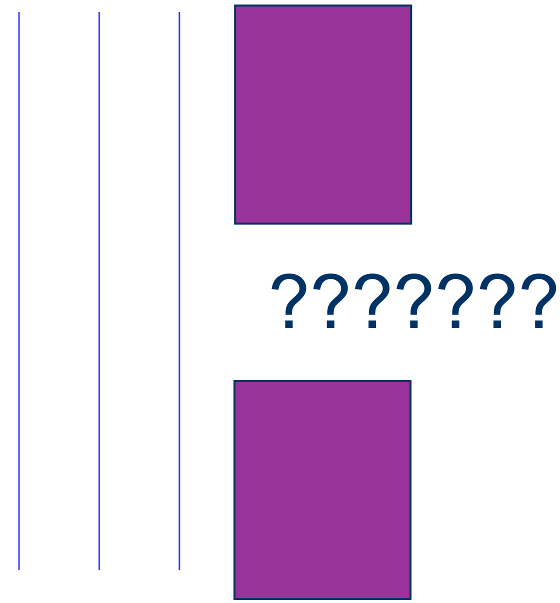
# Diffraction of light

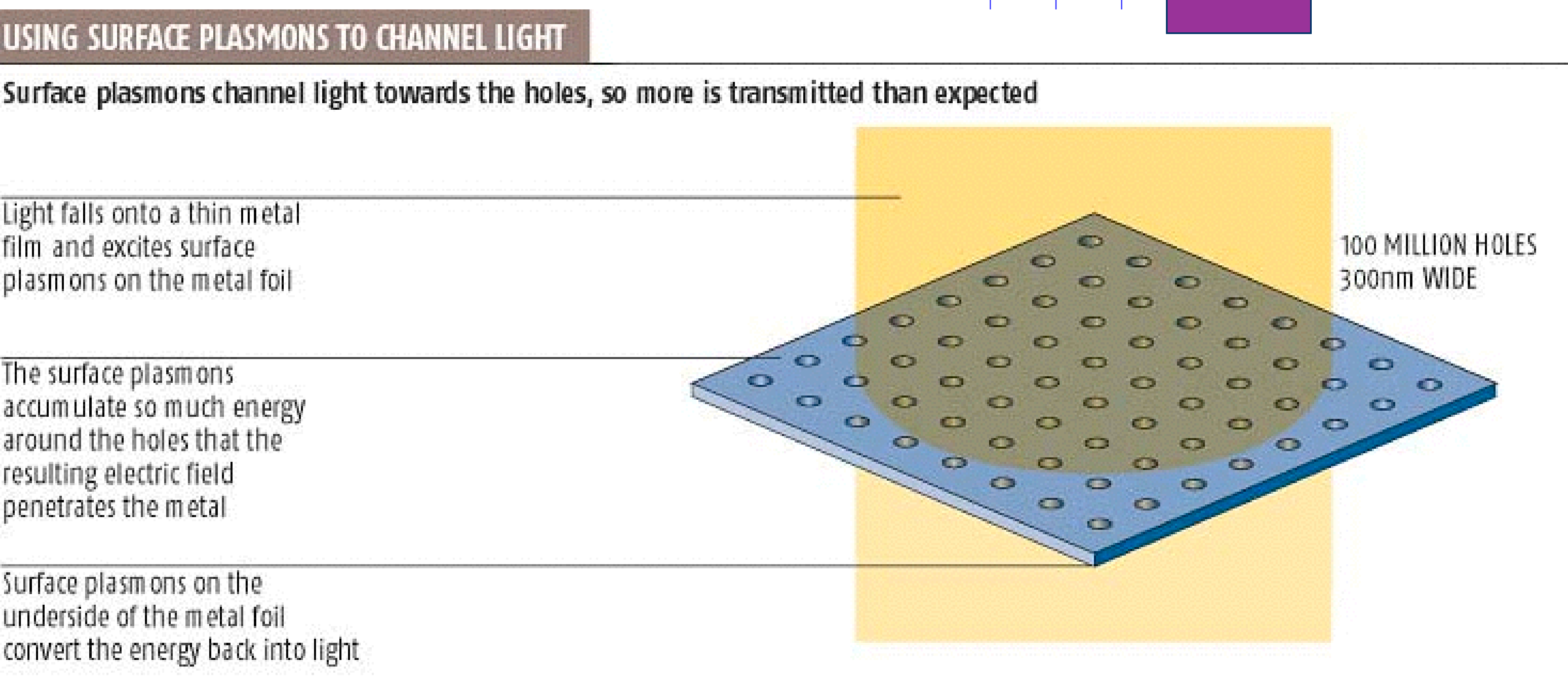
Here, edge effects are small



# Diffraction of light

When edges are thick and holes are small, scalar diffraction theory is no longer valid

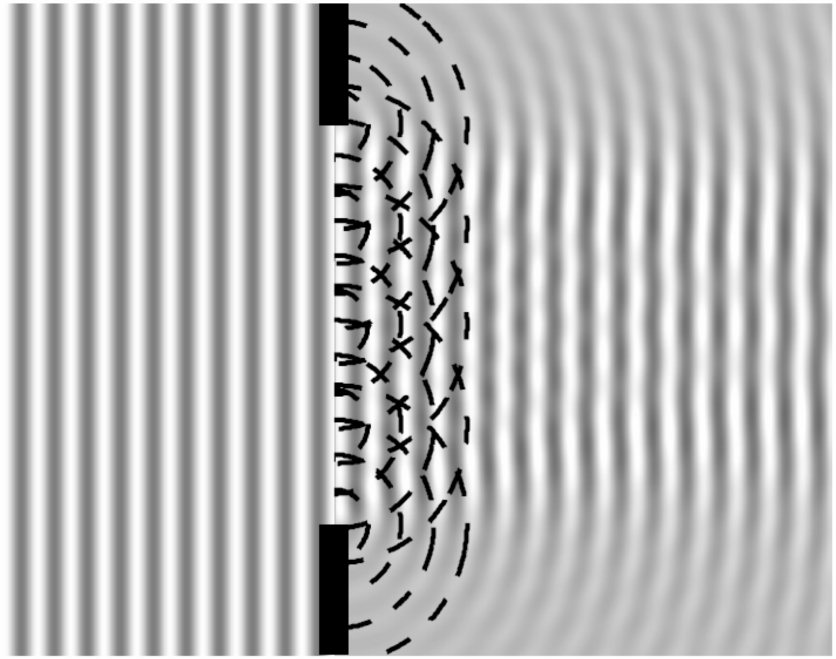


# The *Huygens-Fresnel principle* says:

**”The light disturbance at a point P arises from the superposition of secondary waves that proceed from a surface situated between this point and the light source.”**

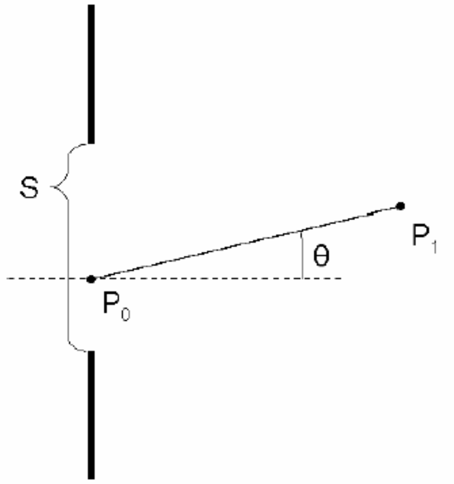
Christiaan Huygens



Augustin-Jean Fresnel

# Diffraction of Light

**A mathematical representation of the Huygens-Fresnel principle:**



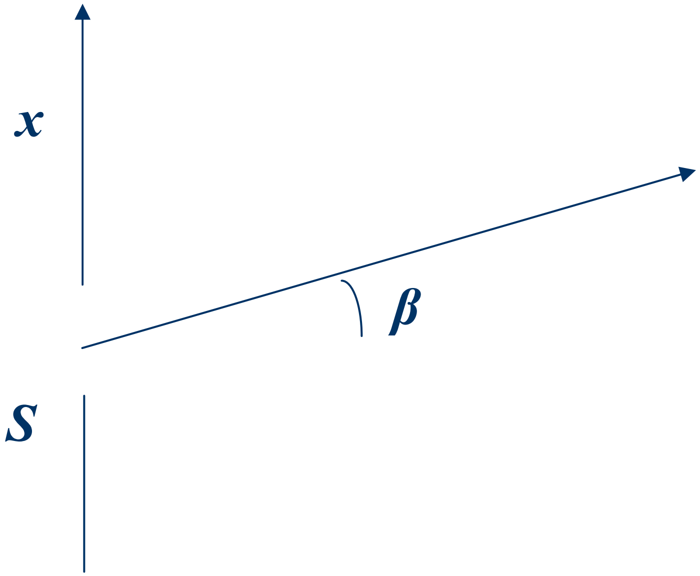

$$U(P_1) = \frac{1}{\mathrm{i}\lambda} \iint_S U(P_0) \frac{\exp(\mathrm{i}kr_{01})}{r_{01}} \cos\theta \mathrm{d}s$$

**Spherical wave**

# Diffraction of Light

**Far away from the aperture, and for small diffraction angles we may use the Fraunhofer approximation.**

$$U(\beta) = C\int_S U(x)\exp(ik\beta x)\mathrm{d}x$$



# Diffraction of Light

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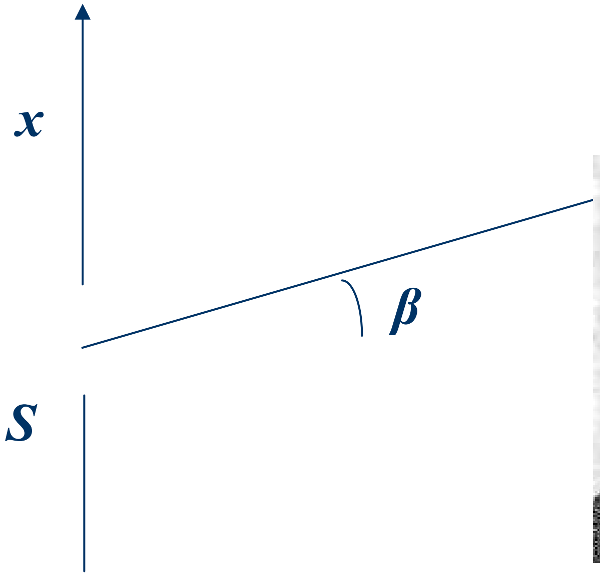


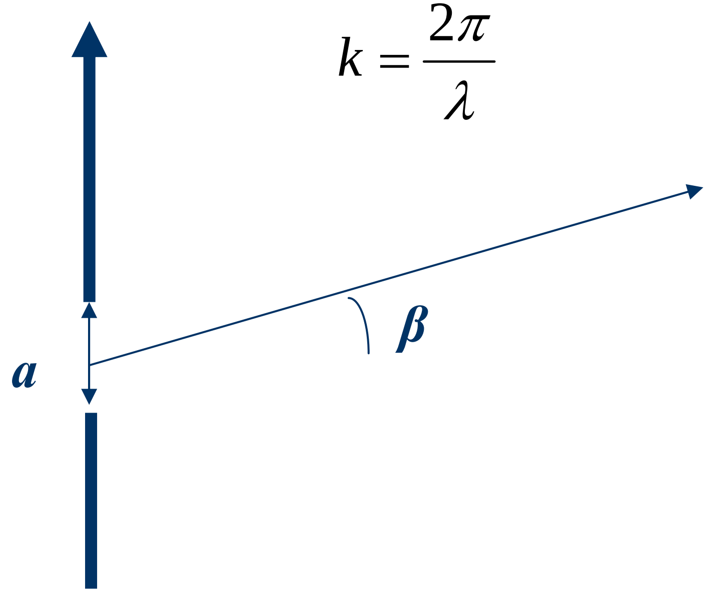

Fourier transform!

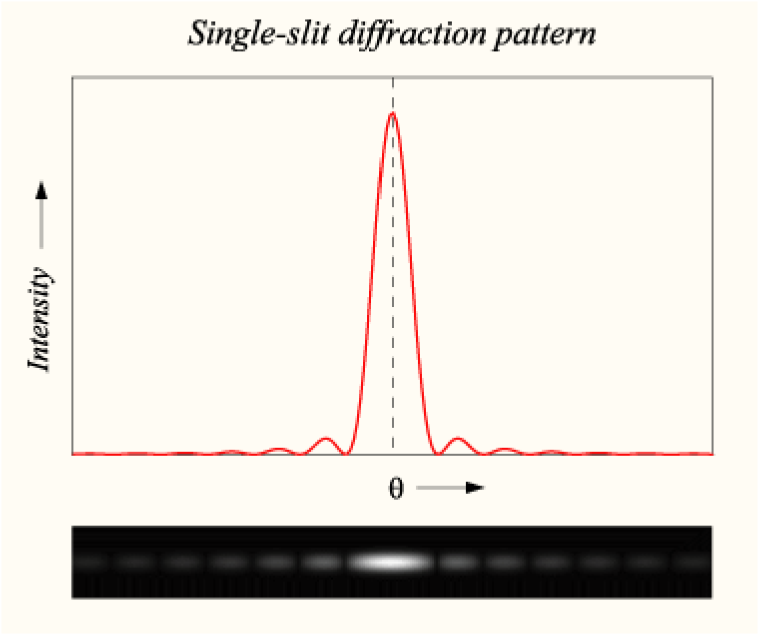
# Diffraction of Light

## We may now calculate the diffraction from a slit:

$$I = \left[ \frac{\sin\left(\frac{k\beta a}{2}\right)}{\left(\frac{k\beta a}{2}\right)} \right]^2$$

$$k = \frac{2\pi}{\lambda}$$

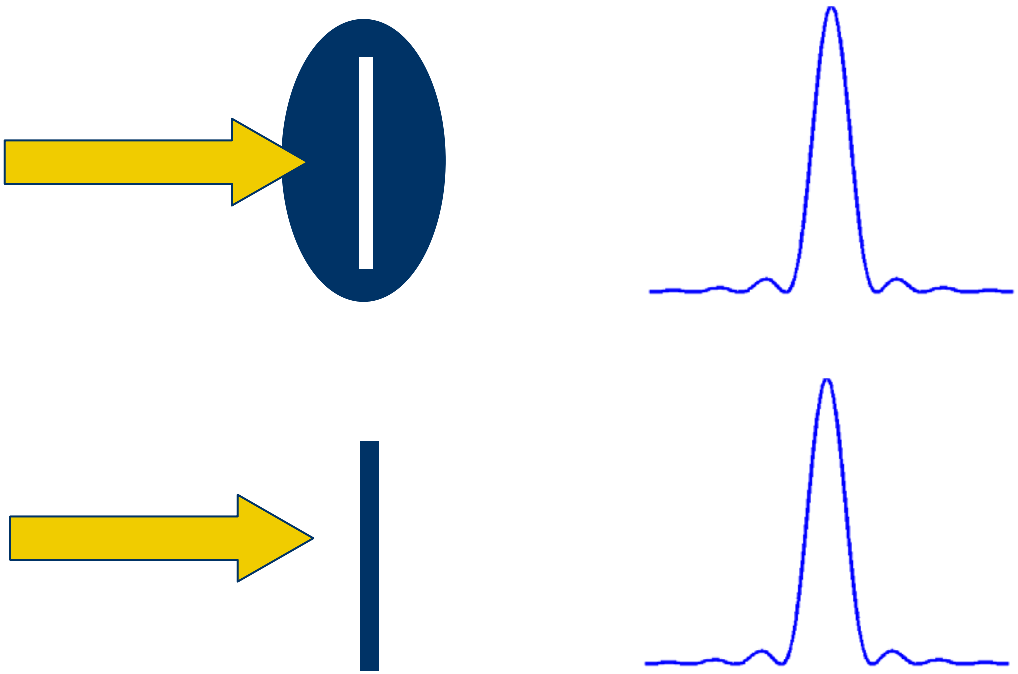


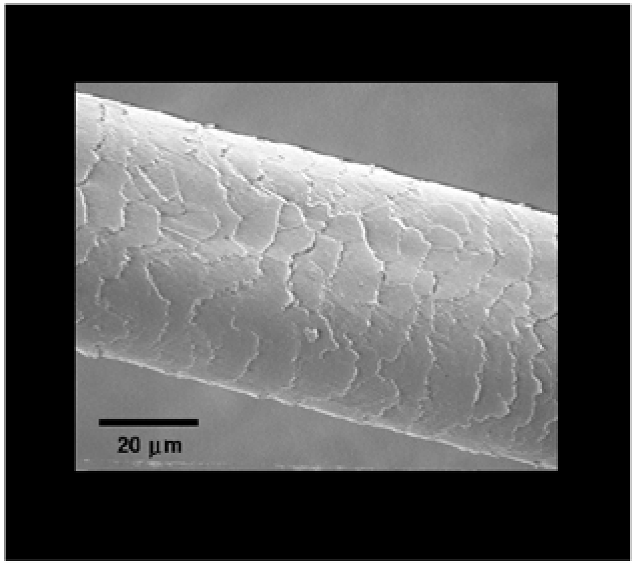




**Minima for:** $$\beta = m\frac{\lambda}{a}$$

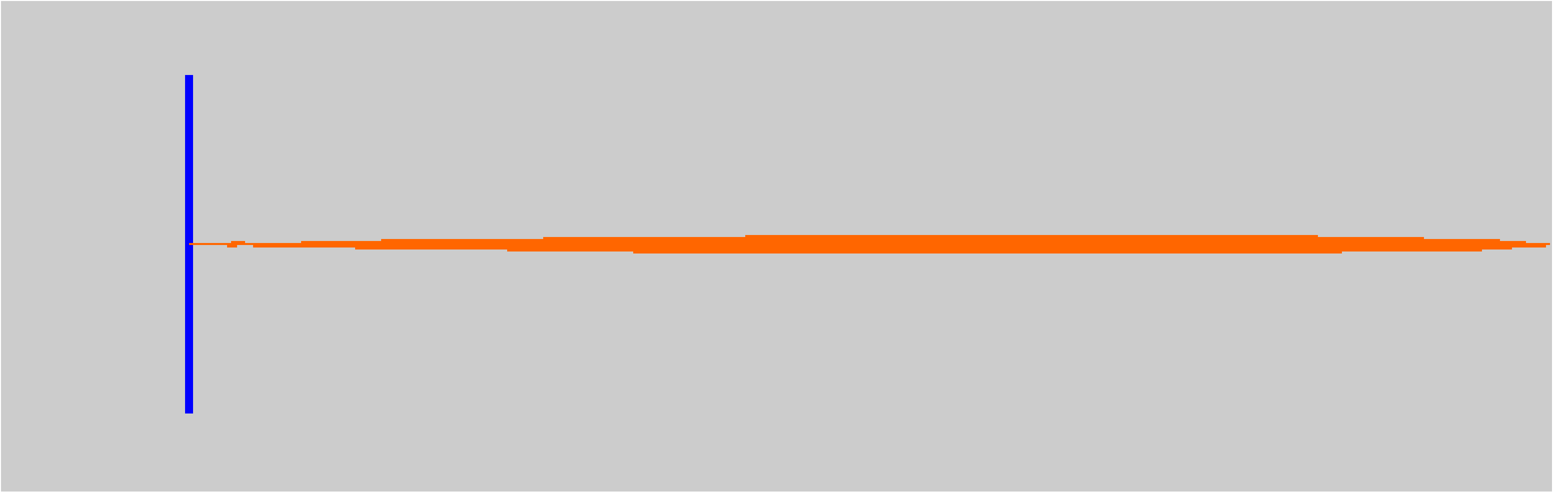
# Babinet's principle

**The diffracted field from an aperture is the same as from an obscuration of the same size and shape**

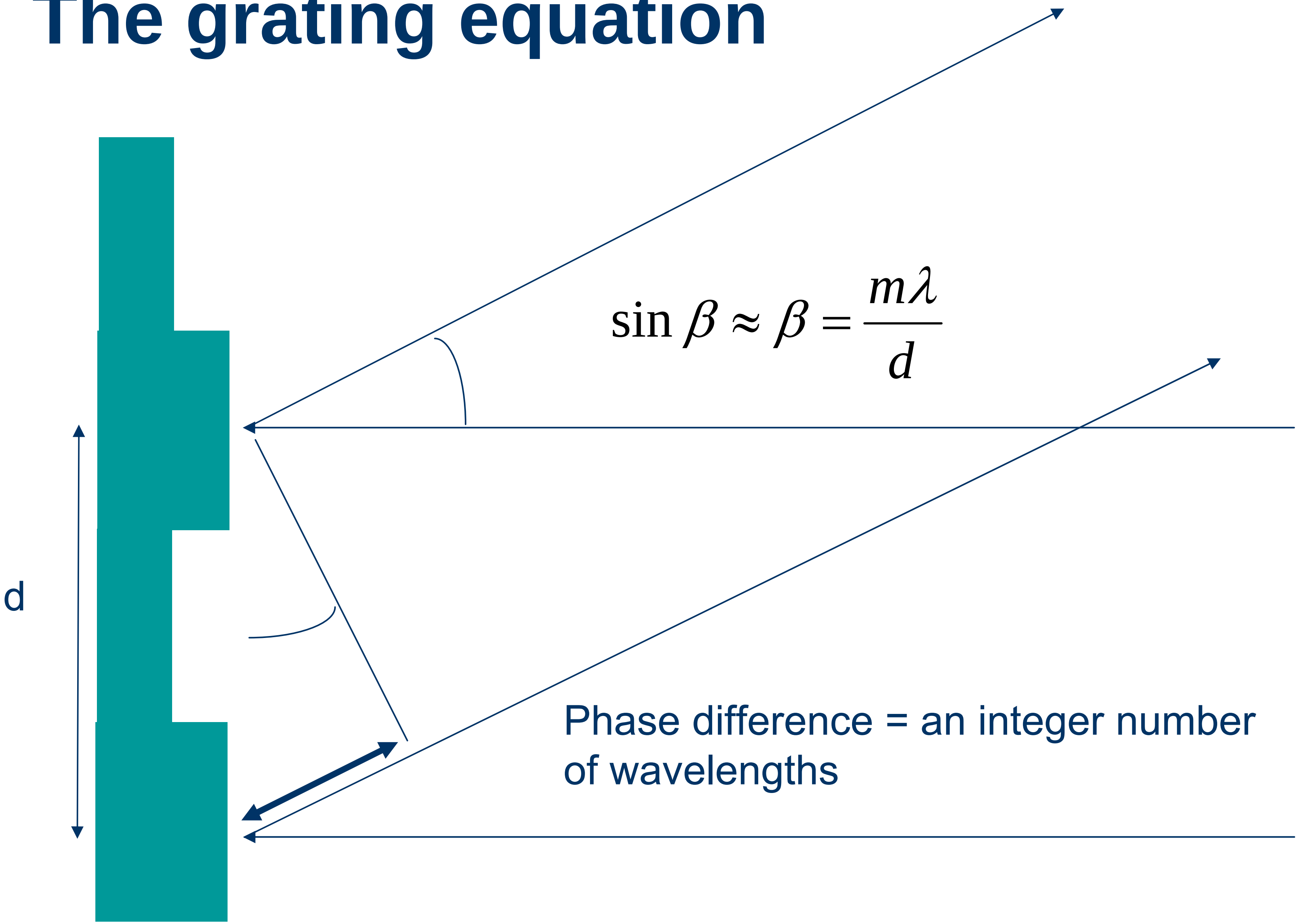


# Diffraction from a grating light valve



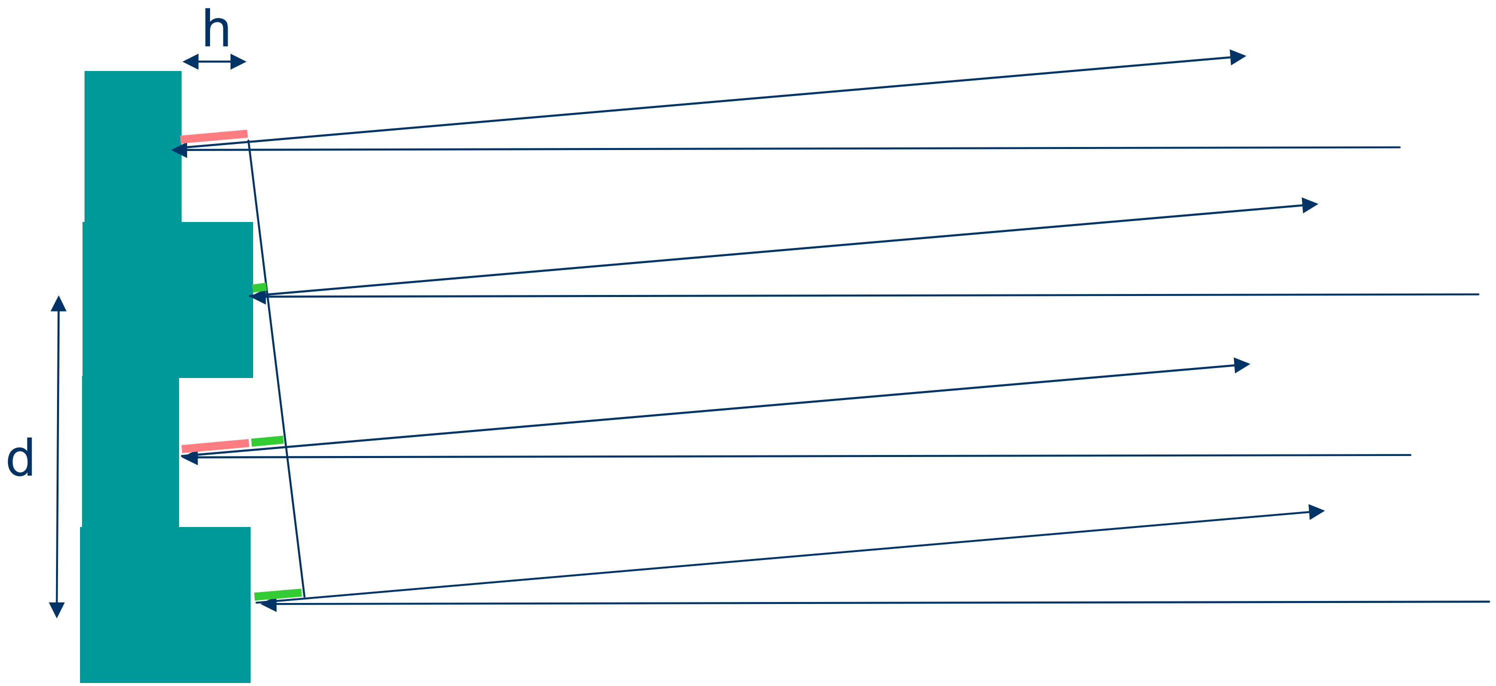
# The grating equation




$$\sin\beta \approx \beta = \frac{m\lambda}{d}$$

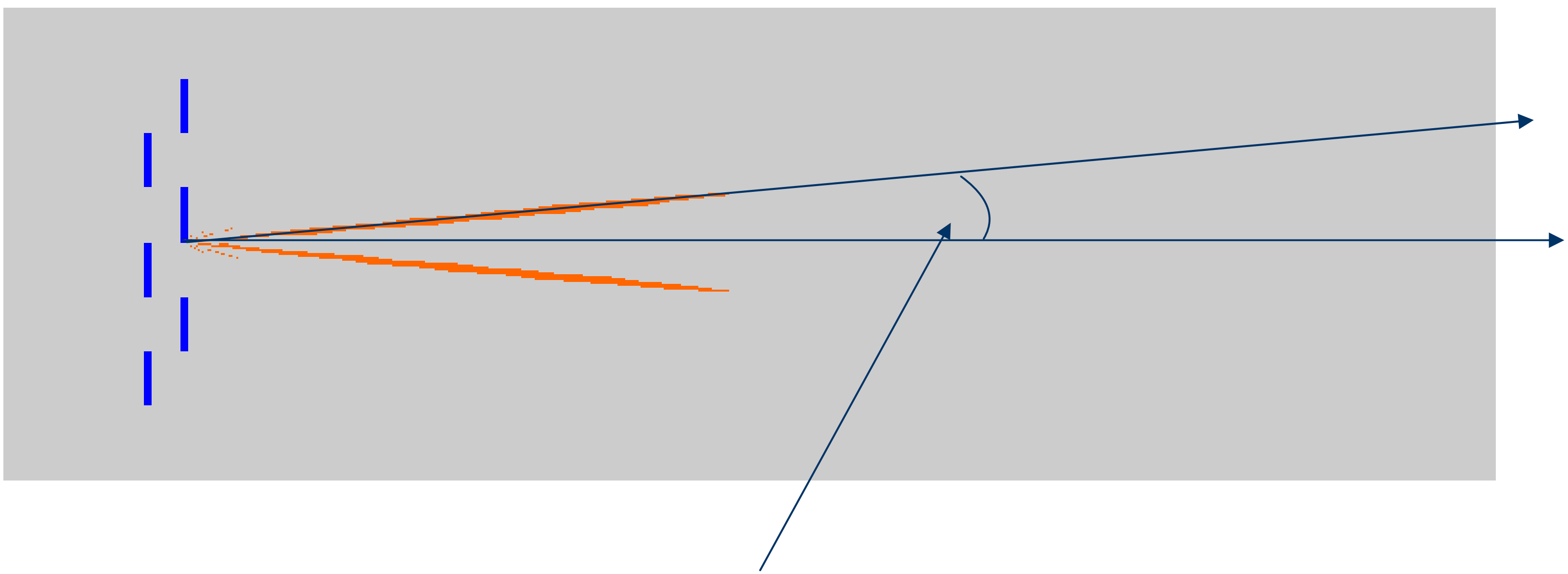
Phase difference = an integer number of wavelengths

# Diffraction from a grating light valve



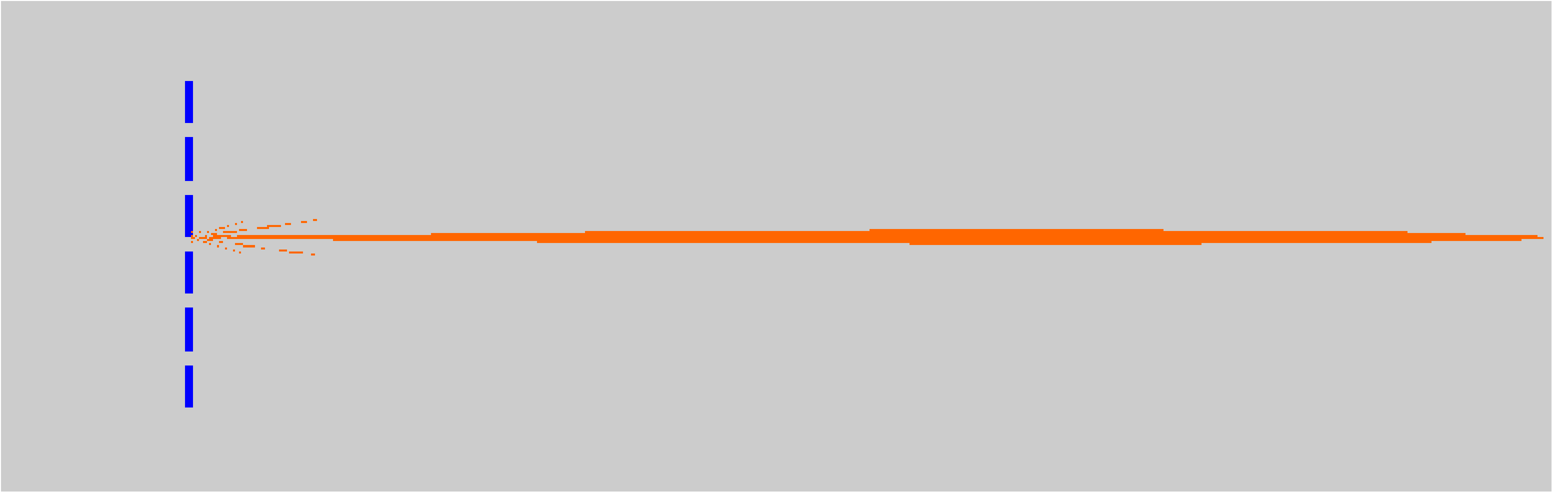

$$\frac{I}{I_0} = \left|\frac{U}{U_0}\right|^2 = \frac{4}{\pi^2}\sin^2(kh)$$

# Diffraction from a grating light valve

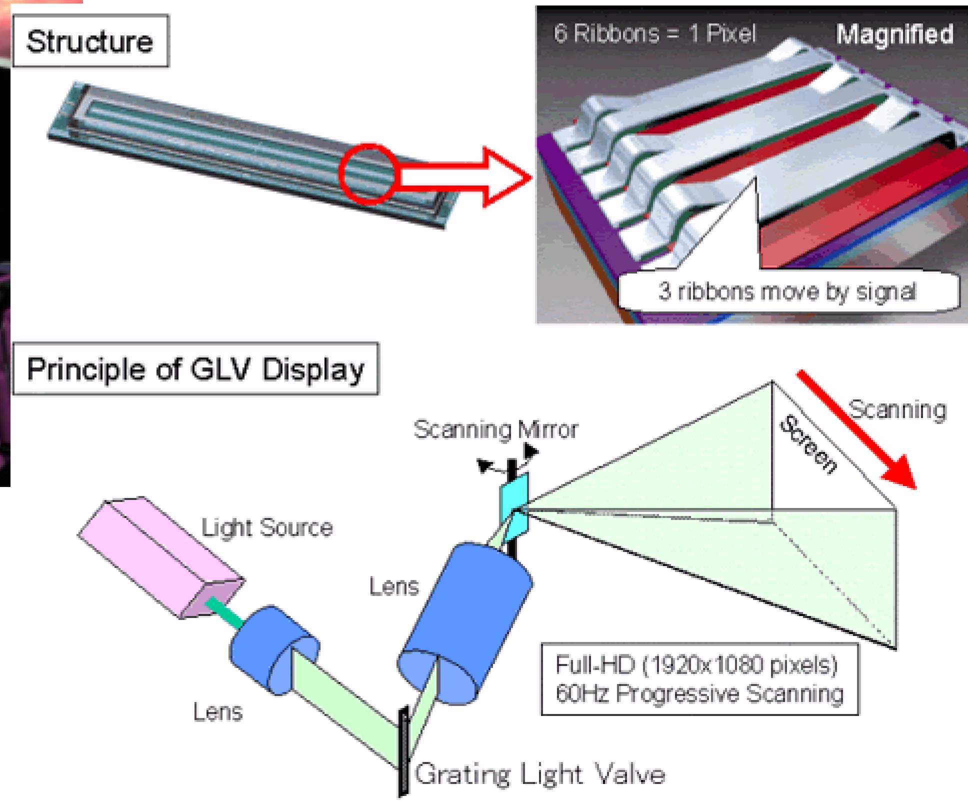


Angle given by the grating equation

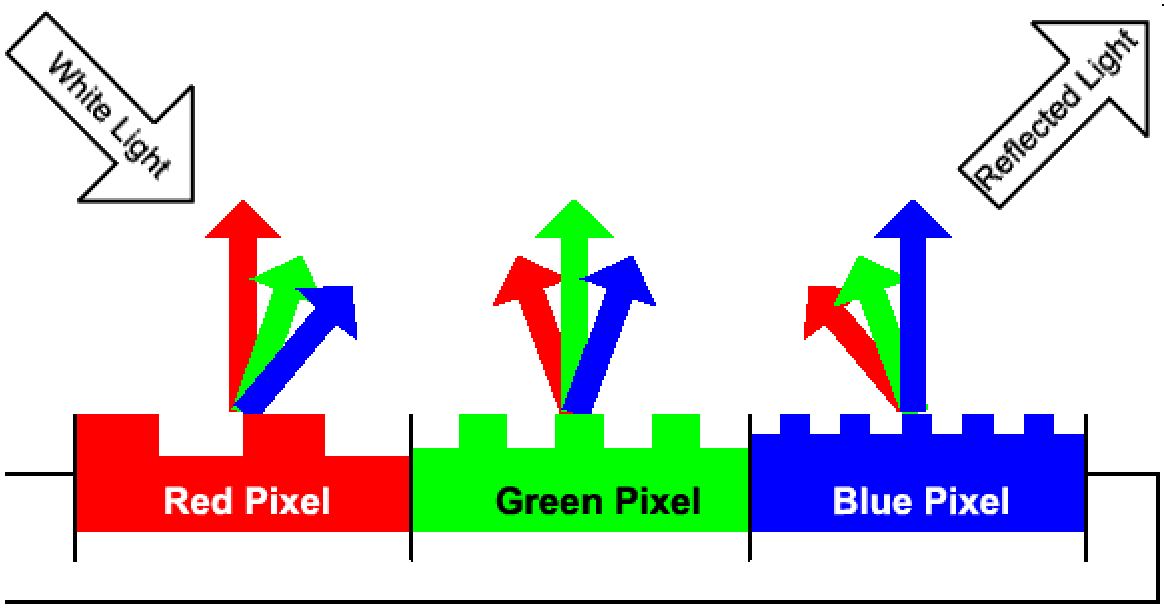
# Diffraction from a grating light valve



# How to design a GLV display device



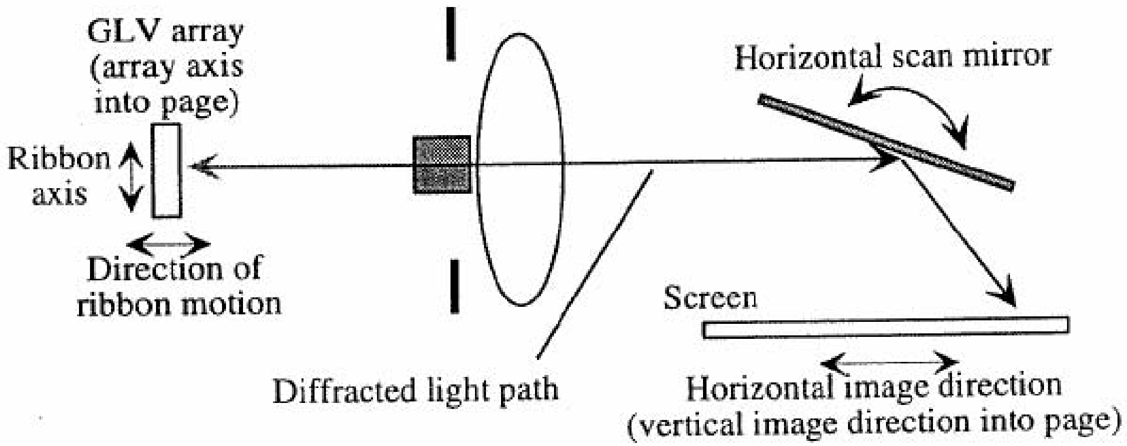
# Different pixels for different wavelengths

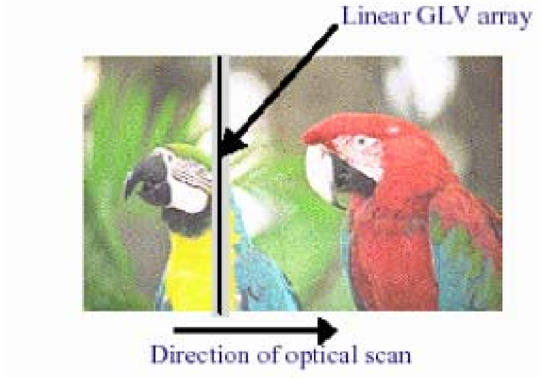



With all ribbons in a pixel in the rest position, light striking the pixel is reflected away from the optical path. When alternate ribbons are pulled down, the diffraction grating is formed and the light's component frequencies spread out. Varying the width and spacing of the ribbons "tunes" pixels to send a single colour into the projector's light path.

# How to design a GLV display device

- One line of mirror elements only



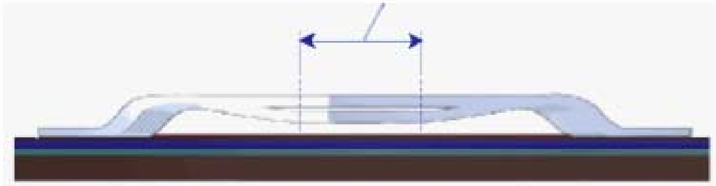
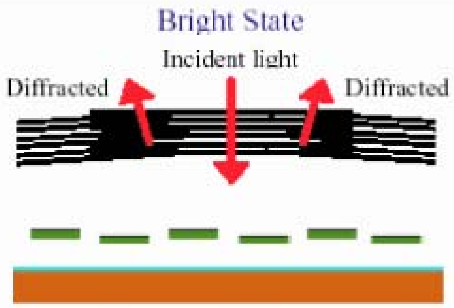
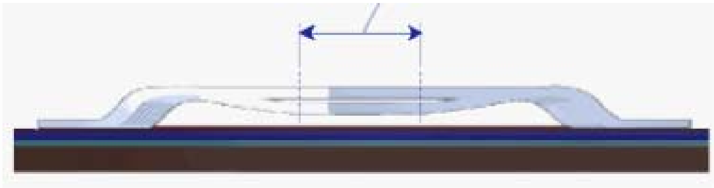



Figure 1: A GLV pixel with alternate reflecting ribbons electrostatically deflected to produce a square-well diffraction grating (vertical deflection greatly exaggerated)



# Grating light valves

- Can you spot the difference between the top and bottom GLV?



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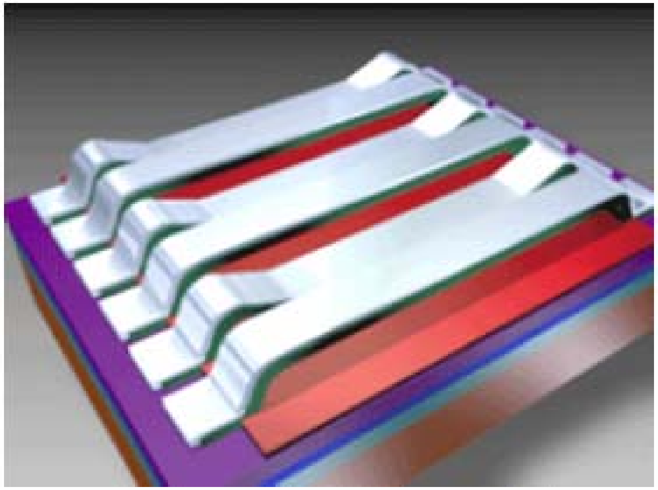
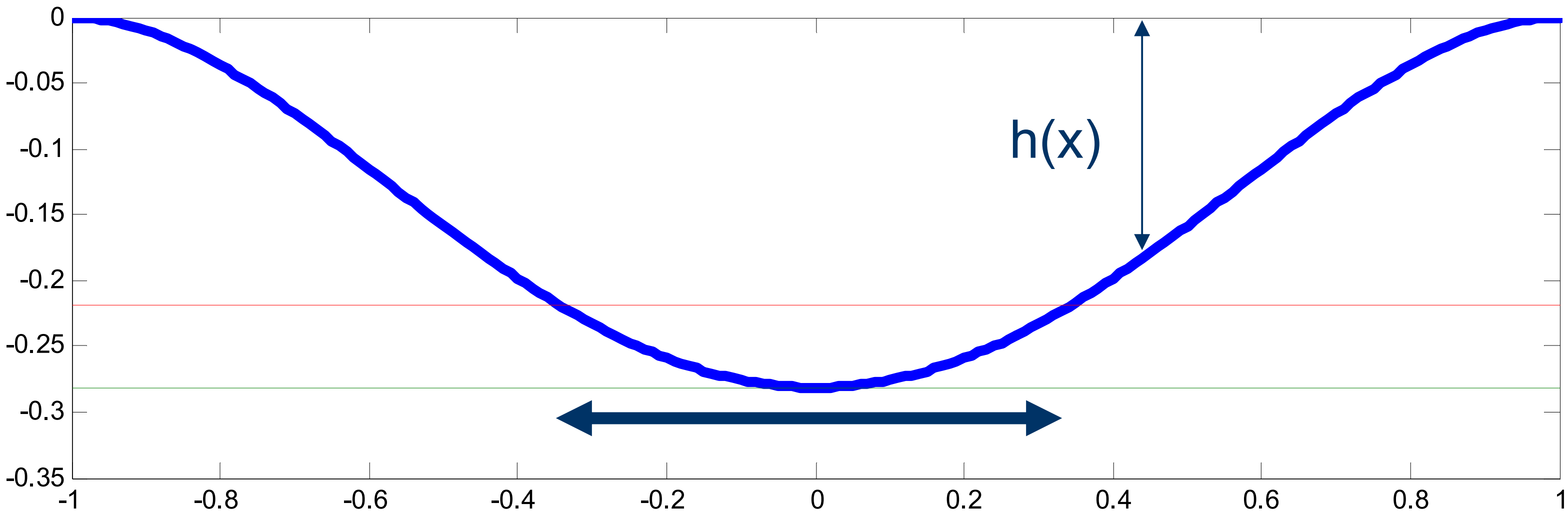


# The clamped-clamped beam with distributed load




Must integrate diffraction efficiency over the length of the beam:

$$\frac{I}{I_0} = \frac{4}{\pi^2 L} \int \sin^2[kh(x)]dx$$

# How to design a GLV display device:

# Challenges

- High optical throughput requires large diffraction angle and short grating periods
- The shorter the period the more light is lost in the gaps between the ribbons
- Clamped-clamped beams/ribbons result in low fill factor
  - Only a fraction of the beam is optically useful
- Different wavelengths require different modulation heights

# ”Grating light valves” for spectroscopy

- ”Polychromator”
- SINTEF CDOE

# Polychromix/Senturia

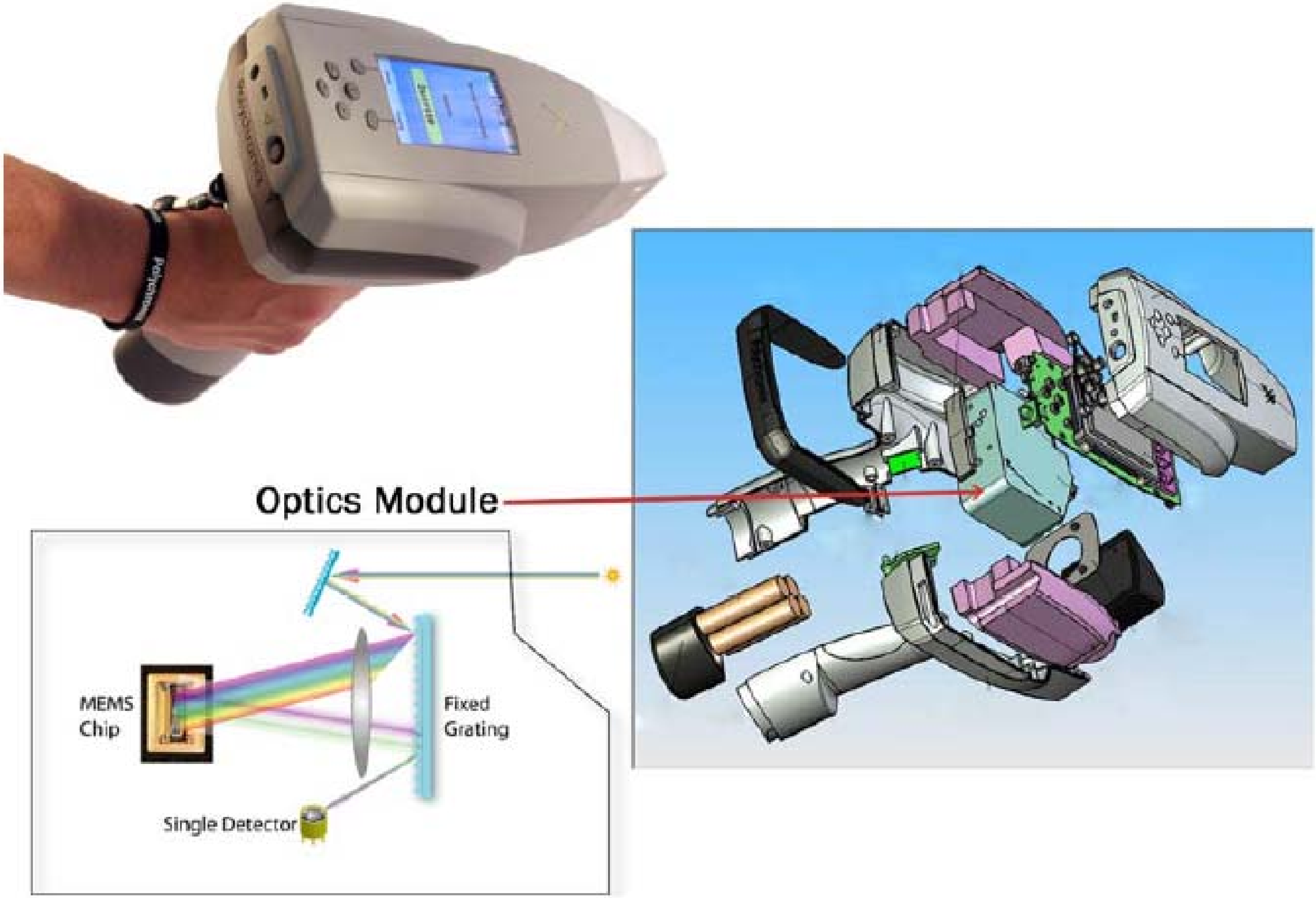



Figure 2: The PHAZIR™ along with an exploded view revealing the optics module with the MEMS chip inside. The optical architecture is shown in the inset.

# Polychromix (Senturia)

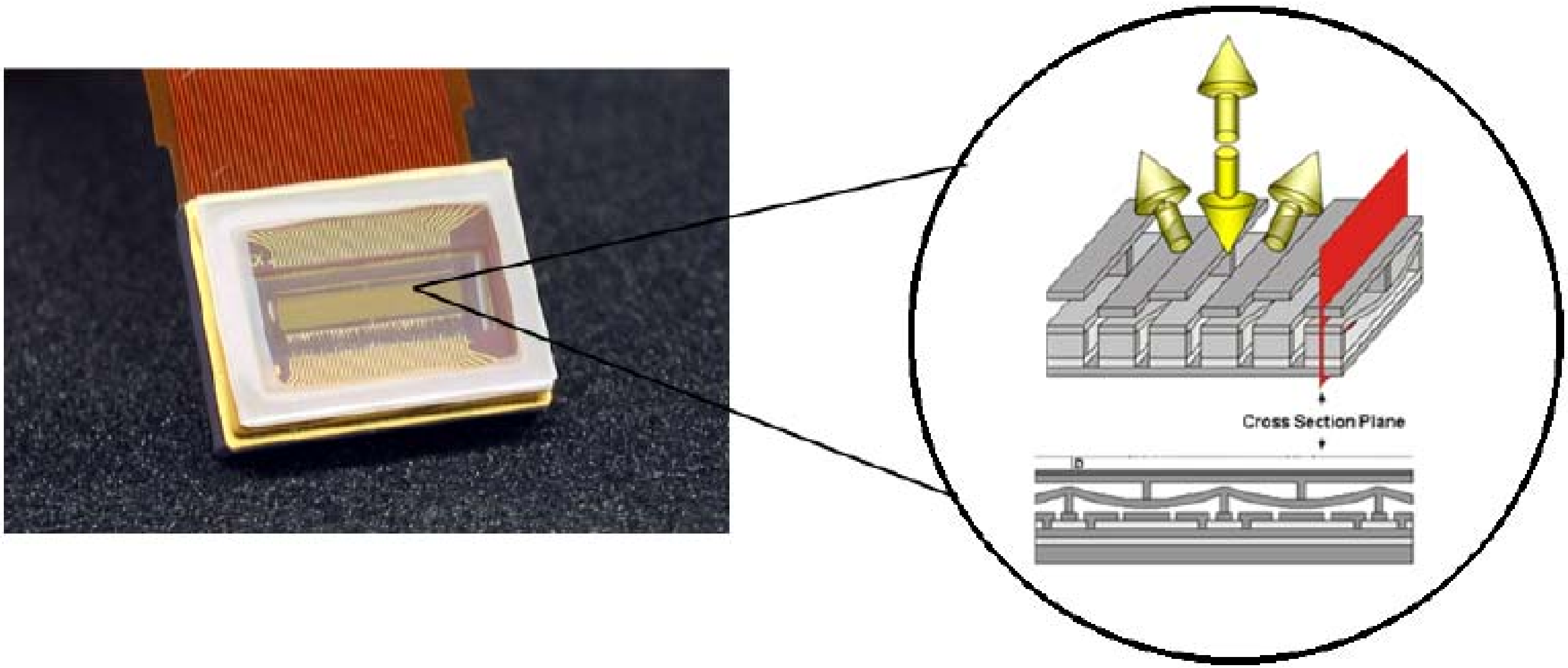
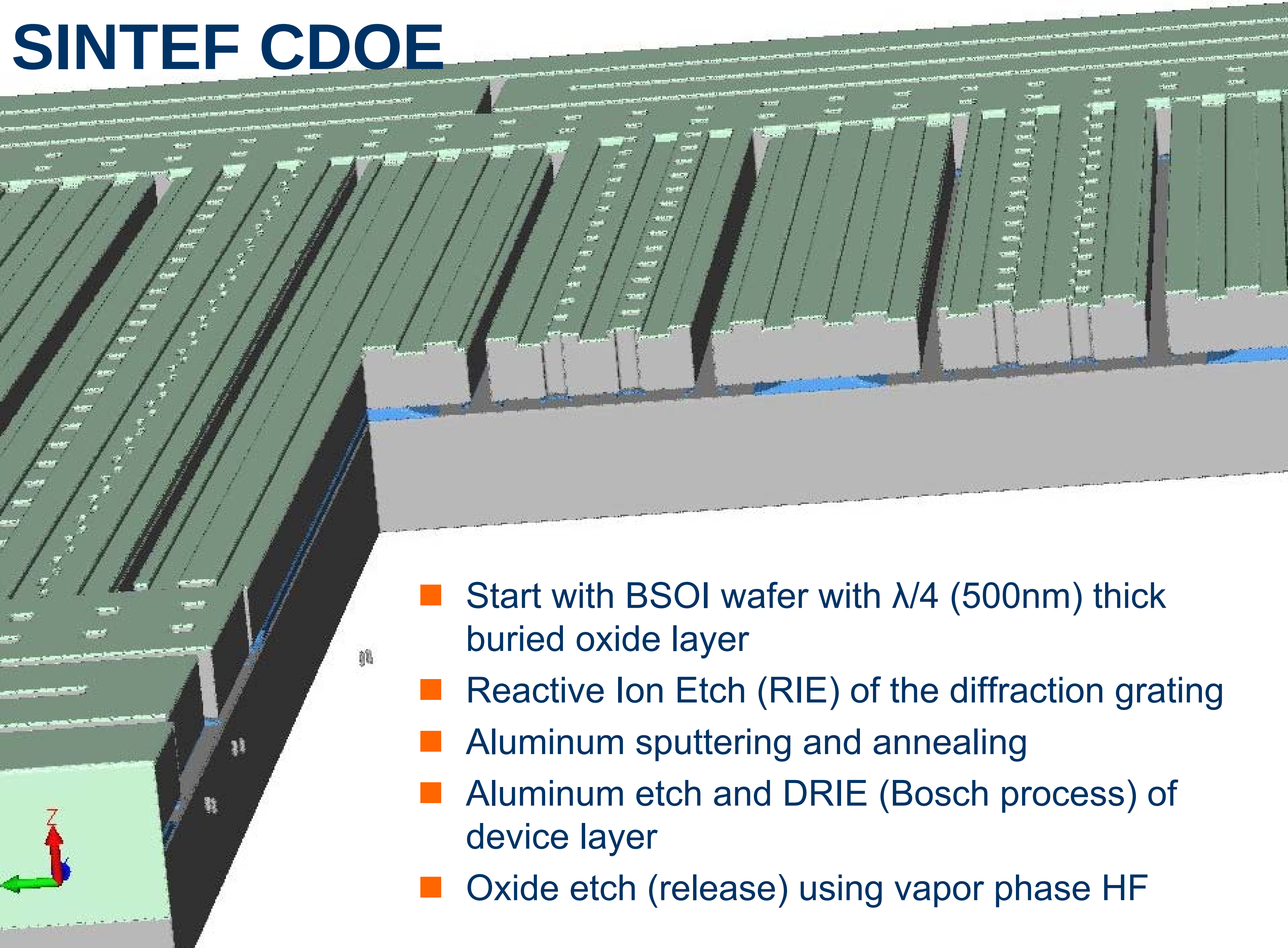


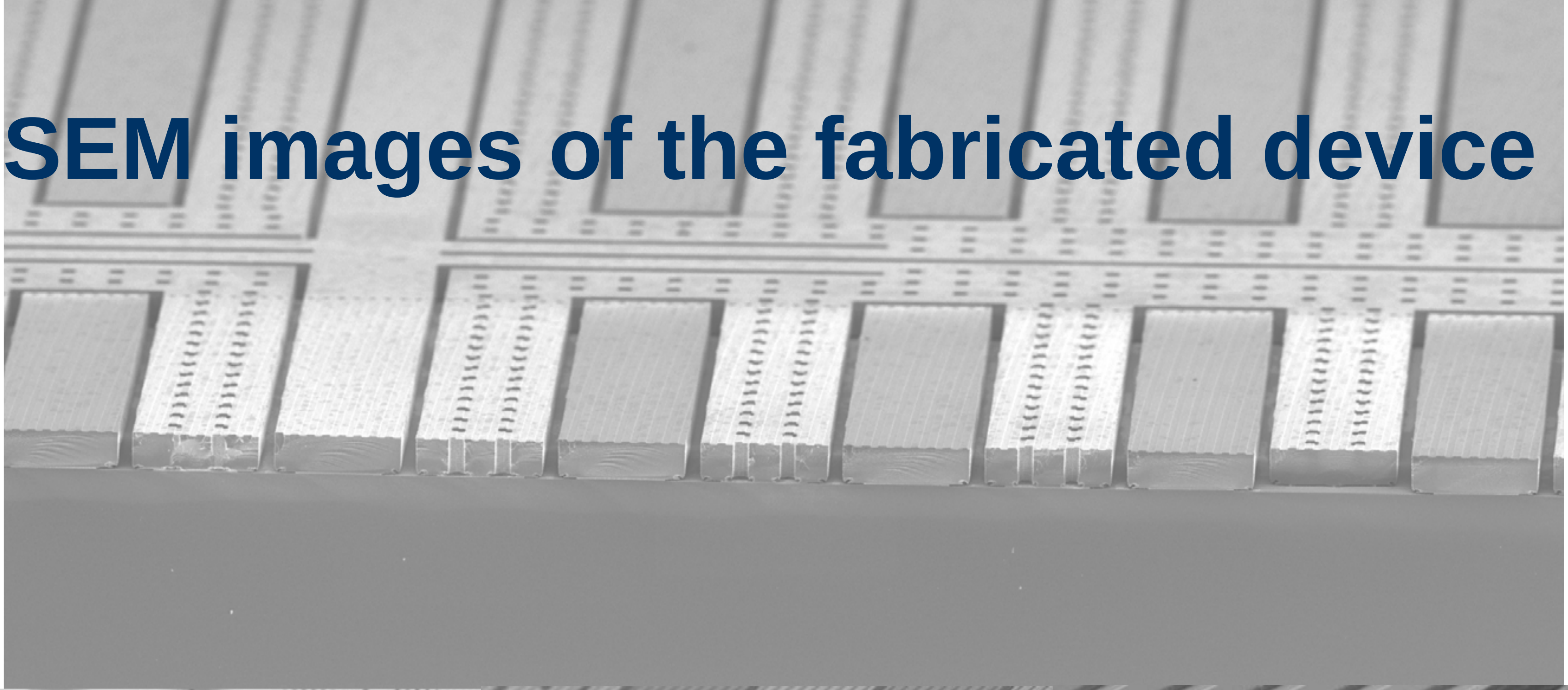

Figure 1: A packaged MEMS chip with a schematic illustration of its operation as an electrically programmable diffraction grating.

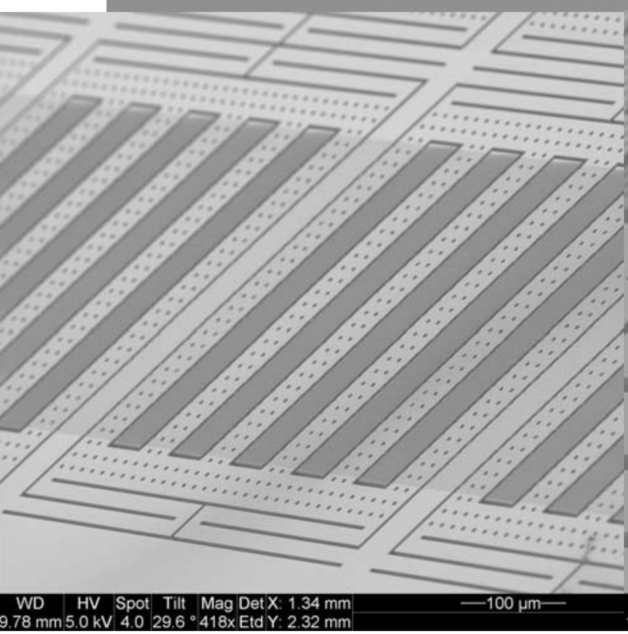
# SINTEF CDOE

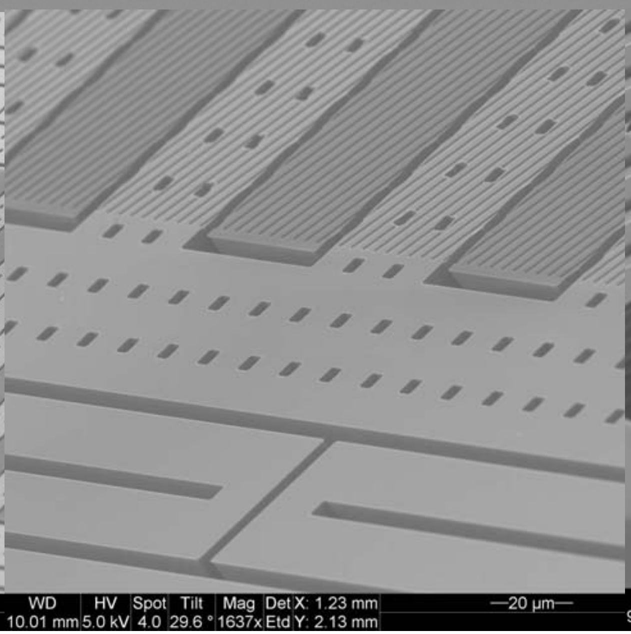


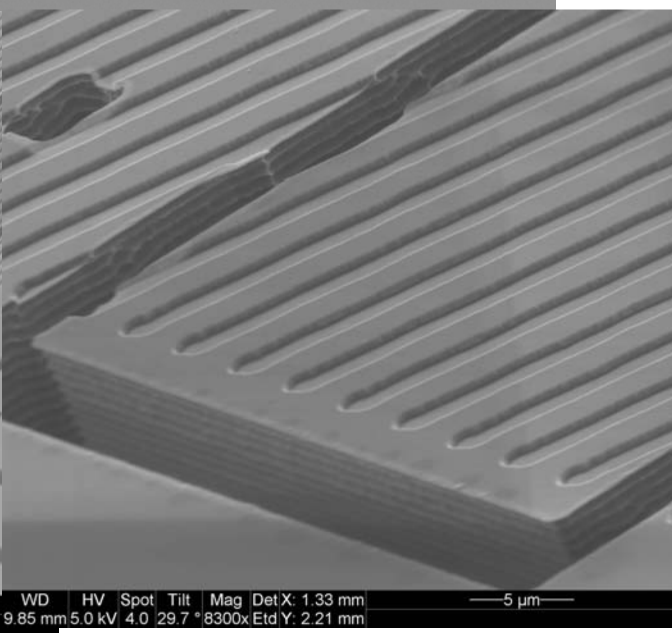
- Start with BSOI wafer with λ/4 (500nm) thick buried oxide layer
- Reactive Ion Etch (RIE) of the diffraction grating
- Aluminum sputtering and annealing
- Aluminum etch and DRIE (Bosch process) of device layer
- Oxide etch (release) using vapor phase HF

# SEM images of the fabricated device

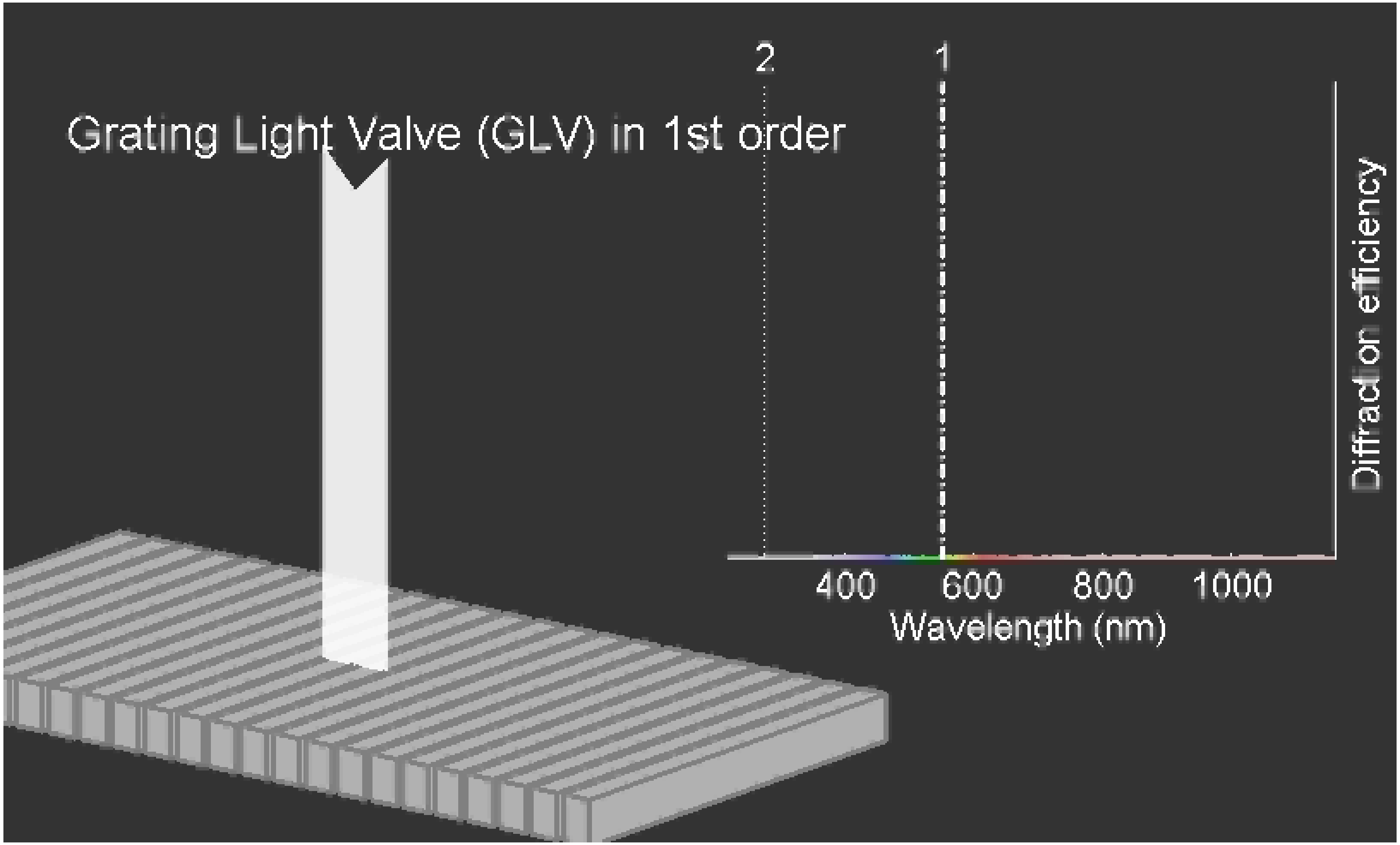




- This animation shows the principle of a first-order grating light valve. Only a narrow exit angle is considered.



# Our aim is to measure *gas concentration* using a *micromechanical infrared filter*

The figure shows an old, established infrared sensing method for measuring gas concentration

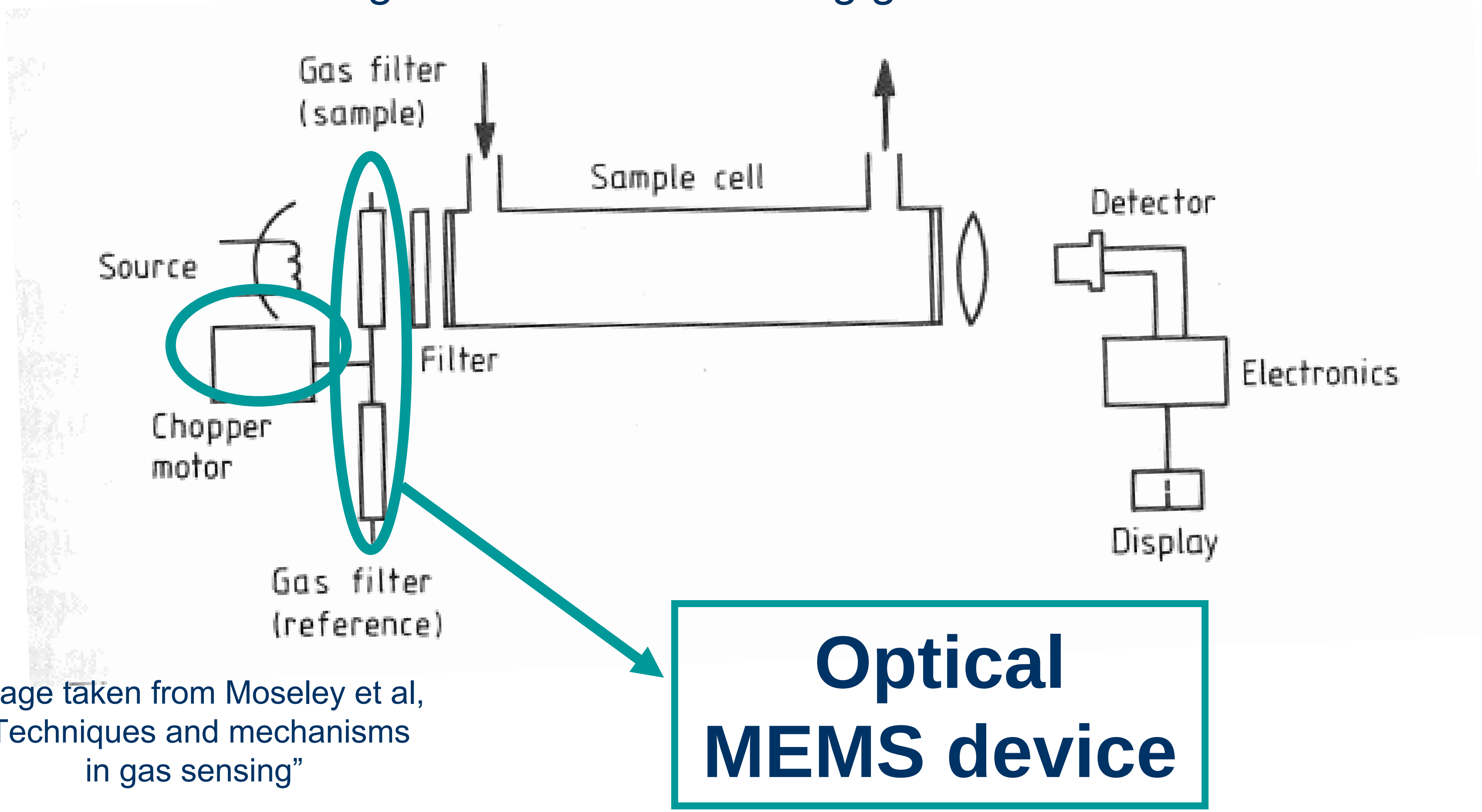
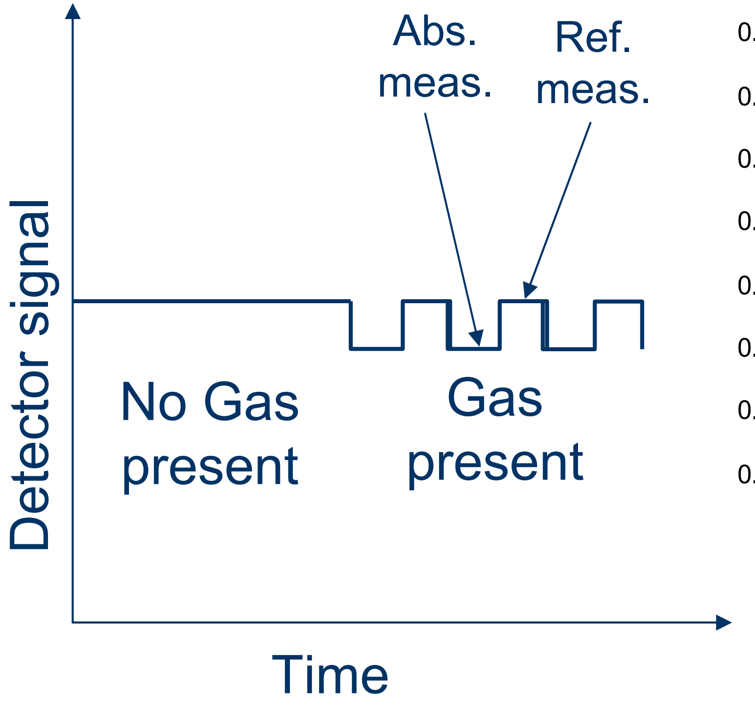


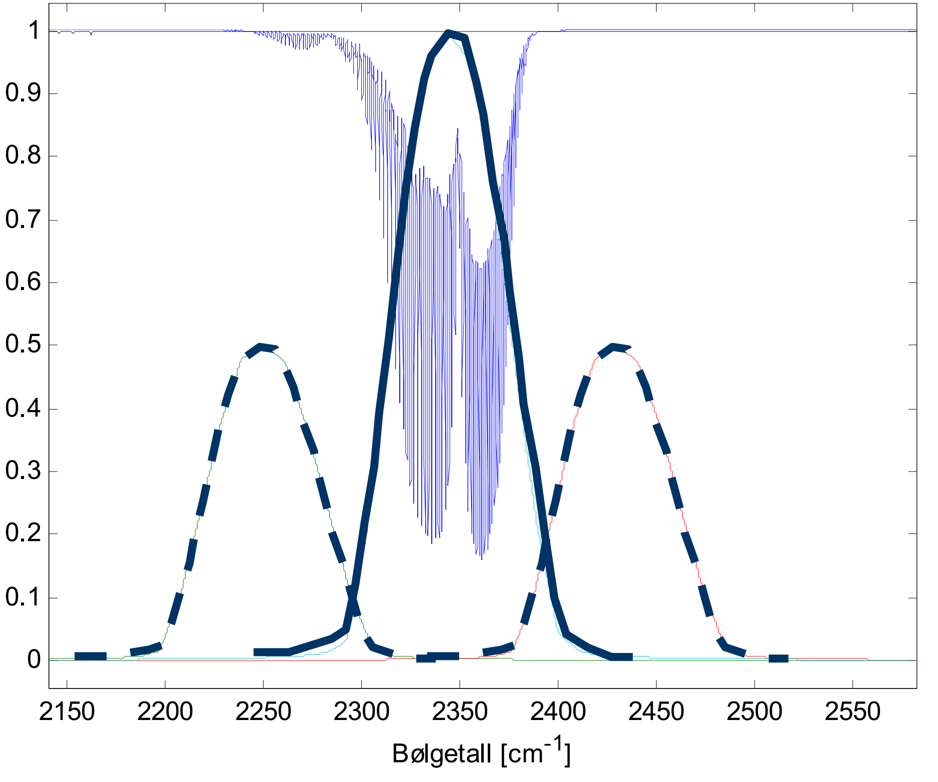

Image taken from Moseley et al, "Techniques and mechanisms in gas sensing"

# ***Reference measurements*** **must be made in one or more wavelength bands outside the absorbing region**

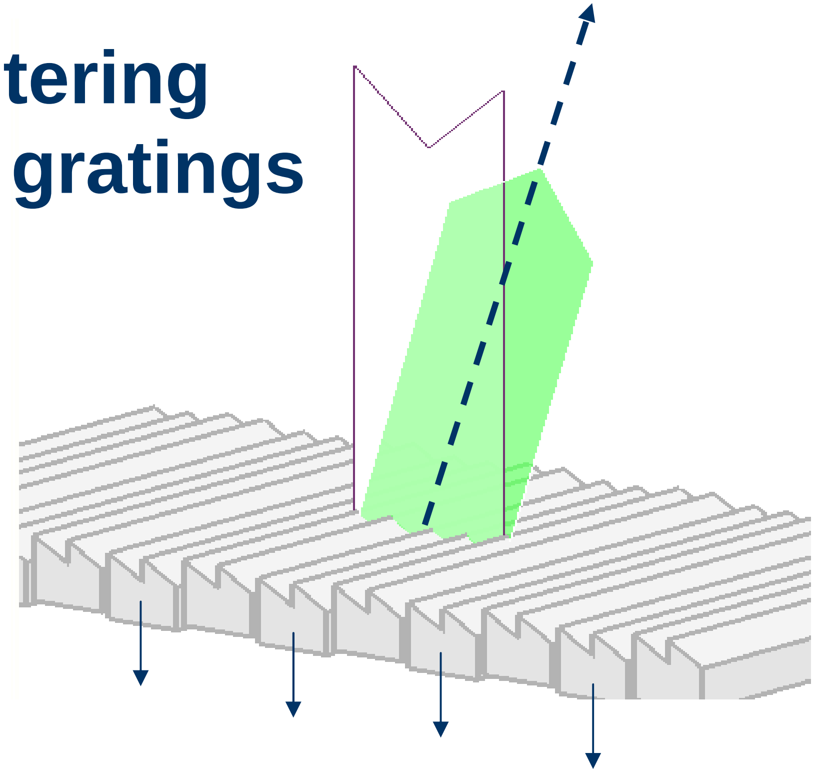
- Example: Carbon dioxide absorption
- Single detector
- Alternating filter



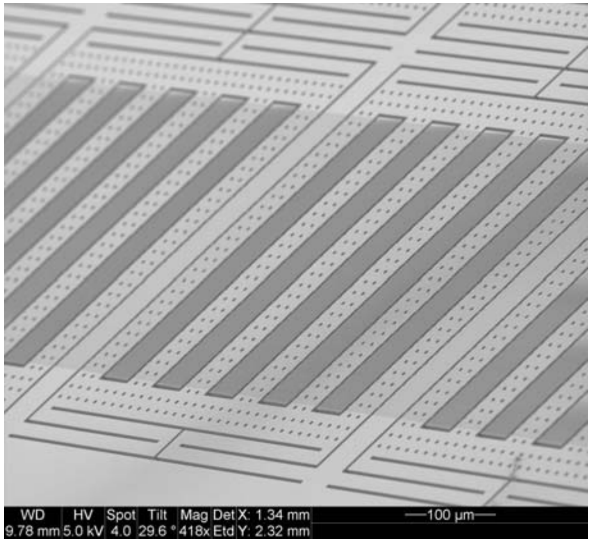

Infrared transmittance spectrum of $CO_2$



# Design concept: Optical filtering with Modulated diffraction gratings

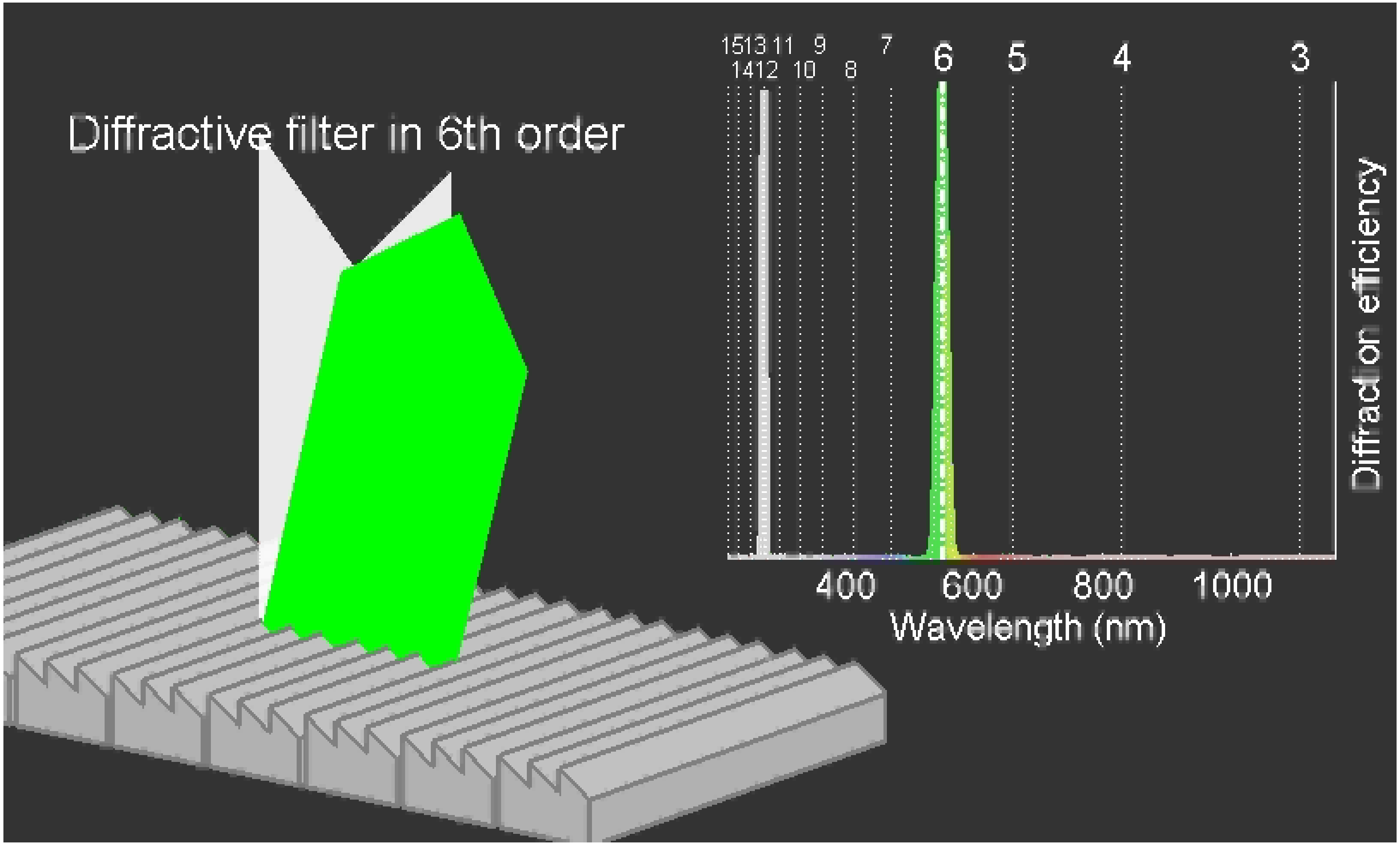


- Shine white light (broadband IR) onto a diffraction grating
- Collect the light diffracted into a chosen angle
- Change the color and intensity of the light by electromechanical modifications of the grating shape

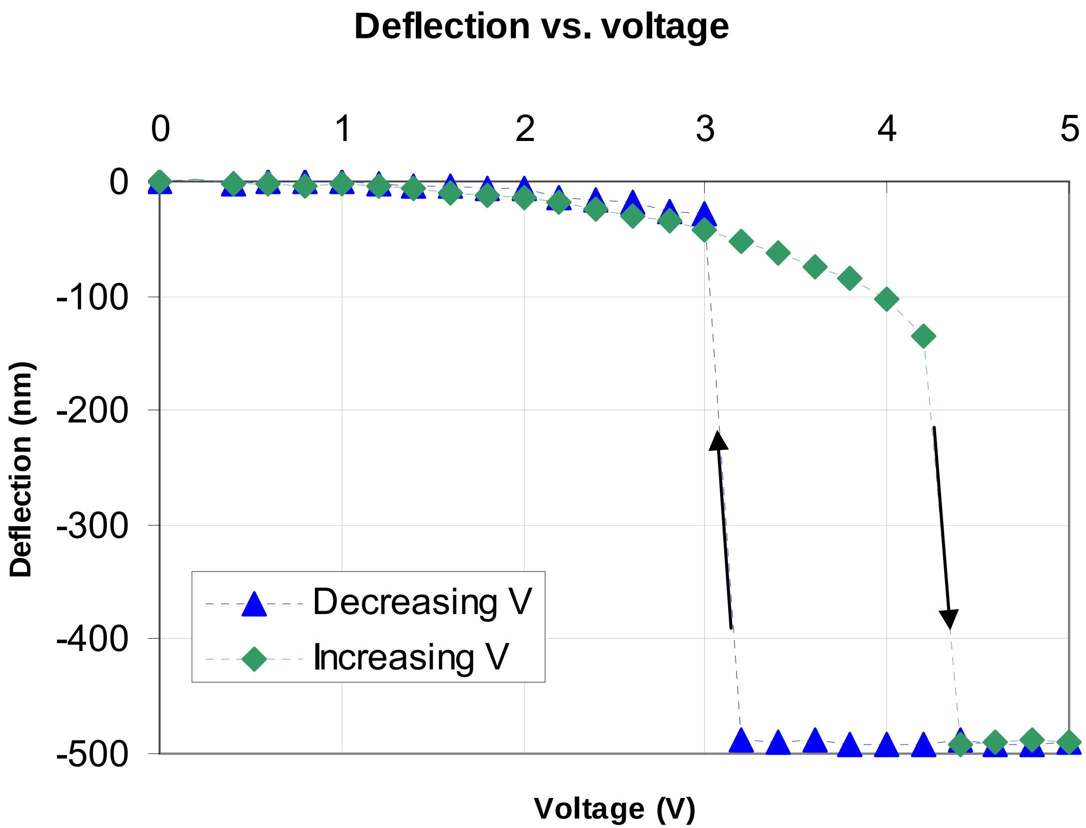


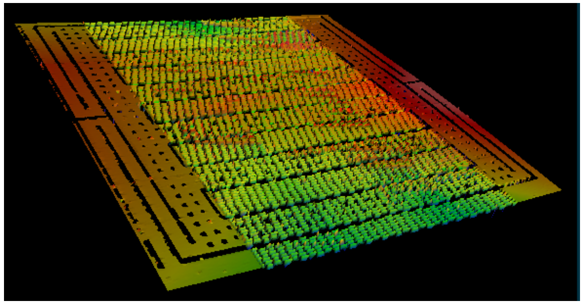

- Design objective:
  - Electromechanically simple
  - No position feedback
  - No calibration
  - No drift
  - Robust
  - Low-cost

- When used with wider grating elements, for diffraction order M=6, the neighboring diffraction orders come closer...

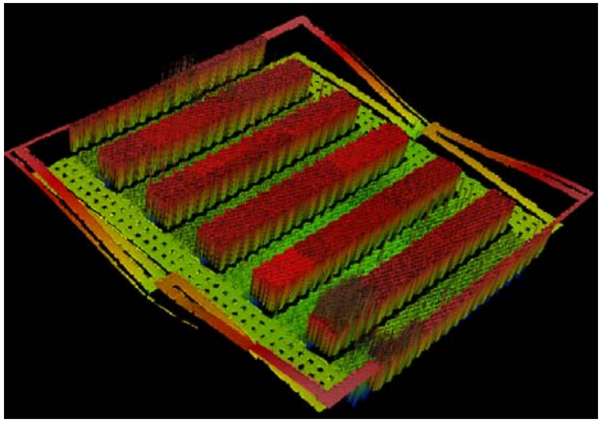


# Actuation characteristic



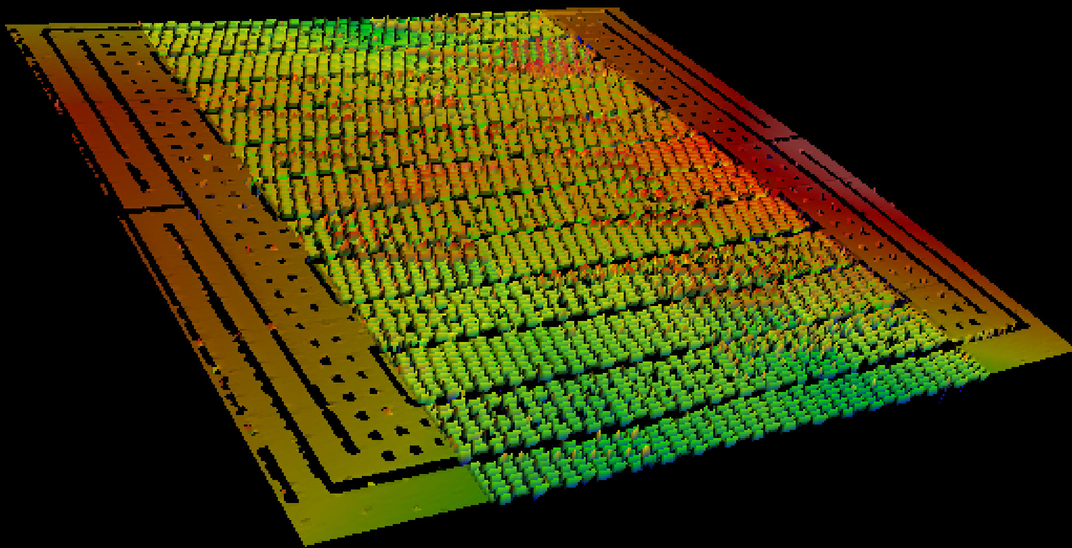



Idle (0V)

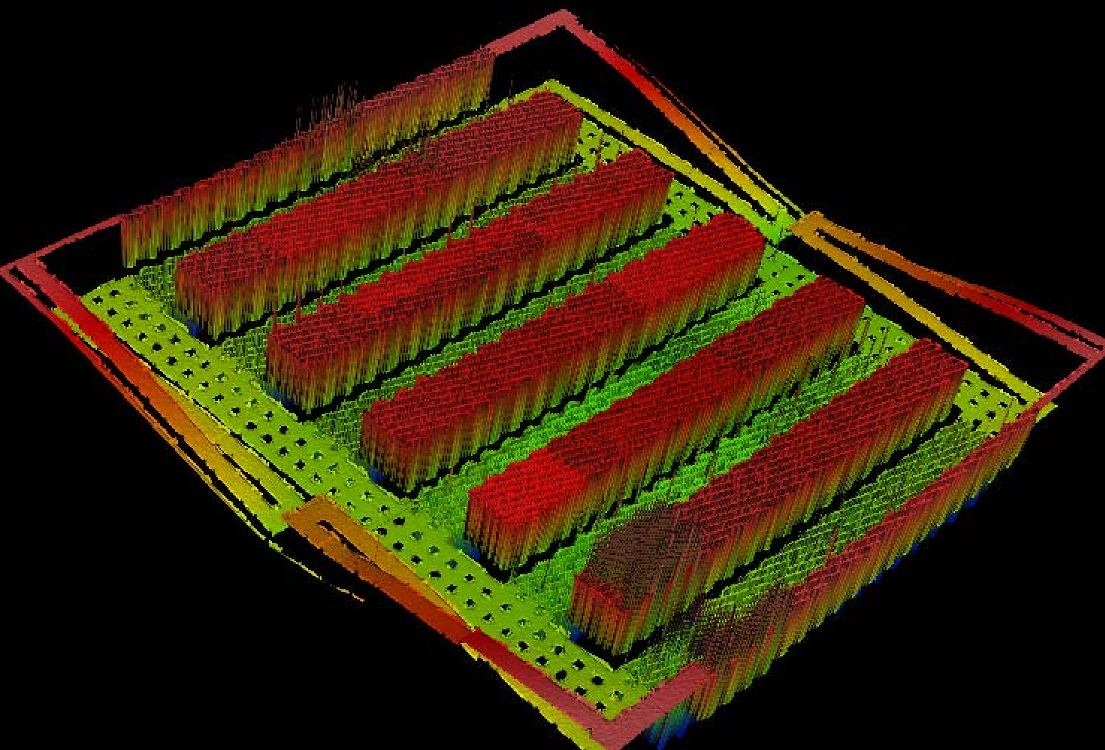


Fully actuated (5V)

- Bistable operation with snap-down at 4.2V
- Hysteresis due to pull-in effect

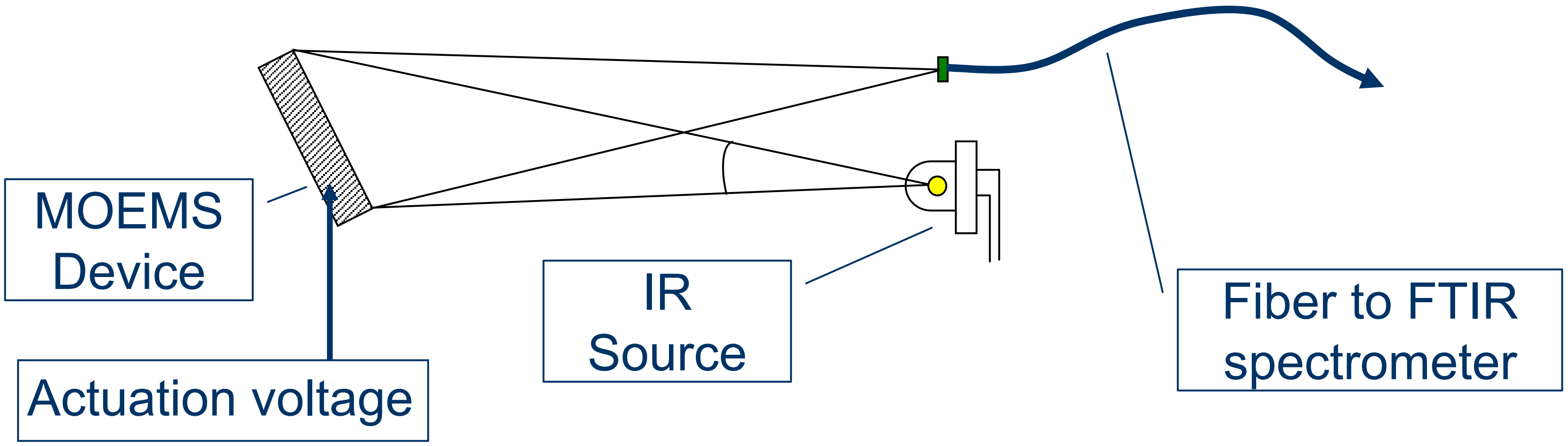


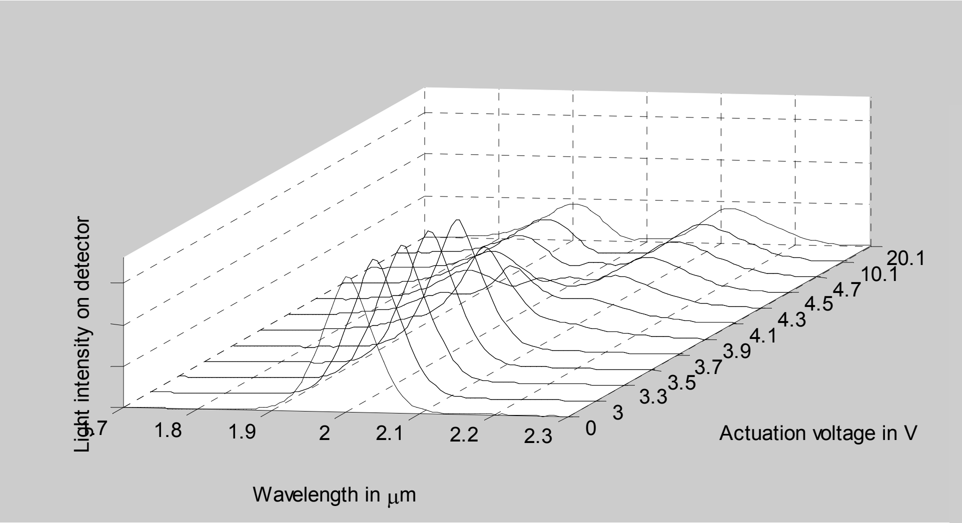
0V

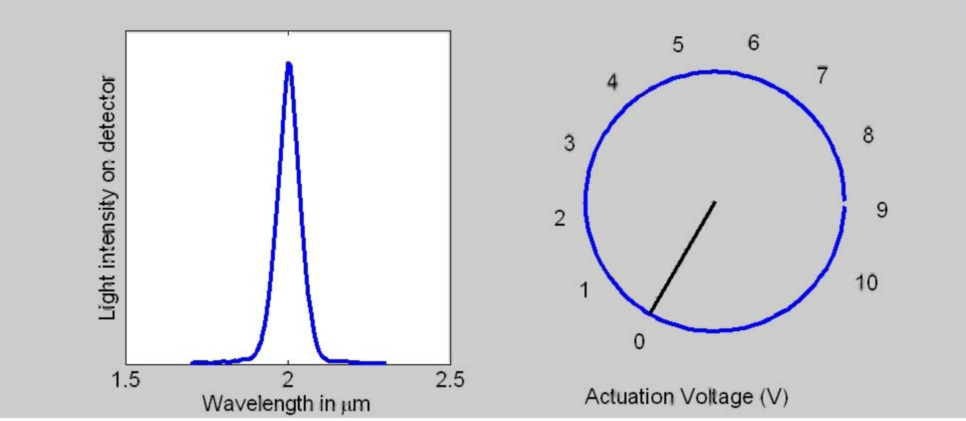


5V

# Infrared spectral characterization



# ”Grating light valves” for displacement sensing (F.L. Degertekin)

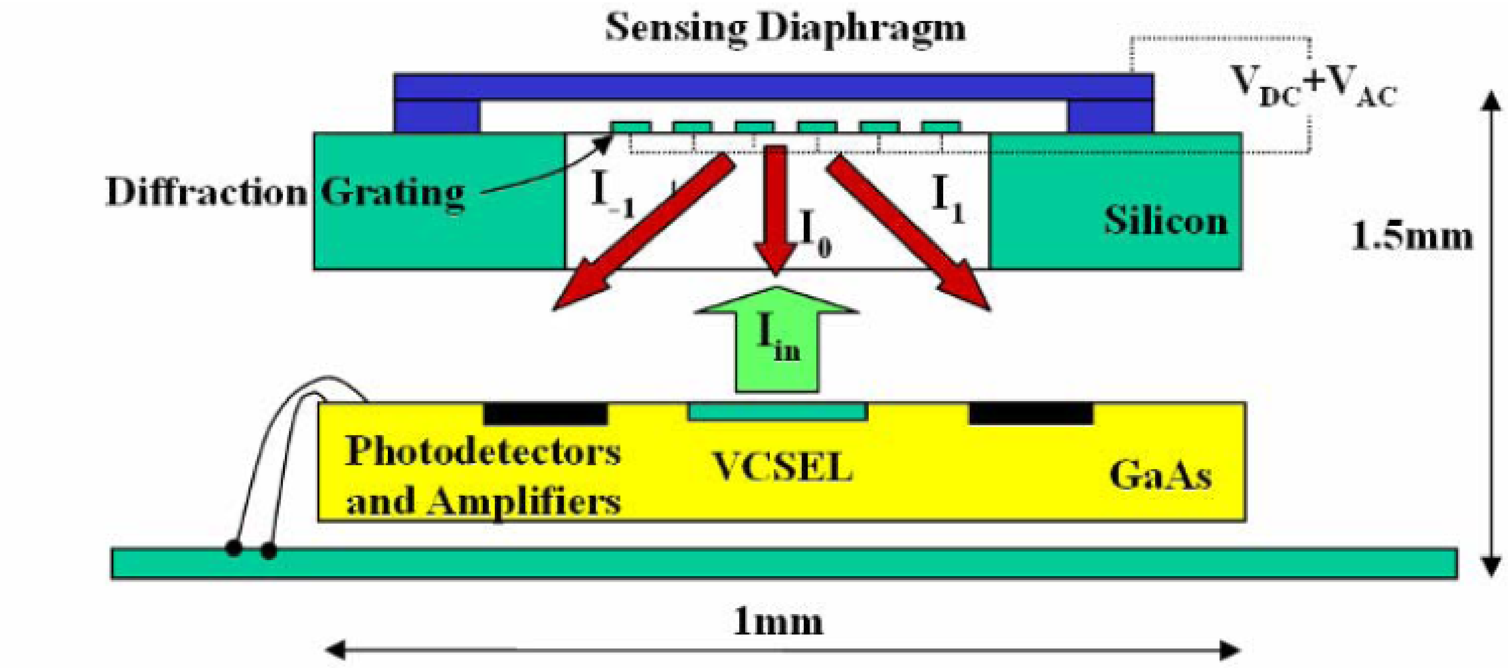



Fig. 1. Schematic of the optical displacement detection scheme. Light from the VCSEL is modulated by the diffraction grating and the reflector providing the same interference behavior and sensitivity as a Michelson interferometer. For a microphone, the top reflector is a rigidly supported membrane.

# ”Grating light valves” for displacement sensing (F.L. Degertekin)

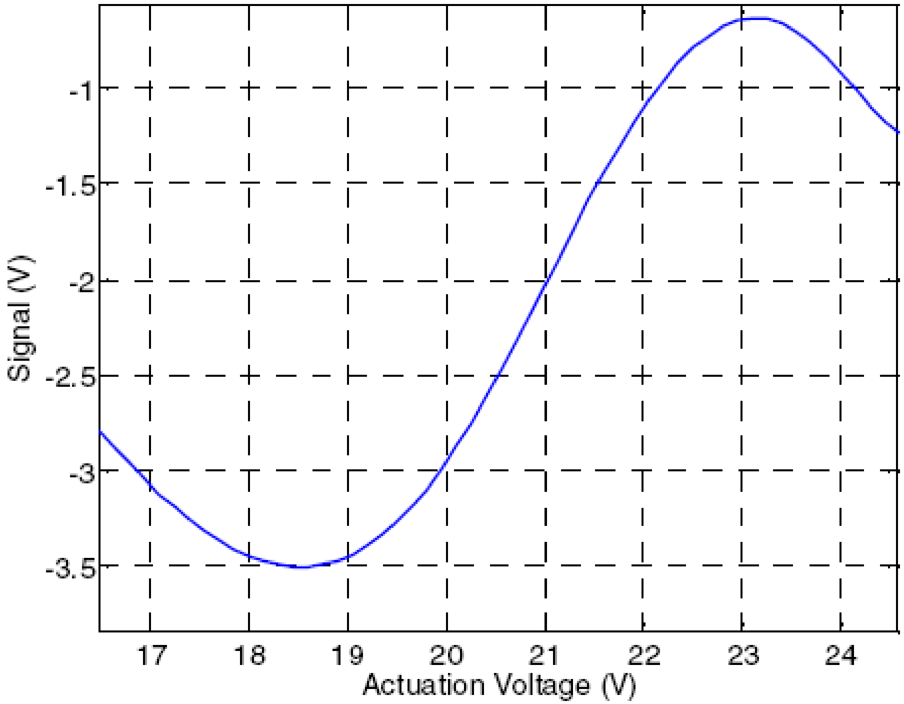



Fig. 2. Experimentally traced interference curve using a VCSEL as the light source [11]