



EPFL Doctoral School – MICRO-605 – November 2023

Optical MEMS and Micro-Optics

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University of Freiburg, Germany



Micro-optics I – Introduction



Course agenda

Day	Time	Instructor	Topic
Tuesday 14.11.2023 Room MC B1 303	13:00 – 16:30	Çağlar Ataman	• Micro-optics: Theory • Micro-optics: Devices and applications
Wednesday 15.11.2023 Room MC B1 283	13:00 – 16:30	Çağlar Ataman	• Micro-optics: Devices and applications (contd.) • Micro-optics: Fabrication
Thursday 16.11.2023 Room MC B1 283	13:00 – 16:30	Çağlar Ataman	• Optical MEMS: Actuation and dynamic modeling • Optical MEMS: Devices
Friday 17.11.2023 Room MC B1 283	13:00 – 16:30	Çağlar Ataman	• Optical MEMS: Applications • Optical MEMS: Emerging topics



Micro-optics I – Introduction

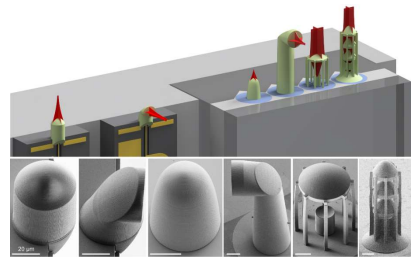
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Micro-605: Optical MEMS and Micro-Optics



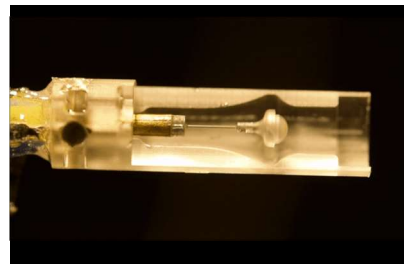
Course content

- Part I: Micro-optics
 - Introduction
 - Theory
 - Devices and application
 - Fabrication
 - From micro to nano



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- Part II: Optical MEMS
 - Introduction
 - From static to dynamic
 - Devices
 - Applications
 - Emerging topics



Micro-optics I – Introduction

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Micro-605: Optical MEMS and Micro-Optics



Where do I come from?

- University of Freiburg founded in 1457
- Department of Microsystems Engineering
 - Founded in 1995
 - Germany's largest MEMS institute
 - 25 Laboratories
 - Over 370 research, teaching, and technical staff
 - 550 microsystems engineering students
- Microsystems for Biomedical Imaging Group
 - Multi-modal endomicroscopy, adaptive optics, rapid prototyping and in-situ manufacturing of freeform optics, 3D nano-printing of optical MEMS



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PART I: Micro-Optics

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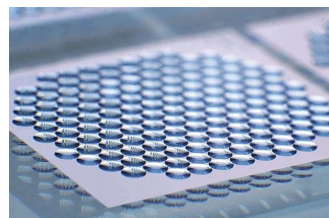
What is micro-optics?

- Optical components and systems with sub-mm and sub- μm features
- Unlike traditional optics, micro-optics are
 - Comparable to wavelength of light in size;
 - Can be free-space or on-chip/integrated
 - Not manufactured through grinding and polishing;
 - Compatible with wafer-scale manufacturing (mostly);

Conventional optics



Wafer-level micro-optics



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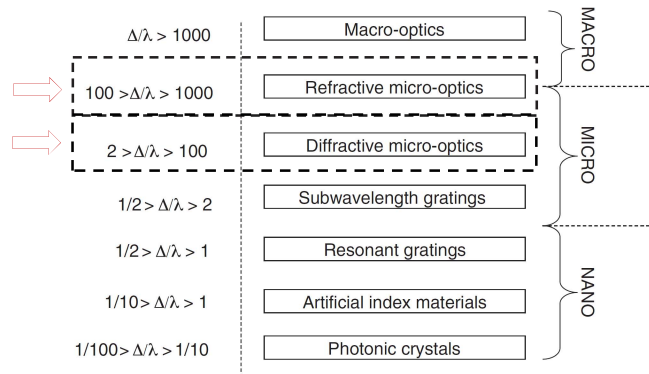
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Scaling down optics



Brief history of micro-optics

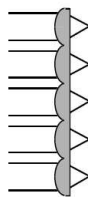
	BC	Scratch-o-grams	
	1785	Rittenhouse	Gratings made of hair
	1882	Rowland	Ruling engines
	1910	Wood	
	1948	Gabor	In-line holography (phase objects)
Holography infancy	1962	Leith/Upatnieks	Off-axis holography and HOEs
	1969	Lohmann/Brown	Synthetic holography (CGHs)
	1972	D'Auria/Huignard	Optical lithography
	1975		CNC precision diamond ruling/turning
Lithography boom	1983	Gale/Knop	Direct analog laser write in resist
	1985	Arnold	Direct binary e-beam write
	1989	Swanson/Weldkamp	Multi-level optical lithography
	1994	Lee/Daschner	Direct analog e-beam write
	1995	Potomac	Direct analog excimer laser ablation
Greyscale	1998	Canyon materials	Greyscale masking lithography
	2002	DOC	Stacked wafer scale (backside alignment)
	2004	UCSD	LAF greyscale masking
Nano-boom	2005		Nano-imprint / soft lithography
	2008		Direct nano-write (fringe writer, two photon, ...)

Micro-optics: pros and cons

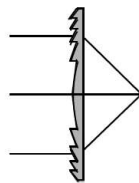
- Why are they great?
 - Manufacturing of large arrays;
 - Much larger design freedom;
 - Low-cost, high-volume manufacturing.
- Why are they, sometimes, not so great?
 - Small apertures limit resolution
 - Complex manufacturing techniques
 - Considerable upfront investment

Micro-optical components

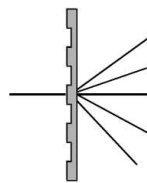
Free-space



microlens array



diffractive optical element



optimized grating

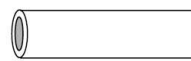
Integrated



grating coupler

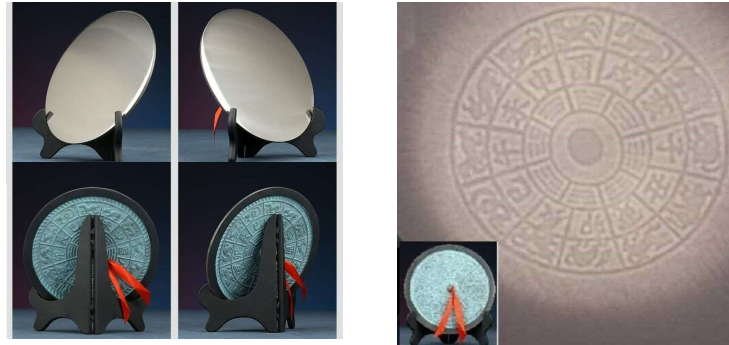


integrated optics



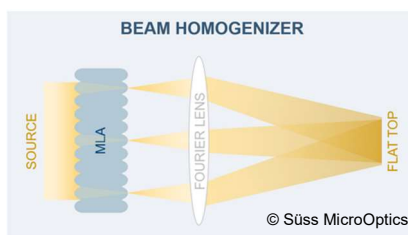
fiber optics

Ancient micro-optics: Chinese's magic mirror



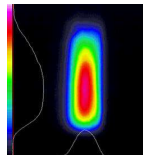
MLAs for beam homogenizing in DUV lithography

- Method developed in Neuchâtel
 - H.P. Herzig and his team
- Homogeneous illumination from inhomogeneous light sources

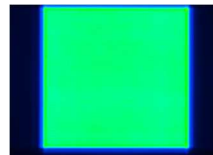


© ASML

with homogenizer



without homogenizer



© Süss MicroOptics

MLAs for automotive lighting



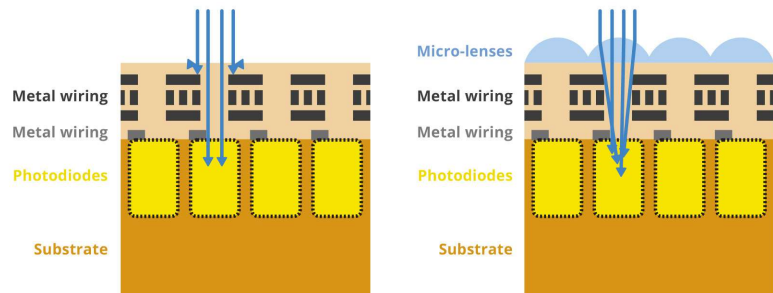
Micro-optics for consumer electronics



© Apple



Microlens arrays (MLAs) for image sensors



© OPTO Engineering



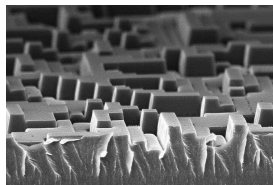
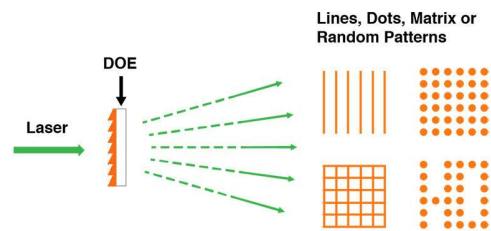
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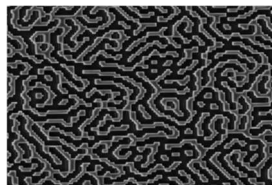
Micro-605: Optical MEMS and Micro-Optics



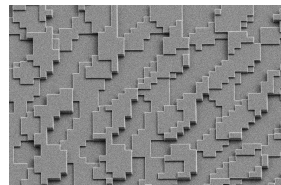
Diffractive Optical Elements (DOEs)



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© Zeiss



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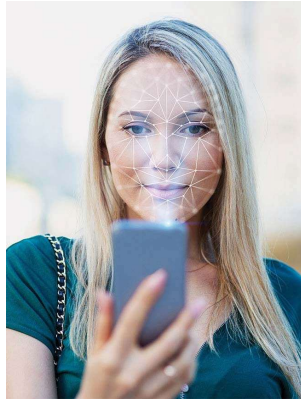
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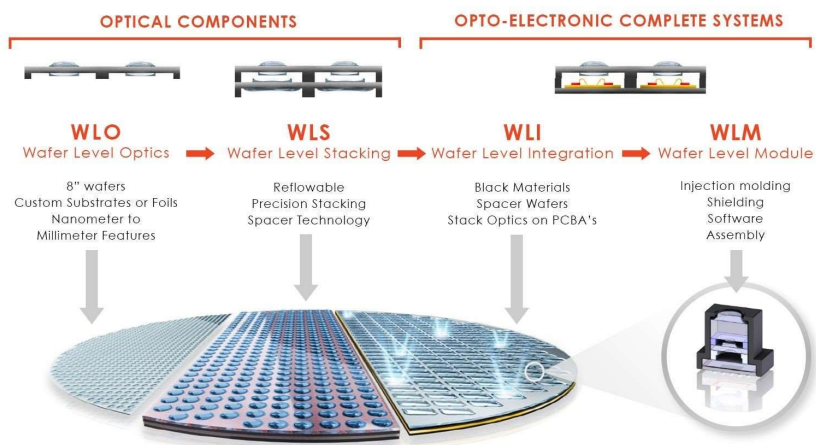


DOEs for 3D imaging

iPhone X dot projector

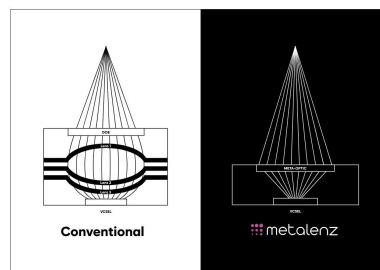
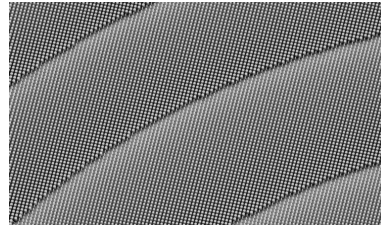


Wafer-level micro-optical systems



Metalenses: A new way?

- First developed by the F. Capasso group at Harvard
- Subwavelength dielectric structures
 - Effective index modulation
- Discrete phase shaping!
 - Can still be considered as diffractive
- Why not just use diffractive optics?
 - Single patterned layer
 - Simple mold manufacturing



Resources

- H. P. Herzig, ed., **Micro-Optics: Elements, Systems, and Applications** (Taylor & Francis, London, 1997).
- J. Turunen, F. Wyrowski, eds., **Diffractive Optics for Industrial and Commercial Applications** (Akademie Verlag, Berlin, 1997).
- S. Sinzinger, J. Jahns, **Microoptics** (Wiley-VCH, Weinheim, 1999/2005).
- H. Zappe, **Fundamentals of Micro-Optics** (Cambridge University Press, 2010).
- S. Kawata, M. Ohtsu, M. Irie, eds., **Nano-Optics** (Springer, Berlin, 2002).
- S. V. Gaponenko, **Introduction to Nanophotonics** (Cambridge U. Press, New York, 2010).
- L. Novotny, **Principles of Nano-Optics** (Cambridge, 2012)

BASIC OPTICAL CONCEPTS



Coming up next....

- The wave equation and its solutions
 - Plane and spherical waves
 - Gaussian waves
- Interference
 - Interferometer & interferogram
 - Spectral width and coherence
- Scalar diffraction theory
 - Fresnel and Fraunhofer approximations
- Quantification of optical performance
 - Point spread function and resolution
 - Modulation transfer function



THE WAVE EQUATION AND ITS SOLUTIONS



Wave Equation

- Equation defining the time and spatial variation of either the **E** or **H** fields
- Using Maxwell's Equations, one might derive that

$$\nabla^2 \mathbf{E} = \frac{1}{v^2} \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

- The general solution is in the form

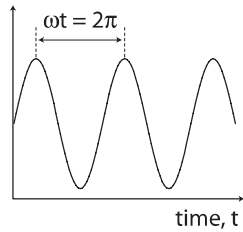
$$\mathbf{E}(\mathbf{r}, t) = E_0 e^{\pm j \mathbf{k} \cdot \mathbf{r}} e^{\pm j \omega t} \quad \mathbf{k} = \frac{2\pi}{\lambda} \mathbf{u}_r$$

- **k** is the wavevector for propagation in the **r** direction
- Solutions of the wave equation define a propagating wave
- Solutions to the Wave Equation in homogeneous media
 - Plane waves
 - Spherical waves
 - Gaussian waves (approximate solution in the paraxial regime)

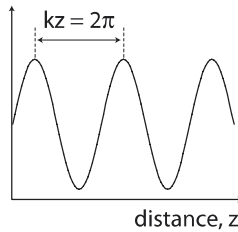


Meaning of k and ω

- $(\pm kz \pm \omega t) = \phi$
 - ϕ is a **phase**
 - Spatial constant $k = 2\pi/\lambda = \omega/v$
 - Time constant $\omega = 2\pi f$



Snapshot in space



Snapshot in time



General 3-dimensional waves

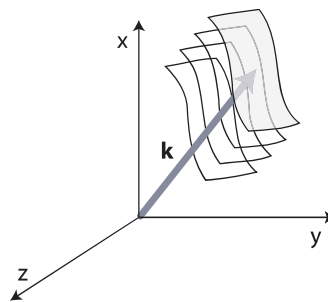
- In one dimension (**z**)

$$E = E_0 \cdot e^{j\omega t} e^{-jkz}$$
- In general

$$r^2 = x^2 + y^2 + z^2$$
 - 3D wave equation

$$\frac{\partial^2 \mathbf{E}}{\partial x^2} + \frac{\partial^2 \mathbf{E}}{\partial y^2} + \frac{\partial^2 \mathbf{E}}{\partial z^2} = \nabla^2 \mathbf{E} = \frac{1}{v^2} \frac{\partial^2 \mathbf{E}}{\partial t^2}$$
 - 3D wave

$$E = E_0 e^{j\omega t} e^{-j(k_x x + k_y y + k_z z)} = E_0 e^{j\omega t} e^{-j\mathbf{k} \cdot \mathbf{r}}$$
 - $\mathbf{k}$ and $\mathbf{r}$ are vectors where $|\mathbf{k}| = 2\pi/\lambda$
- The **wavefront** is the surface of constant phase

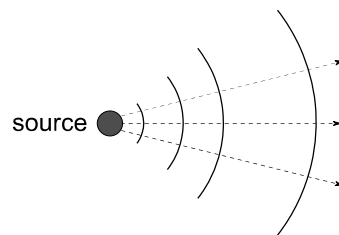


Spherical waves

- A point source uniformly emitting in all directions
- With r as the radial distance from the source

$$E(r) = \frac{E_0}{r} e^{-jkr}$$

- Surfaces of constant phase form concentric spheres

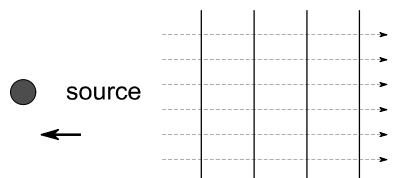


Plane waves

- The source is at infinity
- All wave vectors are parallel
- With propagation the z-axis

$$E(z) = E_0 e^{-jkz}$$

- This is an idealized case, as no wave is of infinite extent



GAUSSIAN BEAMS: PARAXIAL SOLUTION OF THE WAVE EQUATION



Paraxial Helmholtz equation

- Special case: paraxial waves, z direction
 - Normals to wavefront are paraxial

$$E(r) = \psi(r)e^{-jkz}$$

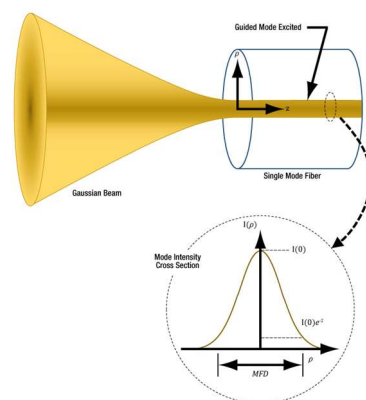
- Envelope $\psi(r)$ varies slowly with z , so

$$\frac{\partial^2 \psi}{\partial z^2} \ll 2k \frac{\partial \psi}{\partial z} \approx 0$$

- Yielding the paraxial wave equation:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} - j2k \frac{\partial \psi}{\partial z} = 0$$

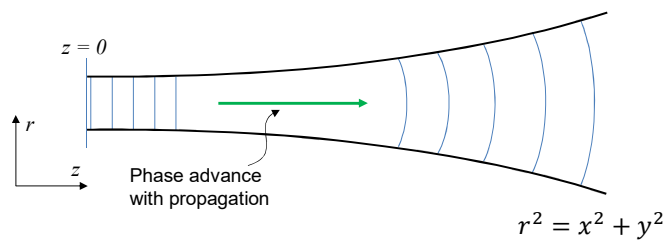
- Solution is a Gaussian wave:



Gaussian Beams (TEM₀₀)

- Approximate solution to the wave equation in the **paraxial regime**
- Accurate description of laser beam propagation and focusing

$$E(r) = E_0 \underbrace{\frac{w_0}{w(z)} e^{-\frac{x^2+y^2}{w^2(z)}}}_{\text{Amplitude factor}} \underbrace{e^{\frac{jk(x^2+y^2)}{2R(z)}}}_{\text{Radial phase factor}} \underbrace{e^{-j\left(kz - \arctan\left(\frac{z}{z_R}\right)\right)}}_{\text{Longitudinal phase factor}}$$

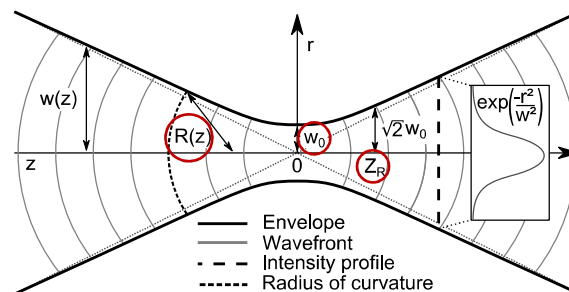


Gaussian Beam Characteristics

- Observations
 - Flat wavefront at the beam waist
 - Tight focusing $\rightarrow$ Short depth of focus
 - Weak focusing $\rightarrow$ Long depth of focus

Gaussian beam intensity profile

$$I(r) = |E(r)|^2 = I_0 e^{-2r^2/w^2}$$



w_0 = Beam waist | z_r = Rayleigh range | $R(z)$ = Radius of curvature

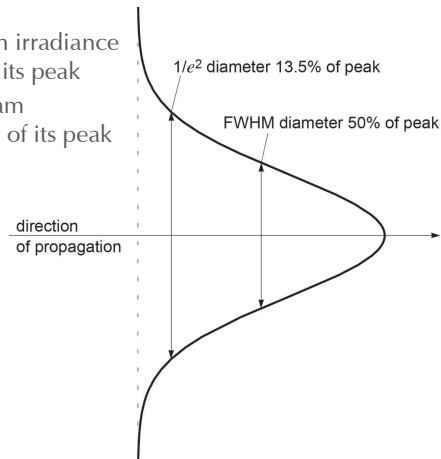


Gaussian Beam Width

- Two common definitions
 - FWE2:** The diameter at which the beam irradiance (intensity) has fallen to $1/e^2$ (13.5%) of its peak
 - FWHM:** The diameter at which the beam irradiance (intensity) has fallen to 50% of its peak

- w_0 = Beam waist defined in FWE2

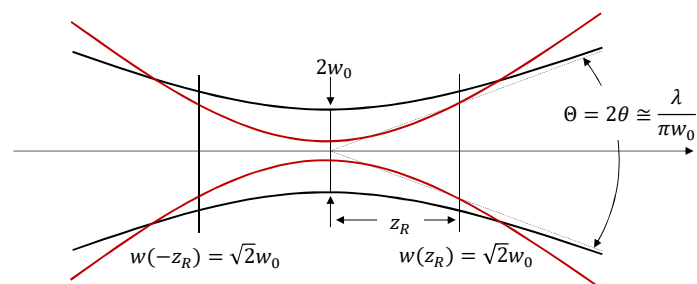
- We will frequently refer to this in
 - Imaging systems
 - Display systems
 - Spectrometers
 - Optical interconnects



Diameter of a Gaussian beam



Rayleigh Range / Depth-of-Focus (DoF)

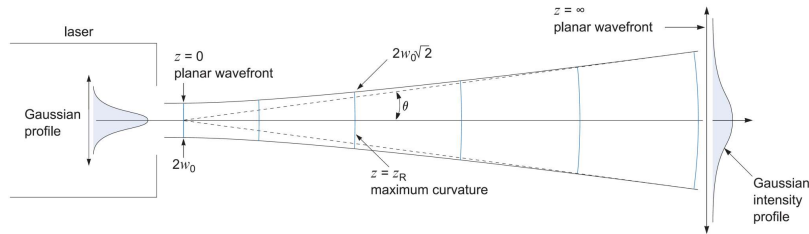


- Rayleigh range (z_R)**
 - Distance over which the beam radius spreads by a factor of $\sqrt{2}$
- Also called **Depth of Focus**
- Trade of between DoF vs. resolution

$$z_R = \frac{kw_0^2}{2} = \frac{\pi w_0^2}{\lambda}$$



Gaussian Beam Propagation



- Good approximation for
 - Laser propagation
 - Propagation after single-mode fibers
- Beam waist expands with propagation
- Radius of curvature
 - ∞ @ $z = 0$
 - max @ $z = z_R$ (where $\text{RoC} = 2z_R$)
 - ∞ @ $z = \infty$

Beam half-width

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

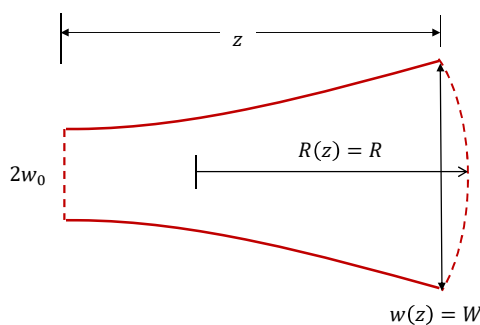
Radius of curvature

$$R(z) = z \left[1 + \left(\frac{z_R}{z}\right)^2 \right]$$



Gaussian Beam Propagation

- Two parameters are enough to define the beam
 - Beam width at a certain location
 - Radius of curvature at that location
- We will use this result to see what happens to a Gaussian beam after a lens



Beam waist

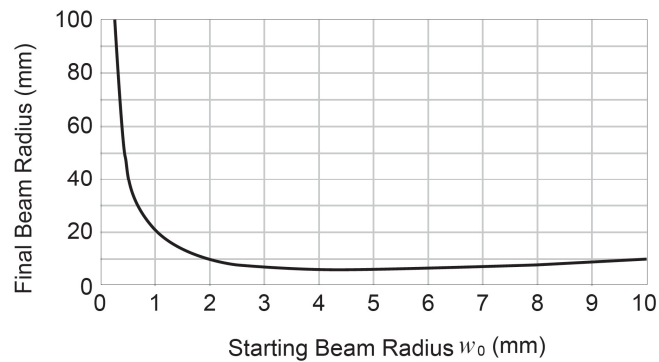
$$w_0 = \frac{W}{\sqrt{1 + \left(\frac{\pi W^2}{\lambda R}\right)^2}}$$

Location of beam waist

$$z = \frac{R}{1 + \left(\frac{\lambda R}{\pi W^2}\right)^2}$$

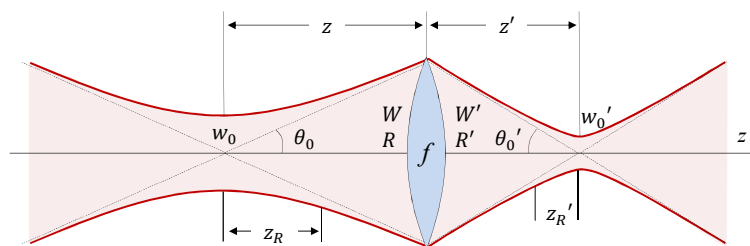


Beam Waist vs. Far-field Beam Width



Beam radius at 100 m as a function of starting beam radius for a HeNe laser at 632.8 nm

Imaging of Gaussian Beams by a Lens



- Lens phase: $A(r) = e^{-j \frac{r^2}{2f}}$
- Phase after the lens: $kz + k \frac{r^2}{2R(z)} - k \frac{r^2}{2f} = kz + k \frac{r^2}{2R'} \Rightarrow \frac{1}{R'} = \frac{1}{R} - \frac{1}{f}$
- Beam width after the lens: $W = W'$

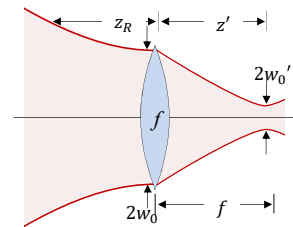
Gaussian Beam Focusing

- For a lens at the waist of a Gaussian beam:

$$w_0' = \frac{w_0}{\sqrt{1 + \left(z_R/f\right)^2}}$$

$$z' = \frac{f}{1 + \left(f/z_R\right)^2}$$

Lens at the beam waist

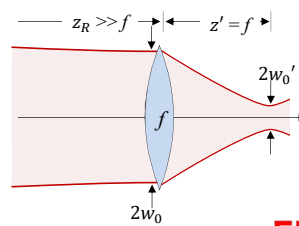


- Special case: $z_R \gg f$

$$w_0' \approx \frac{\lambda}{\pi w_0} f$$

$$z' \approx f$$

Focusing a collimated beam



Gaussian Beams - Recap

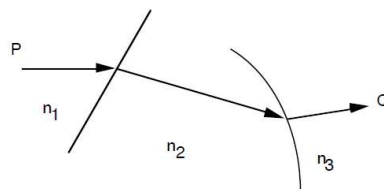
- Accurately models beam propagation
 - Laser beam propagation
 - Beams emanating from single mode fibers
- Trade-off between “spot size” and “depth-of-focus”
 - Tight focusing leads to large beam divergence
 - Depth of focus increases alongside the beam waist
- A lens:
 - Modifies the radius of curvature
 - Leaves beam width intact (assuming no clipping)

INTERFERENCE



Optical path difference (OPD)

- Product of the geometric length of the optical path followed by light and the refractive index of the medium



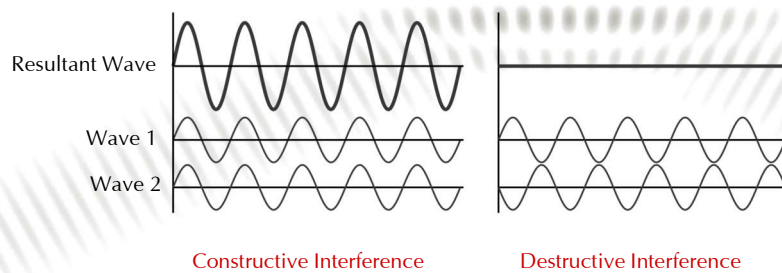
$$OPD = \sum n_i L_i$$

$$\Delta\Phi = \frac{2\pi}{\lambda} \sum n_i L_i$$

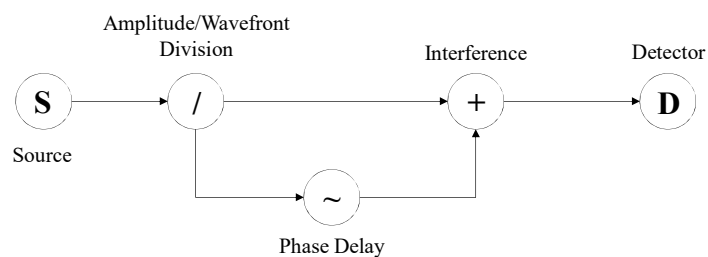


Interference

- Arises from the wave nature of light
- Superposition of two or more waves with a **well defined phase relation**
 - ❑ Constructive Interference
 - ❑ Destructive Interference
- Observed in all types of waves
- **Interferogram:** interference intensity profile as a function of path difference



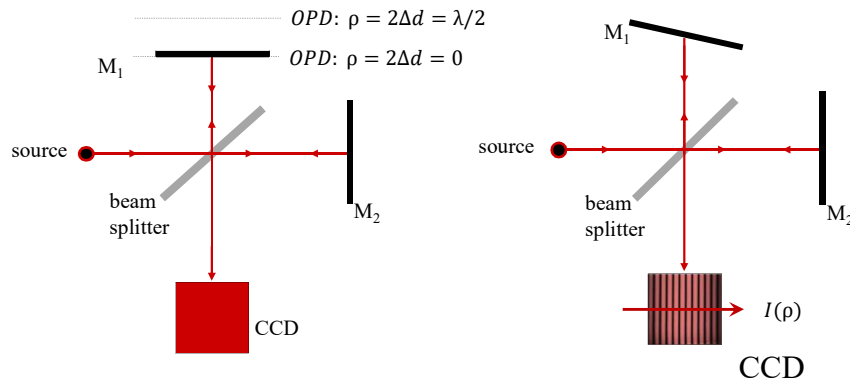
The Interferometer



- Amplitude division interferometers
 - Michelson, Mach-Zehnder, Twyman-Green, etc.
- Wavefront division interferometers
 - Young's double slit interferometer
- Multiple beam interferometers
 - Diffraction gratings
 - Fabry-Perot interferometers



Amplitude Division Interferometers



- Applications
 - Surface characterization / 3D Profiling
 - Spectroscopy
 - Laser Doppler vibrometry



Interference Theory

- When multiple waves are superposed, the complex amplitude is given by

$$\mathbf{E}(x, y, z, t) = \sum_i \mathbf{E}_i(x, y, z, t)$$

- With two waves, the time-averaged interference intensity is

$$I(x, y, z, t) = \left\langle \left| \sum_i \mathbf{E}_i(x, y, z, t) \right|^2 \right\rangle = \underbrace{\langle |\mathbf{E}_1|^2 \rangle}_{I_1} + \underbrace{\langle |\mathbf{E}_2|^2 \rangle}_{I_2} + \langle \mathbf{E}_1 \cdot \mathbf{E}_2^* \rangle + \langle \mathbf{E}_1^* \cdot \mathbf{E}_2 \rangle$$

- Now assume we have two linearly polarized monochromatic waves:

$$\mathbf{E}_i(x, y, z, t) = \mathbf{A}_i(x, y, z, t) e^{j(\omega_i t - \phi_i(x, y, z))}$$

- The interference intensity now becomes:

$$I(x, y, z, t) = I_1 + I_2 + 2(\mathbf{A}_1 \cdot \mathbf{A}_2) \cos((\omega_1 - \omega_2)t - \Delta\phi(x, y, z))$$

Dot product!

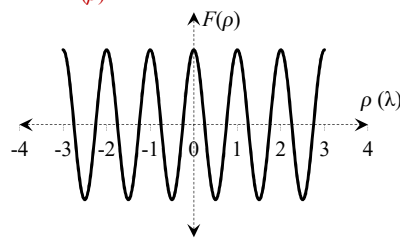
Beat frequency



Interference and Interferogram

- If E_1 and E_2 are
 - ❑ Of the same wavelength λ and wavenumber $\sigma = 1/\lambda$
 - ❑ Of the same optical frequency $\rightarrow \omega_1 = \omega_2 = \omega$
 - ❑ Linearly polarized and parallel $\rightarrow \mathbf{A}_1 \cdot \mathbf{A}_2 = \sqrt{I_1 I_2}$
 - ❑ Of optical path difference (OPD) of $\rho \rightarrow \Delta\varphi = 2\pi\rho/\lambda = 2\pi\rho\sigma$
- The interference intensity becomes

$$I(\rho) = I_1 + I_2 + \underbrace{2\sqrt{I_1 I_2} \cos(2\pi\sigma\rho)}_{F(\rho)} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi\rho}{\lambda}\right)$$



Interferogram and Spectrum

- If E_1 and E_2 are
 - from the same non-monochromatic source with power spectral density $B(\sigma)$
 - of the same amplitude

$$\begin{aligned} I(\rho) &= \int_0^\infty B(\sigma) (1 + \cos(2\pi\sigma\rho)) d\sigma \\ &= \int_0^\infty B(\sigma) d\sigma + \int_0^\infty B(\sigma) \cos(2\pi\sigma\rho) d\sigma \\ &= \bar{I} + \underbrace{\int_0^\infty B(\sigma) \cos(2\pi\sigma\rho) d\sigma}_{F(\rho)} \end{aligned}$$

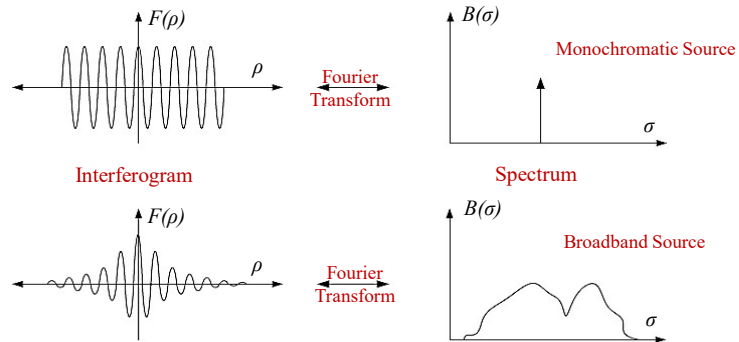
- $F(\rho)$ is the interferogram.
- $B(\sigma)$ and $F(\rho)$ are therefore Fourier pairs:

$$\begin{aligned} F(\rho) &= \int_{-\infty}^\infty B(\sigma) \cos(2\pi\sigma\rho) d\sigma \quad (W) \\ B(\sigma) &= \int_{-\infty}^\infty F(\rho) \cos(2\pi\sigma\rho) d\rho \quad (W/cm^{-1}) \end{aligned}$$

Interferogram and Spectrum

$$F(\rho) = \int_{-\infty}^{\infty} B(\sigma) \cos(2\pi\sigma\rho) d\sigma \quad (W)$$

$$B(\sigma) = \int_{-\infty}^{\infty} F(\rho) \cos(2\pi\sigma\rho) d\rho \quad (W/cm^{-1})$$



Temporal Coherence and Coherence Length

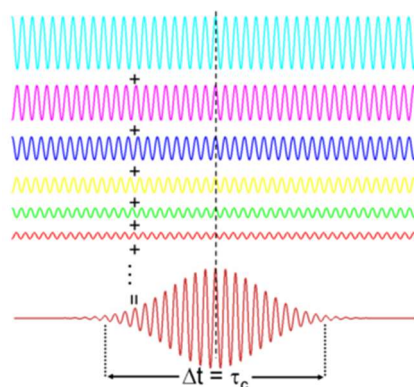
- Temporal coherence tells us how monochromatic a source is
 - ❑ Laser → High coherence
 - ❑ White Light → Low coherence
- Coherence Time:

$$\Delta\tau\Delta\omega \geq 1$$

- Coherence Length:

$$\Delta l = c\Delta\tau \approx c/\Delta\omega$$

- Measured with an interferometer

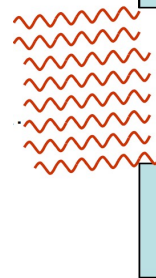


SCALAR DIFFRACTION THEORY



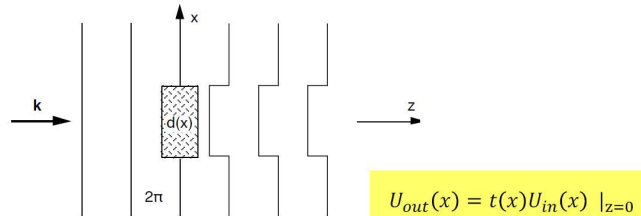
Scalar Diffraction Theory: Basic Approximations

- Maxwell's equations operate on vector quantities
- Scalar wave equation is obeyed if the media is
 - ❑ Linear
 - ❑ Isotropic and homogeneous
 - ❑ Nondispersive and Nonmagnetic
- *Boundaries do not normally satisfy these conditions*
- Good approximation in two conditions:
 - ❑ The aperture must be large compared with a wavelength.
 - ❑ The fields must not be observed too close to the aperture.
- Our treatment will **not** be useful for
 - ❑ Subwavelength gratings
 - ❑ Photonic crystals
 - ❑ Waveguides and dispersive media
- No polarization nor edge effects



Complex amplitude transmittance

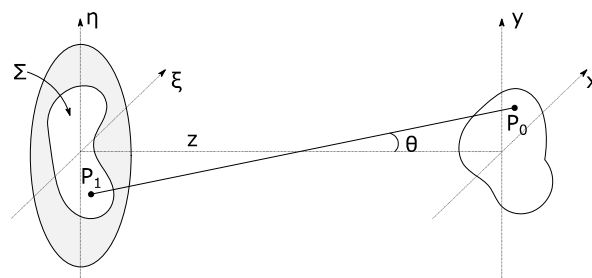
- Thin element approximation
 - Model elements as a spatial amplitude and phase function
 - No edge effects



transmittance: $t(x) = e^{-i\Phi(x)}$

with $\Phi(x) = d(x)(n-1)\left(\frac{2\pi}{\lambda}\right)$

The Huygens-Fresnel Principle



$$U(x, y) = \frac{1}{j\lambda} \iint_{\Sigma} U(\xi, \eta) \frac{\exp(jkr_{01})}{r_{01}} \cos\theta d\xi d\eta$$

$$r_{01} = \sqrt{z^2 + (x - \xi)^2 + (y - \eta)^2}$$

Fresnel Approximation

- If θ is within the paraxial region

$$r_{01} \approx z \left[1 + \frac{1}{2} \left(\frac{x-\xi}{z} \right)^2 + \frac{1}{2} \left(\frac{y-\eta}{z} \right)^2 \right]$$

- Then, the Huygens-Fresnel principle becomes

$$U(x, y) = \frac{e^{jkz}}{j\lambda z} \int \int_{-\infty}^{\infty} U(\xi, \eta) \exp \left\{ j \frac{k}{2z} [(x-\xi)^2 + (y-\eta)^2] \right\} d\xi d\eta$$

- After factorization of the exponent within the integral

$$U(x, y) = \frac{e^{jkz}}{j\lambda z} e^{j \frac{k}{2z} (x^2 + y^2)} \underbrace{\int \int_{-\infty}^{\infty} \left\{ U(\xi, \eta) e^{j \frac{k}{2z} (\xi^2 + \eta^2)} \right\} e^{-j \frac{2\pi}{\lambda z} (x\xi + y\eta)} d\xi d\eta}_{\text{Fourier Transformation}}$$



Fraunhofer Approximation

- If the following stronger (Fraunhofer) approximation holds

$$z \gg \frac{k(\xi^2 + \eta^2)_{max}}{2}$$

- The Fresnel approximation becomes

$$U(x, y) = \frac{e^{jkz} e^{j \frac{k}{2z} (x^2 + y^2)}}{j\lambda z} \int \int_{-\infty}^{\infty} U(\xi, \eta) e^{-j \frac{2\pi}{\lambda z} (x\xi + y\eta)} d\xi d\eta$$

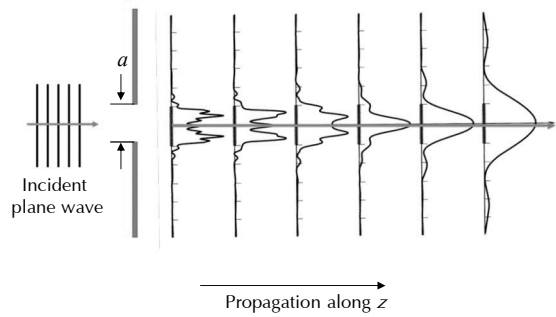
- Which is the Fourier transform of the input aperture function evaluated at

$$f_X = x/\lambda z, \quad f_Y = y/\lambda z$$

- In practice, this approximation holds if $z \geq \frac{2D^2}{\lambda}$ (D : aperture size)



From Fresnel to Fraunhofer

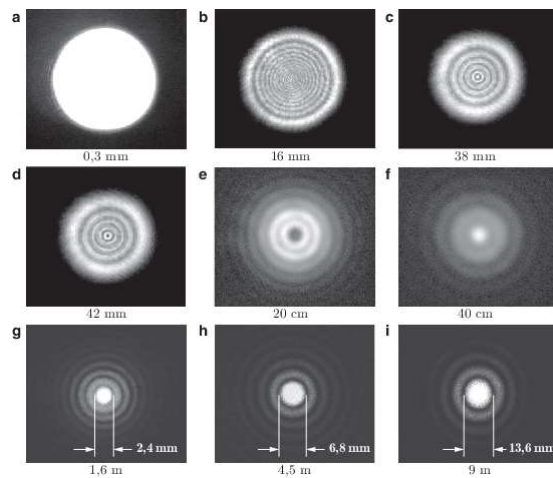


Fresnel number

$$F = \frac{a^2}{L\lambda}$$



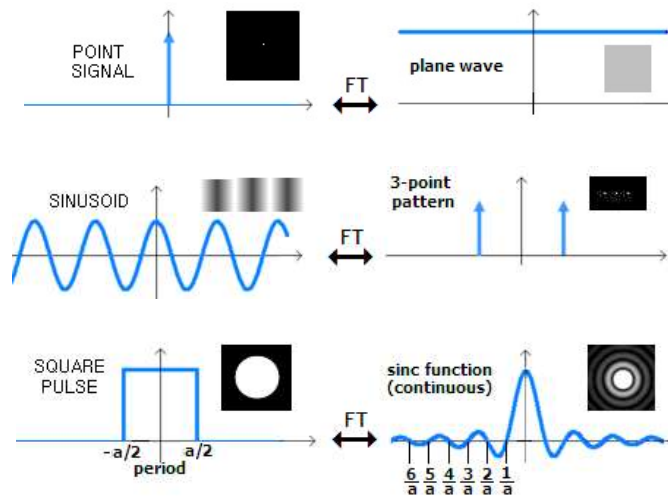
From Fresnel to Fraunhofer: Circular aperture



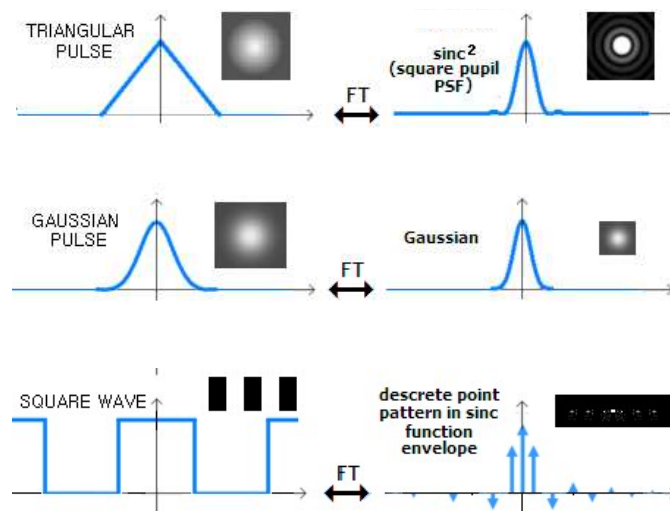
Lehrbuch zur Experimentalphysik Band 4: Wellen und Optik



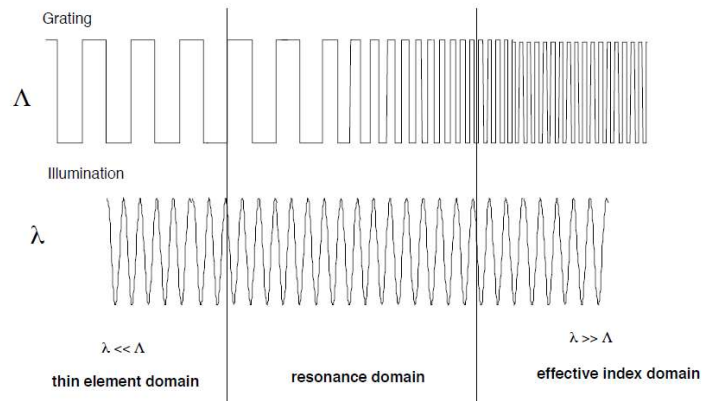
Fraunhofer Diffraction Examples



Fraunhofer Diffraction Examples

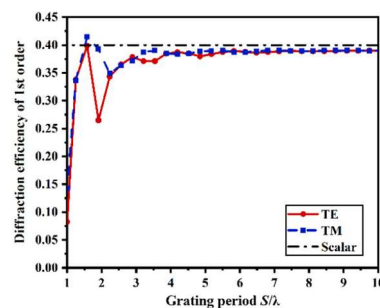
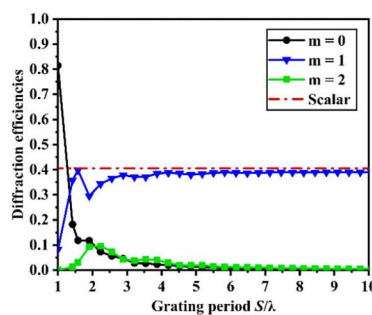


Limits of scalar theory



Scalar vs. rigorous diffraction

- Scalar theory breaks down when $\Lambda \sim \lambda$
- Rigorous analysis based solving Maxwell's equations
 - Needs numerical methods
 - Polarization effects are included



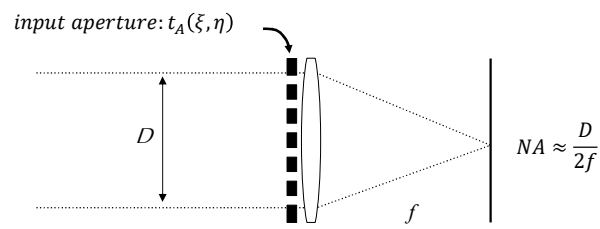
Appl. Sci. 2021, 11, 6897

QUANTIFICATION OF IMAGING PERFORMANCE



A Thin Lens as a Fourier Transformer

- Let's see what happens after a lens
 - Aperture illuminated by a plane wave
 - Aperture placed right before a lens of focal length f and diameter D
 - We are interested in the profile at the focal plane!



- The lens adds a phase function

$$t_A'(\xi, \eta) = t_A(\xi, \eta) e^{-j\frac{k}{2f}\xi^2 + \eta^2}$$



A Thin Lens as a Fourier Transformer

- Rewrite the Fresnel integral after the lens

$$U_f(x, y) = \frac{e^{jkz} e^{j\frac{k}{2z}(x^2+y^2)}}{j\lambda z} \int \int_{-\infty}^{\infty} \boxed{t_A(\xi, \eta) e^{-j\frac{k}{2f}(\xi^2+\eta^2)}} e^{j\frac{k}{2z}(\xi^2+\eta^2)} e^{-j\frac{2\pi}{\lambda z}(x\xi+y\eta)} d\xi d\eta$$

Aperture after lens

- To find the profile at the focal plane, evaluate at $z = f$!

$$= \frac{e^{jkf} e^{j\frac{k}{2f}(x^2+y^2)}}{j\lambda f} \int \int_{-\infty}^{\infty} \boxed{At_A(\xi, \eta) e^{-j\frac{2\pi}{\lambda f}(x\xi+y\eta)} d\xi d\eta}$$

Quadratic
Phase Function

Fourier Transform of the
Aperture Function

- **Thus, a lens is a Fourier transformer!**



Diffraction-Limited Spot-Size / Airy Disk

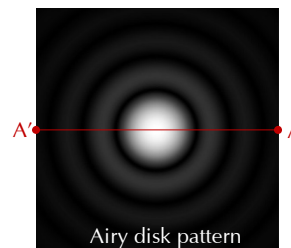
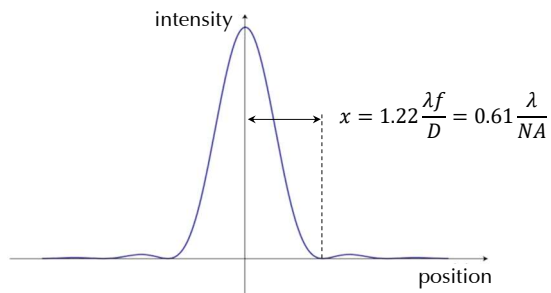
- Theoretical limit on imaging system performance
 - Aberration-free performance
- Sets smallest possible spot size
 - Assumes plane wave illumination
 - Beam size is limited by lens aperture
 - Notice the size bands!



George Biddell Airy
1081 - 1892

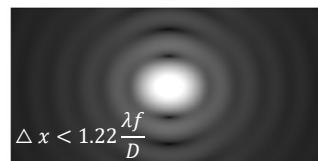
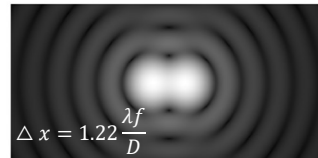
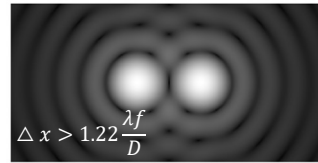
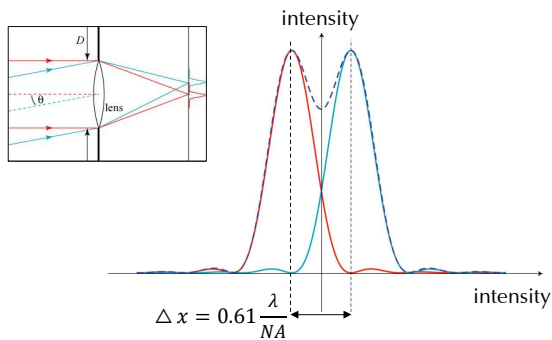


Ernst Abbe
1840 - 1905



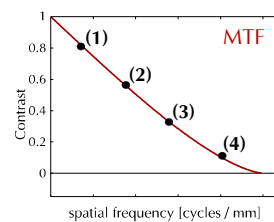
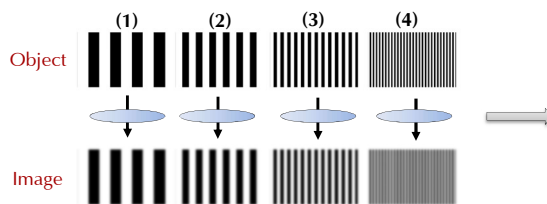
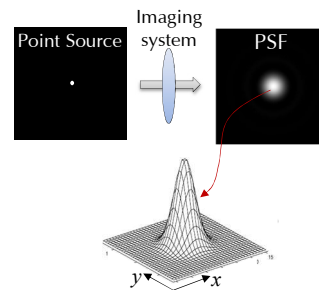
Diffraction-limited spot size vs. Resolution

- Diffraction limits system resolution
 - Remember! Lens is a Fourier transformer!
- Rayleigh criterion: $\Delta x = 0.61 \frac{\lambda}{NA}$
- Abbe criterion: $\Delta x = 0.5 \frac{\lambda}{NA}$



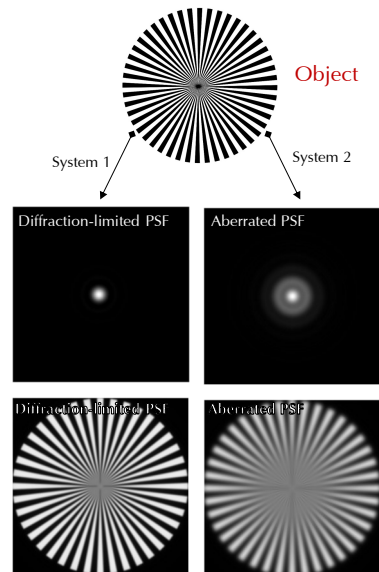
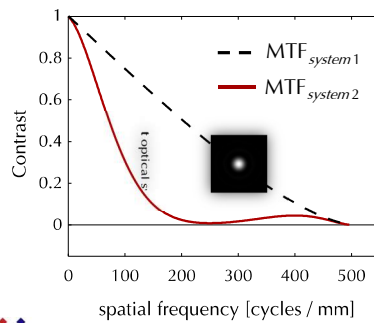
Quantifying Imaging Performance

- Point Spread Function (PSF)
 - ❑ **Impulse response** in incoherent imaging
 - ❑ Defined by the diffraction-limit
 - ❑ Tells how well a point source is imaged
 - ❑ Acts as a smoothing spatial filter
- Modulation Transfer Function (MTF)
 - ❑ Frequency response in incoherent imaging
 - ❑ Contrast vs. spatial frequency in [cycles / mm]



PSF vs. MTF (For Incoherent Imaging)

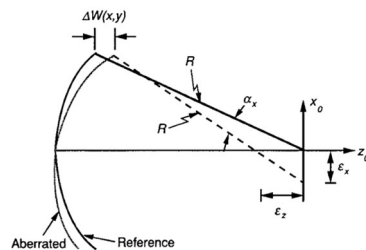
- $MTF = Re(\mathcal{F}\{PSF\})$
 - ❑ Small $PSF \rightarrow$ MTF falls off slowly
 - Good image resolution (**system 1**)
 - ❑ Large $PSF \rightarrow$ MTF falls off quickly
 - Poor image resolution (**system 2**)
- Q: How would the MTF and PSF of a **perfect** optical system look?



Micro-optics II – Theory

EPFL

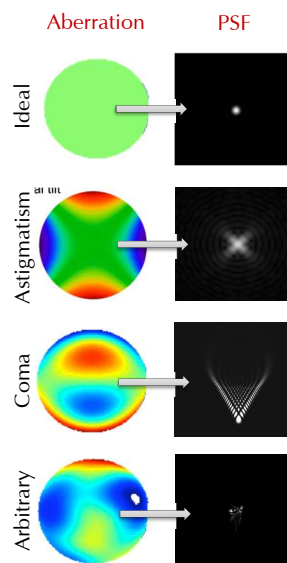
Wavefront Error and Aberrations



Root-mean-square
wavefront error

$$WE_{RMS} = \sqrt{\frac{\iint \Delta W(x,y)^2 dx dy}{\iint dx dy}}$$

- WE_{RMS} : Deviation from an “ideal” wavefront
 - ❑ Quantitative measure for aberrations
- Diffraction-limited performance criteria
 - ❑ Marechal criteria: $WE_{RMS} < \lambda / 13.4$
 - ❑ For more sensitive applications: $WE_{RMS} < \lambda / 50$

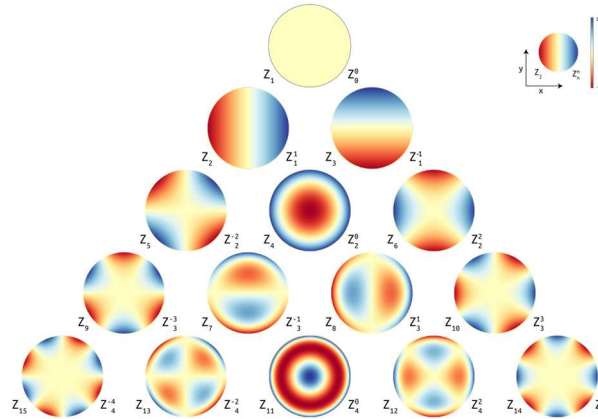


Micro-optics II – Theory

EPFL

Modelling aberrations: The Zernike Modes

- Orthonormal set of basis functions defined on a unit circle
- Any arbitrary wavefront can be represented as a linear combination
- Coincides with fundamental aberrations



Micro-optics II – Theory

EPFL

Theory- Take home messages!

- **Gaussian Optics**
 - ❑ A paraxial approximation
 - ❑ Depth of focus and spot-size are correlated
- **Interference and Interferogram**
 - ❑ Interference is the superposition of multiple beams
 - ❑ Coherence length of a source is related to its spectrum
 - ❑ Interferogram and spectrum are Fourier pairs
- **Diffraction - Fourier Optics**
 - ❑ An aperture profile and its far field diffraction pattern form a Fourier pair
 - ❑ A lens is essentially a Fourier transformer
 - ❑ Diffraction puts a limit on the resolution of an optical system
- ❑ **Quantifying Image Performance**
 - ❑ Point spread function (PSF) and modulation transfer function (MTF)
 - ❑ PSF and MTF are Fourier pairs



Micro-optics II – Theory

EPFL

DEVICES AND APPLICATIONS

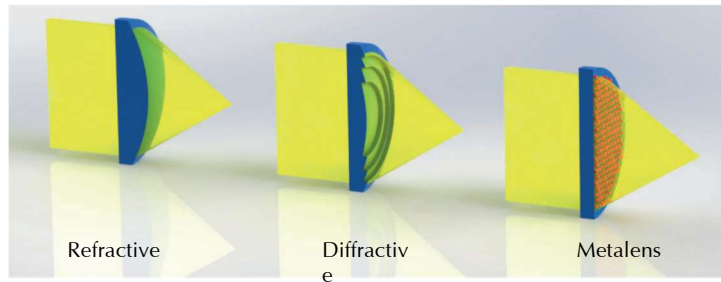


Devices and applications

- Refractive microlenses
 - Fresnel lens
 - GRIN lenses
 - Microlens arrays
- Diffractive microlenses
 - The diffractive “Fresnel” lens
- Diffraction gratings
 - Case study: How to solve a diffraction problem?
- Diffractive optical elements



Microlenses



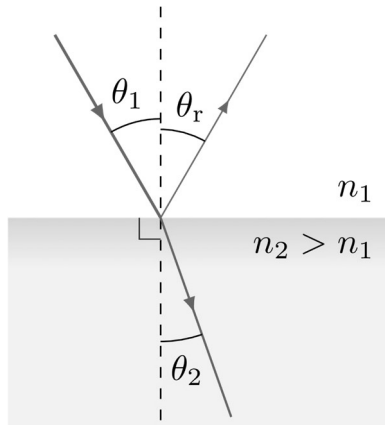
Nature Communications, (2020)
11:1991



REFRACTIVE MICROLENSES



Refraction

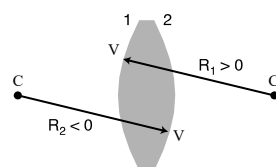
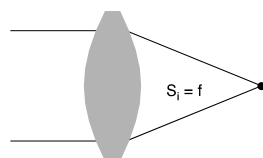


$$n_1(\lambda) \sin \theta_1 = n_2(\lambda) \sin \theta_2$$



Refractive lenses

- Smooth curved surfaces
- Volume (and weight) grows rapidly with aperture size



- Focal Length

$$\frac{1}{f} = \left(\frac{n_L}{n_0} \right) \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$

- Refractive power

$$C = \frac{1}{f}$$

- Lensmaker's formula

$$\frac{1}{f} = \frac{1}{S_i} + \frac{1}{S_o}$$

S_o : Object distance
 S_i : Image distance



The Fresnel lens

- “The invention that saved a million ships”
- Independently invented by Georges-Louis Leclerc and Augustin-Jean Fresnel
- Lighthouse lenses with
 - Large aperture
 - Short focal length
 - Low mass
- $d \gg \lambda \rightarrow$ not diffractive!

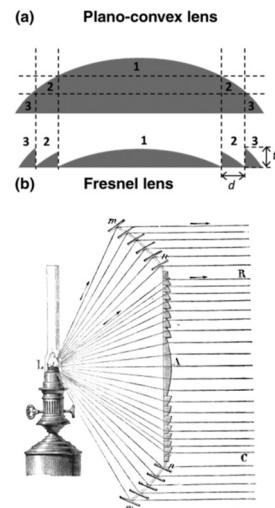


<https://commons.wikimedia.org/w/index.php?curid=150664>



Micro-optics III – Devices and Applications

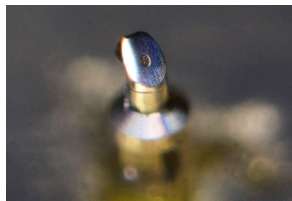
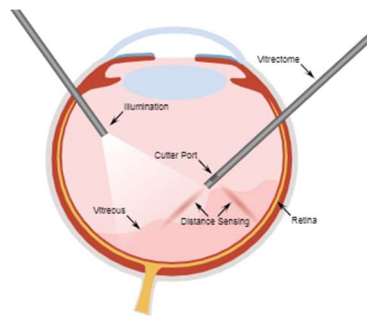
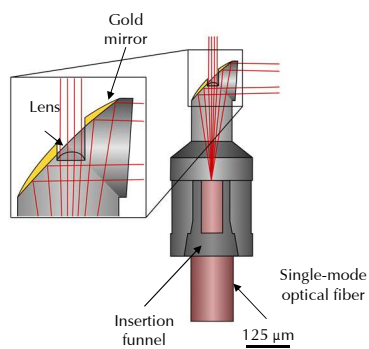
79



Micro-605: Optical MEMS and Micro-Optics

EPFL

Beam shaping on fiber-tips



Micro-optics III – Devices and Applications

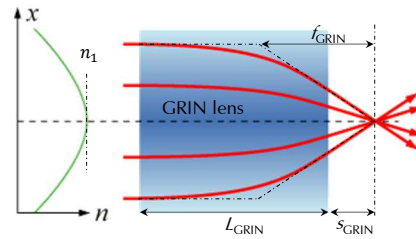
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Micro-605: Optical MEMS and Micro-Optics

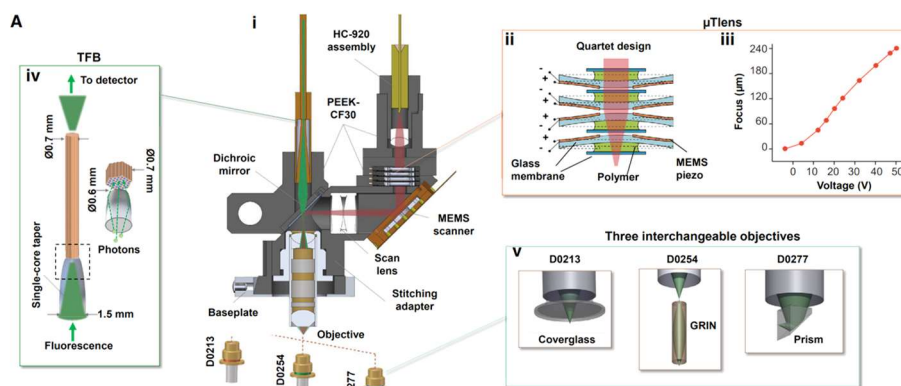
EPFL

Gradient-index (GRIN) optics

- Affects the optical path by varying the index of refraction within the lens
- Fabricated by ion diffusion
- Ultra-compact lenses with flat surfaces
 - No grinding & simple surface polishing
 - Control of aberrations through the index profile
- Applications
 - Photocopiers & scanners
 - Optical communication networks
 - Endoscopic imaging
 - Neuroscience & optogenetics



GRIN optics for neuroscience



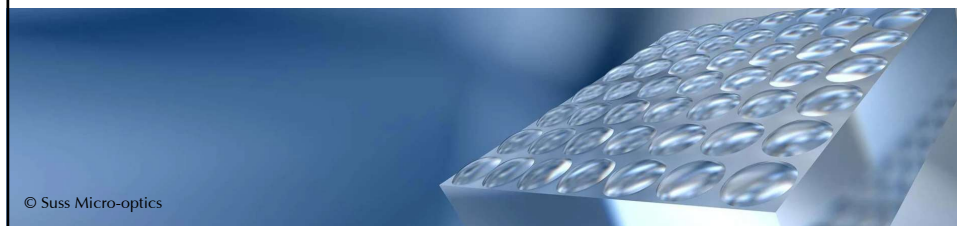
Cell 185, 1240–1256, March 31, 2022





Microlens arrays (MLAs)

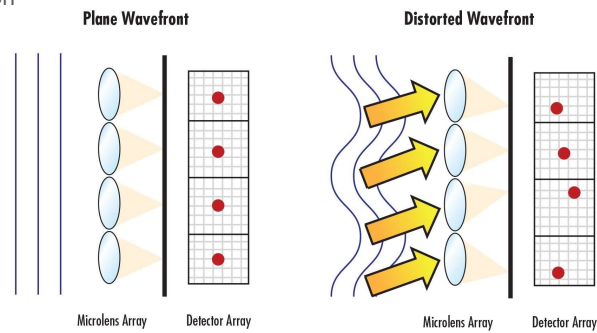
- Applications
 - Digital photography and IR imaging
 - Retinal scanning displays
 - 3D and integral imaging
 - Source-to-fiber light coupling
 - Automotive lighting
 - Laser beam shaping
 - Illumination optics
 - Optical switches and cross-connects
- Fabrication methods
 - Reflow
 - Grayscale lithography
 - Nanoimprint lithography
 - Injection molding
 - Wafer-level imprinting
 - Ion diffusion
 - Femtosecond laser ablation
 - 3D nano-printing



© Suss Micro-optics

Shack-Hartmann Wavefront Sensors

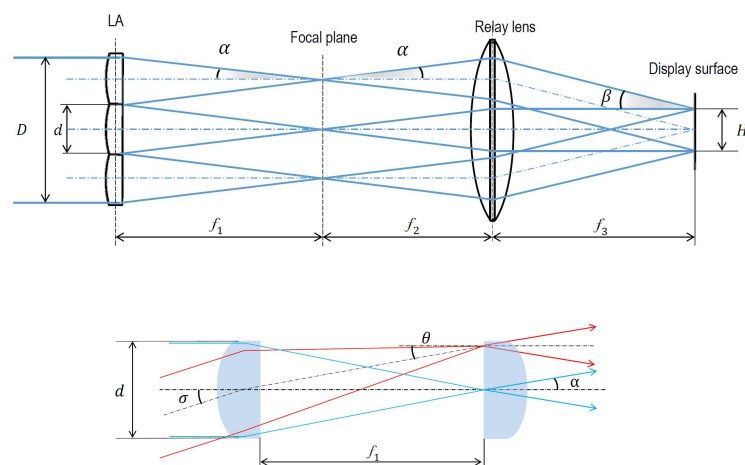
- Ideal for characterizing continuous wavefronts
- Key component in many adaptive optics systems
 - Astronomy
 - Ophthalmology
 - Laser beam correction



© Edmund Optics



Fly's eye beam homogenizer

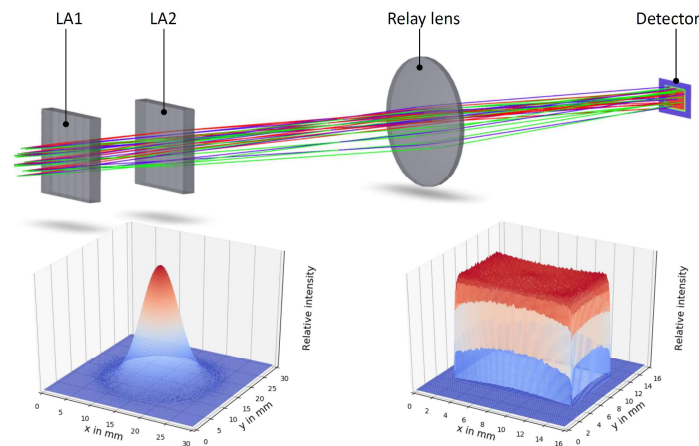


Li et al., Appl. Sci. 2020, 10, 4569



Fly's eye beam homogenizer

- DUV Lithography, automotive lighting, laser machining, etc.



Li et al., Appl. Sci. 2020, 10, 4569



Micro-optics III – Devices and Applications

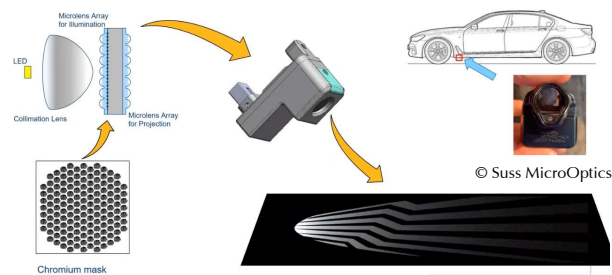
87

Micro-605: Optical MEMS and Micro-Optics



Automotive lighting: light carpets

- **Micro-projector array** with double-sided MLAs
- Combines beam homogenization and imaging
- Wafer-level imprint manufacturing in Neuchatel!!
- Chromium mask with slightly different image for each channel
- Overlapped projections form an achromatic, long depth-of-focus image



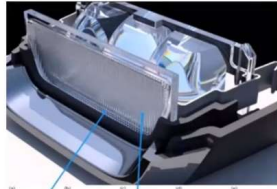
Micro-optics III – Devices and Applications

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Micro-605: Optical MEMS and Micro-Optics

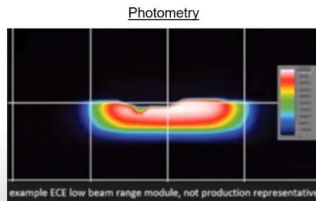
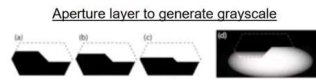


Automotive lighting: Precision headlights



Different aperture shapes in each channel

- + High contrast with > 2000 individual projectors
- + Modular construction
- + Less weight compared to conventional systems
- + Combination of several benefits
(Modular, Slim, lightweight, High Contrast, High Efficiency)



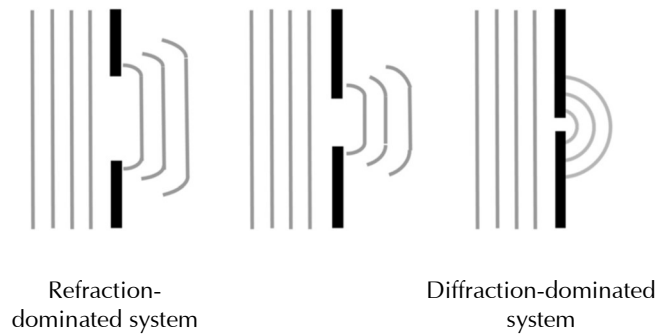
© Suss MicroOptics & Lucid Motors



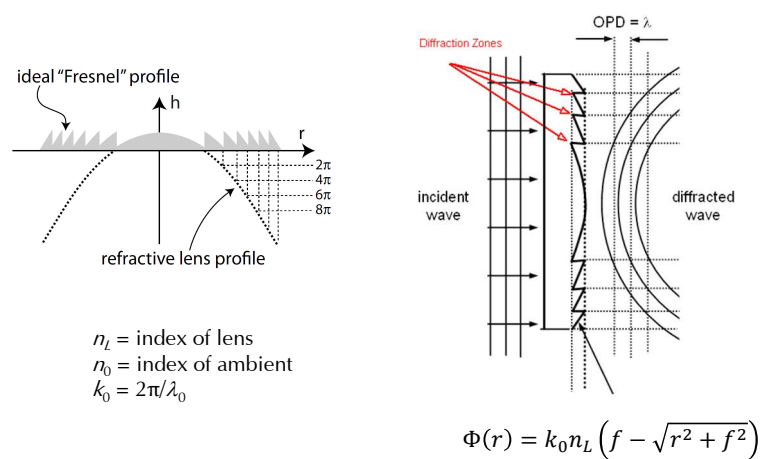
DIFFRACTIVE MICROLENSES



Refraction → Diffraction

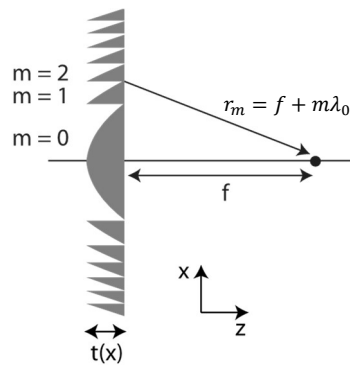


The diffractive “Fresnel” lens



The diffractive “Fresnel” lens: Profile

- Constructive interference of each zone on the optical axis
- *Focal length defined by the geometry of the zones and λ_0 !*



- With r_m the radius at the beginning of zone m ; we have

$$r_m^2 + f^2 = (f + m\lambda_0)^2$$

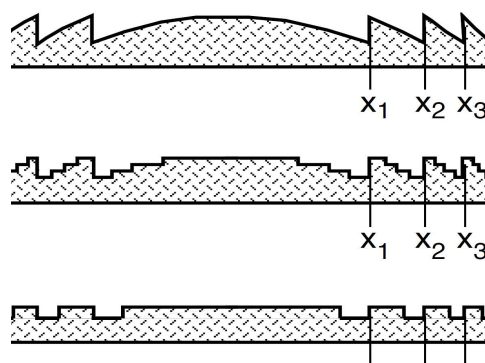
- Focal length in the paraxial regime

$$f = \frac{r_m^2}{2m\lambda_0}$$

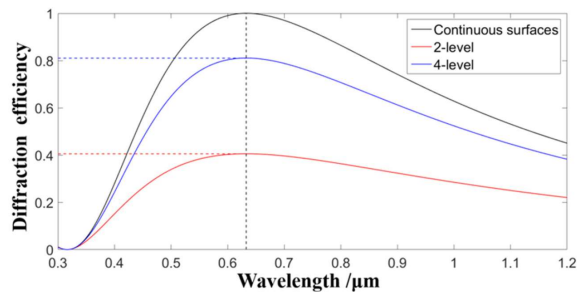
- Radii of consecutive zones

$$r_m = \sqrt{2m\lambda_0 f}$$

The diffractive “Fresnel” lens: Implementation



Diffraction efficiency vs. wavelength



$$\eta = \frac{1}{L^2} \cdot \sin^2\left(\frac{i}{L}\right) \cdot \frac{\sin^2\left[\frac{\pi(\alpha - i)}{L}\right]}{\sin^2\left[\frac{\pi(\alpha - i)}{L}\right]}$$

i : diffraction order
 L : number of levels
 α : λ_0/λ

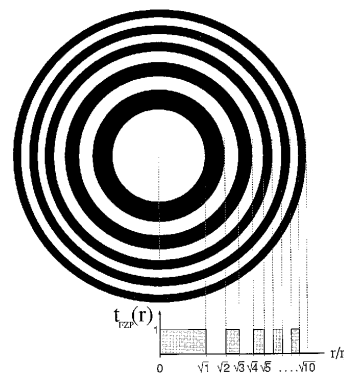


The zone plate

- The simplest form of diffractive lens
- Consecutive opaque and transparent zones
- Constructive interference of the transmitted light on the axis
- Applications
 - X-ray optics

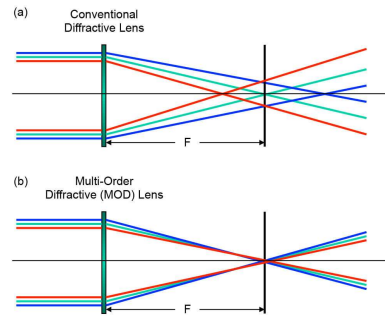
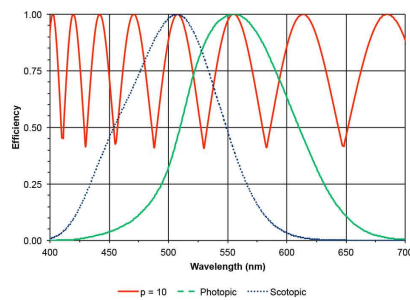


Ion Beam Milled Fresnel Zone Plate



Multi-order lens (MOD)

- Combines refractive and diffractive characteristics
- Multiple waves of phase shift at each zone -> multi-order
- High efficiency at multiple wavelength



© Apollo Optical Systems



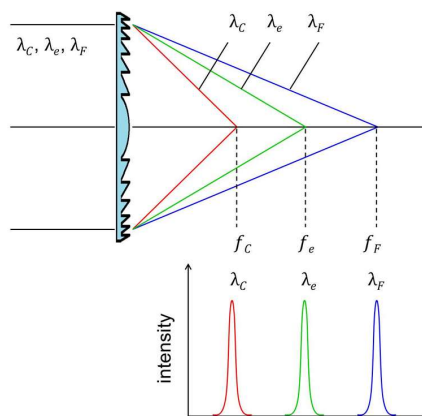
Micro-optics III – Devices and Applications

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Micro-605: Optical MEMS and Micro-Optics



Dispersion of diffractive lenses



$$f(\lambda) = f_0 \frac{\lambda_0}{\lambda}$$



Micro-optics III – Devices and Applications

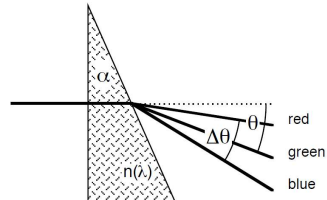
98

Micro-605: Optical MEMS and Micro-Optics



Abbe numbers of diffractive and refractive lenses

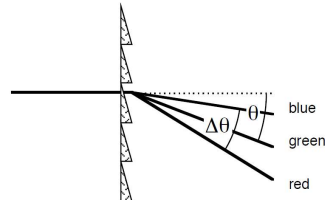
Refraction



$$v_r = \frac{\theta}{\Delta\theta} = \frac{n_d - 1}{n_F - n_C}$$

$$\begin{aligned}\lambda_d &= 587.6 \text{ nm} \\ \lambda_F &= 486.1 \text{ nm} \\ \lambda_C &= 656.3 \text{ nm}\end{aligned}$$

Diffraction

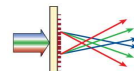
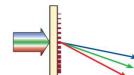
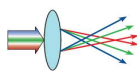
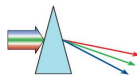


$$v_r = \frac{\theta}{\Delta\theta} = \frac{\lambda_d}{\lambda_F - \lambda_C}$$

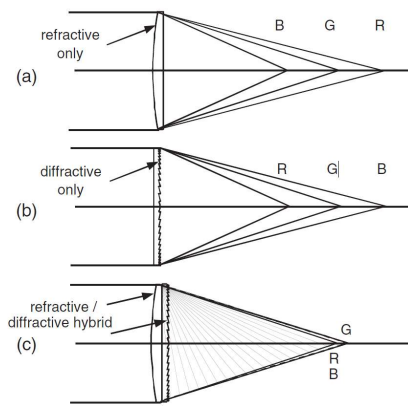


Refractive vs. diffractive dispersion

	Refractive	Diffractive
Abbe number:	$v_r = \frac{n(\lambda_1) - 1}{n(\lambda_2) - n(\lambda_3)}$	$v_d = \frac{\lambda_1}{\lambda_2 - \lambda_3}$
$\lambda_1 = 587.6 \text{ nm}$ $\lambda_2 = 486.1 \text{ nm}$ $\lambda_3 = 656.3 \text{ nm}$	$v_r = 80 \text{ to } 20$	$v_d = -3.45$



Hybrid achromats



- Refractive and diffractive dispersion cancel each other out

$$\frac{C_{ref}}{v_{ref}} + \frac{C_{diff}}{v_{diff}} = 0$$

- Refractive powers add up

$$C_{hybrid} = C_{ref} + C_{diff}$$

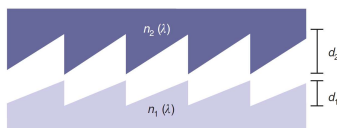
- Effective focal length

$$\frac{1}{f_{hybrid}} = \frac{1}{f_{ref}} + \frac{1}{f_{diff}}$$

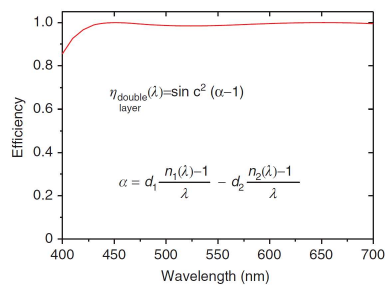


Multilayer diffractive lens

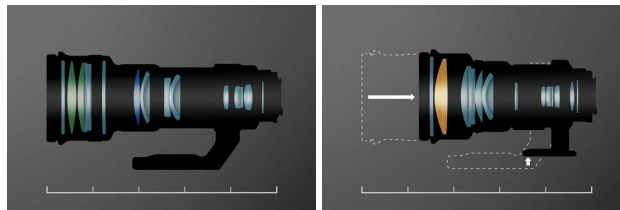
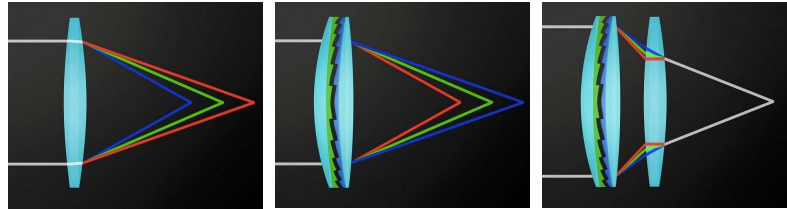
- Developed by Canon to achromatize efficiency
- Two equal-period diffractive lens with
 - Different step height
 - Different material
- Commercialized around 2013



Advanced Optical Technologies 2.5-6 (2013): 351-359.



Canon multilayer hybrid achromat



© Canon



Micro-optics III – Devices and Applications

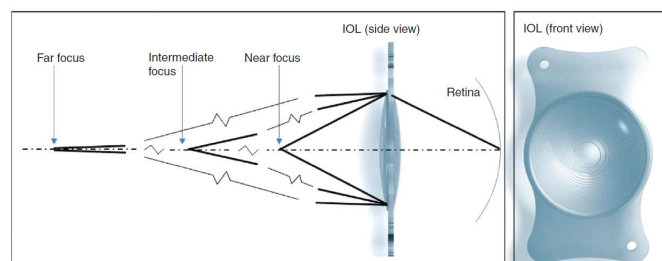
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Micro-605: Optical MEMS and Micro-Optics



Diffractive intra-ocular lens

- Multifocal intraocular lenses
 - Multiple diffractive lenses each optimized for a different focus
 - Single diffractive lenses operating at multiple diffraction orders
- Compensates for the lack of accommodation



Advanced Optical Technologies 2.5-6 (2013): 351-359.



Micro-optics III – Devices and Applications

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Micro-605: Optical MEMS and Micro-Optics



DIFFRACTION GRATINGS

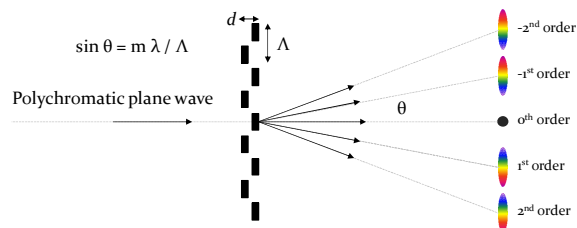


Micro-optics III – Devices and Applications

EPFL

Diffraction Gratings

- Optical component with a periodic structure
 - Period in the order of the wavelength
 - Transmission amplitude/phase gratings
 - Reflection binary/blazed gratings
- Splits light into multiple **diffraction orders**
- Orders separated by the **diffraction angle**
 - Defined by the period and the wavelength
- 2nd most common MOEMS component



Micro-optics III – Devices and Applications



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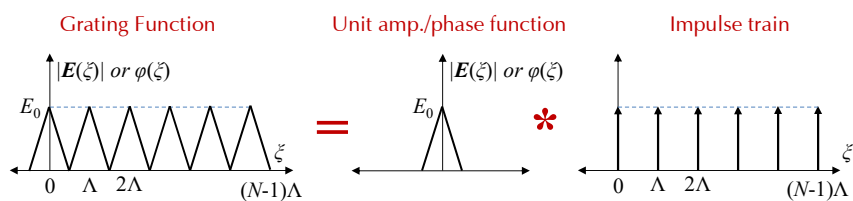
CASE STUDY: ANALYSIS OF DIFFRACTION GRATINGS USING FOURIER OPTICS



Micro-optics III – Devices and Applications

EPFL

How to Solve a Grating Problem



- Can be represented as the convolution of
 - A unit amplitude/phase function
 - An impulse train
- Our analysis will follow
 - Diffraction analysis of an impulse train
 - Array of point emitters
 - A binary phase grating
 - What does “tuning” a grating do ?

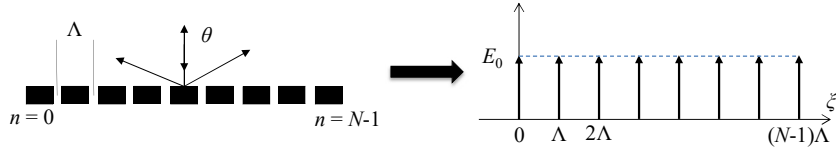


Micro-optics III – Devices and Applications

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EPFL

Diffraction for a Point Emitter Array



- For a 1D point emitter array, the E-field at the grating plane is

$$E_g(\xi) = E_0 \sum_{n=0}^{N-1} \delta(\xi - n\Lambda)$$

- The E-field the image plane is the Fourier transform of $E_g(\xi)$

$$E_i(x) = E_0' \sum_{n=0}^{N-1} e^{-jnk\Lambda \frac{x}{z_i}} \quad k = 2\pi / \lambda; z_i: \text{propagation distance}$$

- Substituting $x / z_i = \sin \theta$ yields $E_g(x)$ as a function of angle

$$E_i(\theta) = E_0' \sum_{n=0}^{N-1} e^{-jnk\Lambda \sin \theta}$$

For oblique incidence $\sin \theta \rightarrow \sin \theta + \sin \theta_i$



Diffraction for a Point Emitter Array- Continued

- With simple trigonometry we get

$$E_i(\theta) = E_0' \frac{e^{-jNk\Lambda \sin \theta} - 1}{e^{-jk\Lambda \sin \theta} - 1} = \frac{\sin(\frac{1}{2}Nk\Lambda \sin \theta)}{\sin(\frac{1}{2}k\Lambda \sin \theta)} e^{-\frac{1}{2} - j(N-1)k\Lambda \sin \theta}$$

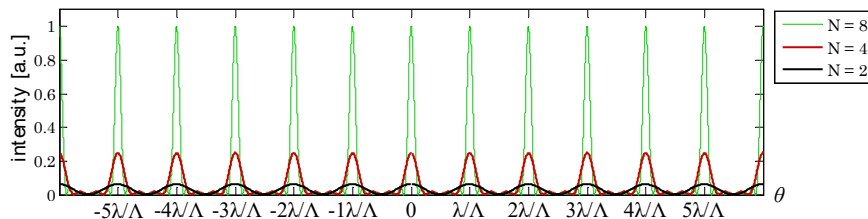
- The intensity profile is thus given by:

$$I_i(\theta) = \frac{I_0}{N^2} \frac{\sin^2(\frac{1}{2}Nk\Lambda \sin \theta)}{\sin^2(\frac{1}{2}k\Lambda \sin \theta)}$$

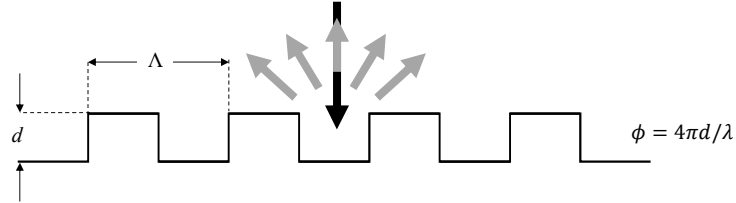
Diffraction profile has maxima at

$$\frac{1}{2}k\Lambda \sin \theta = \pm n\pi \Rightarrow \sin \theta = \pm n\lambda / \Lambda$$

$$\theta \approx \pm n\lambda / \Lambda$$

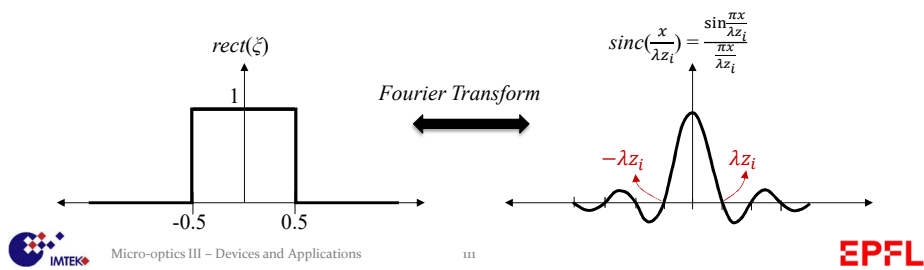


Reflective Binary Diffraction Grating



- The reflected/transmitted field:

$$E_g^b(\xi) = \left(e^{-j\phi/2} \text{rect}(2\xi/\Lambda - \Lambda/4) + e^{j\phi/2} \text{rect}(2\xi/\Lambda + \Lambda/4) \right) * E_g(\xi)$$



Binary Diffraction Grating

- Beyond Fraunhofer distance, the diffracted field is given by

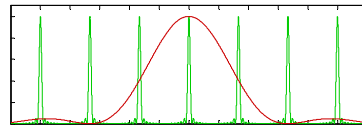
$$E_i^b(x) = \left(e^{-j\phi/2 - 2\pi\Lambda x/(4\lambda z_i)} \text{sinc}\left(\frac{\Lambda x}{2\lambda z_i}\right) + e^{j\phi/2 + 2\pi\Lambda x/(4\lambda z_i)} \text{sinc}\left(\frac{\Lambda x}{2\lambda z_i}\right) \right) \cdot E_i(x)$$

- If the diffracted light is focused with a thin lens of focal length z_f

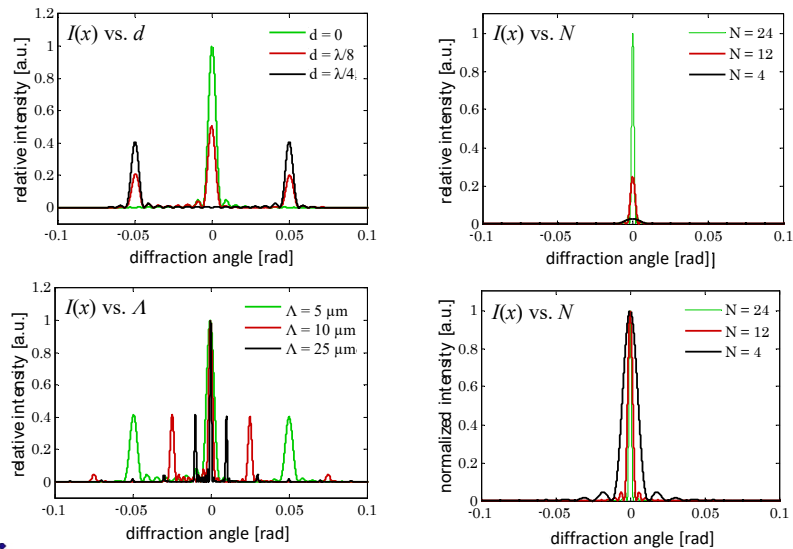
$$E_i^b(x) = \text{sinc}\left(\frac{\Lambda x}{2\lambda z_i}\right) \cdot \sin\left(\frac{\phi}{2} - \frac{2\pi\Lambda x}{4\lambda z_i}\right) \cdot E_i(x)$$

- Therefore, the intensity profile is

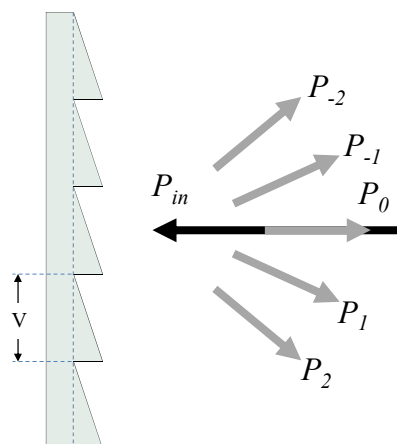
$$I_i^b(x) = \underbrace{\text{sinc}^2\left(\frac{\Lambda \sin\theta}{2\lambda}\right)}_{\text{envelope}} \cdot \underbrace{\sin^2\left(\frac{\phi}{2} - \frac{2\pi\Lambda \sin\theta}{4\lambda}\right)}_{\text{Intensity modulation}} \cdot \underbrace{I_i(\sin\theta)}_{\text{periodicity}}$$



Binary Diffraction Grating



Diffraction Efficiency

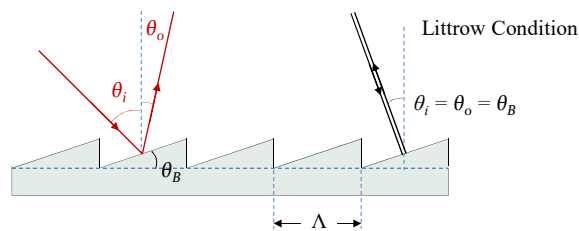


$$\eta = \frac{P_1}{\sum P_n}$$

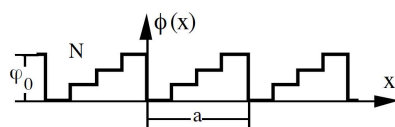
$$\eta_{total} = \frac{P_1}{P_{in}}$$

Blazed Diffraction Gratings

- High efficiency in a given diffraction order (up to 90%)
- Grooves with a “blaze angle” θ_B
- Diffraction angle: $\sin \theta_o + \sin \theta_i = \pm n\lambda/\Lambda$
- Littrow condition: $\theta_i = \theta_o = \theta_B$
 - The input and output rays, propagate along the same axis.
 - Blaze wavelength: $\theta_B = \text{asin} \frac{\pm n\lambda_B}{2\Lambda}$.



Multi-level blazed grating



blazed grating: $\varphi_0 = 2\pi$,

$$|A_n| = \frac{1}{N} \text{sinc}\left(\frac{n}{N}\right) \frac{\sin\left[\pi\left(\frac{n-1}{N}\right)\right]}{\sin\left[\pi\left(\frac{n-1}{N}\right)\right]}$$

$$|A_1|^2 = \left[\frac{N}{\pi} \sin\left(\frac{\pi}{N}\right) \right]^2$$

N: number of phase levels
n: diffraction order

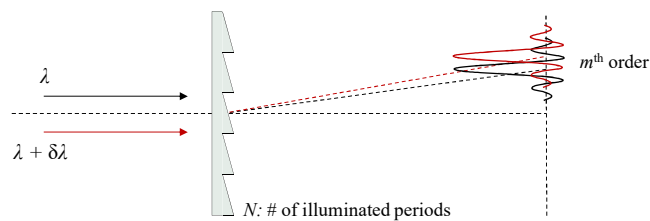
N =	2	4	8	16
$ A_1 ^2 =$	40.5%	81.1%	95.0%	98.7%

Resolving Power of a Grating

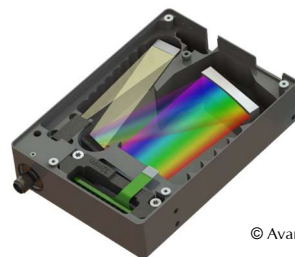
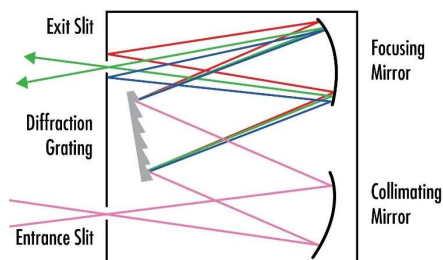
- Ability to separate two adjacent wavelengths λ and $\lambda + \delta\lambda$

$$\mathcal{R} \stackrel{\text{def}}{=} \frac{\lambda}{\delta\lambda} = mN$$

- Very important for grating based spectrometers
- Can you derive the resolving power expression?
 - Hint: The minima for λ and the maxima for $\lambda + \delta\lambda$ overlap at the order n



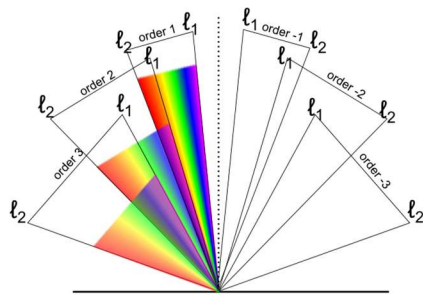
Grating spectrometer



© Avantes



Grating spectrometer: Free spectral range



- Assume the range without overlap at order m covers $\lambda \rightarrow \lambda + \Delta\lambda$.
- Then, the condition for no overlap at is given by

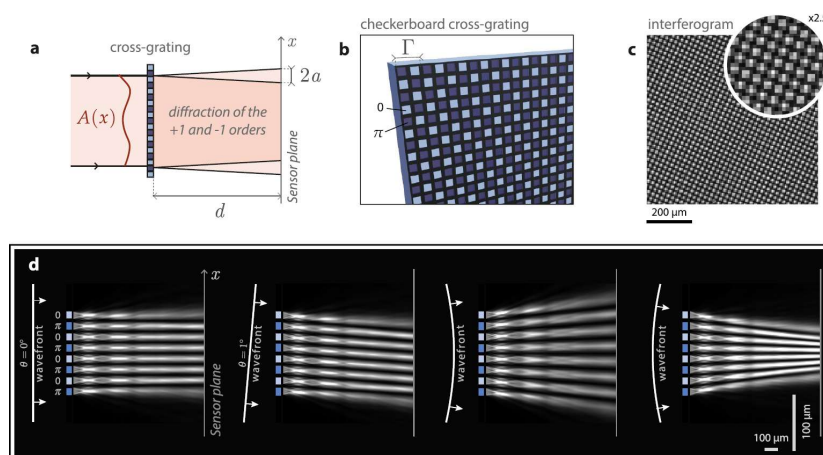
$$(m + 1)\lambda = m(\lambda + \Delta\lambda)$$

- Solving for $\Delta\lambda$ yields

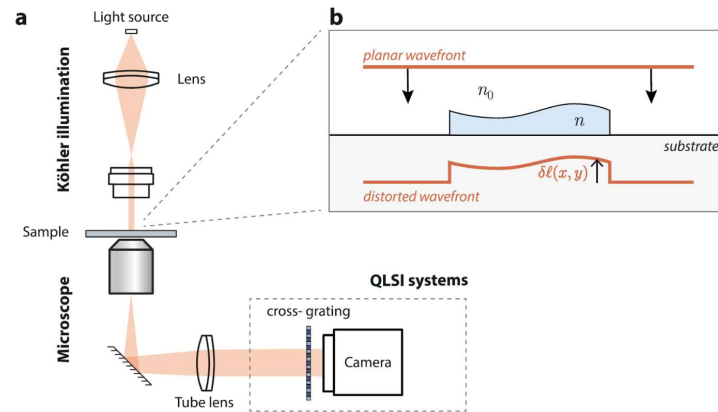
$$\Delta\lambda = \frac{\lambda}{m}$$



Quadriwave Lateral Shearing Interferometry (QWSLI)



Quantitative phase microscopy with QWSLI



ACS Photonics 2023, 10, 322–339



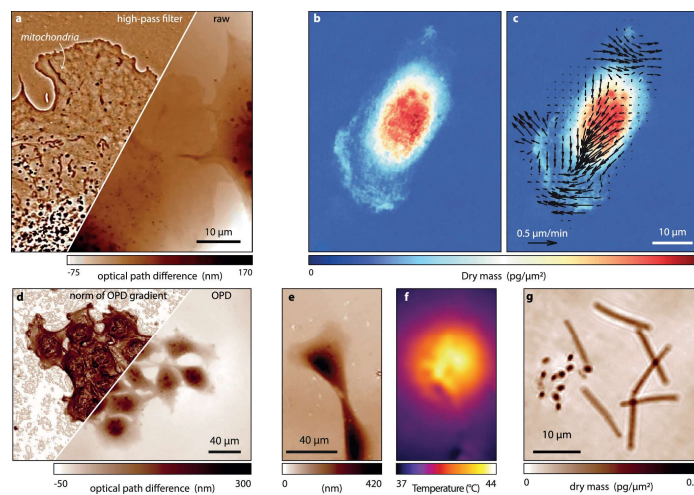
Micro-optics III – Devices and Applications

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Micro-605: Optical MEMS and Micro-Optics



Quantitative phase microscopy with QWSLI



ACS Photonics 2023, 10, 322–339



Micro-optics III – Devices and Applications

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Micro-605: Optical MEMS and Micro-Optics



DIFFRACTIVE OPTICAL ELEMENTS (DOEs)

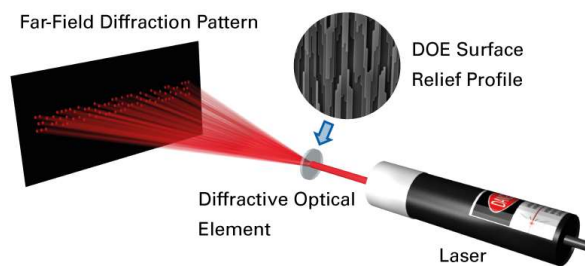


Micro-optics III – Devices and Applications

EPFL

Diffraction optical elements

- General name diffraction-based optical components
 - Sometimes called DOEs, CGHs, phase plates, kinoforms, ...
 - Highly λ -dependent
 - Includes a wide variety of optical structures
- Optical functionality
 - Arbitrary wavefront sculpting to form complex far-field patterns



© Holoeye



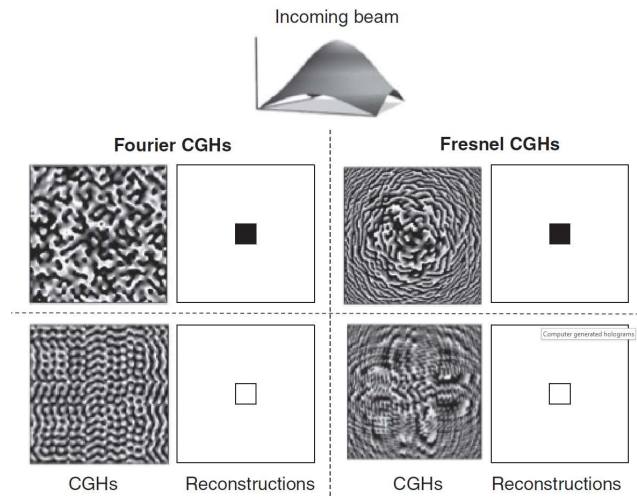
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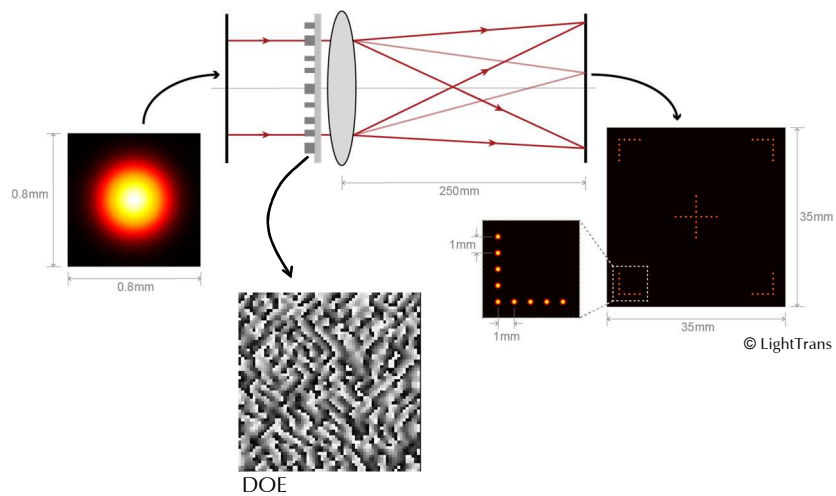
Micro-605: Optical MEMS and Micro-Optics

EPFL

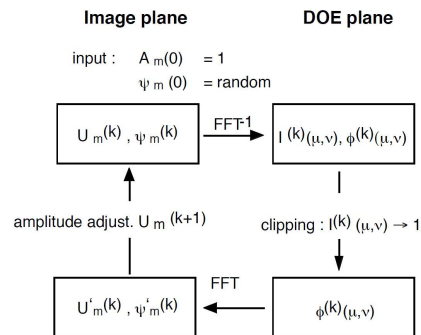
Computer generated holograms



Fourier array generator



Iterative Fourier transform algorithm (IFTA)

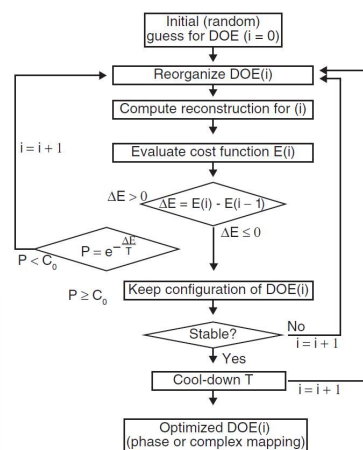
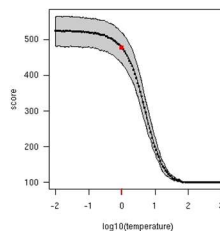
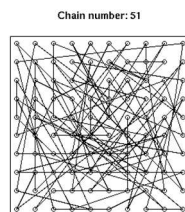


Ripoll, Olivier, Ville Kettunen, and Hans Peter Herzig. "Review of iterative Fourier-transform algorithms for beam shaping applications." *Optical Engineering* 43.11 (2004): 2549-2556.



Simulated annealing algorithm

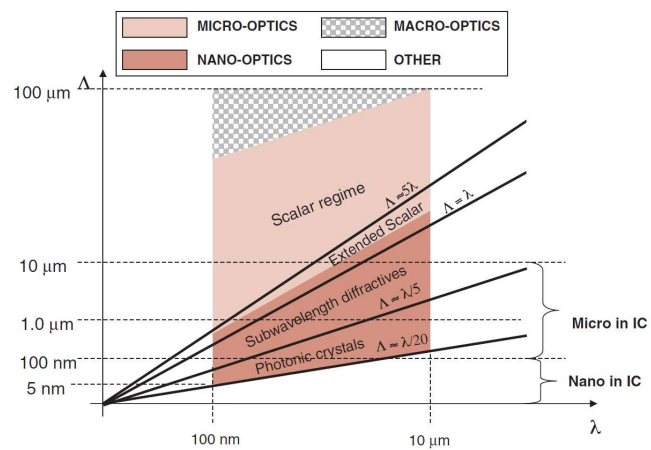
- A stochastic global search optimization algorithm
- Can prevent the cost function from being trapped in local minima
- Should be used alongside IFTA for fine tuning of the design



SUBWAVELENGTH OPTICS

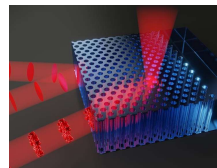
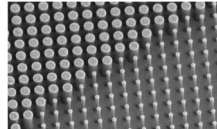
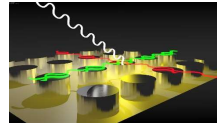


Subwavelength optics

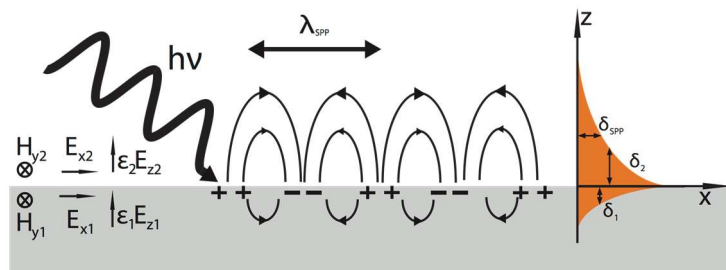


Subwavelength optics

- Plasmonic lenses
- Metasurface optics
- Photonic crystals

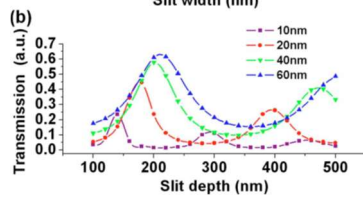
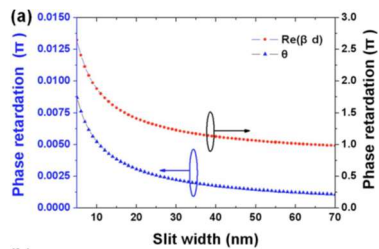
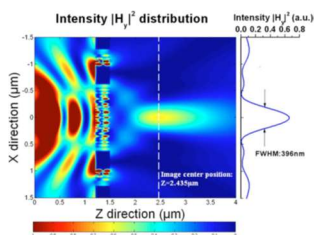
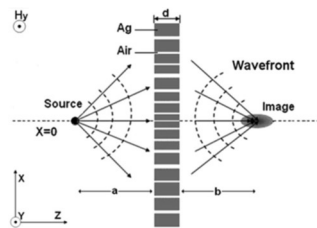


Surface plasmons



Wikipedia

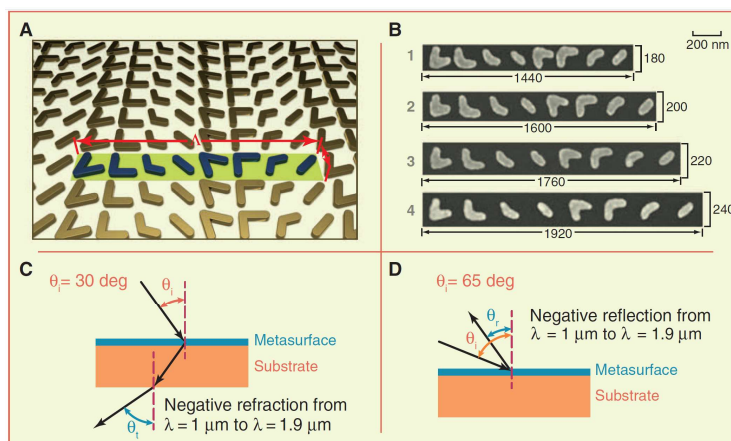
Metallic slab lens with nanoslits



APL91, 201501 2007



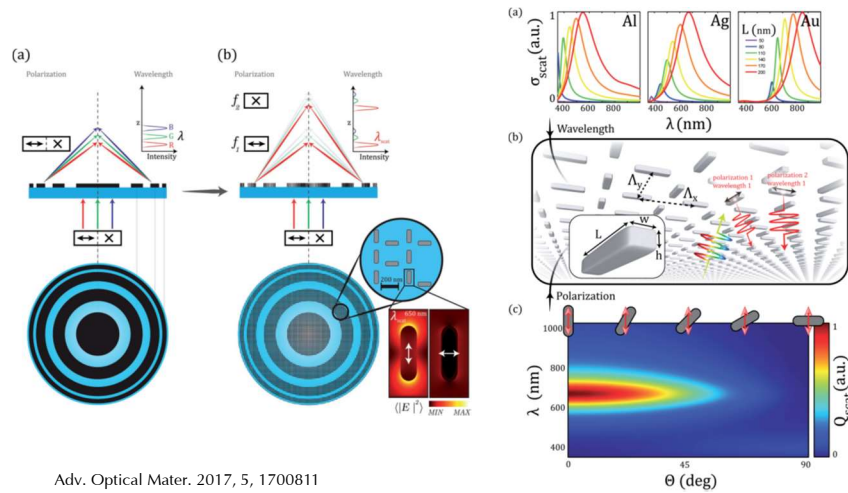
Plasmonic near-field optics



Science 339.6125 (2013): 1232009



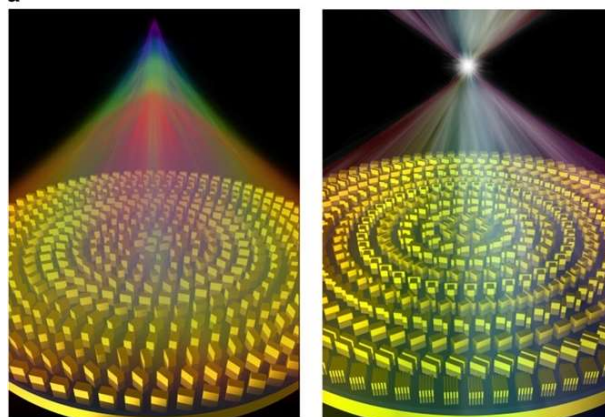
Plasmonic metalenses:



Adv. Optical Mater. 2017, 5, 1700811



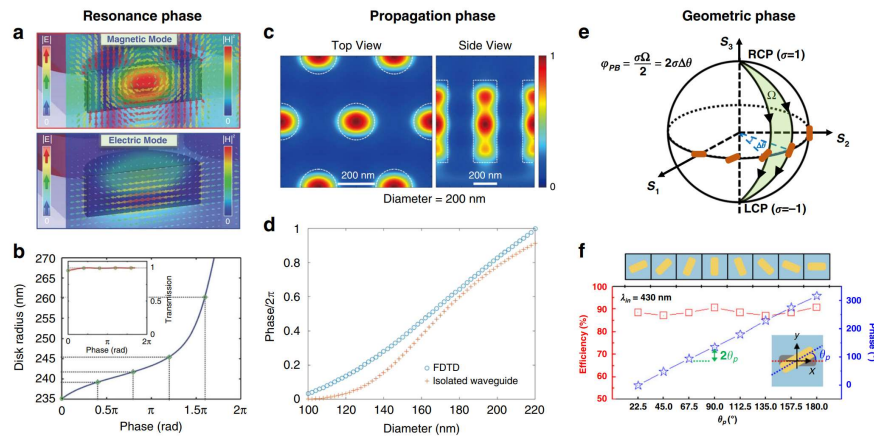
Dielectric metalens: Principle



Nature Communications 8:187 (2017)



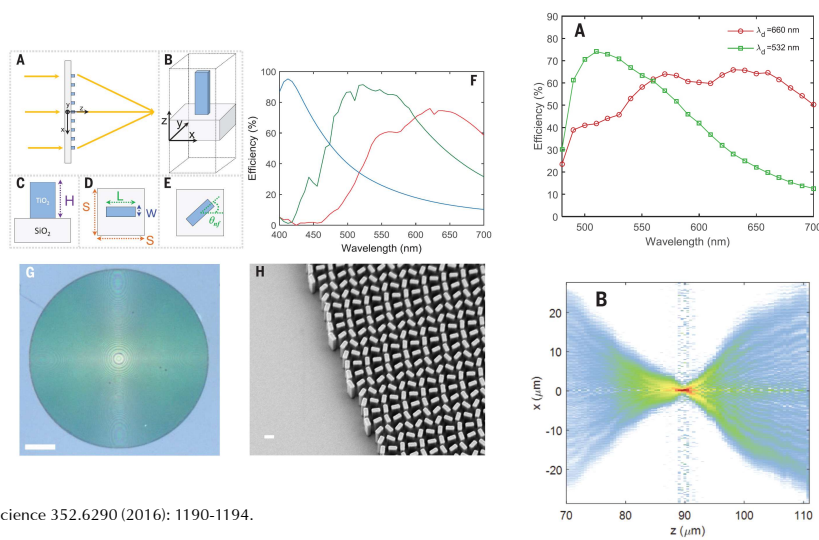
Controlling phase with meta-atoms



Light: Science & Applications (2022)11:195



Dielectric metalens

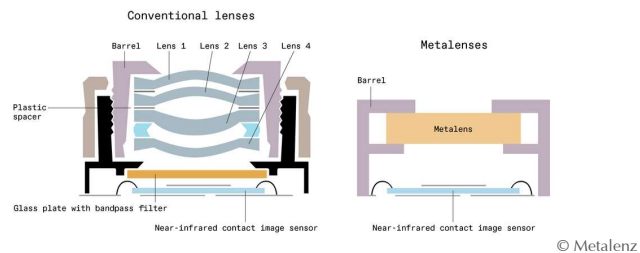


Science 352.6290 (2016): 1190-1194.

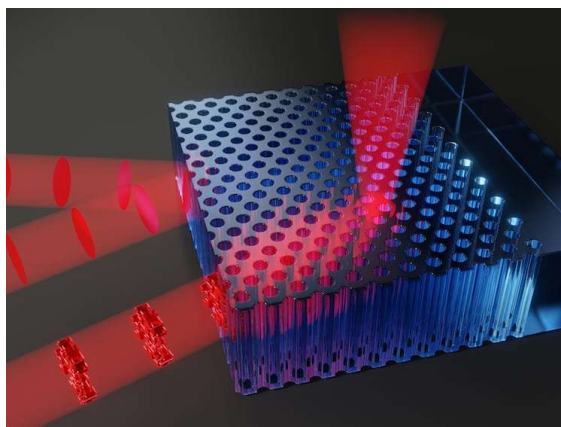


Metalenses with dielectric nanostructures

- *Potential* advantages compared to diffractive optics
 - Reduced thickness
 - Binary structure
 - CMOS compatibility
 - High numerical-aperture capability
 - Chromatic correction
 - Tunability
 - Polarization sensitivity

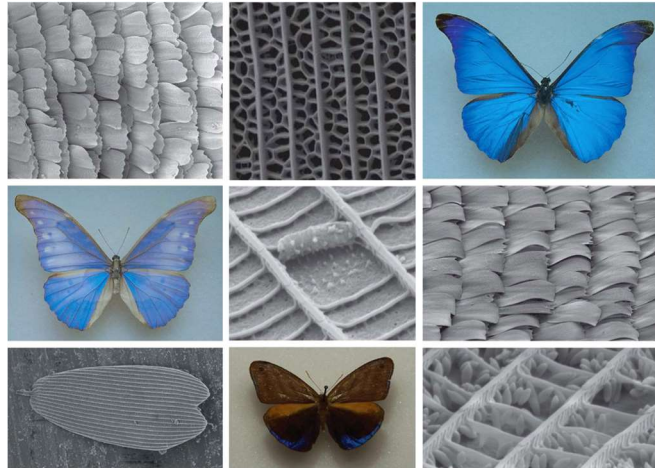


Photonic crystals



Courtesy: R Uppu (via Physics World)

Photonic crystals: Structured color



optoelectronics.eecs.berkeley.edu



Micro-optics III – Devices and Applications

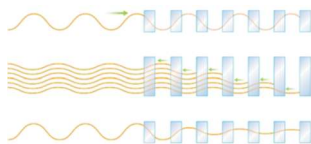
141

Micro-605: Optical MEMS and Micro-Optics

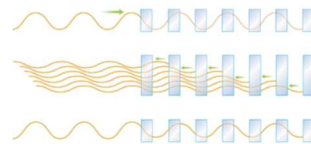


Photonic crystals. Operation principle

Resonant



Non-resonant



Micro-optics III – Devices and Applications

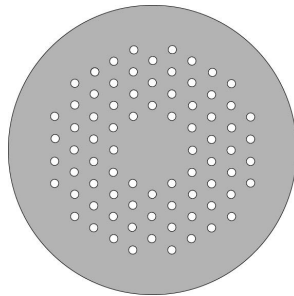
142

Micro-605: Optical MEMS and Micro-Optics

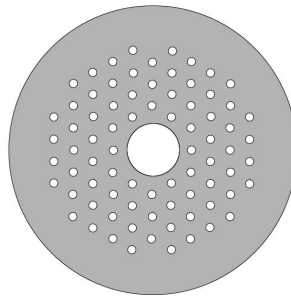


Photonic crystal fibres

Index guiding



Photonic bandgap



MICRO-OPTICS MANUFACTURING



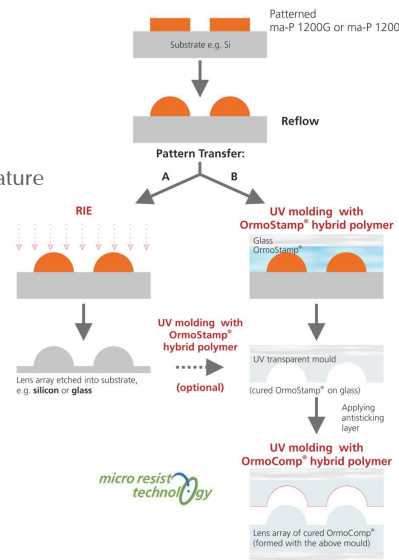
Micro-optics manufacturing

- Resist & Plasma Etching (RIE)
- Greyscale Lithography
- Imprint Technology
- Laser Ablation
- Injection Molding
- Ion Diffusion (GRIN)
- Direct Laser Writing
- Holography
- Diamond Turning
- Embossing or Mold Pressing



Reflow microlenses

- Thermal reflow
 - Melt PR cylinders
 - Hotplate / oven
- Lens shape depends on:
 - Surface tension
 - Temperature ramps & Maximum temperature
 - Photoresist viscosity
- Photoresist lenses
 - Only for $\lambda > 600$ nm
 - Limited robustness
- Or: transfer into substrate
 - Dry etch
 - Silicon
 - Glass
- Or: use as mold
 - For replication in polymers
 - PC, PMMA, SU8...



Geometry of reflow microlenses

- Focal length

$$f = \pi \frac{R}{n_L - 1}$$

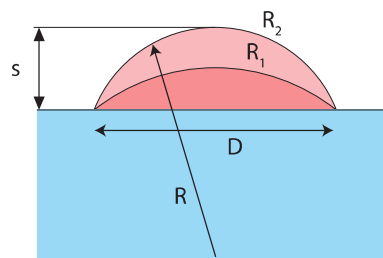
- Radius of curvature R
- Refractive index n_L

- Sag height

$$s = R - \sqrt{R^2 - \frac{D^2}{4}}$$

- PR thickness required

$$t_{PR} = \frac{s}{6} \left(3 + 4 \left(\frac{s}{D} \right)^2 \right)$$



Typical reflow lens characteristics

- Required f :

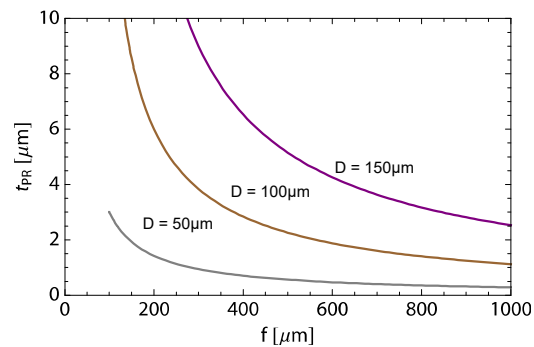
- $f = 100 \mu\text{m}$ $R = 60 \mu\text{m}$ $s = 15 \mu\text{m}$
- $f = 400 \mu\text{m}$ $R = 240 \mu\text{m}$ $s = 2.6 \mu\text{m}$

- Limits

- $t_{PR} > 10 \mu\text{m}$ difficult

- Typical ranges

- $D \leq 500 \mu\text{m}$
- $0.15 \leq NA \leq 0.45$
- $f/1 - f/3$
- Aberrations
 - $\leq \lambda/4$ typical



Micro-contact printing

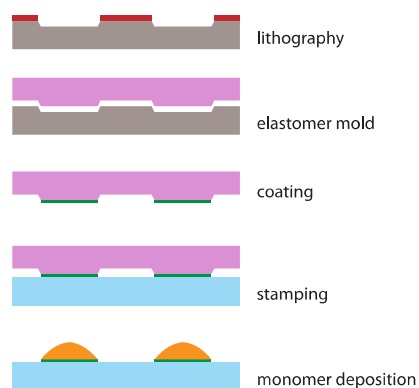
- Also called “soft lithography”

- Process steps

- Make a master relief structure
 - Typically Si
- Replicate in elastomer
 - Typically PDMS
- “Ink” with wetting agent
- Print patterns
- Self-assembly in hydrophilic regions
- Thermal or UV curing

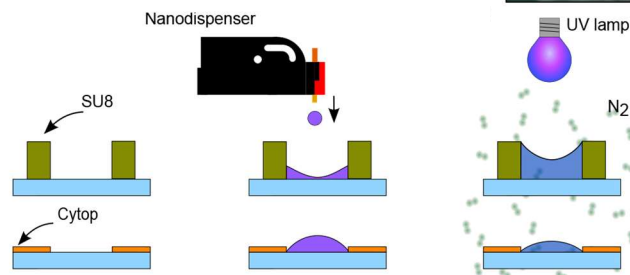
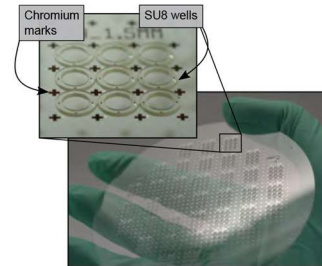
- Typical features

- Formation of large arrays
- Excellent surface quality
- Presence of radially symmetric aberrations (e.g. Spherical aberration)
- Low non-radially symmetric aberrations (e.g. coma, astigmatism)



Inkjet printing

- Lens printing with controlled volume
 - Print using “ink-jet” dispenser
 - “Drop on demand” UV-curable polymer
 - Structured surface patterns
 - Hydrophobic Cytop
 - Hydrophilic SU8



Blattmann et al., Optics Express 23.19 (2015): 24525-24536.



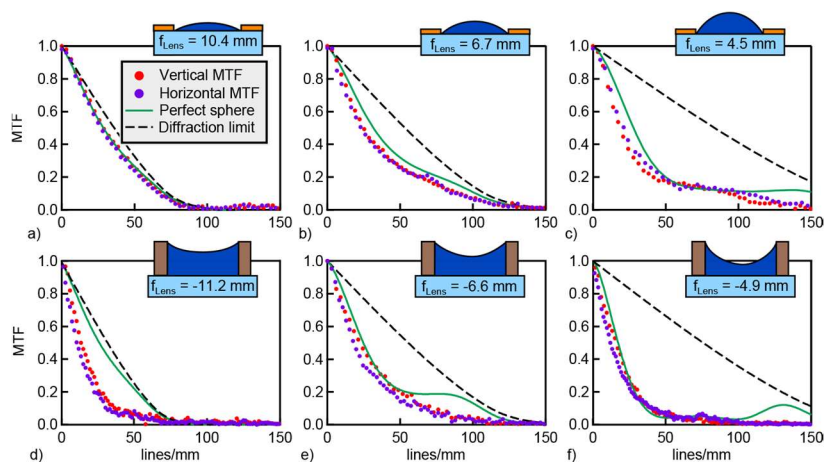
Micro-optics IV - Fabrication

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Micro-605: Optical MEMS and Micro-Optics



Optical performance of inkjet printed microlenses



Blattmann et al., Optics Express 23.19 (2015): 24525-24536.



Micro-optics IV - Fabrication

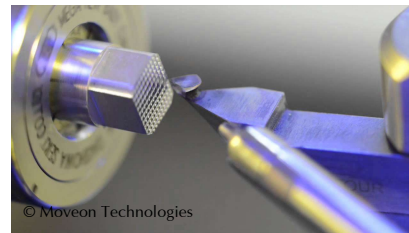
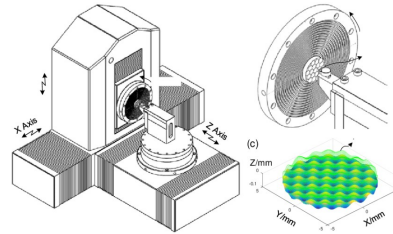
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Micro-605: Optical MEMS and Micro-Optics



Diamond turning/ruling

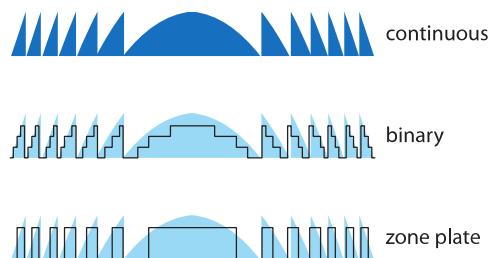
- Used for prototyping or tooling for large-dimension and/or deep gratings, especially reflection gratings
- Well-suited to produce circularly symmetric grooves
 - Fresnel lenses
 - Circular grating
 - Microlenses
- Four/five-axes machines for freeform optics manufacturing
- The geometry of the diamond tool's tip must be carefully chosen to for each part.



LITHOGRAPHIC METHODS

Binary-mask lithography

- Approximate the continuous lens profile by a stepped structure
 - Use standard “binary” lithography
 - 2^N levels for N lithography steps
 - More exposure steps
 - Closer approximation to ideal
 - Degrading efficiency due to alignment errors

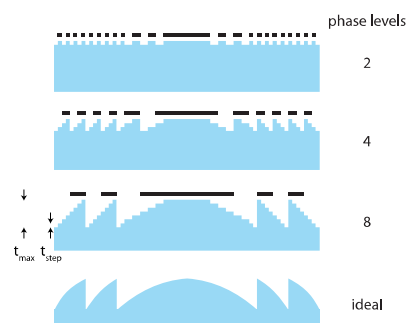


Phase levels & efficiency (η)

- Phase levels N
 - $N = 2^M$
 - M photolith steps
 - η increases with N

- Example
 - 4 photolith steps
 - $M = 4 \Rightarrow N = 16$
 - Then $\eta \sim 99\%$

- Limitations
 - Mask linewidth: $0.1 \mu\text{m}$ error $\Rightarrow \eta$ reduced by 10%
 - Alignment: $0.3 \mu\text{m}$ error $\Rightarrow \eta$ reduced by 10%
 - Etch depth: $\pm 2.5\%$ error $\Rightarrow \eta$ reduced by 1%

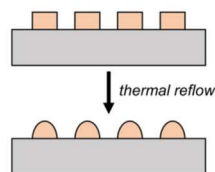


Grayscale/Continuous-relief lithography

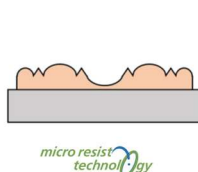
- Forming continuous (2.5D) features on a resist layer
- Fabrication of components, molds or etching masks
- Extremely high precision (<10 nm possible)
- Available technologies
 - Direct laser writing
 - Electron beam or focused ion beam (FIB) patterning
 - Thermal scanning probe lithography

HEIDELBERG
INSTRUMENTS

binary photolithography



greyscale lithography



Micro-optics IV - Fabrication

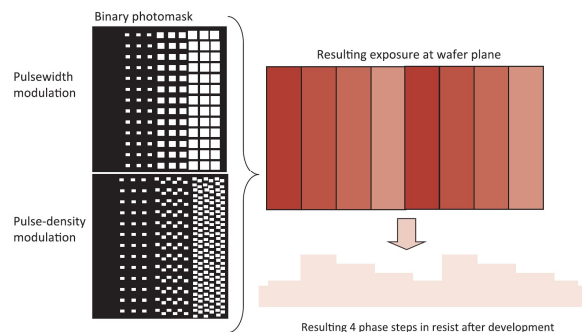
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Micro-605: Optical MEMS and Micro-Optics



Binary grayscale lithography

- Chromium mask with PWM or PWM for controlling dosage
- Features much smaller than the resolution of the tool
- Up to 1000 levels possible within OD range of 0 to 2.0 (1% transmission)
- A standard mask aligner in proximity mode



SPIE, Field guide to Digital Micro-optics



Micro-optics IV - Fabrication

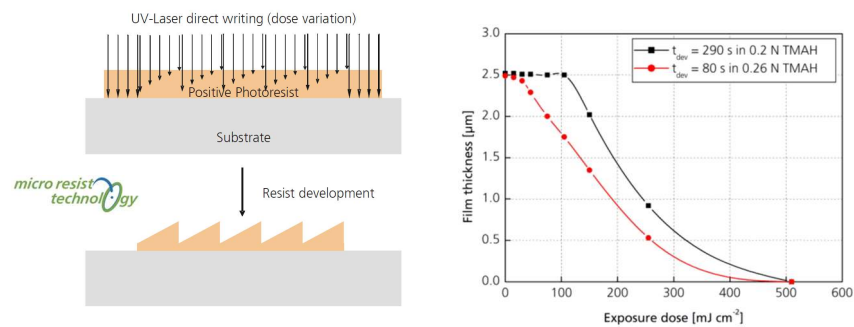
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Micro-605: Optical MEMS and Micro-Optics



Direct laser writing lithography

- UV sensitive photoresist exposed with an intensity-modulated beam
- No need for a mask
- A development step is needed
- Commercial system specifications
 - Up to 1,000 gray levels
 - Substrates up to 800 mm x 800 mm



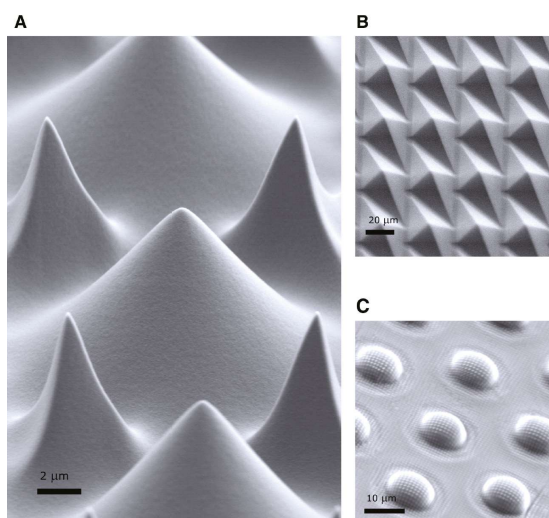
Micro-optics IV - Fabrication

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Micro-605: Optical MEMS and Micro-Optics



Direct laser writing lithography: Examples



Micro-optics IV - Fabrication

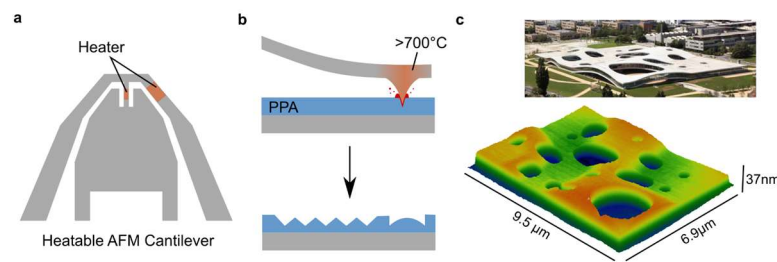
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Micro-605: Optical MEMS and Micro-Optics



Thermal scanning probe lithography (t-SPL)

- Local removal of material with an AFM probe with heated tip
 - No development needed
- Uses a resist that decomposes upon exposure to heat (>300°C, ~10µs)
- Double heaters
 - Material removal
 - Monitoring of the removal process
- Instrument available at EPFL (NanoFrazor from Heidelberg Instruments)



Courtesy of LMIS1 (Microsystems Laboratory / Jürgen Brugger)



Micro-optics IV - Fabrication

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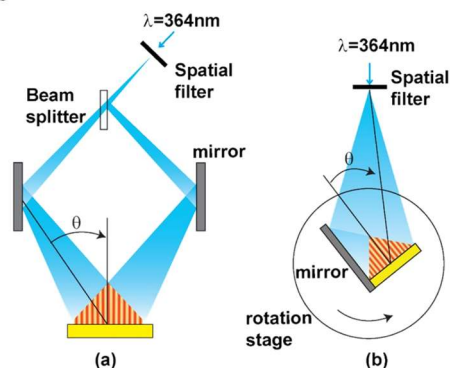
Micro-605: Optical MEMS and Micro-Optics



Laser interference lithography

- Approach related to holography
 - Simple gratings: parallel definition, single exposure
 - More complex structures with multiple exposure
 - Curved & chirped gratings possible
 - Large areas possible
- Used for large area coatings
 - Reflectors and anti-reflectors
 - Holographic gratings

$$\Lambda = \frac{\lambda}{2 \sin \theta}$$



Joong et al. (2011 InTech)



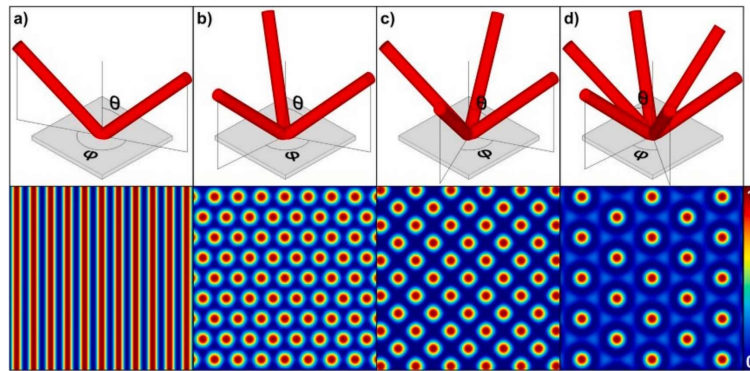
Micro-optics IV - Fabrication

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Micro-605: Optical MEMS and Micro-Optics



Multi-beam interference lithography



Mulko et al., Nanophotonics, 2021



Micro-optics IV – Fabrication

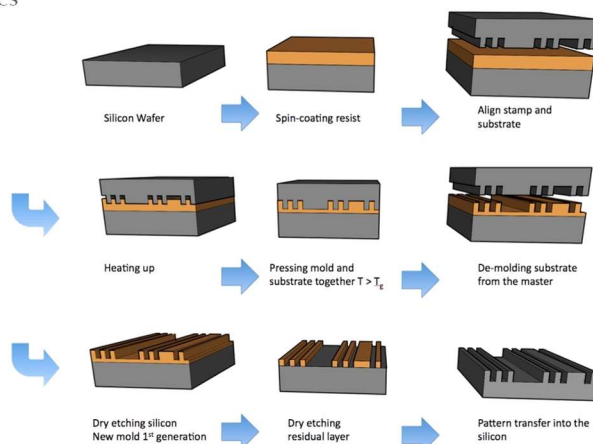
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Micro-605: Optical MEMS and Micro-Optics



Nanoimprint lithography

- Reproduce microstructures using molding techniques
 - Polymer / plastic optics
 - Integrated optics
 - Micro-optics
- Low cost
 - Mass production
 - € 0.001 – 0.01 / cm²
- Feature sizes
 - Down to sub-5 nm!
 - Sub-nm roughness



Paul Scherer Institute



Micro-optics IV – Fabrication

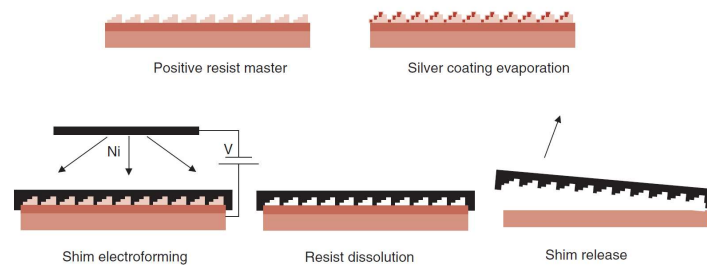
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Micro-605: Optical MEMS and Micro-Optics



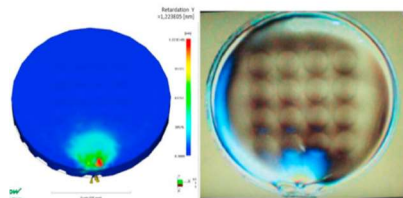
Shim manufacturing

- Materials
 - Glass, Ni, Brass
- Electroplated
 - PR master, Electroplated Ni
- Solid metals
 - Ultra-high precision machining
- LIGA

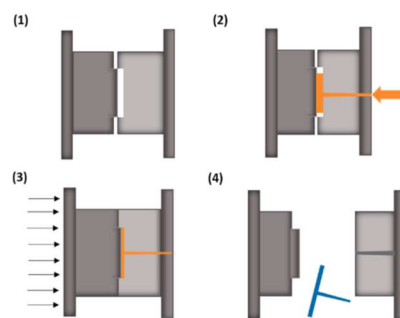


Injection molding

- Mass production of plastic optics
- Being developed for glass components
- Possible defect
 - Stress-induced birefringence
 - Aberrations due to non-uniform shrinkage and/or local refractive



Simulated residual stress vs. measured birefringence of an injection molded MLA

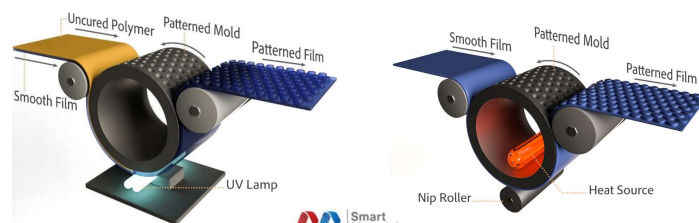


- Closing the mold;
- Filling
- Compression
- Cooling and ejection



Roll-to-roll nanoimprint lithography

- Ideal for large-area, polymeric optics
- Step-and-repeat or rotating mould type
- Applications
 - Fresnel lenses as micro-concentrators in photovoltaics
 - Lighting and illumination
 - 3D displays and VR
 - CCD and CMOS sensors
 - Display back- and front light guides



Micro-optics IV - Fabrication



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Micro-605: Optical MEMS and Micro-Optics



RAPID PROTOTYPING OF MICRO-OPTICS



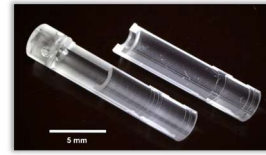
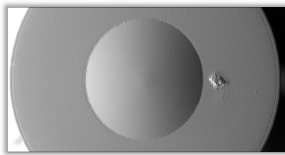
Micro-optics IV - Fabrication

Micro-605: Optical MEMS and Micro-Optics

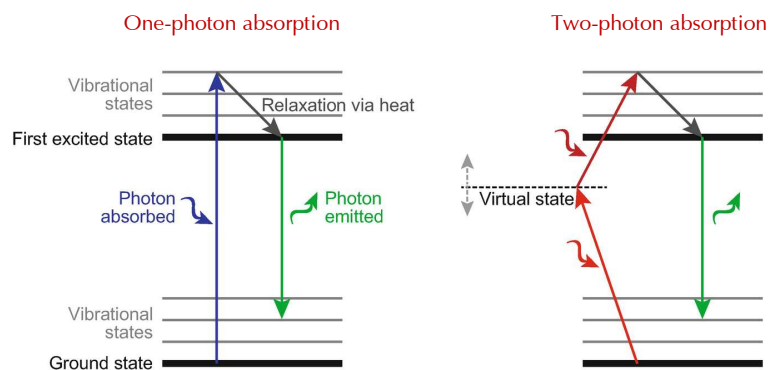


Rapid Prototyping of Micro-optics and MOEMS

- Motivation
 - How can we cut down design cycle time?
 - How to realize low-volume, high-complexity devices?
 - Can we manufacture optical surfaces and actuators monolithically?
- Most promising methods are
 - Laser ablation
 - Two-photon polymerization
 - Selective laser etching



Two-photon absorption process

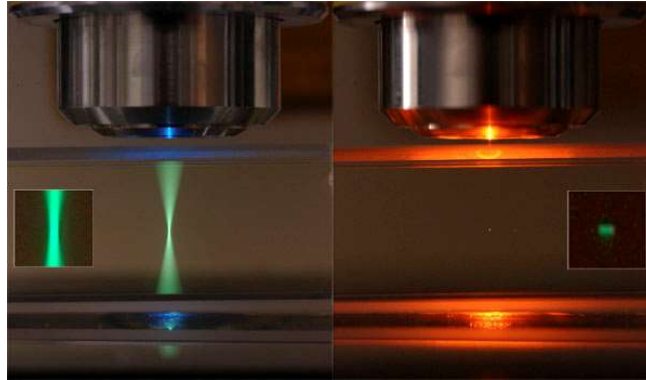


© Simon Thiele, ITO Stuttgart.

Two-photon absorption process

Conventional
fluorescence

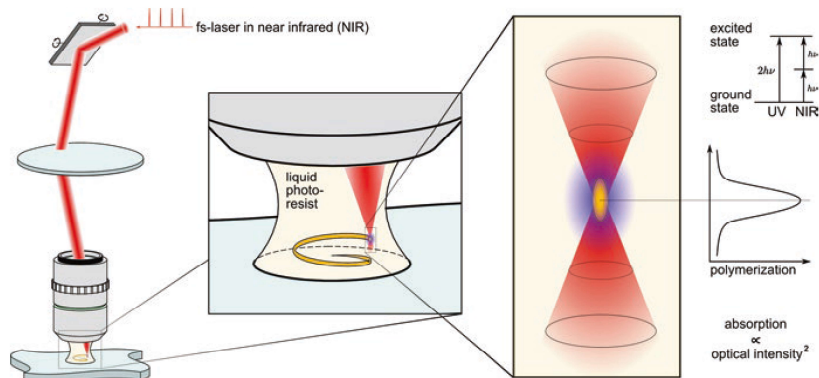
Two-photon excitation
fluorescence



© S. Ruzin and H. Aaron, UC Berkeley.

3D Printing by 2PP

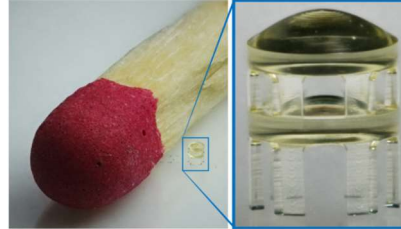
- Based on 3D scanning of a focal spot
- Overlapping of neighbouring voxels can lead to < 10 nm surface roughness
- Limited in maximum sample dimensions



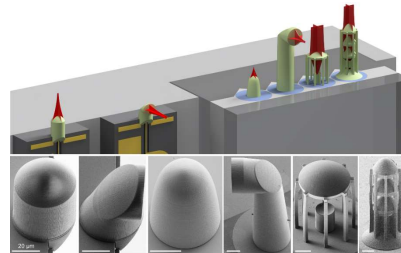
© Simon Thiele, ITO Stuttgart.

3D Printing by 2PP

- Voxel size depends on NA
 - 63X objective: $0.2 \times 0.2 \times 0.7 \mu\text{m}$
 - 20X objective: $0.6 \times 0.6 \times 5 \mu\text{m}$
- Optical quality surfaces possible by process optimization
 - Free-form optics
 - Complex optical surfaces
- Emerging actuator concepts
 - EM actuation via magnetic liquids
 - Electrostatic actuators



© ITO, Stuttgart



© Vanguard Photonics

microlight3D

upnano

nanoscribe



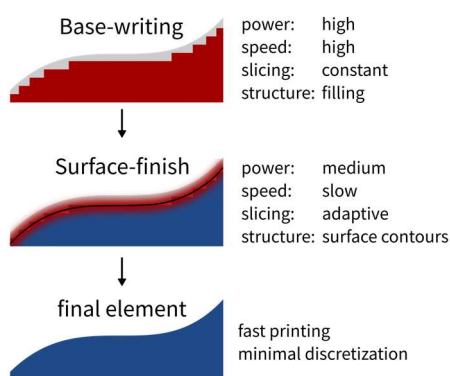
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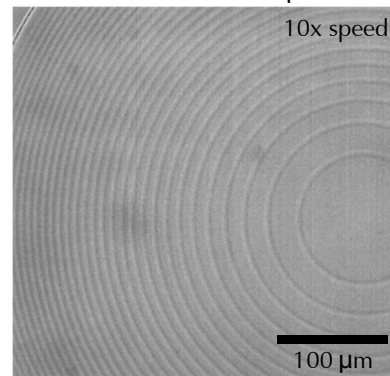
Micro-605: Optical MEMS and Micro-Optics

EPFL

3D Printing by 2PP: Adaptive surface finish



Surface-finish of a $\varnothing 750 \mu\text{m}$ lens



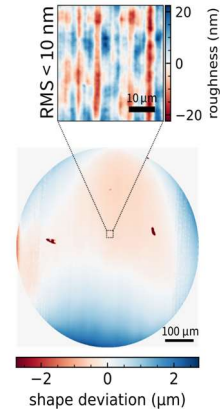
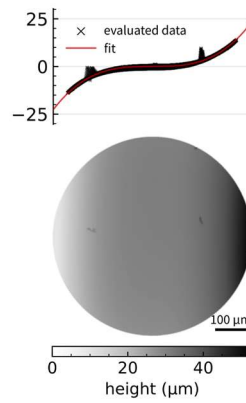
Micro-optics IV - Fabrication

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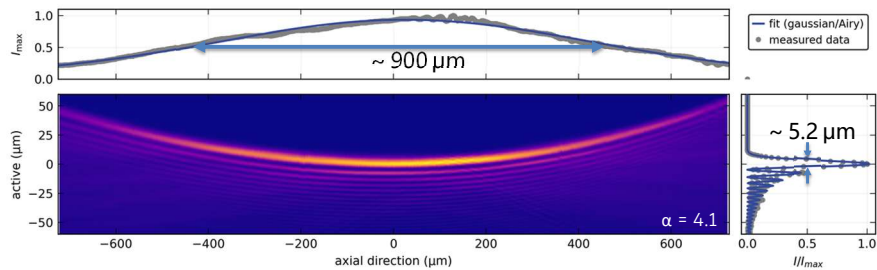
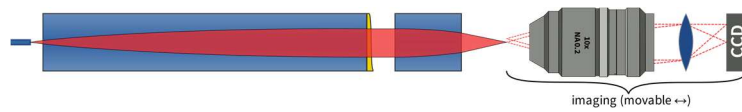
Micro-605: Optical MEMS and Micro-Optics

EPFL

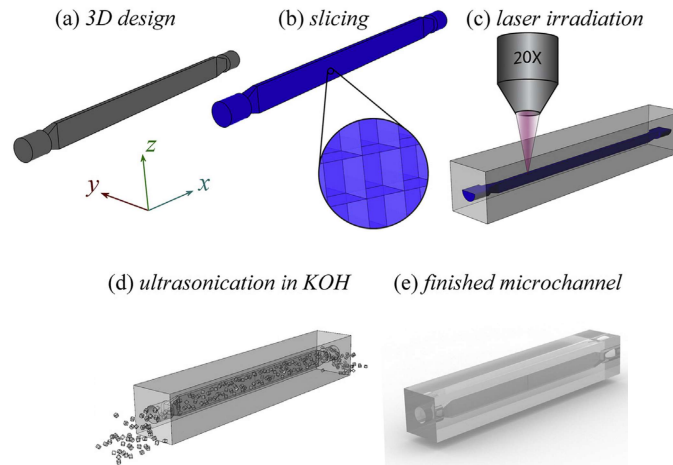
3D printing on GRIN lenses



3D printing on GRIN lenses



Selective Laser-Induced Etching of Glass



Current Opinion in Colloid & Interface Science 2019, 43:1–14



Micro-optics IV – Fabrication

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Micro-605: Optical MEMS and Micro-Optics



Selective Laser-Induced Etching of Glass

- Process details
 - Fused silica, quartz substrates
 - Two-photon based absorption
 - KOH etching of exposed areas
 - >1500 aspect ration (with fused silica)
 - $\sim 1/2 \mu\text{m}$ resolution/accuracy
- Potential for Optical MEMS
 - System integration platforms
 - Plug-and-play fibre interfacing
 - Actuators with 3D complexity
 - Electrostatic actuators
 - Magnetic actuators



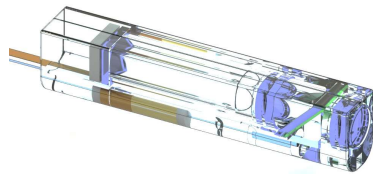
Micro-optics IV – Fabrication

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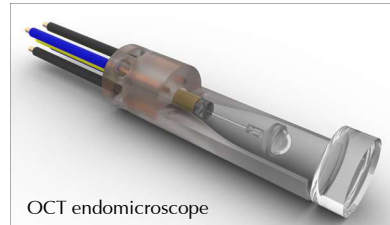
Micro-605: Optical MEMS and Micro-Optics



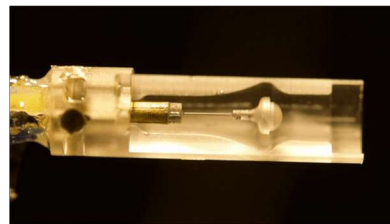
Use of SLE at IMTEK



JMM, 28 (10), 105009, 2018



OCT endomicroscope



Micro-optics IV - Fabrication

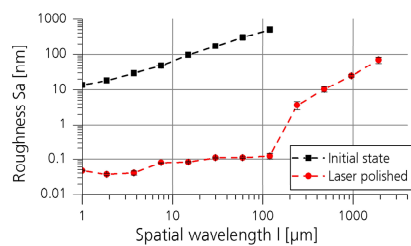
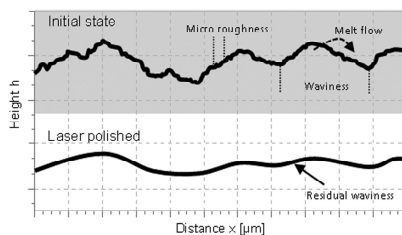
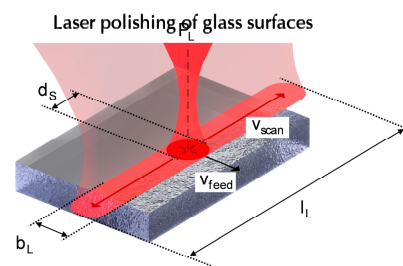
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Micro-605: Optical MEMS and Micro-Optics



SLE for Micro-optics?

- Can we also “write” the optics.
- SLE processed surfaces have
 - ~ 100 nm RMS roughness,
 - ~ 5 μm peak-to-peak flatness error,
 - Therefore a need for polishing
- Laser polishing eliminates roughness, but does not help with shape errors



J. Laser Appl. 29(1) 2017



Micro-optics IV - Fabrication

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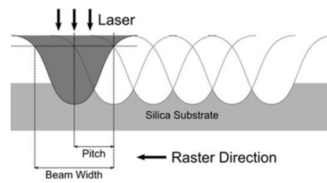
Micro-605: Optical MEMS and Micro-Optics



Femtosecond laser ablation

- Surface-relief type glass micro-optics
- Laser machining
 - Step 1: Laser ablation
 - Pulsed laser raster scanned on the surface
 - Pulses ablate a **precise volume of material**
 - Complete part formed by scanning
 - Ends up with a rough surface
 - Step 2: Laser polishing
 - Raster scanning over the surface
 - A very thin surface layer melts
 - Molten silica reflows due to surface tension
- Commercial rapid-prototyping service offered by Powerphotonic

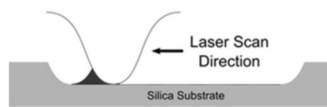
Laser ablation process



Remaining surface



Laser polishing of the surface



Currie, M., et al., Proc. SPIE. Vol. 9727. 2016.

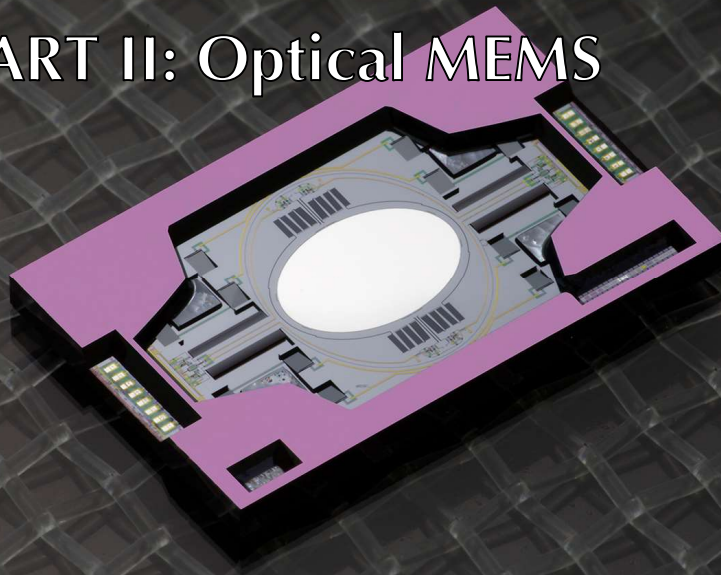


PowerPhotonic LightForge™

- Rapid prototyping service
- Process specs:
 - Substrate dimensions: 25.4 x 25.4 x 1 mm
 - Sag 0 - 65 μm
 - Slope (form error PV < 500nm): 0 - 8 degrees
 - Slope 0 - 45 degrees
 - Feature Size 200 - 15000 μm
 - Steps & Discontinuities smoothed over 150 μm



PART II: Optical MEMS



© Fraunhofer IPMS



MOEMS I – Introduction

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Micro-605: Optical MEMS and Micro-Optics



What is MOEMS (or Optical MEMS)?

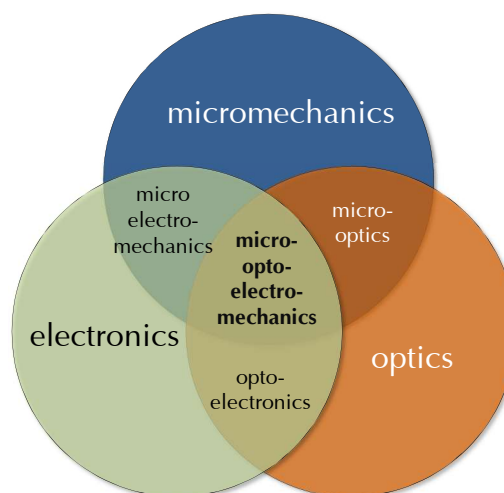


Image first created by Dr. M. Edward Motamedi



MOEMS I – Introduction

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Micro-605: Optical MEMS and Micro-Optics

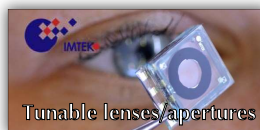


Optical MEMS – Components and Devices



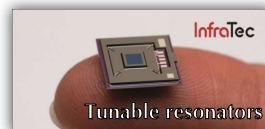
- Projection and scanning displays
- Imaging systems
- Optical interconnects
- Spectrometers

- Projection Displays -
- Wavelength selective switches -
- Spectroscopy -
- Maskless Lithography -



- Autofocus and zoom cameras
- Stereo (3D) imaging
- Endoscopic imaging systems
- Laser-to-fiber couplers

- Tunable lasers and optical filters -
- Reflective displays -
- Spectrometers -
- Add-drop multiplexers -



MOEMS EXAMPLES

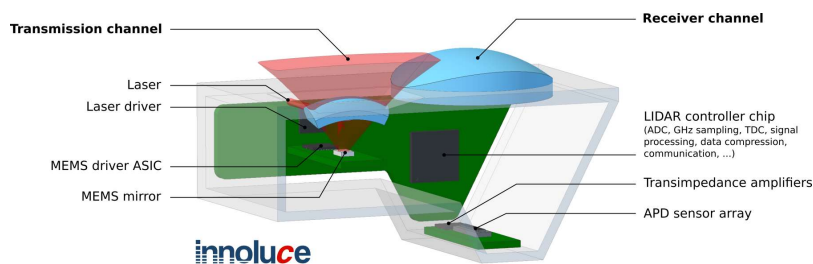


MOEMS-Based LIDAR Systems

- LIDAR: Light Detection and Ranging
- 3D mapping of the environment
- High-speed MOEMS scanners
- Applications
 - Robotic vision
 - Landscape monitoring
 - Autonomous driving



© New York Times



MOEMS I – Introduction

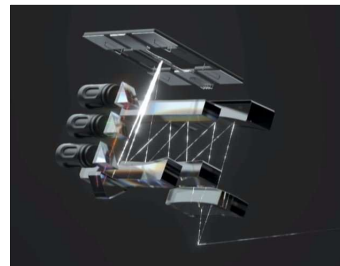
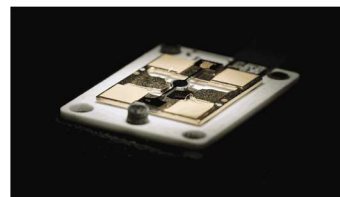
186

Micro-605: Optical MEMS and Micro-Optics



MOEMS Display Engines for AR/VR

- Augmented/Virtual Reality
- 3D image generation
- Numerous micro-optics and MOEMS
 - Waveguide arrays
 - Diffractive couplers
 - MOEMS display engines



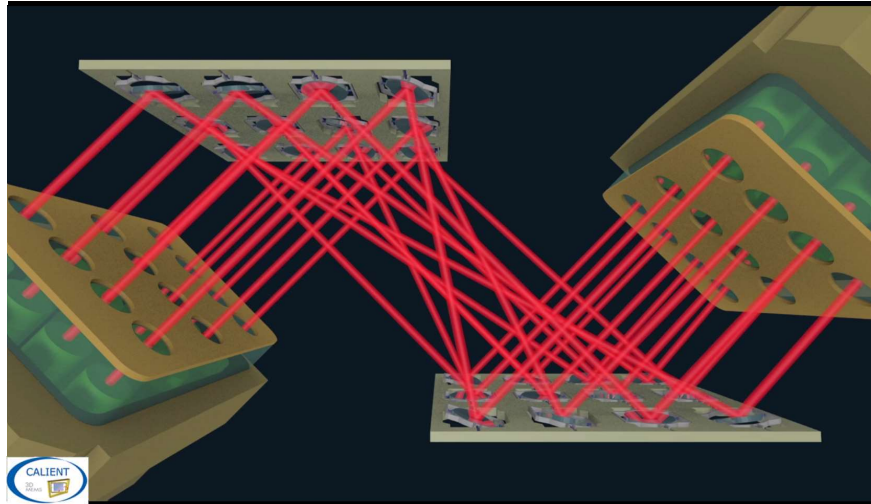
MOEMS I – Introduction

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Micro-605: Optical MEMS and Micro-Optics

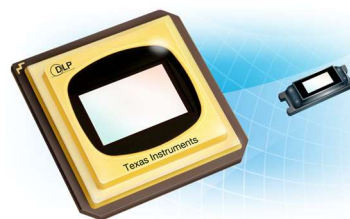


MOEMS for Telecom: 3D Optical Switches

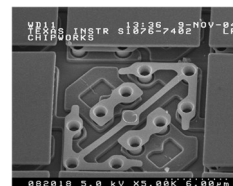
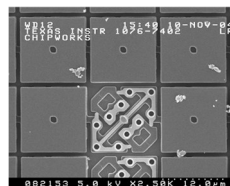


TI Digital Light Processor

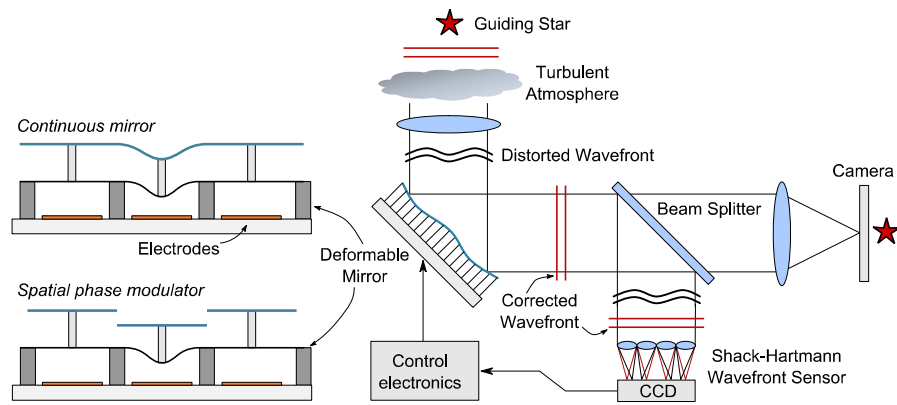
- **3-times Emmy award winner technology! (No kidding)**
- Array of active micromirrors
 - Up to 4 million individual mirrors!
 - Up to 8 KHz refresh rate
 - 7.6 μm mirror pitch
- 20 years of development
- Remarkable process chain
- Applications
 - Projectors
 - Automobile head-up displays
 - Maskless lithography
 - Structure illumination
 - Optical metrology
 - Machine vision



SEM images of DLP mirrors



Deformable Mirrors for Adaptive Optics



Deformable Mirrors for Adaptive Optics

Image of galactic center with and without AO

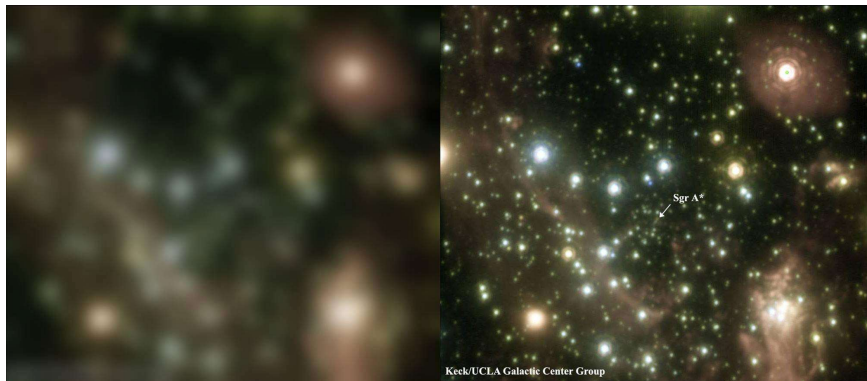
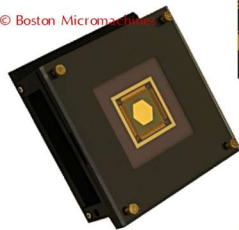


Image by the Keck Observatory

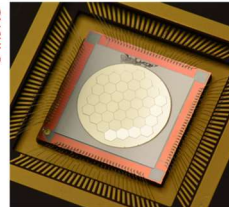
MOEMS Deformable Mirrors

- Advantages of MOEMS Technology
 - Impeccable surface quality
 - Large actuator count
 - Large bandwidth
 - Relatively low cost
- Spin-off applications
 - AO microscopy
 - Ophthalmology
 - Laser communication systems
 - Femtosecond pulse shaping

© Boston Micromachines



© Iris AO



© Flexible Optical B.V



MOEMS I - Introduction

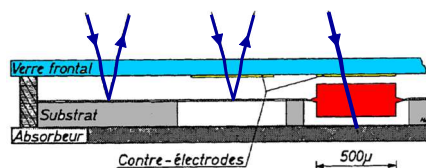
192

Micro-605: Optical MEMS and Micro-Optics

EPFL

MOEMS in Neuchatel

- A shutter based reflective display
- CEH... now CSEM in 1983 !!!
 - Very nice demonstrator array
 - Electrostatic actuator
 - Torsion beams
 - "parallel" plate actuation
 - 200 nm thick aluminum for shutter and beams
 - 70 V driving voltage
 - ...too early, no market in 1983 ???



R. Vuilleumier et al., *Bulletin Annuel Societe Suisse de Chronometrie*, vol.12, pp 37-40, 1983

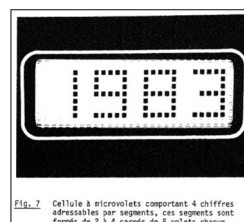
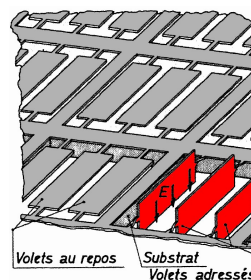


Fig. 7 Cellule à microvolets comportant 4 chiffres adressables par segments, ces segments sont formés de 2 à 4 carrés de 5 volets chacun.



MOEMS I - Introduction

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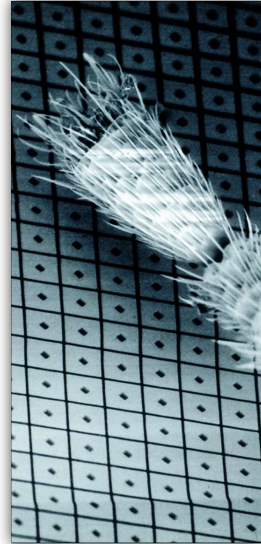
Micro-605: Optical MEMS and Micro-Optics

EPFL

Content

- **MOEMS: Fundamentals**
 - Actuators and sensors
 - Design and modeling
- **MOEMS: Devices**
 - Micromirrors
 - Tunable gratings
 - Tunable lenses
 - Tunable resonators
- **MOEMS: Systems**
 - Display systems
 - Imaging systems
 - Telecommunication network components
 - Advanced instrumentation
- **Emerging Topics**

TI Digital Micromirror Device



Resources

- **An Introduction to Microelectromechanical Systems Engineering** *by N. Maluf*
- **Microsystem Design** *by Stephen Senturia*
- **Micromachined Transducers Sourcebook** *by G. Kovacs*
- **Fundamentals of Microfabrication** *by Marc Madou*
- **Micro Electro Mechanical System Design** *by J. Allen*
- **Analysis and Design Principles of MEMS Devices** *by Minhang Bao*
- **The MEMS Handbook** *by Mohamed Gad-el-Hak*
- **MOEMS: Micro-Opto-Electro-Mechanical Systems** *by Manouchehr E. Motamedi*
- **Foundations of MEMS** *by Chang Liu*
- **MEMS & Microsystems** *by Tai-Ran Hsu*



FROM STATIC TO DYNAMIC MICRO-OPTICS

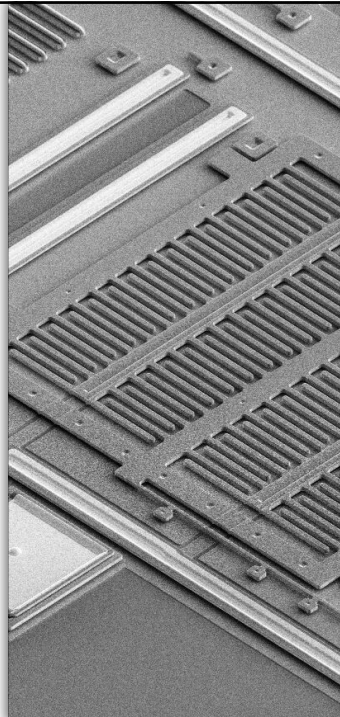


ACTUATORS AND SENSORS



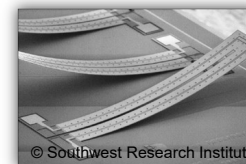
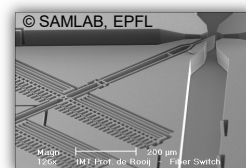
Actuators and Sensors

- Electrostatic Actuators and Position Sensors
- Electromagnetic Actuators
- Thermal Actuators
- Piezoelectric Actuators and Sensors
- Piezoresistive Sensors



M(O)EMS Actuators

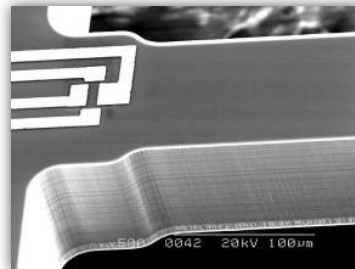
- Converts energy into mechanical motion
- Actuator defines dynamic performance
- Requirements
 - Compact size
 - Low power consumption
 - Linear and hysteresis-free operation
 - High-speed, repeatable and stable motion
- Wide range of actuator types
 - Electrostatic
 - Electromagnetic
 - Piezoelectric
 - Thermal
 - Pneumatic/pressure
 - Opto-mechanical
 - Shape-memory



Position Sensing in M(O)EMS

- Real-time monitoring of motion
- Integral part of commercial M(O)EMS devices
- Close-loop device control
- Most actuators can be used as sensors as well
 - Electrostatic Actuators → Capacitive Sensing
 - Thermal Actuator → Thermoresistive Sensing
 - Piezoelectric Actuation → Charge Sensing
- Challenges
 - Small displacements
 - Low power consumption
 - Noise
 - Bandwidth
 - Integration

Microvision, Inc.



Piezo resistive position sensor on a torsional flexure

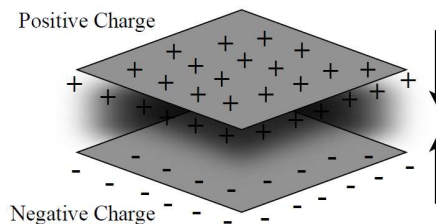


ELECTROSTATIC ACTUATORS



Electrostatic Actuators

- Utilizes capacitive attraction forces (Coulomb's force) between electrodes held at different potential
- By far the most common actuation and sensing method in MEMS
- Device and substrate typically on ground
- No charge flow (ideally!)
- Advantages
 - Very low power
 - Fast
 - Easily integrated with electronics
- Disadvantages
 - Relatively large surfaces
 - Inherently nonlinear F-V behavior
 - Small forces → only attracting!
 - Actuation and sensing with similar structures



Electrostatic Actuation

- The total energy stored in a capacitors is given by

$$U_E = \frac{1}{2} CV^2$$

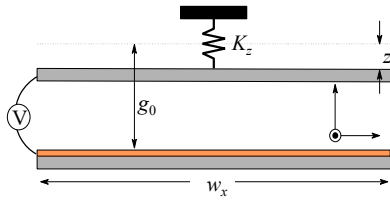
- Actuator force is defined by the rate of change energy with displacement

$$F = -\Delta U_E \Rightarrow F_x = -\frac{\partial U_E}{\partial x}, F_y = -\frac{\partial U_E}{\partial y}, F_z = -\frac{\partial U_E}{\partial z}$$

- Usually applied potential is independent of displacement. Thus,

$$F = -\frac{1}{2} V^2 \Delta C$$

Electrostatic Actuators



Stored Energy

$$U_E = \frac{1}{2} C V^2 = \frac{1}{2} \epsilon_0 \frac{w_x w_y}{(g_0 - z)} V^2(t)$$

Electrostatic Force

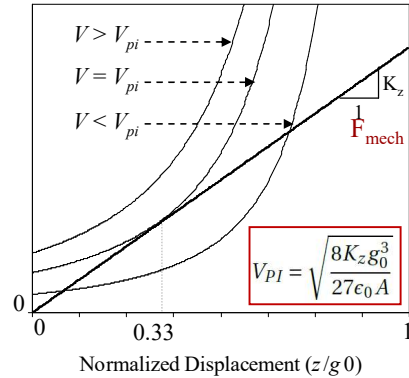
$$F_z = \frac{\partial U_E}{\partial z} = -\frac{1}{2} \epsilon_0 \frac{w_x w_y}{(g_0 - z)^2} V^2(t)$$

Mechanical Restoring Force

$$F_{mech} = K_z z$$

Equilibrium points are given by:

$$F_z = F_{mech}$$

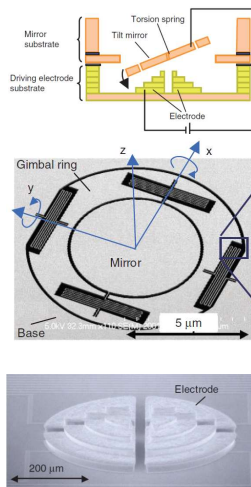


- Susceptible to pull-in instability
 - Maximum travel limited to $g_0/3$
 - Limits analog operation range
 - Provides well-defined digital operation
- Trade-off between voltage and travel range

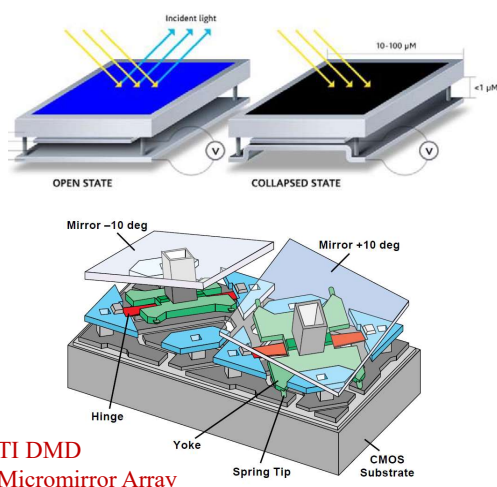


Parallel-Plate ES Actuators: Examples

Calient/NTT: MEMS Mirror



Qualcomm IMOD Display

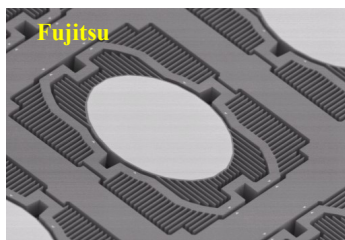
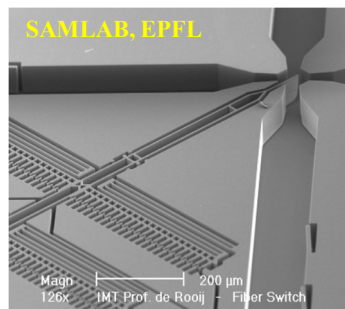
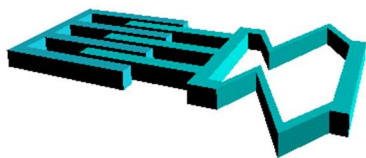


TI DMD Micromirror Array



Electrostatic Comb Drive Actuators

- High force density
- Lateral actuation
 - In-plane (IP) motion
- Vertical actuation
 - Out-of-plane (OOP) motion
 - Rotational motion
- Vary accurate movement
- The contribution from 'fringe capacitance' is substantial, and cannot be ignored.
- 'Fringe capacitance' is highly non-linear



Force in ES Comb Drive Actuators

Individual capacitance contributions:

$$C_{\perp} = \epsilon_0 \epsilon_r \frac{h(l+x)}{g} \quad \text{and} \quad C_{\parallel} = \epsilon_0 \epsilon_r \frac{h w}{d-x}$$

Total capacitance:

$$C_{tot} = (2 C_{\perp} + 2 C_{\parallel}) \times N_F$$

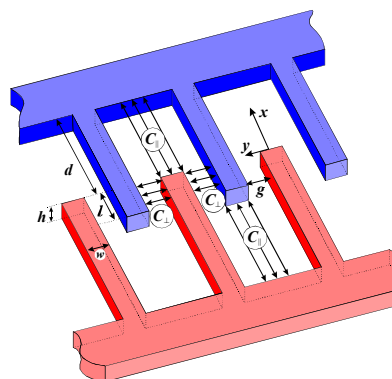
$$C_{tot} = 2 \epsilon_0 \epsilon_r \left[\frac{h(l+x)}{g} + \frac{h w}{d-x} \right] \times N_F$$

Electrostatic force:

$$F_E = -\frac{1}{2} \frac{\partial C}{\partial x} V^2 = -\epsilon_0 \epsilon_r \left[\frac{h}{g} + \frac{h w}{(d-x)^2} \right] N_F V^2$$

$$\Rightarrow F_E \approx -\epsilon_0 \epsilon_r \frac{h N_F}{g} V^2$$

!! Independent of displacement !!



Linearization of Comb Drive ES Actuators

- The applied potentials are given by

$$V_1(t) = V_{DC} + V_{AC} \Rightarrow F_1 = a_0 (V_{DC} + V_{AC})^2$$

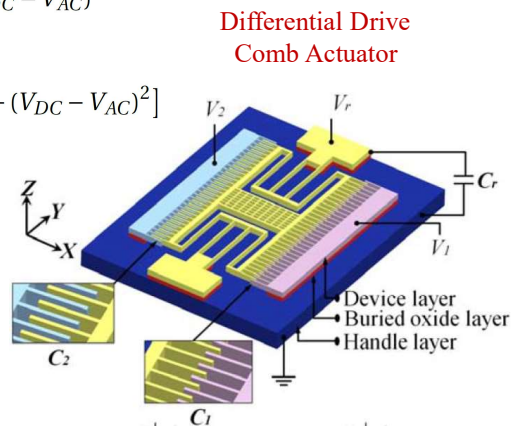
$$V_2(t) = V_{DC} - V_{AC} \Rightarrow F_2 = a_0 (V_{DC} - V_{AC})^2$$

- Resultant ES force:

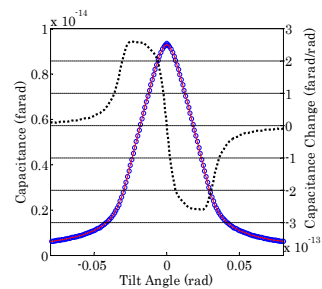
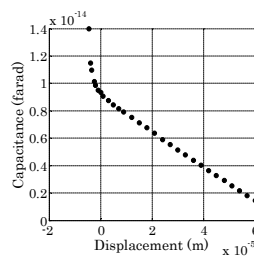
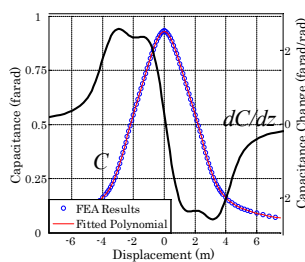
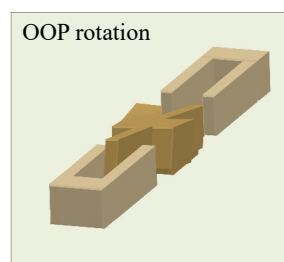
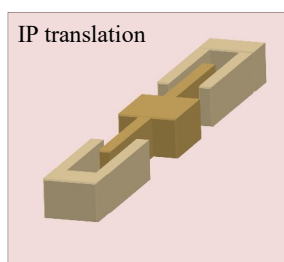
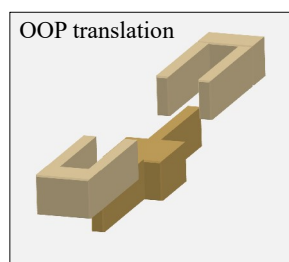
$$F_e = F_1 - F_2 = a_0 [(V_{DC} + V_{AC})^2 - (V_{DC} - V_{AC})^2]$$

- The total force is found to be

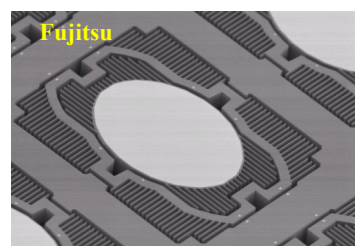
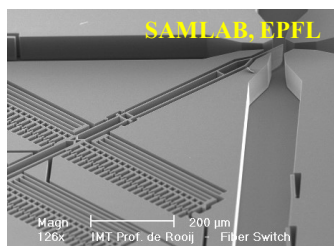
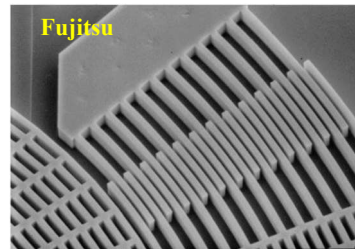
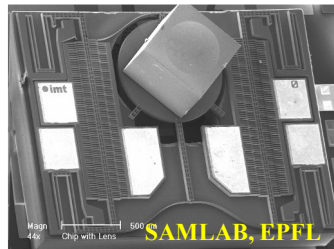
$$F_e = 4a_0 V_{AC} V_{DC}$$



ES Comb Actuation Modes



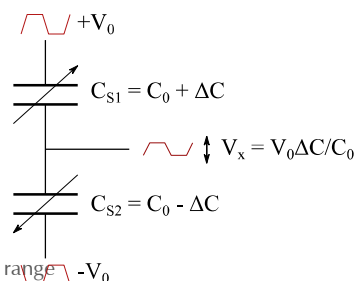
ES Comb Drive Actuators: Examples



Capacitive Position Sensing

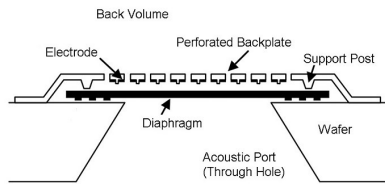
- Widely used for accelerometers and gyroscopes
- Identical to ES actuators in structure
- External capacitive readout circuitry
- Advantages
 - Simple structure identical to the actuators
 - Large bandwidth (limited by electronics)
 - When designed well, very good sensitivity
 - Well studied; commercial ICs available
- Challenges
 - Presence of noise and interference
 - Extremely small typical capacitance values
 - Static capacitance values are in the picoFarad range
 - Capacitance changes are in femtoFarad range
 - Carefully designed complex and sensitive ICs

A simplified capacitance readout circuit

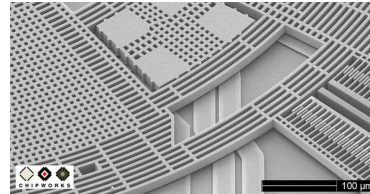


Capacitive Sensing Configurations

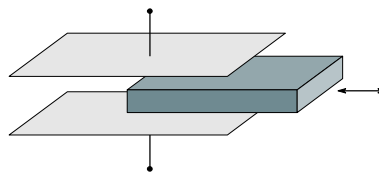
Gap-closing Sensors



Comb-drive Based Sensors

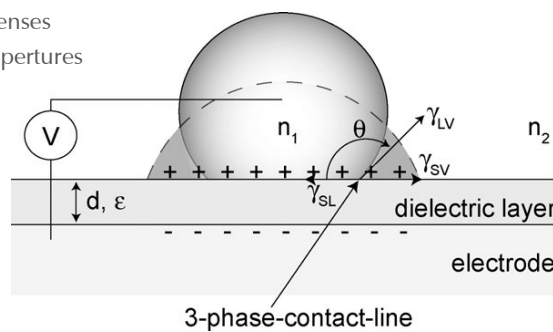


Dielectric Constant Sensors



Electrowetting on Dielectrics (EWOD)

- Contact angle modification with electric field
- Liquid encapsulation of the tunable lens
- Fast tuning speed
- Commercialized technology
- Applications
 - Tunable lenses
 - Tunable apertures

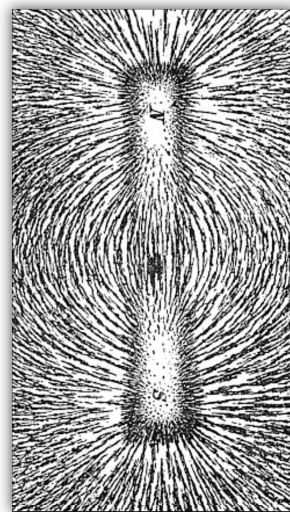


ELECTROMAGNETIC ACTUATORS



Electromagnetic Actuation

- Exploits electromagnetic interaction forces
- Comes in two common flavours
 - Moving-coil Actuation
 - Moving-magnet Actuation
- Advantages
 - Well-established principles
 - High force density
 - Moderately high speed
 - Possibility of remote actuation
- Disadvantages
 - Power consumption
 - Fabrication challenges
 - Material limitations
 - Integration limitations
 - Process limitations



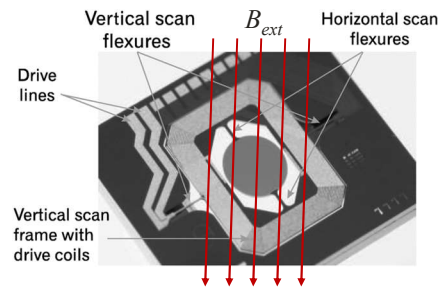
Moving Coil Electromagnetic Actuation

- μ Coil on fabricated on moving features
- External magnetic field
 - + Low mass $\rightarrow$ Fast operation
 - Heat generation on the device
 - Electrical access to the device
- Usually Cu; Au and Pt also used

$$\mathbf{F} = \oint_L I d\mathbf{l} \times \mathbf{B}$$

$\mathbf{F}$ = Force acting on the current loop
 I = Current in the conductor
 $\mathbf{B}$ = External Magnetic Field

! Right Hand Rule !



Moving Magnet Electromagnetic Actuation

- Interaction between permanent magnet or “soft magnet” and DC magnetic field
 - Torque to align with external field.
 - *Non-zero force if field is non-uniform*
- Hard magnets: NdFeCo, SmCo, etc.
 - Electroplating
 - Manual assembly
- Soft magnets
 - Ni/NiFe
 - Electroplating
 - Sputtering/evaporation
 - Polymer magnets
 - Spin coating, casting
 - 3D Printing

$$F = M (wt) \Delta H$$

M = Magnetization ($\mu_0 \chi H$)

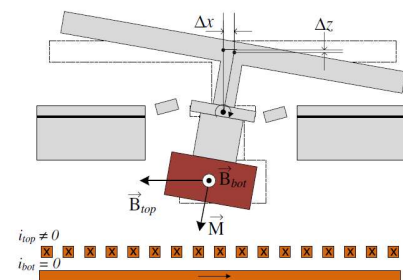
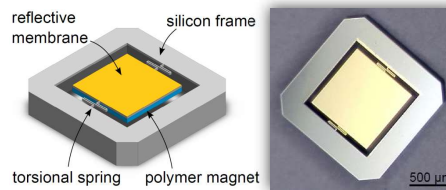
wt = cross-sectional area

ΔH = difference in magnetic field

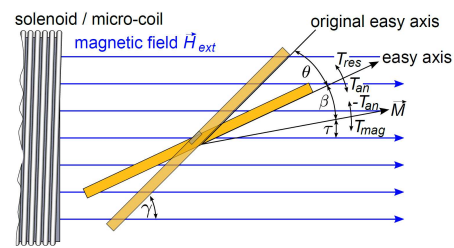


Moving Magnet Electromagnetic Actuator

- Magnetic materials on device
- External magnetic field
- + No heat generation on the device
- + Electrically passive device
- High mass $\rightarrow$ Slow operation



Ataman et al. / J. Micromech. Microeng. **23** (2013) 025002



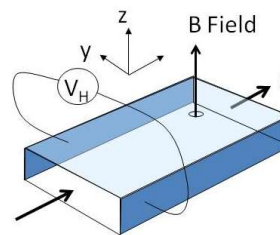
Weber et al. / J. Microelectromech. Syst. **21** (5) (2012) 1098-1106



Magnetic Position Sensing

• Hall Effect Sensors

- Direct voltage output as a function of magnetic field
- Particularly suitable for moving magnet actuators
 - Multiple sensors for absolute position encoding
- Advantages
 - High speed
 - Non-contact
 - DC and AC



• Back - EMF Sensing

- Used for moving magnet type actuators
- Motion of the magnet induces current on a secondary sensing coil
- Advantages
 - Remote Sensing
 - Self powering
 - No additional device complexity
- Only for AC operation



THERMAL ACTUATORS



Thermal Actuation

- Actuation using the thermal expansion of materials
- Required heat can be generated by
 - Joule (resistive) heating
 - Optical excitation
- Advantages
 - Strong force
 - Large displacement
 - Linear response
 - Potentially small / CMOS compatible
- Disadvantages
 - Slow
 - High power consumption
 - Heat generation
- Speed is limited by the heat transfer process
 - How fast you can heat and cool down the actuator



Thermal Transducers – Basic Concepts

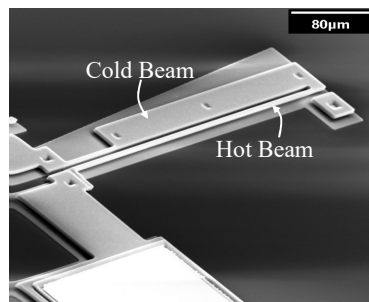
- **Heat capacity (c):** Energy needed to temperature of unit mass in unit amount
 - Ability to store thermal energy
 - Measured in J/kg·K
 - Analogous to electrical capacitor
- **Thermal conductivity (κ):** Ability of a material to transfer heat
 - Measured in W/m·K
 - Analogous to electrical conductivity
- **Coefficient of thermal expansion (CTE, α):** Change in length per unit temperature change ($\Delta l = l_0 \alpha \Delta T$)
 - Measured in 1/K



In-Plane Thermal Actuation

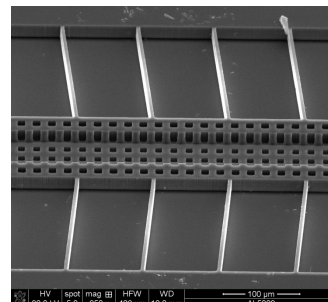
Pseudo-Bimorph Actuator

- Based on heterogeneous beam pairs
- Provides arc motion
- With current between the anchors:
 - I. Hot beam heats and expands more
 - II. Long beam expands more



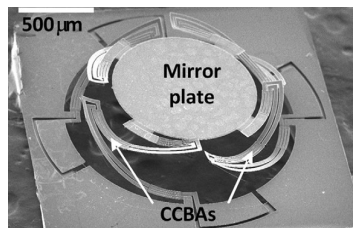
Chevron Actuator

- Large linear displacement and force
- Cascades V-shaped beams
- Up to 800 μN of force demonstrated
- With applied current beams expand and push the shuttle forward

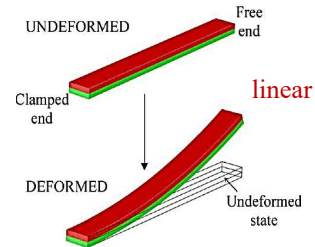


Bimorph and Multimorph Thermal Actuators

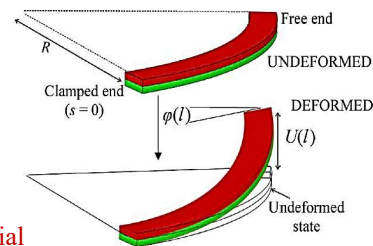
- Most common thermal actuator type
- Surface micromachined
- Based on the difference of CTE
- One layer is used as a heating resistor
- Commonly used for
 - Micromirrors
 - Tunable capacitors
 - Microgrippers



Sen. and Act. A, 188, 349–358, 2012



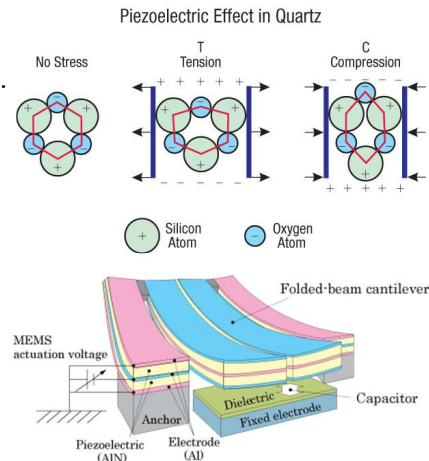
JMEMS, 21 (5), 1241-1251, 2001



PIEZOELECTRIC ACTUATORS

The Piezoelectric Effect

- Voltage/E-field on crystal causes displacement
- MEMS coatings: PZT, ZnO, AlN, ...
- III-V substrate: GaAs, ...
- Advantages
 - High force density
 - Low power
 - Very high speed
 - Potentially small
 - Temperature stability
- Disadvantages
 - Low displacement
 - Difficult to fabricate

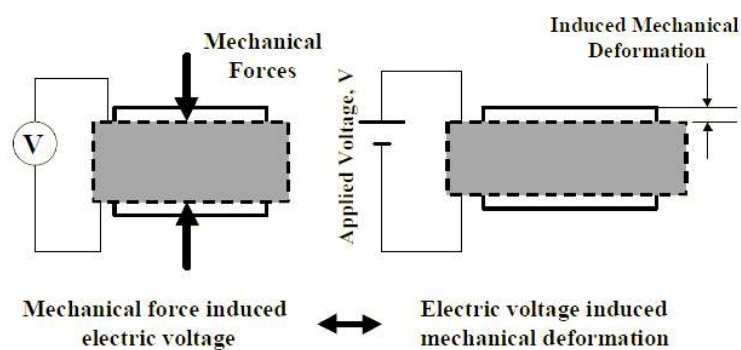


Schematic of folded-beam type piezoelectric tunable capacitor

<http://www.toshiba.co.jp>



Piezoelectric Actuation and Sensing



- Electric field induces stress (and therefore strain)
- External stress induces electric field (and therefore voltage)
- Tensor analysis is necessary for complete modelling



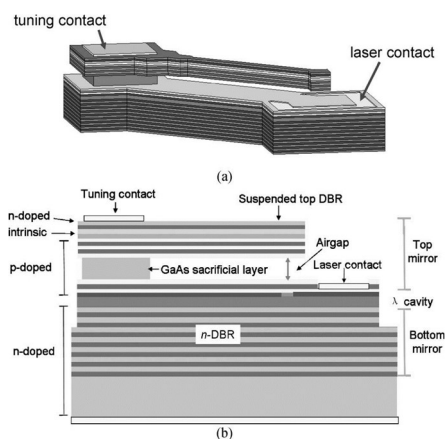
Piezoelectric Materials

Typical piezoelectric properties of different piezoelectric films

Parameter	ZnO [1]	AlN [1]	PZT [1]	PMN-PT [29]
$e_{31,f}$ (Cm ⁻²)	-1.0	-1.05	-8 to -12	-9 to -20
$d_{33,f}$ (pmV ⁻¹)	5.9	3.9-5.5	60-130	100-350
ϵ_{33}	10.9	10.5	300-1300	1000-3000
$\tan \delta$ (10 ⁵ Vm ⁻¹)	0.01-0.1	0.003	0.01-0.03	

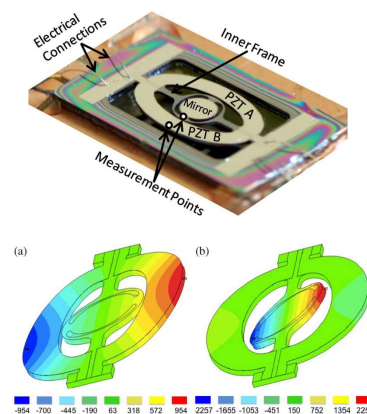
Piezoelectric Actuation Examples

A MEMS Tunable VCSEL



Huang et al., JSTQE, vol. 13, no. 2, 2007.

High Frequency Scanning Micromirror



Baran et al. JMEMS, vol. 21, no. 6, 2012

Piezoresistive Sensing

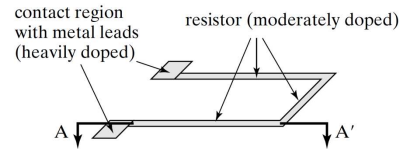
- Piezoresistive Effect: Change in resistance due to deformation (stress)
- Change in geometry $\rightarrow$ Change in R

$$R = \rho \frac{l}{A}$$

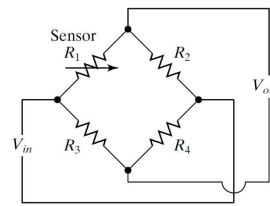
ρ $\rightarrow$ resistivity
 l $\rightarrow$ length
 A $\rightarrow$ area

- Additional effect in SC-silicon
 - Stress also changes electron mobility
 - Silicon should be doped
 - Very compact position sensors
 - Need careful design
- Piezoresistors are *implemented on flexures*
- Readout with Wheatstone bridge circuitry

Silicon Piezoresistors



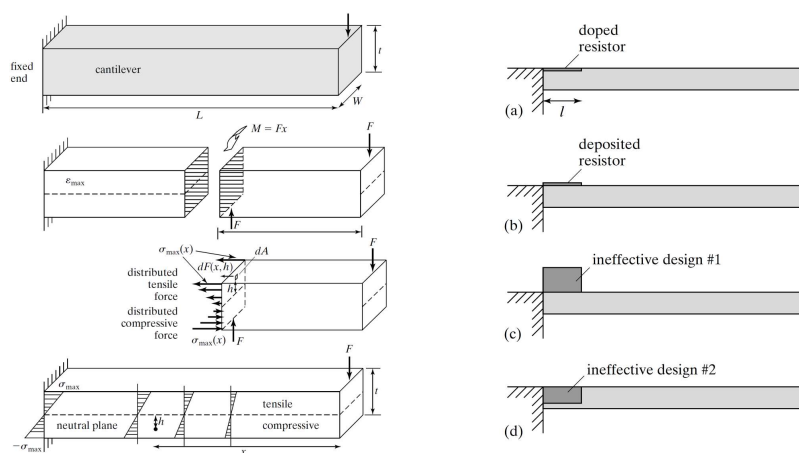
Wheatstone Bridge for Readout



$$V_{out} = \left(\frac{-\Delta R}{2R + \Delta R} \right) V_{in}$$



Effective Piezoresistive Sensor Design



Chang Liu, Foundations of MEMS, 2nd Edition



Comparison of Actuation Methods

	Force Density	Speed	Stroke	Power Consump.	Complexity and Cost	Size
<i>Parallel-plate ES</i>	Low	High	Short	Low	Low	Medium
<i>Comb-drive ES</i>	Medium	High	Medium	Low	Low	Small
<i>Electromagnetic</i>	High	High	Long	High	High	Large
<i>Piezoelectric</i>	High	High	Short	Low	Medium	Small
<i>Thermal</i>	High	Low	Long	High	Low	Small
<i>Shape-memory alloy</i>	High	Low	Long	Medium	High	Small
<i>Scratch-drive</i>	Medium	Medium	Medium	Low	High	Medium
<i>Pneumatic</i>	High	Low	Long	High	Medium	Large

Large variety of actuation methods

No “one size fits all” solution

Choice depends heavily on the application



Comparison of Sensing Methods

Method	Advantages	Disadvantages
Electrostatic	Simplicity of materials Low Power Rapid Response	Large footprint Electronics complexity Sensitive to particles and humidity
Thermal	Simplicity of materials Elimination of moving parts	Large power consumption Slower response (than electrostatic)
Piezoresistive	High sensitivity achievable Simplicity of materials	Requires doping of silicon to achieve high performance Sensitive to environmental temperature changes
Piezoelectric	Self generating → No power necessary	Complex material growth and process flow Cannot sustain high temperature operation
Magnetic	High sensitivity	Complex material growth and process flow Power consumption
Optical	Accuracy, high bandwidth	Requires external components (e.g. light sources, detectors), power consumption



REDUCED ORDER MODELING



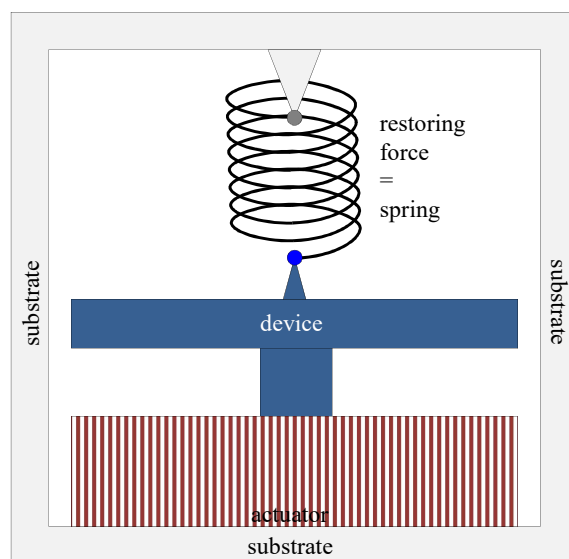
Reduced Order Device Model

MEMS Elements

1. **Device**
2. **Actuator**
3. **Restoring force**

Constraints:

- **Device:**
 - Not affected
 - Free from substrate
- **Actuator:**
 - Connected to the device and the substrate
- **Spring:**
 - Freely moving
 - Released from substrate

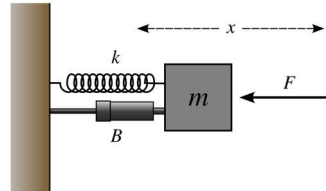


EoM for 2nd Order Systems

Linear System Model

$$m \frac{\partial^2 x}{\partial t^2} + b \frac{\partial x}{\partial t} + k_x x = F(x, t)$$

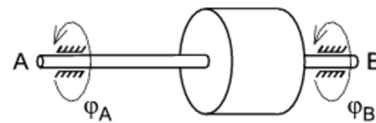
m : Mass k_x : Linear stiffness
 b : Damping coefficient F : Force



Rotational System Model

$$I_m \frac{\partial^2 \theta}{\partial t^2} + b \frac{\partial \theta}{\partial t} + k_m \theta = \tau(\theta, t)$$

I_m : Moment of inertia k_m : Torsional stiffness
 b : Damping coefficient τ : Torque



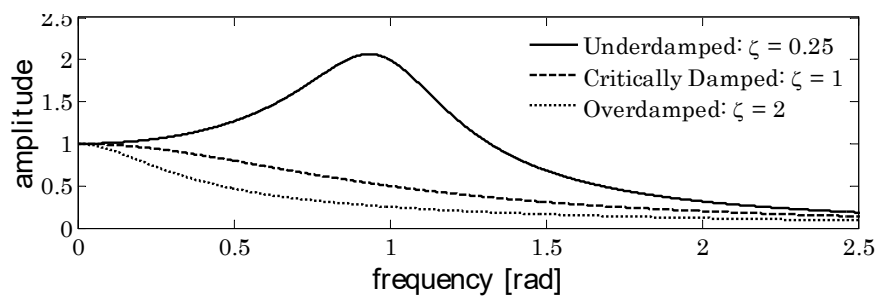
Reduced Order Device Model

- Construction and solution of equations of motion (EoM)
- **Best way to gain intuition on the system**
- Basic elements in a mechanical system:
 - **Inertia**
 - Mass (for linear motion)
 - Moment of inertia (for rotational motion)
 - **Spring elements**
 - Flexures, Beams, Deformable membranes
 - **Damper elements**
 - Air/liquid friction, Structural damping, Reaction forces (Eddy currents, etc.)
 - **Force/Torque**
 - Actuator modeling
 - Force/moment as a function of displacement/rotation



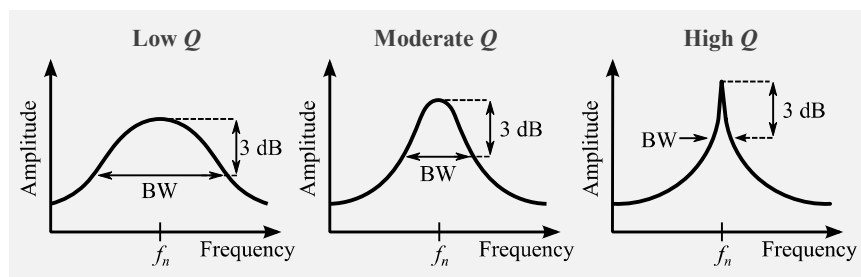
Frequency Response

- Response as a function of harmonic excitation frequency
- Fourier transform of the impulse response
- Contains amplitude and phase information
- Very low frequency region is called the **DC response**
- Maximum amplitude at the natural frequency
 - Small excitation/large response
 - **Resonant response/drive**



Quality (Q) Factor

$$Q = \frac{\text{maximum energy stored during cycle}}{\text{energy lost per cycle}} = \frac{\text{resonant frequency}}{\text{bandwidth at } 1/\sqrt{2} \text{ of maximum}}$$



Q vs. Bandwidth

$$Q = \frac{f_n}{\Delta f} = \frac{\omega_n}{\Delta \omega}$$

Q vs. Damping Ratio

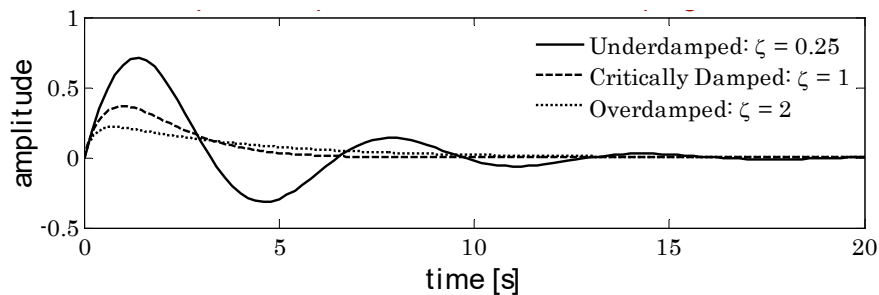
$$Q = \frac{1}{2\zeta}$$

Q vs. Time constant

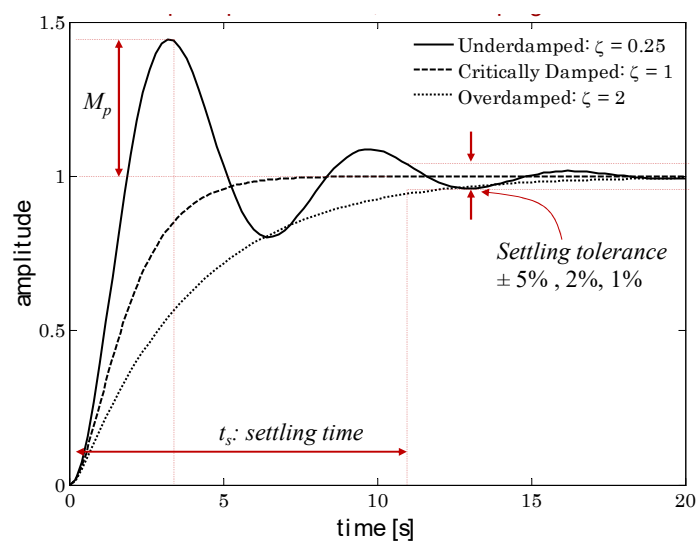
$$Q = \frac{\tau \omega_n}{2}$$

Impulse Response

- Response of the system to a “kick”
- All you need to know to calculate the response to any force
- An impulse has infinite extent frequency content
 - Impulse response and frequency response are Fourier pairs



Step Response with Different Damping

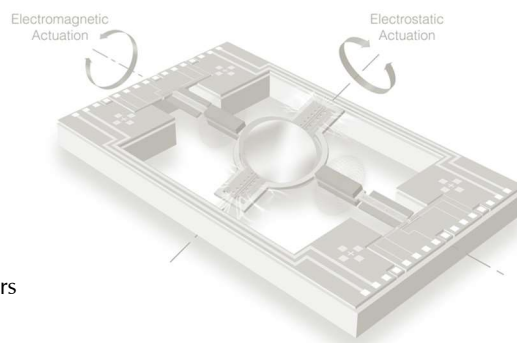


MOEMS DEVICES



MOEMS: Devices

- Reflective: Micromirrors
 - Operation principle and basic characteristics
 - Beam clipping and focusing properties
- Diffractive: Active Diffraction Gratings
 - Depth tuning
 - Period tuning
 - Rotation
- Refractive: Active Microlenses
 - Movable microlenses
 - Tunable microlenses
- Tunable Optical Resonators
 - Tunable cavities
 - Tunable optical ring oscillators

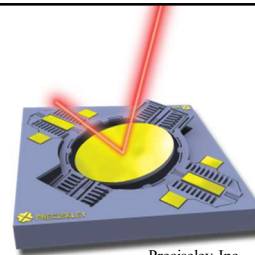


MICROMIRRORS

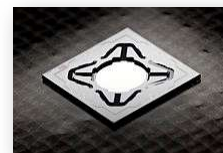


Micromirrors

- Tiny movable mirrors for...
 - Off-resonance steering
 - Resonance scanning
 - DC and AC Phase retardation
- 1-2-3D rotational variants in single mirror or array configurations
- Advantages
 - Small and Light weight
 - Fast movement
 - Low-cost batch fabrication
 - CMOS compatible technology (mostly!)
 - High level of integration with position feedback and electronics
- Disadvantages
 - Small optical apertures ($< \sim 2$ mm)
 - Static and dynamic mirror warp



Preciseley Inc.

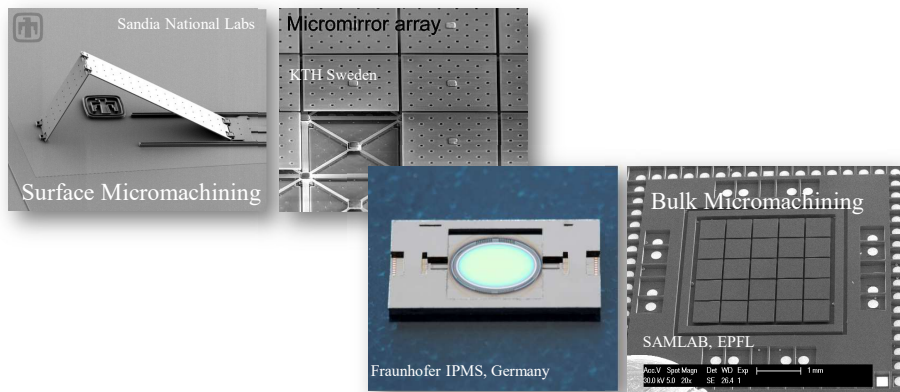


Fraunhofer IPMS



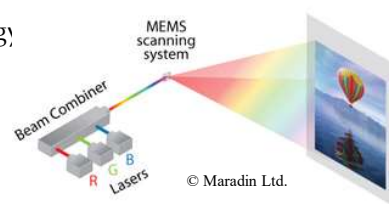
What is a Micromirror?

- By far the most common component in MOEMS
- Huge variety in shape/actuation/configuration
- The basic building block for the most commercial MOEMS products

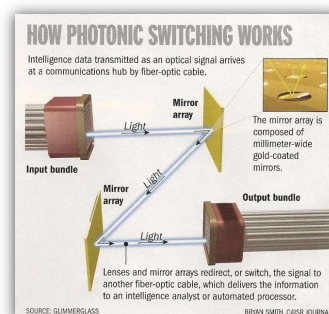


Micromirror Applications

- The work horse of MOEMS technology
 - Versatile
 - Precise
 - High speed
- Systems employing micromirrors
 - Projection and scanning displays
 - Endoscopic imaging
 - 3D imaging & LIDAR
 - Optical X-connects
 - Spectrometers
 - ... and many more



© Maradin Ltd.



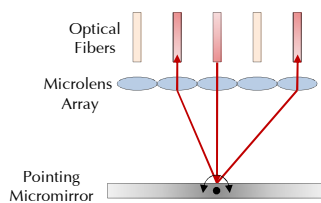
<http://www.enterrasolutions.com/>



Pointing vs. Scanning Micromirrors

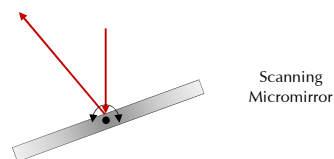
Pointing Micromirrors

- Point-to-point addressing
- Switching time defined by
 - ❑ Resonance frequency
 - ❑ Damping (settling time)
- Applications
 - ❑ Vector displays
 - ❑ Optical X-connects



Scanning Micromirrors

- Continuous (raster) scanning
- Sinusoidal position and speed
- Scan properties defined by
 - ❑ Resonance frequency (speed)
 - ❑ Damping (amplitude)
- Applications
 - ❑ Projection displays
 - ❑ Spectrometers



MOEMS III - Devices: Micromirrors

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Micro-605: Optical MEMS and Micro-Optics



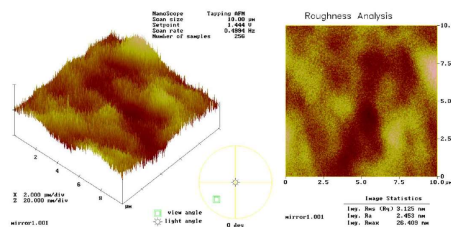
Mirror Quality: Surface Roughness

- A measure of surface texture
- Represented in terms of RMS
- Can rise from:
 - Poly-crystalline membrane material
 - Fabrication residues
 - Deposition process variation (local)

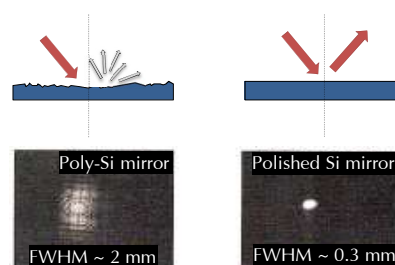
Irregular Surface Variations on a Small-scale



Mirror Roughness Characterized by AFM



Effect of Roughness on PSF



Z.F. Wang et al. / Sensors and Actuators A 114 (2004) 80-87

Su et al., Phot. Tech. Let. 13 (6) 2001



MOEMS III - Devices: Micromirrors

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Micro-605: Optical MEMS and Micro-Optics



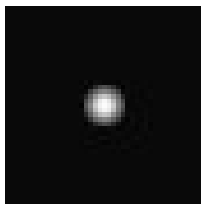
Mirror Quality: Static Deformation

- Flatness of the mirror surface is crucial for quality of the optical beam
- Static Warp
 - Due to stress effects
 - Match CTEs for bimorphs
- Dynamic Deformation
 - Due to inertial forces
 - Reinforce mirror plate

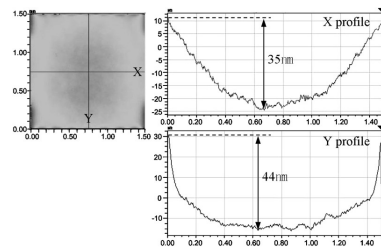
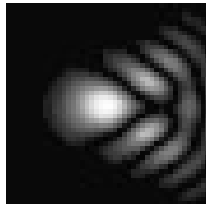


Mirror Warp measured by Interferometry

PSF with flat mirror

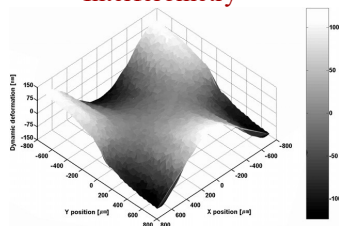


PSF with warped mirror

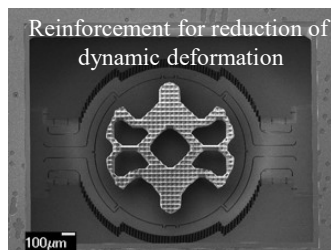


Dynamic Mirror Deformation

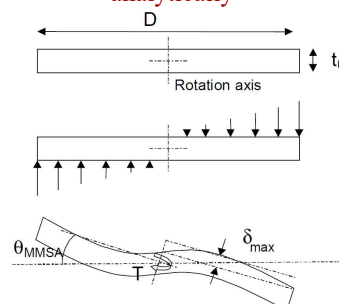
Characterized by Stroboscopic Interferometry



Reinforcement for reduction of dynamic deformation



Dynamic deformation can be analyzed analytically



$$\delta(u) = \delta_{\max} (u^5 - 10u^3 + 20u^2 - 1) / 1.83$$

$$\delta_{\max} = 0.217 \frac{\rho f^2 D^5 \theta_{MMSA}}{Et_m^2}$$

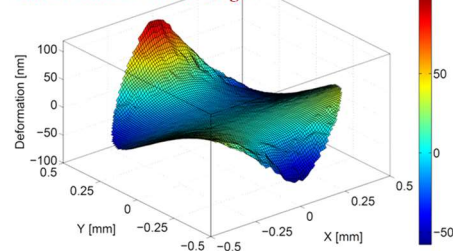
u : Normalized position



Dynamic Mirror Deformation: Example

- Measurement conditions
 - 17.3° mechanical rotation
 - 38.1 KHz oscillation frequency
 - **162 nm peak-to-valley deformation**
- Simulated PSF degradation
 - 20% reduction in maximum intensity
 - Side-lobe intensity up to 12.5%.

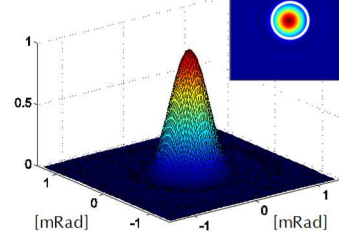
Mirror surface at full angle



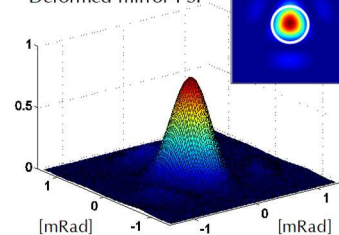
MOEMS III - Devices Micromirrors

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Flat mirror PSF



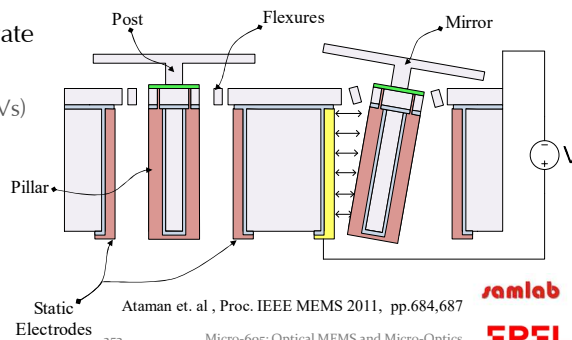
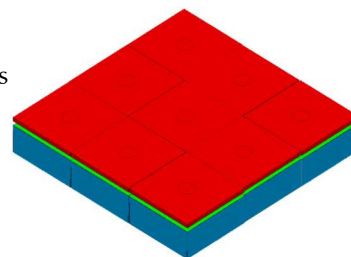
Deformed mirror PSF



EPFL

Example: Electrostatic 2D Micromirror Array

- Developed by SAMLAB
- High-power beam shaping applications
- 2D pointing mirror matrix
 - DC operation
 - 4° rotation around any arbitrary axis
- Optimized for high thermal loads
- High linearity
- Electrodes buried in substrate
- Multi-wafer stacking
 - Through-silicon-vias (TSVs)
 - Eutectic bonding



Ataman et. al, Proc. IEEE MEMS 2011, pp.684,687

Micro-605: Optical MEMS and Micro-Optics



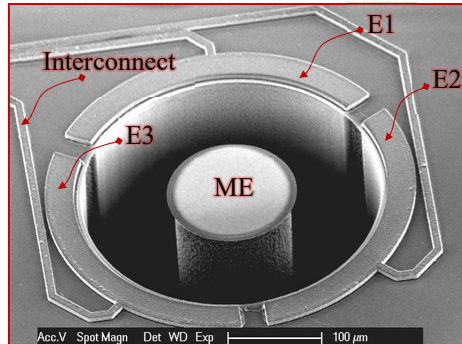
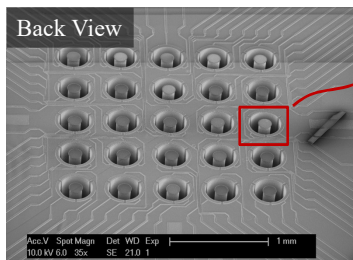
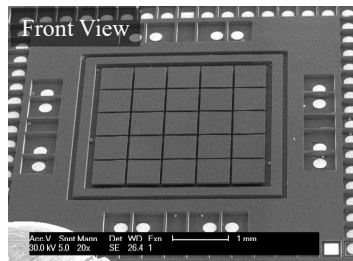
MOEMS III - Devices: Micromirrors

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samlab

EPFL

2D MMA with Vertical Electrostatic Actuators



Ataman et. al , Proc. IEEE MEMS 2011, pp.684,687

samlab



MOEMS III - Devices: Micromirrors

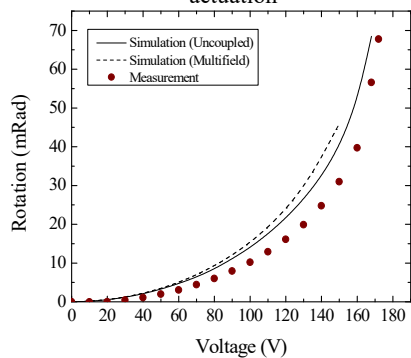
254

Micro-605: Optical MEMS and Micro-Optics

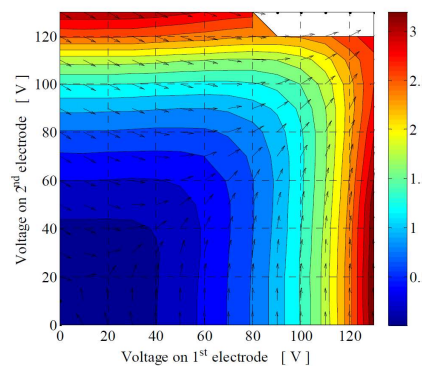
EPFL

2D MMA with Vertical Electrostatic Actuators

V - θ behavior with single electrode actuation



V - θ behavior with two-electrode actuation



Complete coverage of the $\theta_{x,y}$ space



MOEMS III - Devices: Micromirrors

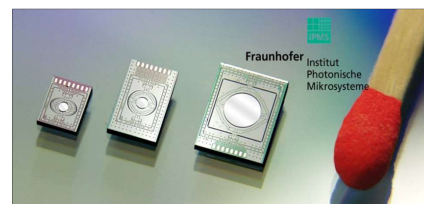
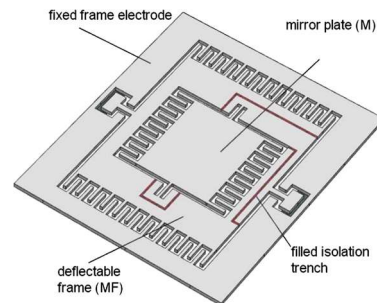
255

Micro-605: Optical MEMS and Micro-Optics

EPFL

Example: Comb- Actuated Microscanners

- Compact and integrated design
- Very low-power operation
- Integrated position detection
 - Piezoresistors on flexures
 - External quad-detector
- Bi-resonant in default form
 - Offset combs for DC operation
- Applications
 - Laser cameras
 - 3D cameras / robotic vision
 - 3D scanning
 - Projection displays
 - Spectrometers

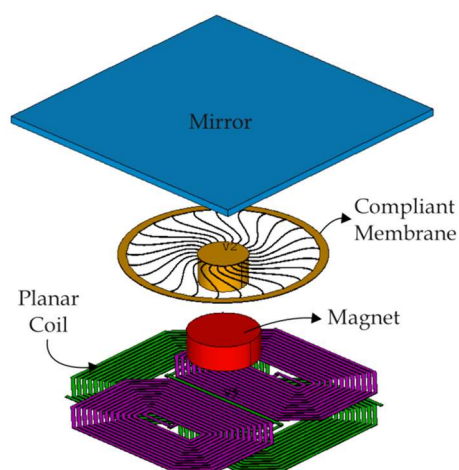


Source: <http://www.ipms.fraunhofer.de/en/products/MSD/msm-e.pdf>



Example: A 2D Electromagnetic Micromirror

- Pointing mirror (DC Operation)
- Designed for high thermal loads
- Bulk mirror
 - Very flat
 - Optimized coatings
- MEMS Base
 - High thermal heat conductance
 - Very flexible
 - Radial array of flexible beams
 - Very reliable
- Magnetic Actuator
 - High force
 - stiffer springs
 - fast mirror
 - Very linear, no snap-in

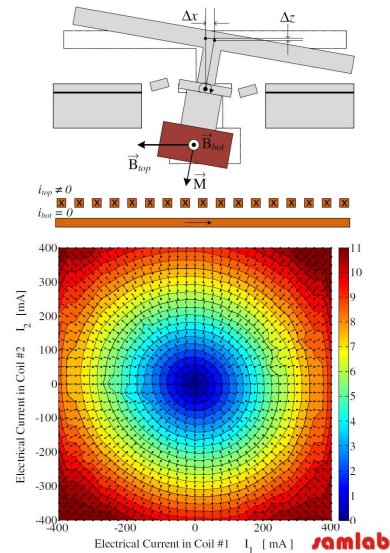


Ataman et al., J. Micromech. Microeng. 23 (2013) 025002

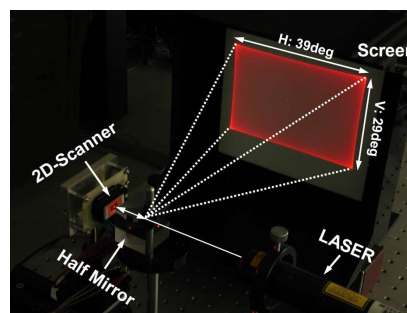
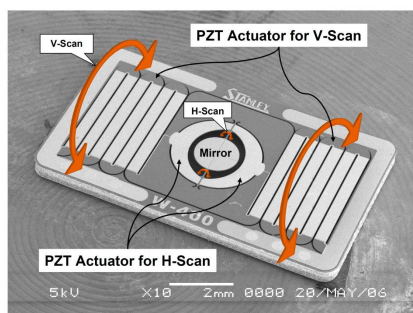
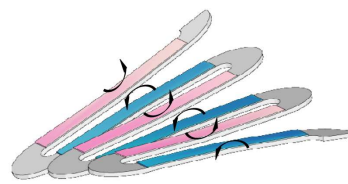
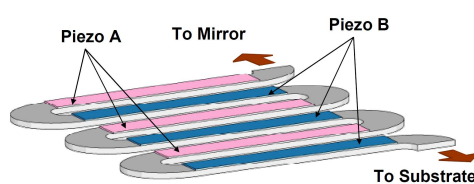


Example: A 2D Electromagnetic Micromirror

- Moving Magnet Actuation
 - Current lines create uniform magnetic field in the lateral plane
 - Magnet rotates to align its magnetization vector with the field
 - Pillar translates the motion to the mirror
- Rotation axis lies in the flexure plane
- Small parasitic displacement of the mirror
- Performance
 - 11° DC mechanical rotation
 - 76nm peak-to-valley static warp
 - $<0.02^\circ$ open-loop position stability over 7h
 - $<0.1^\circ$ open-loop repeatability over 5000 cycles



Example: Scanning Piezoelectric Micromirrors



M. Tani et al., Optical MEMS 2006

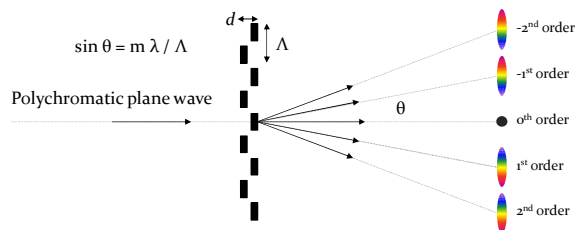


TUNABLE DIFFRACTION GRATINGS



Diffraction Gratings

- Optical component with a periodic structure
 - ❑ Period in the order of the wavelength
 - ❑ Transmission amplitude/phase gratings
 - ❑ Reflection binary/blazed gratings
- Splits light into multiple **diffraction orders**
- Orders separated by the **diffraction angle**
 - ❑ Defined by the period and the wavelength
- 2nd most common MOEMS component

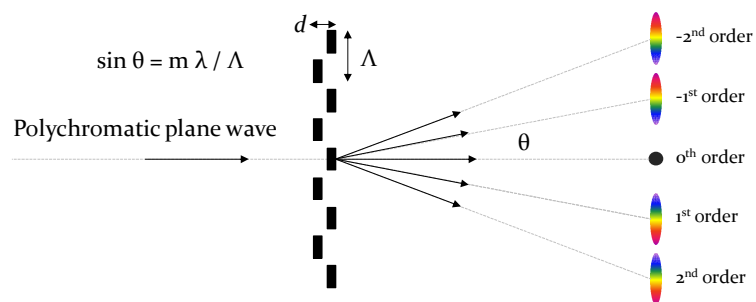


TUNABLE-DEPTH GRATINGS



Diffraction Gratings

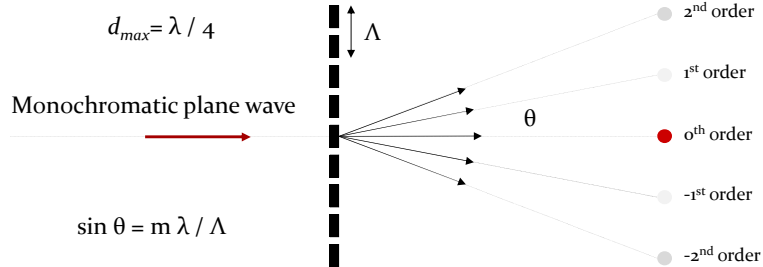
- A periodic structure, which splits and diffracts light into several beams
- ! Refer to the Micro-Optics part of this course for grating theory !



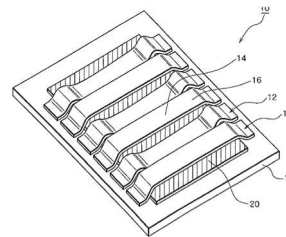
- MOEMS Tunable Diffraction gratings
 - **Grating depth:** Modulate the light intensity at different diffraction orders
 - **Grating Period:** Modulates the diffraction angle
 - **Grating Angle:** Rotating the entire diffraction profile



Tunable-Depth Gratings: Concept



- By changing the depth of the diffraction grating
 - Intensity of diffraction orders is modified
 - Diffraction angle is intact
- Digital or analog modulation of light intensity
- Works for binary and blazed gratings
- Most common MEMS tunable grating variety



Tunable-Depth Gratings: Principle

- Narrower diffraction orders with increasing N
- A sinusoidal function of grating depth
- 0th order contrast is low due to stray light
- Most modulators work in the 1st order
 - High contrast
 - Low efficiency (solution: blazed gratings)

For a binary grating, the diffraction profile is:

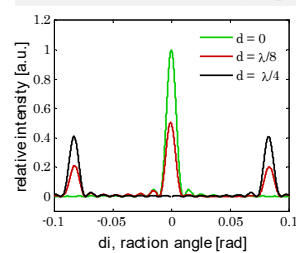
$$I = I_{in} \frac{\sin^2 \left[\frac{\delta}{2} \right] \sin^2 \left[N \frac{\delta}{2} \right]}{\left[\frac{\delta}{2} \right]^2 \sin^2 \left[\frac{\delta}{2} \right]}$$

$$\delta = \frac{2\pi}{\lambda} d \sin \theta$$

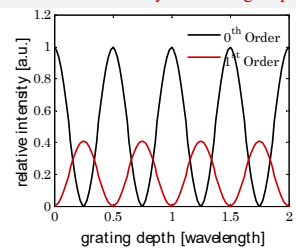
N = Number of illuminated periods

$$I_0 = I_{in} \cos^2 \left(\frac{2\pi d}{\lambda} \right) \quad I_{\pm 1} = \frac{4I_{in}}{\pi^2} \sin^2 \left(\frac{2\pi d}{\lambda} \right)$$

Diffraction Profile vs. Grating Depth

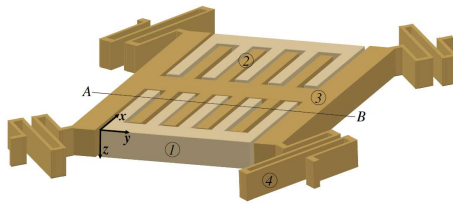


0th & 1st Order Intensity vs. Grating Depth



Tunable-Depth Gratings: Implementation

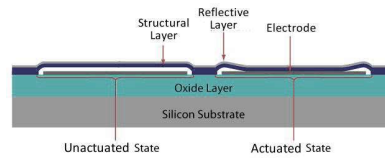
- Surface micromachining for ribbons
 - Small displacements are enough
- Bulk micromachining for some variants
 - Ideal for Fourier transform spectrometers
- Electrostatic Actuation
 - Full modulation at $\lambda/4$ displacement
 - Very fast modulation



C. Ataman et al., J. Micromech. Microeng. 16 (2006) 2517–2523



Cross-section of GLV fabrication and actuation

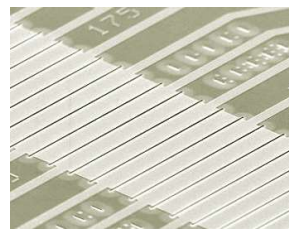


Grating Light Valve™ array structure
(Silicon Light Machines)

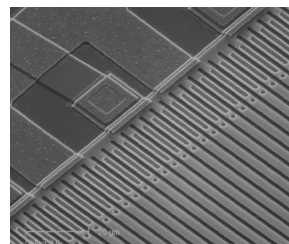


Tunable-Depth Gratings: Examples

- Large effects with miniscule displacements
- $\lambda/4$ displacement for full contrast
- Electrostatic actuation
- Applications
 - Projection Displays
 - Wavelength selective switches
 - Spectroscopy
 - Maskless Lithography
- Major Developers/Suppliers
 - Silicon Light Machines – Grating Light Valve
 - Micralyne
 - Fraunhofer IPMS
 - Boston Micromachines



<http://www.micralyne.com/spatial-light-valve/>



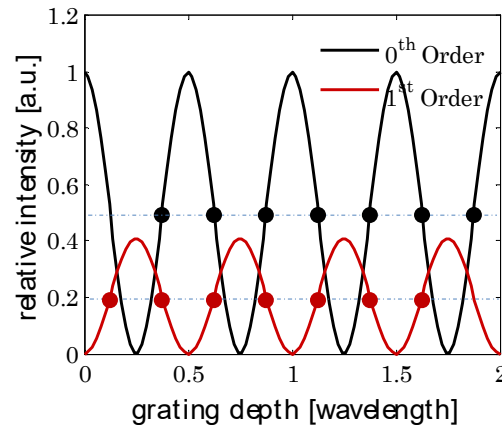
Silicon Light Machines



Tunable-Depth Gratings for Sensing

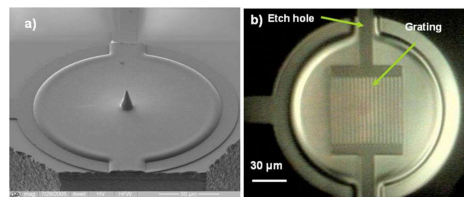
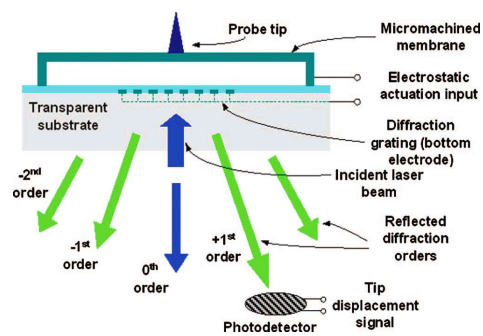
$$I_0 = I_{in} \cos^2\left(\frac{2\pi d}{\lambda}\right)$$

$$I_{\pm 1} = \frac{4I_{in}}{\pi^2} \sin^2\left(\frac{2\pi d}{\lambda}\right)$$



Tunable-Depth Gratings for Sensing

- Diffraction gratings can also be used for precision displacement sensing of MEMS
- Advantages
 - Integrated sensor
 - Extremely sensitive
 - No electrical connection
- Grating sensors are used for...
 - Atomic force microscopy
 - Bio-sensors
 - Process monitoring
 - Microphones
 - Pressure sensors
 - Strain sensors



Onaran et al. Rev. Sci. Instrum. 77, 023501 2006

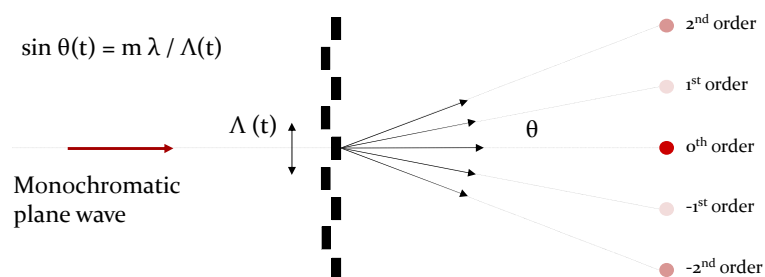
TUNABLE-PITCH GRATINGS



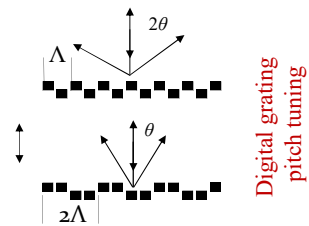
MOEMS III - Devices:

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Tunable-Pitch Gratings: Concept and Operation



- By changing the pitch of the diffraction grating
 - Diffraction angle is modified
 - Diffraction intensities remain relatively intact
- Digital or analog operation
- Works for binary and blazed gratings



MOEMS III - Devices: Diffraction Gratings

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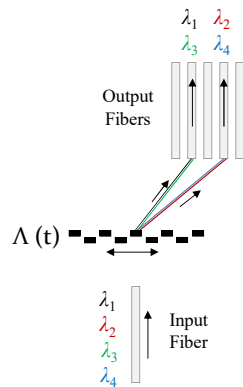
Micro-605: Optical MEMS and Micro-Optics

EPFL

Tunable-Pitch Gratings - Applications

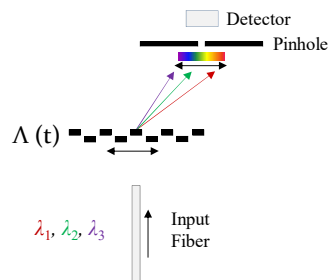
Wavelength selective switching

- Telecommunication networks
- Operates in the 1st order
- Precision control of grating period



Spectrometer/Monochromator

- Chemical analysis
- Operates in the 1st or higher orders
- Pinhole selects a single wavelength
- Time resolved spectrum
- Examples in Lecture 13



MOEMS III - Devices: Diffraction Gratings

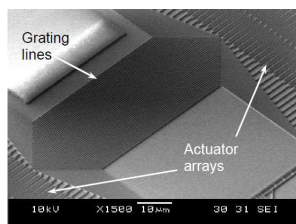
272

Micro-605: Optical MEMS and Micro-Optics

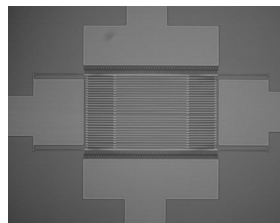


Tunable-Pitch Gratings: Examples

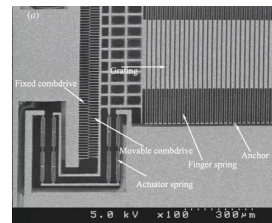
Sub-wavelength Grating



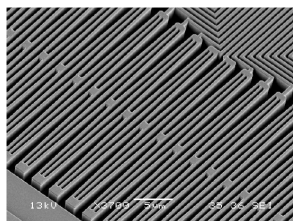
Blazed Grating



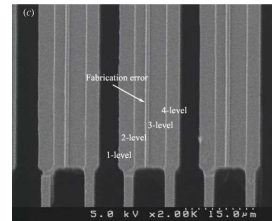
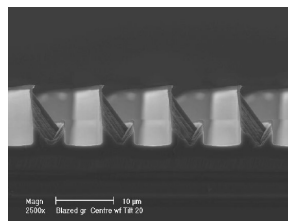
4-Level Grating



Tormen et al., Proc. of SPIE Vol. 6114 61140C-1



X. M. Zhang et al., Transducers 07



Y. Wong et al., J. Micromech. Microeng. 19 (2009) 025019



MOEMS III - Devices: Diffraction Gratings

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Micro-605: Optical MEMS and Micro-Optics



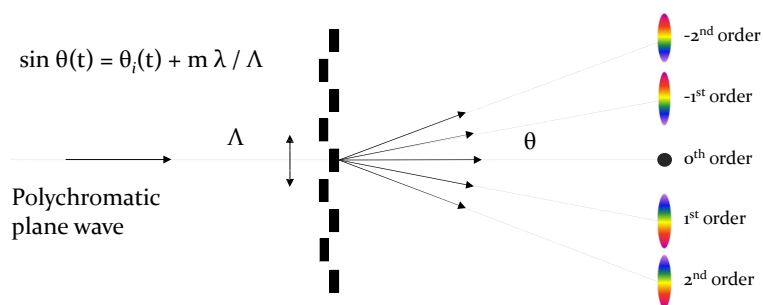
ROTATING GRATINGS



MOEMS III - Devices:

EPFL

Rotating Gratings: Concept and Operation



- By rotating the diffraction grating
 - ❑ Entire diffraction profile is displaced
 - ❑ Diffraction intensities remain relatively intact
- Mostly analog variants
- Works for binary and blazed gratings



MOEMS III - Devices:

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Rotating Gratings: Spectroscopy

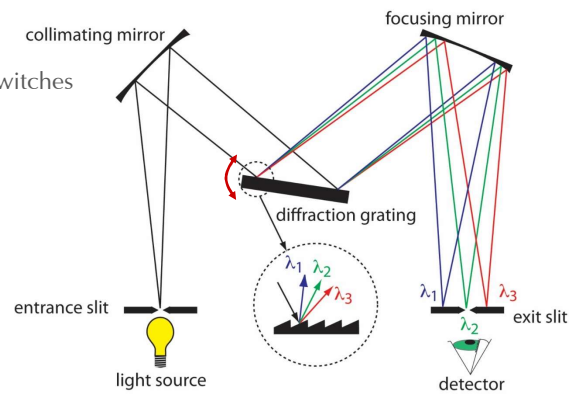
➤ Applications

- ❑ Spectrometers / Monochromators
- ❑ External cavity lasers
- ❑ Tunable filters
- ❑ Wavelength selective switches

➤ Limitations

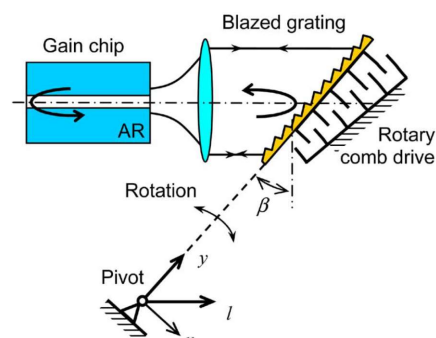
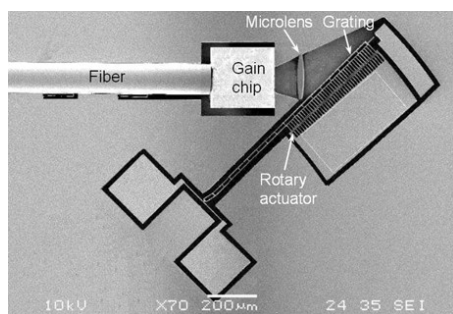
- ❑ Free spectral range
- ❑ Resolution

➤ Examples in Lecture 13



Rotating Gratings: Tunable Laser

- External cavity laser with a grating mirror
- Only selected wavelengths are coupled back into the fiber
- Blazed grating in Littrow configuration
 - ❑ Incidence and reflection angles are the same
- Compact tuning



Liu, Zhang, J. Micromech. Microeng. 17 (2007) R1-R13



TUNABLE LENSES



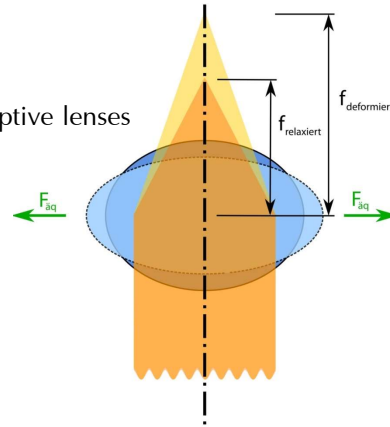
What is a Microlens?

- Lenses with diameters from $\sim 5 \mu\text{m}$ to 1 mm
- Refractive or diffractive
- Easy to pack in large arrays (a la compound eye)
- Single lenses or microlens arrays
- Wide range of fabrication methods
 - Large scale/wafer level fabrication
- Commercially used in
 - Digital photography and IR imaging
 - Retinal scanning displays
 - 3D and light-field cameras
 - Source-to-fiber light coupling



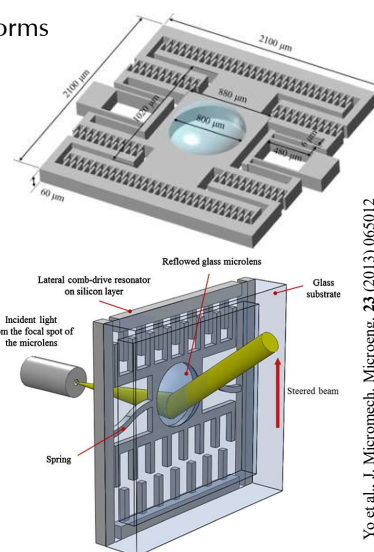
Active Microlenses

- Microlenses with tunable...
 - **Lateral position** for rotating of optical axis
 - **Vertical position** for defocusing
 - **Radius of curvature** for focal length tuning
- New materials are commonly used for adaptive lenses
 - Optical fluidics
 - Wide variety of polymers
- Applications
 - Laser-to-fiber coupling
 - Confocal microscopy
 - Autofocus an zoom objectives
 - Optical image stabilization



Microlenses on MEMS Platforms

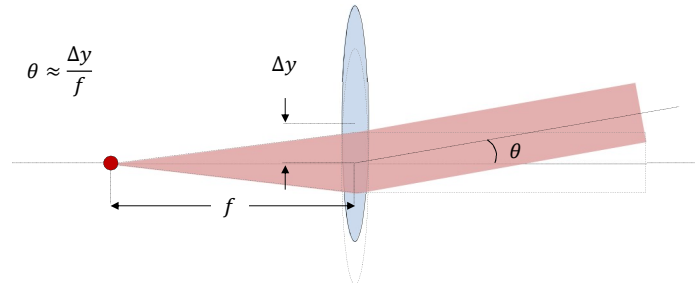
- Polymer/glass microlenses on MEMS platforms
- Refractive and diffractive lenses
- Compact solutions for complex imaging
- In-line steering of light (unlike mirrors)
- Limited freedom in lens design
- Fabrication Methods
 - Reflow on MEMS
 - Electrostatic shaping + UV curing
 - Molding/Hot embossing
 - Micro-assembly
- Applications
 - Beam steering (in-plane translation)
 - Focusing and zooming (piston)



Yo et al., J. Micromech. Microeng. **23** (2013) 065012

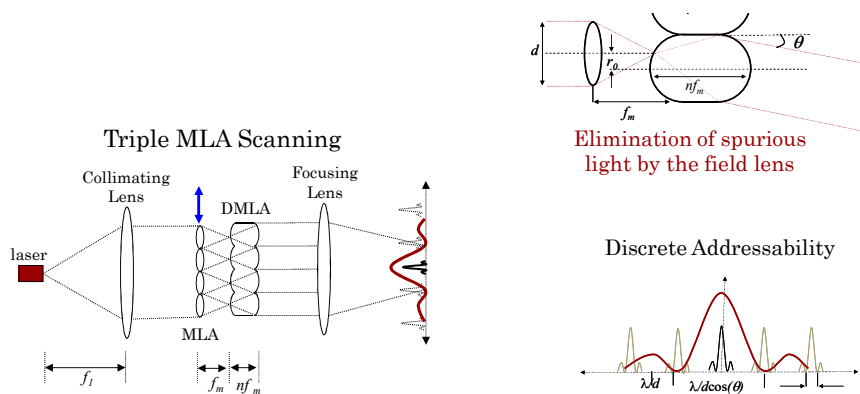


Laterally Translating A Lens



- Lens translation leads to beam rotation
- Beam rotation increases with
 - Lens focal length
 - Translation stroke
- Large displacements for notable steering angles

Refractive beam scanning

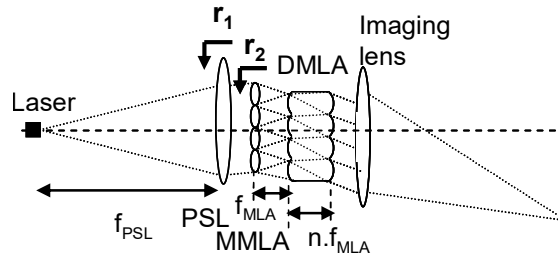


Elimination of spurious light by the field lens

$$t(x) = [\exp(-i2\pi_0 x / \lambda f) \bullet \text{rect}(x/a)] \bullet [(1/d) \text{comb}(x/d) \text{rect}(x/Nd)]$$

$$I(\theta) = (Nad)^2 [\text{sinc}[(a/\lambda)(\sin \theta - r_0/f)] \bullet [\text{comb}(d \sin \theta / \lambda) \bullet \text{sinc}(Nd \sin \theta / \lambda)]]^2$$

Refractive beam scanning



$$\theta_T = -\frac{r_1}{f_{PSL}} + \frac{r_2}{f_{MLA}}$$

$$OPD_T = -d \frac{2r_1}{f_{PSL}} + d \frac{r_2}{f_{MLA}}$$

Phase Condition

$$r_1 = (\theta_T - n\lambda / d) f_{PSL}$$

$$r_2 = (\theta_T + r_1 / f_{PSL}) f_{MLA}$$

A. Akatay, C. Ataman, H.Urey" Optics Letters, vol.31, no. 19, pp. 2861-2863, 2006.

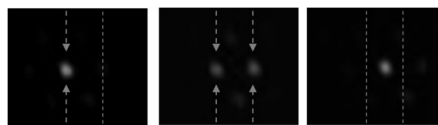


MOEMS III - Devices:

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MLA Scanner: Proof of Principle



(a)

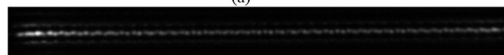
(b)

(c)

(a) All lenses on-axis, (b) Only the MMLA is moved (c) Both the PSL and the MMLA is moved to meet the phase condition



(a)



(b)

(a) The MMLA motion only produces discrete addressing (b) The PSL and the MMLA move synchronously

A. Akatay, C. Ataman, H.Urey" Optics Letters, vol.31, no. 19, pp. 2861-2863, 2006.



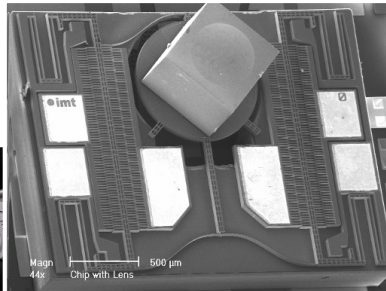
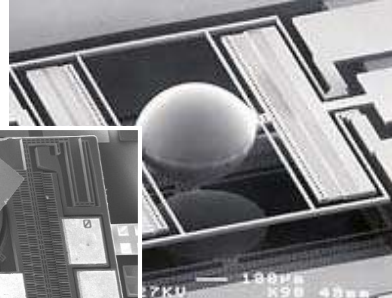
MOEMS III - Devices:

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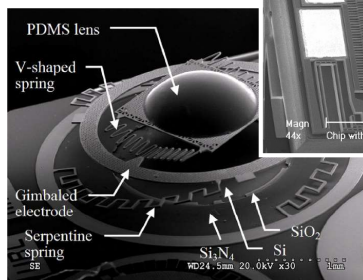
EPFL

Microlenses on MEMS Platforms: Examples

Kwon et al. Optics Letters 24 (7), 2004, 706-708



SAMLAB, EPFL



Siu et al., IEEE MEMS 2009



MOEMS III - Devices: Microlenses

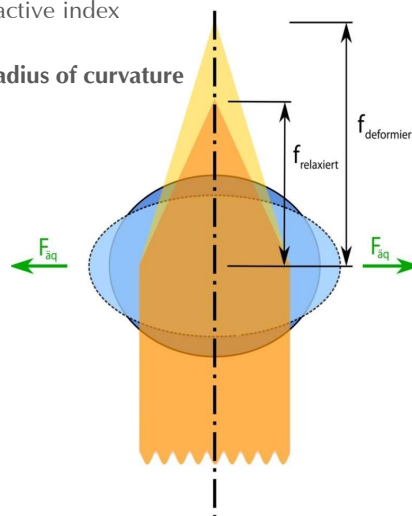
286

Micro-605: Optical MEMS and Micro-Optics



Lenses with Adaptive Radius of Curvature

- Focal length can be tuned by
 - Electro-optic effect → Changing lens refractive index
 - Fast yet limited in tuning range
 - **Physical deformation** → **Changing the radius of curvature**
 - Large tuning range, yet relatively small
- Main challenges
 - Tuning range and speed
 - Maintaining good optical quality
 - Mechanical reliability
- Applications
 - Autofocus and optical zoom systems
 - Confocal microscopy
 - Machine vision



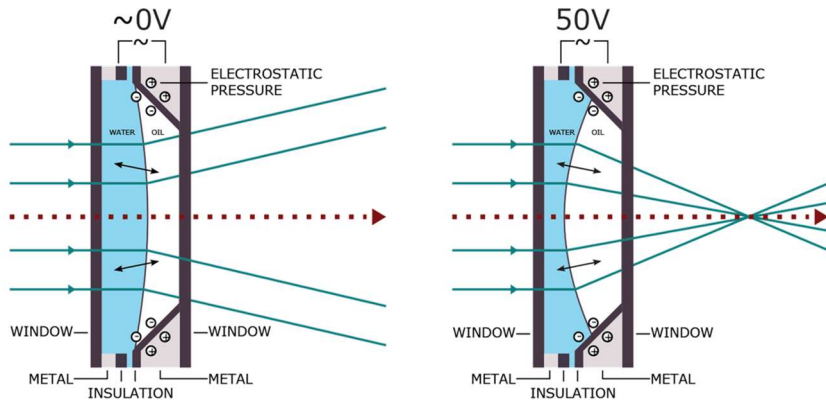
MOEMS III - Devices: Microlenses

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Micro-605: Optical MEMS and Micro-Optics



Electrowetting Based Tunable Microlenses



- Liquid-liquid interface
- Different refractive index
- Density matching for eliminating gravitational effects

© Varioptic



MOEMS III - Devices: Microlenses

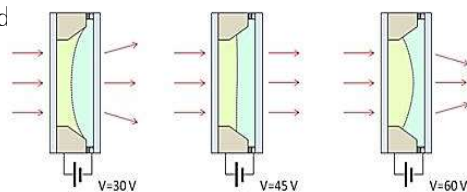
288

EPFL

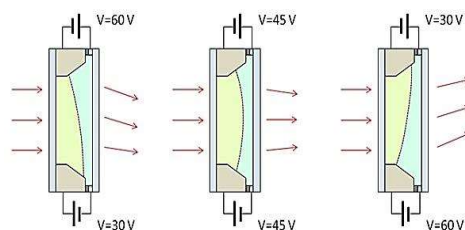
Corning® Varioptic® Tunable Lenses

- Electrowetting based liquid lens
- Water-oil interface for refractive index
- Density matching!
- Applications
 - ❑ Autofocus and zoom optics
 - ❑ Optical image stabilization

Autofocus mode



Optical image stabilization mode



CORNING
Varioptic® Lenses



<http://www.varioptic.com/>



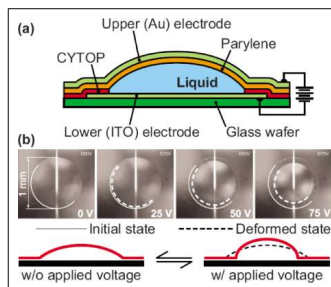
MOEMS III - Devices: Microlenses

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Liquid Tunable Microlenses

- Microlens with flexible membrane capping
- Large tuning range
- Positive and negative curvature
- External pumps or integrated actuators
- Optical fluid + flexible membranes
- Prone to aberrations



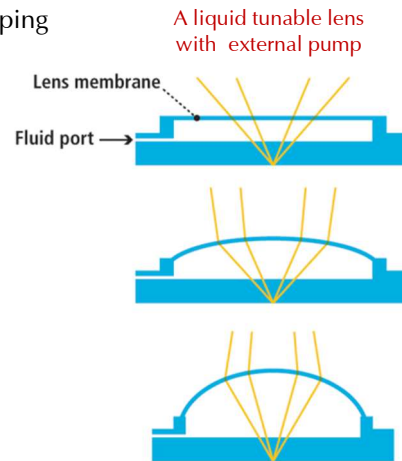
Zeng et al. J. Phys. D: Appl. Phys. 46 323001



MOEMS III - Devices: Microlenses

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Micro-605: Optical MEMS and Micro-Optics



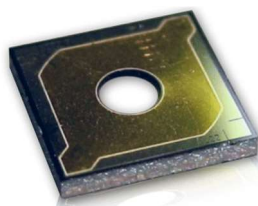
A liquid tunable lens with integrated actuator

Commercial Liquid Tunable Lenses

Polight (Norway) TLens

- Deformable membrane lens
- Piezo actuation
- Specifications
 - >95% transmittance
 - Dimensions: 3.2 x 3.2 x 0.4 mm
 - Response time : <1 ms
 - Power Consumption: 1 mW

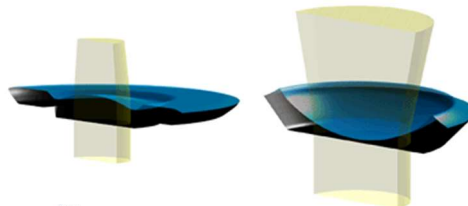
<http://www.polight.no/>



Optotune (Switzerland)

- Deformable membrane lens
- Electroactive polymer actuation
- Optical liquid with polymer membrane
- Spun off the NextLens AG!

<http://www.optotune.com>



MOEMS III - Devices: Microlenses

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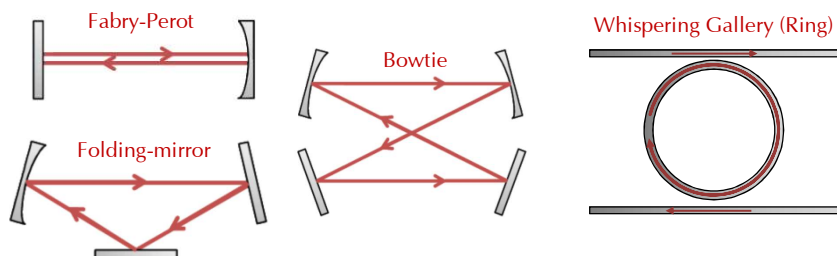
Micro-605: Optical MEMS and Micro-Optics



TUNABLE RESONATORS

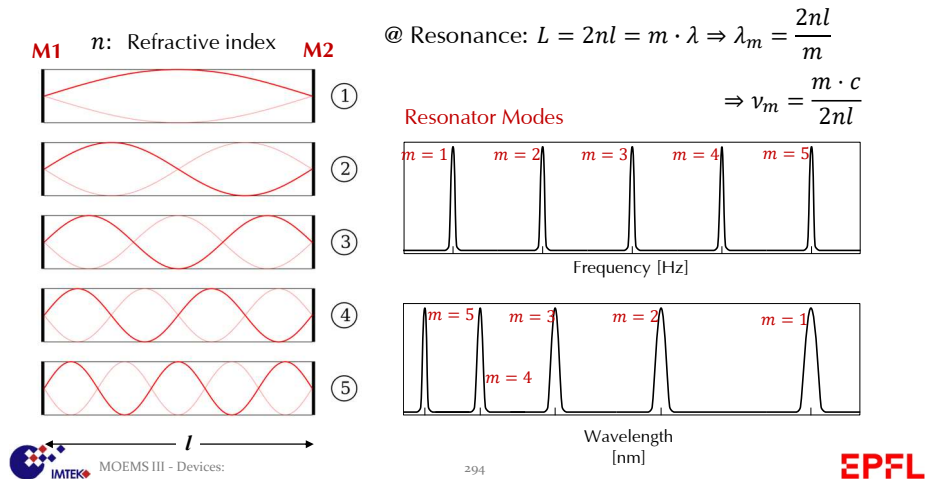
What is an Optical Resonator?

- An optical arrangement that allows a beam to circulate in a *closed path*.
- Discrete resonant frequencies (longitudinal modes)
- Major component for
 - ❑ Virtually all types of laser
 - ❑ Filters and frequency selective components
- Can be linear or ring type



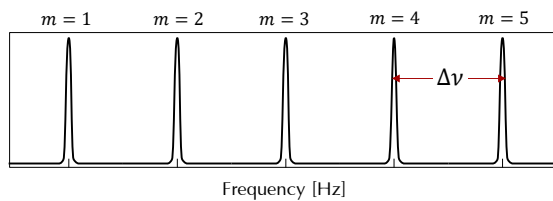
Longitudinal Resonator Modes

- Self-consistent field distributions self-reproducing in each round trip.
- Constructive self-interference after one round trip
- Free Spectral Range (FSR): distance between two resonator modes



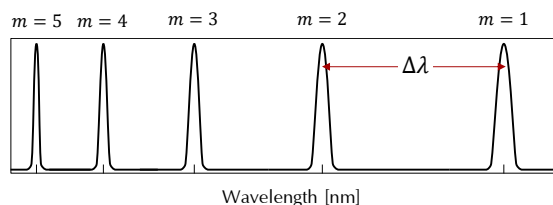
Free Spectral Range (FSR)

Frequency Domain



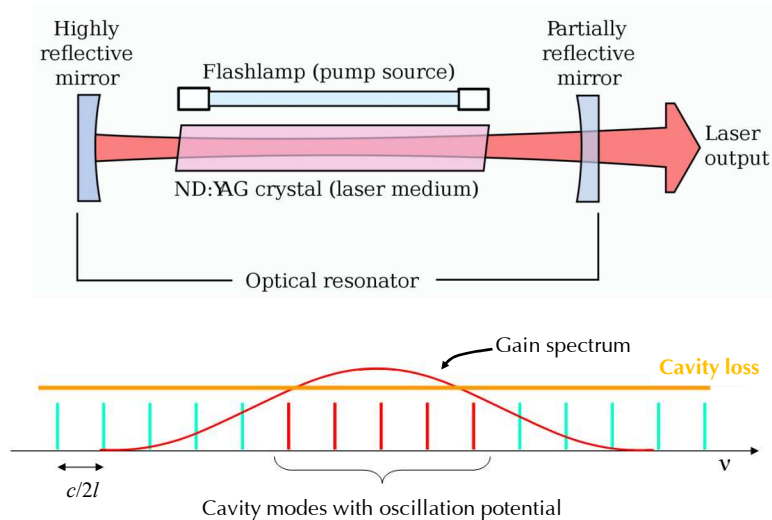
$$\Delta\nu \approx \frac{c}{2nl}$$

Wavelength Domain



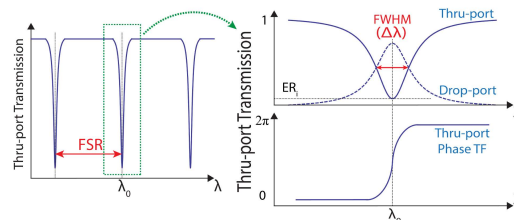
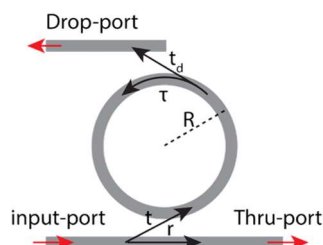
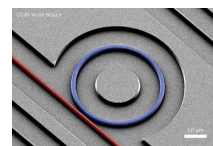
$$\Delta\lambda_m \approx \frac{\lambda_m^2}{2nl}$$

Example: Nd:YAG Solid-State Laser



Example: Ring Resonator Notch Filter

- Cavity length equals to the resonator circumference
- Near-field in and out coupling via waveguides
- Very high quality factor
- Key components in photonic transceiver ICs
- MOEMS for PICs is an emerging topic!



$$\lambda_0 = \frac{n_{eff} 2\pi R}{m} \quad mn = 1, 2, 3, \dots$$

TUNABLE FABRY-PEROT RESONATORS



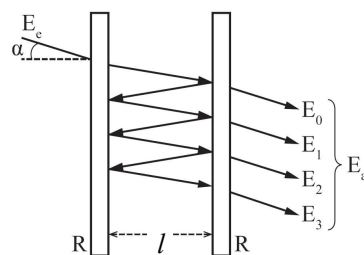
MOEMS III - Devices:

EPFL

Fabry-Perot Resonator (FPI) Basics

- Also called FP interferometer or *etalon*
- Linear resonator with two mirrors
- Mirrors are partially reflective
- Mirror separation of l
- At the resonant wavelengths,
 - ❑ Transmitted beams interfere constructively
 - ❑ All the incident energy is transmitted.
- Control and measurement of spectra
 - ❑ Optical filters
 - ❑ Tunable lasers
 - ❑ Spectrometers
 - ❑ Dichroic mirrors
 - ❑ ...and many more

Basic Fabry-Perot interferometer



$$\Delta\phi = \frac{4\pi}{\lambda} n l \cos \alpha$$



MOEMS III - Devices:

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FPI Transmission Spectrum

- Total E-field after the FPI:

$$E_a = \sum_{n=0}^{\infty} E_n = T E_e \sum_{n=0}^{\infty} R^n e^{-in\Delta\phi} = \frac{T E_e}{1 - R e^{-i\Delta\phi}},$$

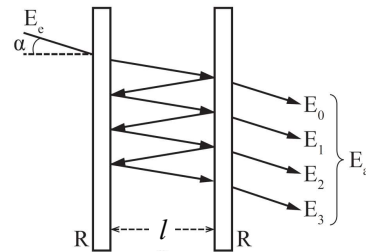
- Transmitted intensity:

$$I_T = I_e \frac{(1 - R)^2}{(1 - R)^2 + 4R \sin^2(\Delta\phi/2)},$$

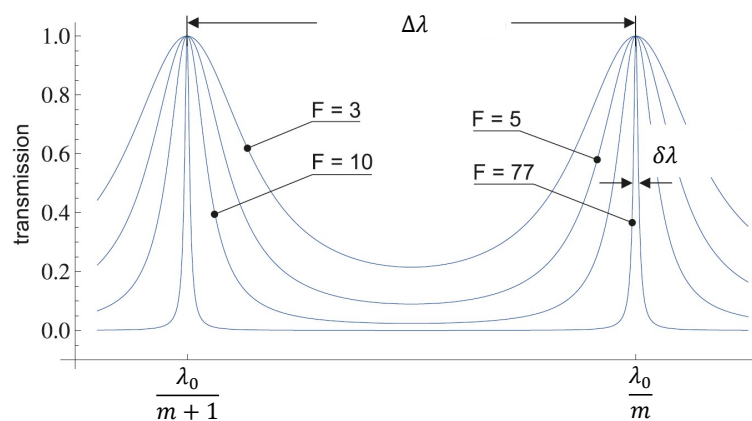
- Define Finesse $\mathcal{F}$

$$I_T = \frac{1}{1 + (2/\pi)^2 \mathcal{F}_R^2 \sin^2(\Delta\phi/2)} \quad \text{with} \quad \mathcal{F}_R \equiv \pi \frac{\sqrt{R}}{1 - R},$$

Basic Fabry-Perot interferometer



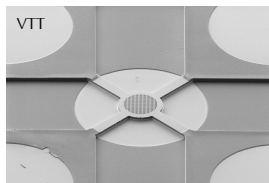
Free Spectral Range vs. Finesse



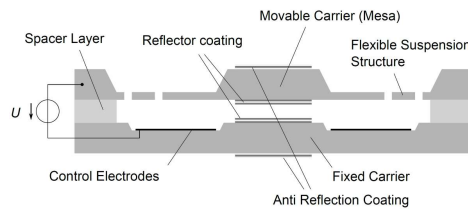
$$\mathcal{F}_R \stackrel{\text{def}}{=} \frac{\Delta\lambda}{\delta\lambda}$$

MEMS Tunable FP Resonators

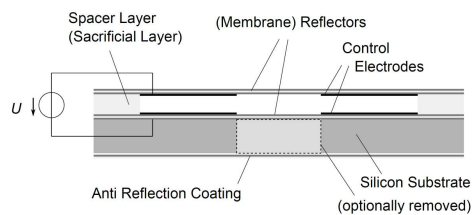
- Tuning of the cavity length
- Mostly electrostatic actuation
- Applications
 - ❑ Tunable filters
 - ❑ Tunable lasers
 - ❑ Tunable amplifiers
 - ❑ Add/drop multiplexers
 - ❑ Spectrometers
 - ❑ Flat panel displays



Bulk micromachined MEMS-FPR



Surface micromachined MEMS-FPR



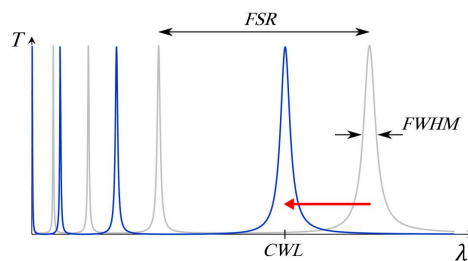
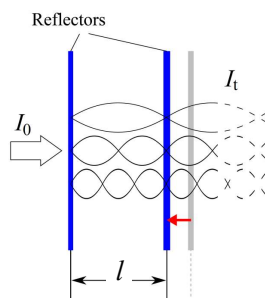
MOEMS III - Devices:

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EPFL

MEMS FPR Operation Principle

- Cavity length tuned by changing the cavity length
- Entire spectrum contracts (or expands)
- Shifting of the transmission peak
- Tuning range limited by FSR
- Resolution limited by spectral width



MOEMS III - Devices:

303

EPFL

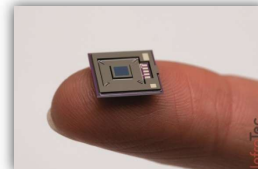
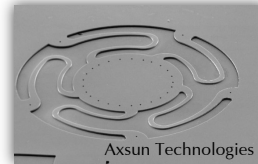
MEMS FPR: Advantages and Requirements

➤ Advantages

- ❑ Exceptional mirror quality
- ❑ Exceptional parallelism
- ❑ Short cavity length → Large FSR
- ❑ Tuning precision and speed
- ❑ Batch fabrication

➤ Requirements

- ❑ Good control over cavity gap
- ❑ Mirror quality
- ❑ Large aperture size
- ❑ Bow-free mirror displacement
- ❑ Pull-in control
- ❑ Extra filters for order selection

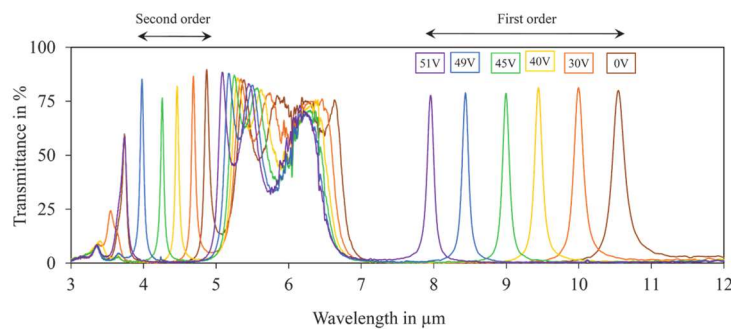
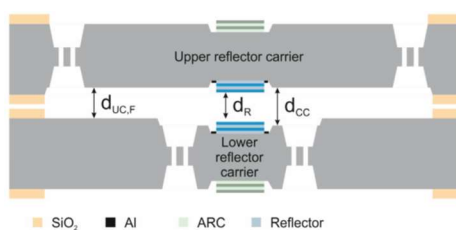


MOEMS III - Devices:

304

EPFL

InfraTec – MEMS FPR Technology

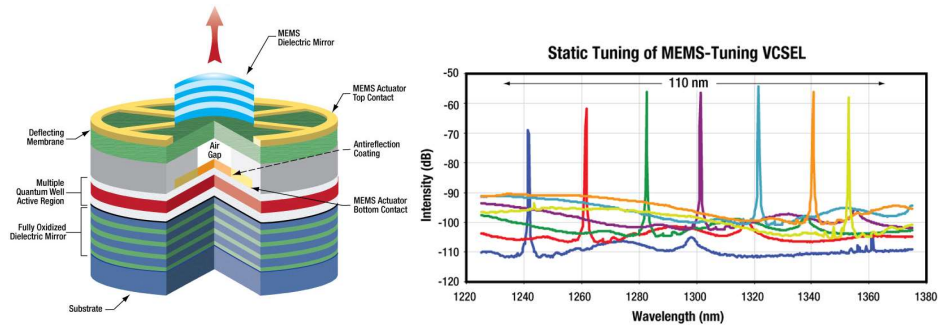


MOEMS III - Devices:

305

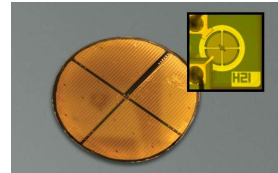
EPFL

Thorlabs MEMS Tunable VCSEL



- Center wavelength: 1300 nm (low scattering in tissue)
- Developed for OCT
- >100 nm tuning with 400 KHz scan rate
- >50 mm coherence length
- 1.06 μm counterpart under development

THORLABS



MOEMS III - Devices:

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EPFL

MEMS FPR FOR SENSING

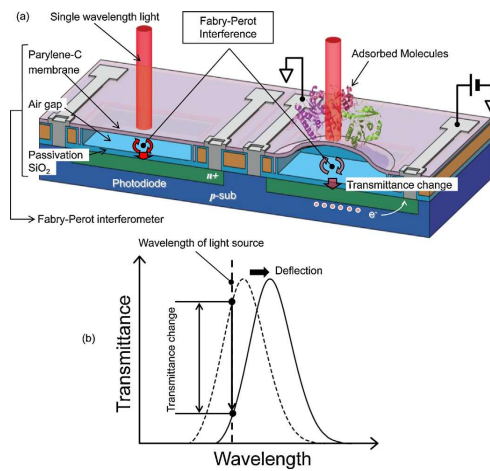


MOEMS III - Devices:

EPFL

MEMS FP Resonator for Sensing

- Cavity with one deformable/movable membrane
- Mass/Pressure/Stress induced displacement leads to a shifted transmission spectrum
 - ❑ Intensity based detection
 - ❑ Spectrograph based detection
- MEMS Fabry-Perot Cavities for
 - ❑ Bio-sensing
 - ❑ Process monitoring
 - ❑ Microphones
 - ❑ Pressure sensors
 - ❑ Strain sensors
 - ❑ Microbolometers



K. Takahashi et al., Sensors and Actuators B 188 (2013) 393–399

MOEMS APPLICATIONS



Part IV - Systems:

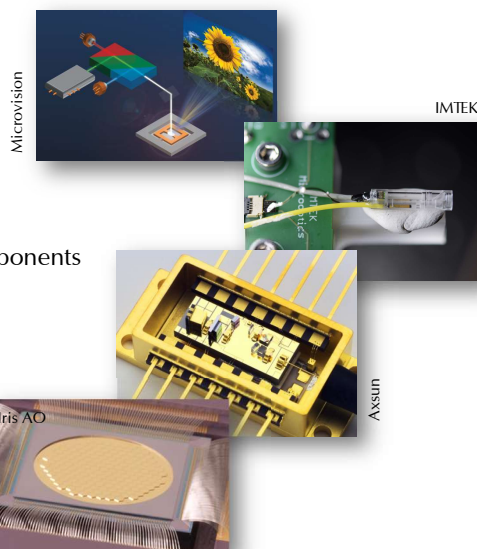
309

Micro-605: Optical MEMS and Micro-Optics



MOEMS Applications: Overview

- Display Systems
 - Scanning Displays
 - Projection Displays
- Imaging Systems
 - Laser Scanned Imaging
 - Endomicroscopy
 - Mobile Photography
 - Infrared Imaging
- Telecommunication Network Components
 - Tunable Laser Sources
 - Optical Cross-Connects
 - Wavelength Selective Switches
 - Variable Optical Attenuators
- Advanced Instrumentation
 - Spectroscopy
 - Adaptive Optics
 - Maskless Lithography



Part IV - Systems:

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Micro-605: Optical MEMS and Micro-Optics



Display Systems

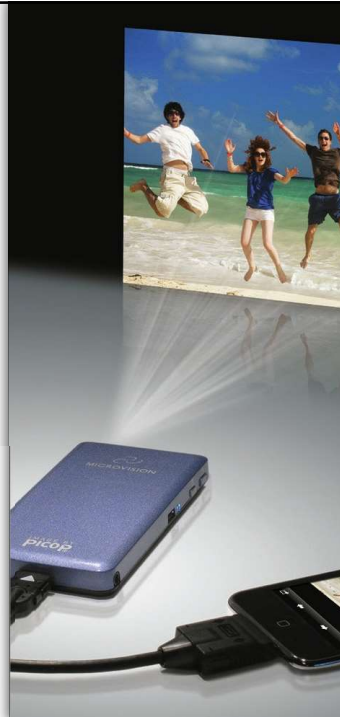
- **Scanning Displays**
 - Uses scanning micromirrors
 - Pocket Projectors, HUDs, HMDs
 - Microvision, Lemoptix, ST
- **Projection Displays**
 - Imaging of a MOEMS array on a screen
 - Projectors, Pocket Projectors, Lithography
 - TI DLP, SLM GLV, Sony GxL
- **Backlit Displays**
 - LCD/OLED Alternatives
 - Mobile devices
 - Qualcomm Pixtronics, Unipixel
- **Reflective Displays**
 - E-Ink Alternatives
 - Mobile devices, e-readers
 - Qualcomm IMOD



Part IV- Systems: Display Systems

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Image courtesy of Microvision, inc.



MICROMIRROR-BASED DISPLAYS



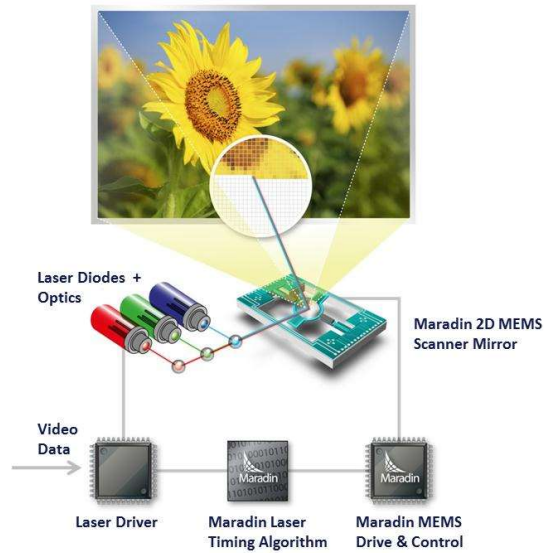
Part IV- Systems: Display Systems

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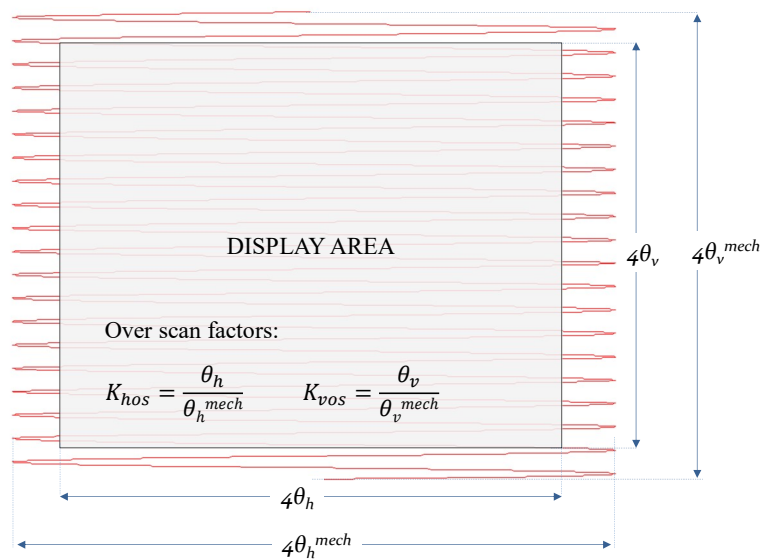
Micro-605: Optical MEMS and Micro-Optics

EPFL

Scanning Display Operation



Scanning Display: Practical Concerns



Scanning Display Resolution

$$N_h = \frac{4\theta_h^{mech} K_{hos} D_h K_{sp}}{K_T \lambda}$$

$$N_v = \frac{4\theta_v^{mech} K_{vos} D_v K_{sp}}{K_T \lambda}$$

N_h : Horizontal resolution

θ_h^{mech} : Maximum horizontal scan angle

K_{hos} : Horizontal overscan factor

D_h : Mirror size along horizontal axis

K_{sp} : Spot-size/pixel size ratio

K_T : Beam-clipping factor

N_v : Vertical resolution

θ_v^{mech} : Maximum vertical scan angle

K_{vos} : Vertical overscan factor

D_v : Mirror size along vertical axis

K_{sp} : Spot-size/pixel size ratio

K_T : Beam-clipping factor



Scanned Display: Refresh Rate and Standards

$$f_s = \frac{F_r N_v}{K_{ub} K_{vos}}$$

f_s : Horizontal scanner frequency

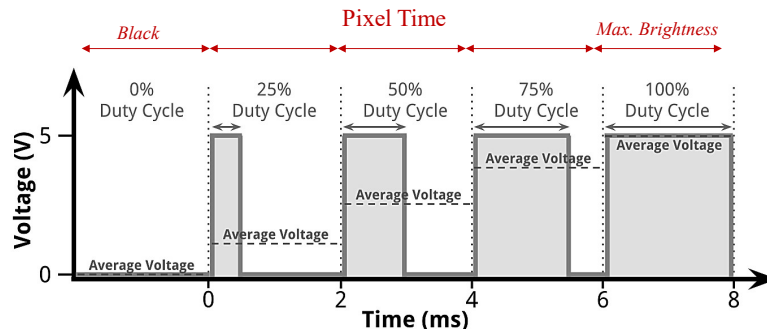
F_r : Refresh rate

K_{ub} : uni/bi-directional scanning

Display Format	N_h	N_v	$\theta_{mech}(deg \cdot mm)$	$f_s(Hz)$
QVGA	320	240	3.9	8000
VGA	640	480	7.8	16000
SVGA	800	600	9.7	20000
XGA	1024	768	12.4	25600
sXGA	1280	1024	15.6	34133
UXGA	1600	1200	19.4	40000
HDTV	1920	1080	23.3	36000



Colour and Grayscale Encoding



- Red, green and blue (RGB) sources for full colour display
- Modulation of the light source for pixel formation
- Intensity encoding:
 - **Pulse Width Modulation (PWM)**

EXAMPLE: MICROVISION PICO^P TECHNOLOGY

Microvision - PicoP

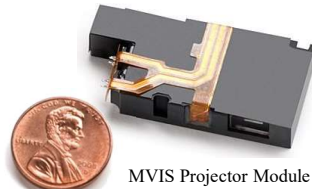
Modulated RGB lasers
MEMS 2D microscanner
Moving-coil actuation

Integrated in

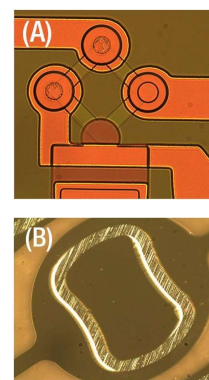
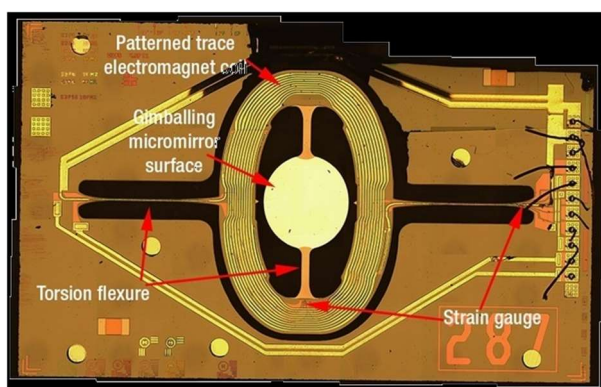
- Pocket projectors and smart phones
- Head mounted displays (HMDs)
- Automobile Head-up Displays (HUDs)

- Specifications

- 1920x710 (claimed!)
- 32 lumens
- Full colour
- >80.000 contrast ratio
- 42.1° field of view



Microvision MEMS Scanner Technology

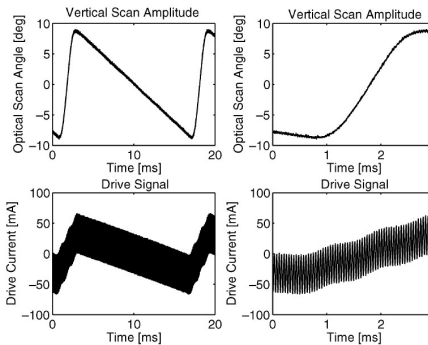
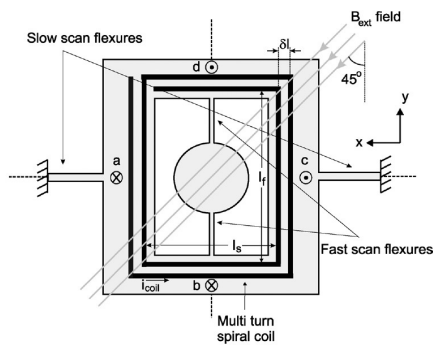


Single-coil for 2D actuation
External magnetic field via permanent magnets
Piezoresistive position sensors
Mirror reinforcement for dynamic deformation minimization

www.microvision.com



Microvision MEMS Scanner Technology



Yalcinkaya et al. JMEMS 25 (4) 2006.



Part IV- Systems: Display Systems

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Micro-605: Optical MEMS and Micro-Optics



Other MEMS Scanning Display Systems

Head-Up Displays (HUDs)

- Automotive Industry
- See-through
- Significant safety advantage



Retinal Scanning Displays (RSDs)

- Projection of the image directly on the retina
- Augmented reality



Other major players in the pico-projector game

- INTEL (through acquisition of Lemoptix)
- ST Microelectronics (through acquisition of bTendo)
- Maradin, Israel
- Opus Microsystems, Taiwan
- BOSCH Sensortec



Part IV- Systems: Display Systems

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Micro-605: Optical MEMS and Micro-Optics



GRATING LIGHT VALVE

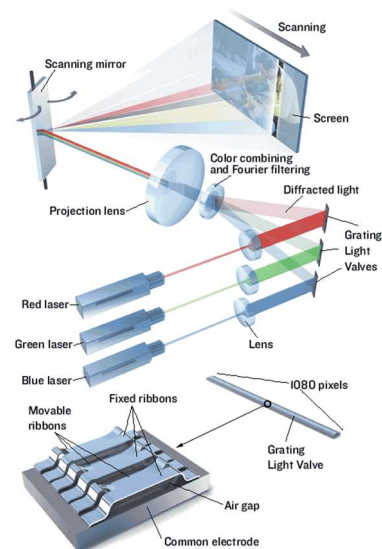


SLM - Grating Light Valve

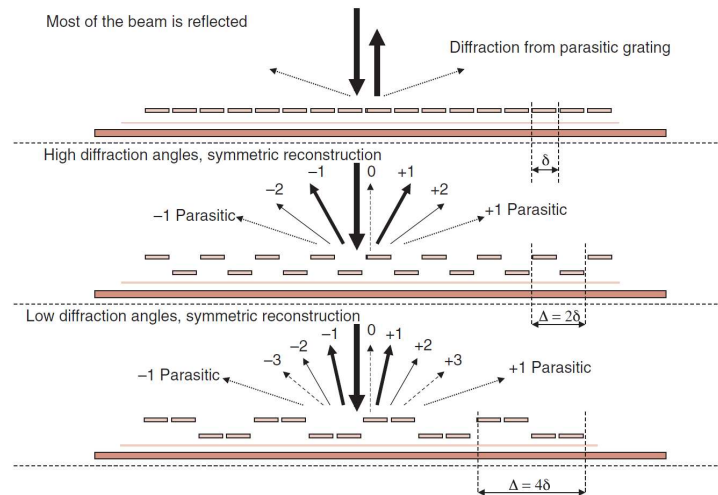
- 1D digitally-tunable grating array
- Combined with a 1D Scanner
- Diffracting grating
 - ❑ Color dependent beam deflection
 - ❑ Modulation rate: > 200 kHz
- Grating/ribbon data
 - ❑ Array: 1 x 8092 pixels
 - ❑ Pixel: 3 active + 3 in-active stripes
 - ❑ Width: 1 – 10 μm
 - ❑ Length: 100 – 1000 μm
 - ❑ Resonance frequency > 10MHz
 - ❑ Displacement: $\lambda/4 \approx 100 - 200 \text{ nm}$



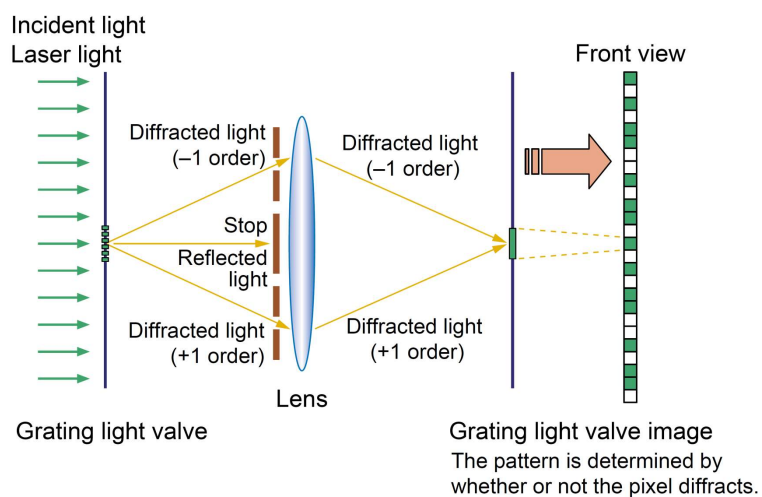
Image source: IEEE Spectrum



GLV operation principle

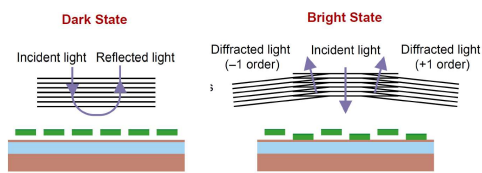
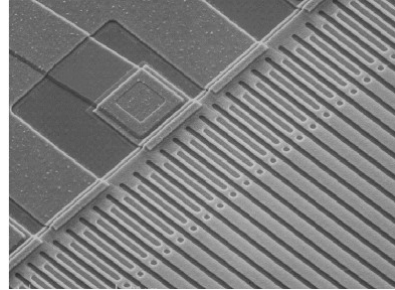


GLV Imaging Optics – Fourier Plane Filtering



SLM – Grating Light Valve

- Large 1D array of ribbons
- 6 ribbons per pixel
- Electrostatic actuation
- Digital or analog operation
- Other applications
 - ❑ Dynamic gain equalization
 - ❑ Head-up displays
 - ❑ Optical maskless lithography

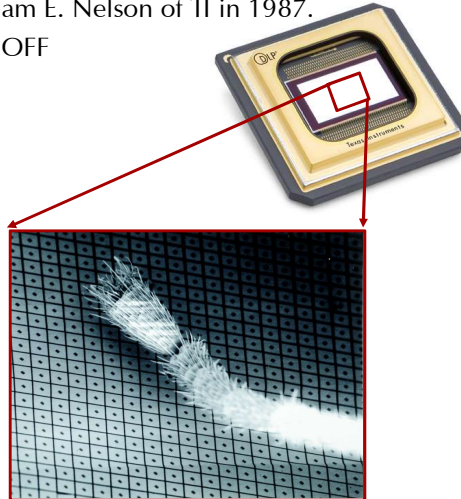


DIGITAL MICROMIRROR DEVICE (DMD)

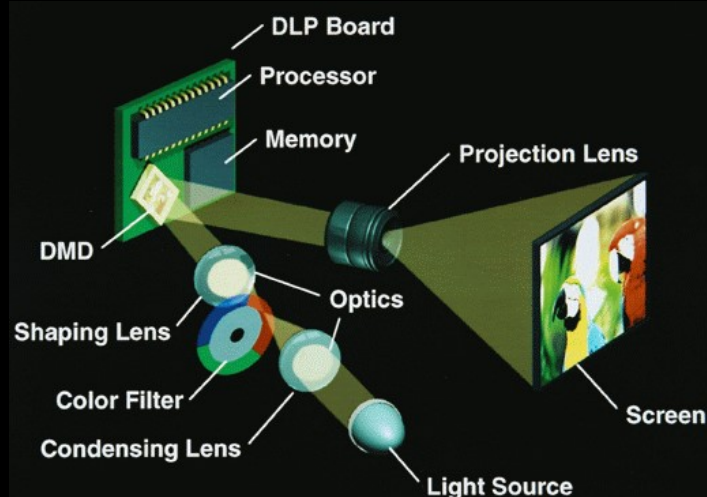


TI – Digital Micromirror Device

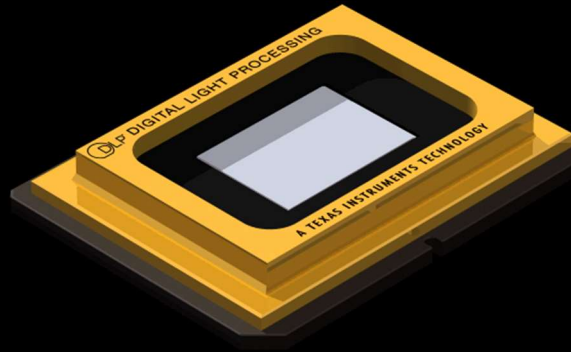
- Dr. Larry Hornbeck and Dr. William E. Nelson of TI in 1987.
- Mirror tilts $\pm 10^\circ$ or $\pm 17^\circ \rightarrow$ ON / OFF
- BPWM for grayscale (16 bits)
- Up to 2560 x 1600 resolution
- Down to 5.4 μm mirror size
- Applications
 - ❑ Televisions and HDTVs
 - ❑ Holographic Versatile Discs
 - ❑ Head-mounted displays
 - ❑ Digital cinema
 - ❑ DLP projector
 - ❑ Optical metrology



TI – Digital Micromirror Device



TI – Digital Micromirror Device



Media source: Presentation from Larry Hornbeck (TI): "DLP - How It Works" (2007)



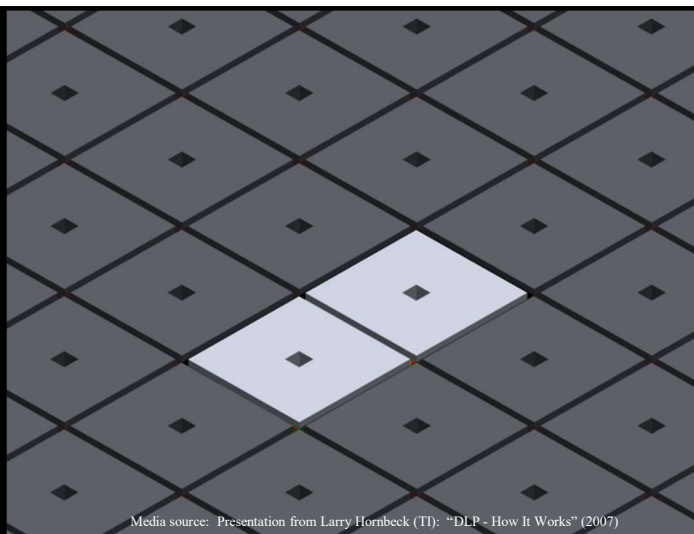
Part IV- Systems: Display Systems

33¹

Micro-605: Optical MEMS and Micro-Optics



TI – Digital Micromirror Device



Media source: Presentation from Larry Hornbeck (TI): "DLP - How It Works" (2007)



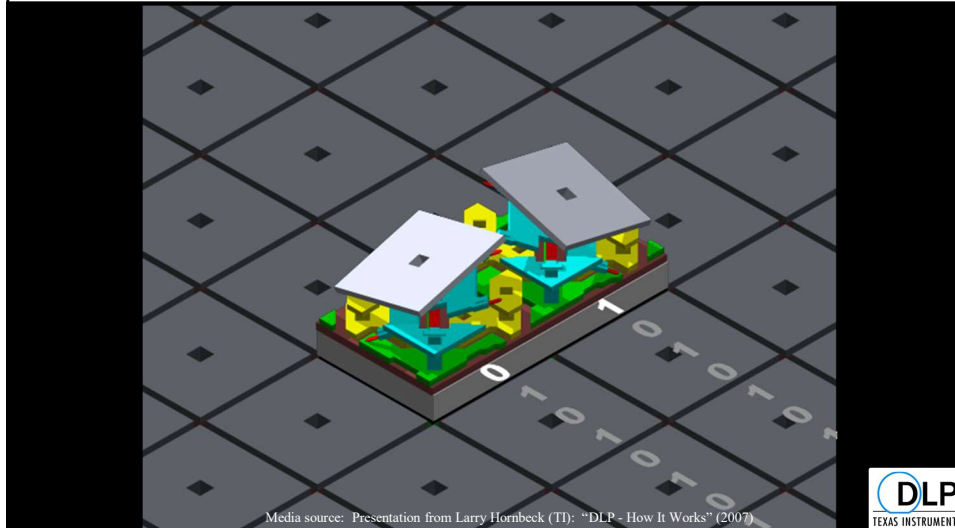
Part IV- Systems: Display Systems

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Micro-605: Optical MEMS and Micro-Optics



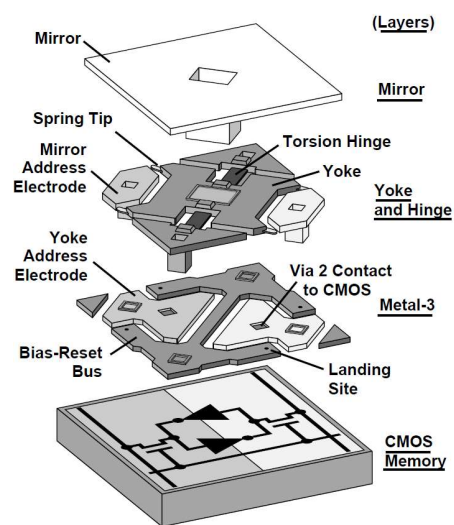
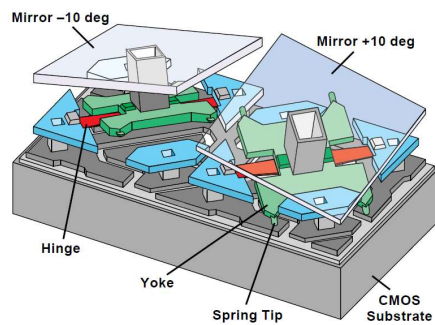
TI – Digital Micromirror Device



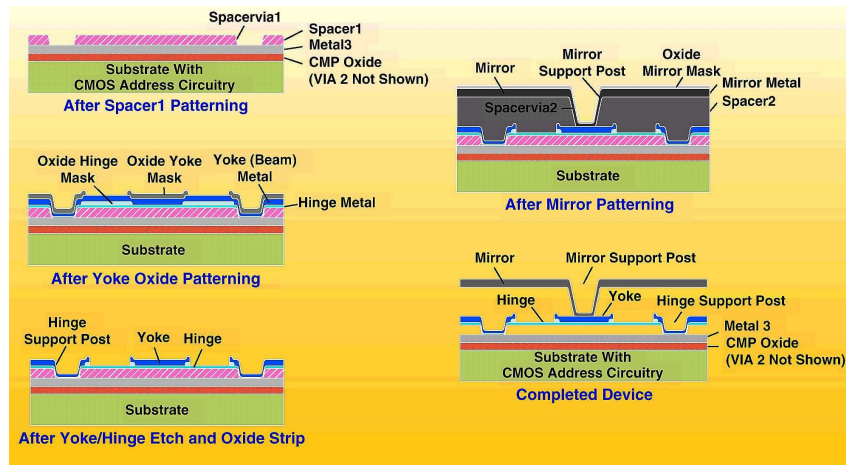
TI DMD – Pixel Structure

DMD Micromirrors

- Tilting $\pm 10^\circ/\pm 17^\circ$
- Pixel size down to $5.4 \mu\text{m}$
- Under each mirror:
 - Driving electronics
 - Memory electronics



DMD Fabrication Process

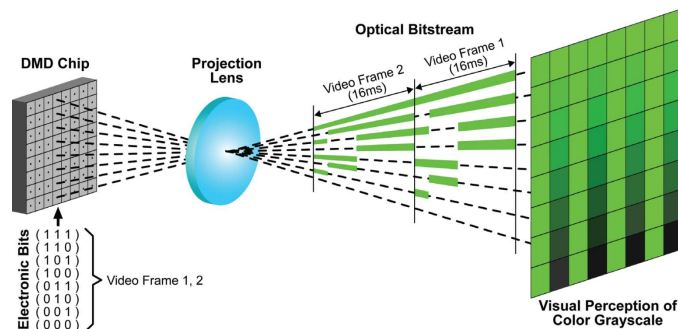


Al mirror ---- CMOS compatible process
 Photoresist sacrificial layer --- removed by plasma etching
 DMD on CMOS SRAM by 6 mask process



DMD – Operation Principle

1. Update SRAM cell.
 2. Remove bias
 - The mirror moves into new position.
 3. Restore bias
 - The mirror is held in position
 4. Update SRAM cell again.
- The bias system
 - Reduces the operation voltage
 - Synchronized mirror position update.
 - Grayscale Rendering
 - Pulse Width Modulation (PWM)



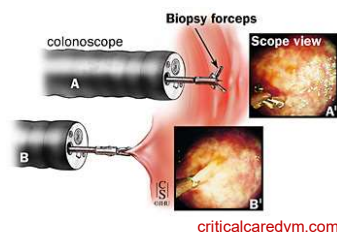
ENDOMICROSCOPY



Conventional vs. Optical Biopsy

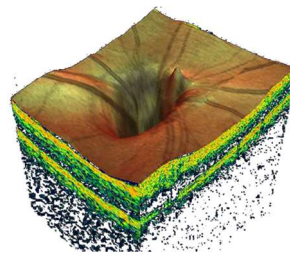
- Biopsy is the gold standard for tissue analysis

- + High-resolution
- + High-specificity and selectivity
- Needs incision
- Slow and costly
- Only vertical sectioning
- Only visual information



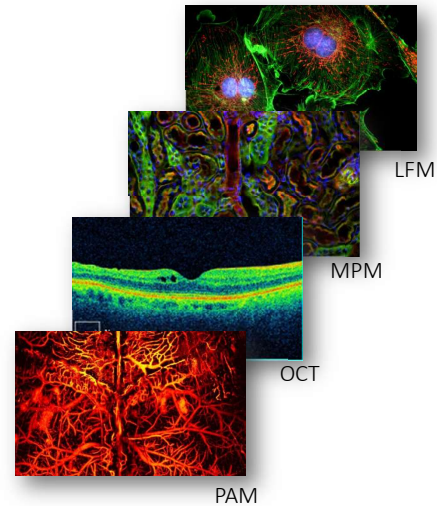
- Optical biopsy is a promising alternative

- Non-invasive
- In-vivo, in-situ, real-time
- Vertical and horizontal sectioning
- Spectroscopic information
- Transient tissue information



Optical Biopsy: Enormous Health Benefits

- Imaging-based diagnosis
 - In-vivo, in-situ, real-time diagnosis
 - No incision, no pathology
 - Pre-malignant tissue identification
- Aided surgical procedures
 - Tumor margin identification
 - Guiding of surgical tools
- Guided conventional biopsy
 - Reduced number of incisions
 - Improved targeting
 - Single endoscope insertion



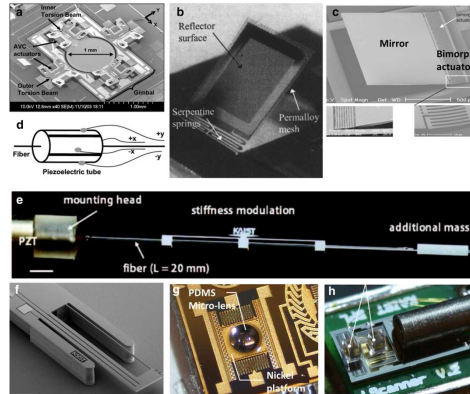
A Big Family of Imaging Methods

Method	Wide-field or Scanning	2D/3D	Structural or molecular
Endomicroscopy/Narrow-band Imaging	wide-field	2D	Structural
(Auto)Fluorescence Microscopy	both	2/3D	Molecular
Confocal Laser Endomicroscopy	scanning	3D	Structural
Optical Coherence Tomography	scanning	3D	Structural
Optical Coherence Microscopy	scanning	2D	Structural
Multiphoton Microscopy	both	2/3D	Molecular
Raman/CAR Spectroscopy	both	2D	Molecular
Second Harmonic Generation Micr.	both	2/3D	Molecular
Photoacoustic Microscopy	scanning	3D	Structural
Elastic Scattering Spectroscopy	scanning	2/3D	Structural



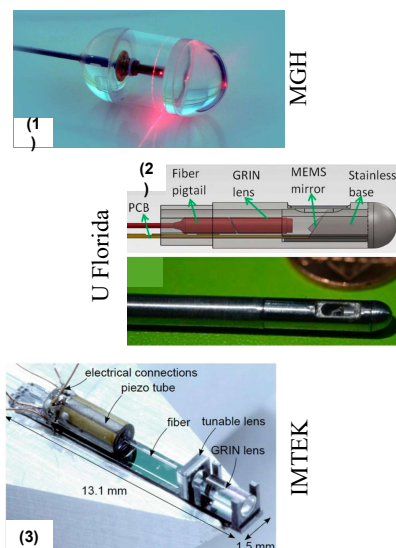
Micro-Optics & Optical MEMS in Endomicroscopy

- **Challenges**
 - Resolution vs. FoV vs. size
 - Optical quality
 - Packaging and reliability
 - Medical requirements
- **What does Optical MEMS offer?**
 - High quality micro-optics
 - Compact laser scanners
 - Adaptive imaging schemes
 - Assembly techniques
- **Beam scanning methods:**
 - Micromirrors
 - Fiber scanners
 - Lens Scanners

Hwang et al. *Micro and Nano Syst Lett* (2017) 5:1

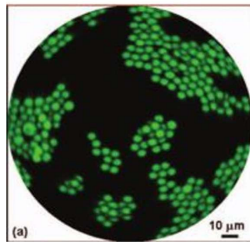
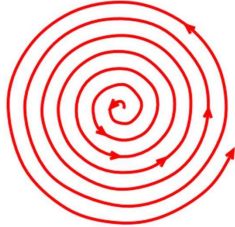
Point-Scanned Imaging

- Light delivery through optical fibers
- Viewing direction
 - Circumferential (1)
 - Side-looking (2)
 - Forward-looking (3)
- Resolution vs. field-of-view
 - Large NA for confocal techniques
 - Low-NA for large imaging depths
 - Remember Gaussian optics!
- Light collection
 - Through the illumination path
 - With extra fibers
- Endoscope type
 - Rigid
 - Flexible

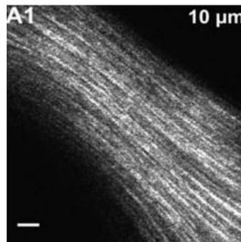
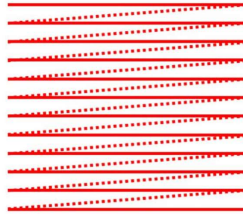


Scanning Schemes

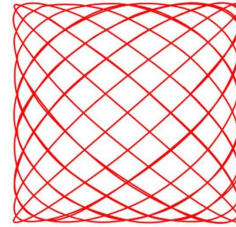
Spiral Scan



Raster Scan



Lissajous Scan



Part IV- Systems: Imaging Systems

EPFL

IMAGING WITH SCANNING FIBERS



Part IV- Systems: Imaging Systems

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Micro-605: Optical MEMS and Micro-Optics

EPFL

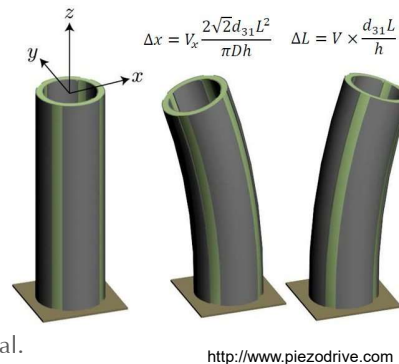
Tubular Piezoelectric Actuators

> Piezoelectric Effect

- ❑ Electric Field → Deformation
- ❑ Depends on crystal orientation
- ❑ Limited by maximum E-field

> Tubular Piezo Actuation

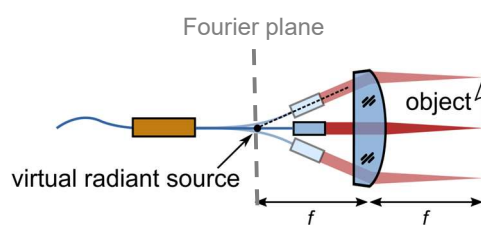
- ❑ Fixed-free cantilever
- ❑ 1 inner, 4 outer electrodes
- ❑ Developed for AFM
- ❑ Adapted for endoscopy by E. Seibel et al.
- ❑ Thinnest available scanning technique



E-OCT Probe with Fourier Plane Scanning

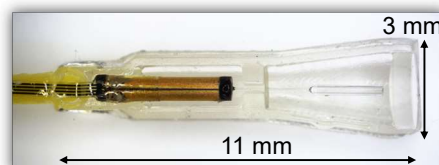
> Features

- ❑ Piezoelectric actuation
- ❑ Fiber-GRIN cantilever
- ❑ Telecentric scanning
- ❑ Low-distortion imaging
- ❑ Uniform PSF over FoV
- ❑ Ideal for multi-modal imaging



> Specifications

- ❑ FOV: 2 mm (telecentric)
- ❑ Working distance: 4.8 mm
- ❑ Lateral resolution = 29 μm
- ❑ Numerical aperture = 0.032
- ❑ Depth of field = 1.65 mm



E-OCT Probe: Scanning Principle

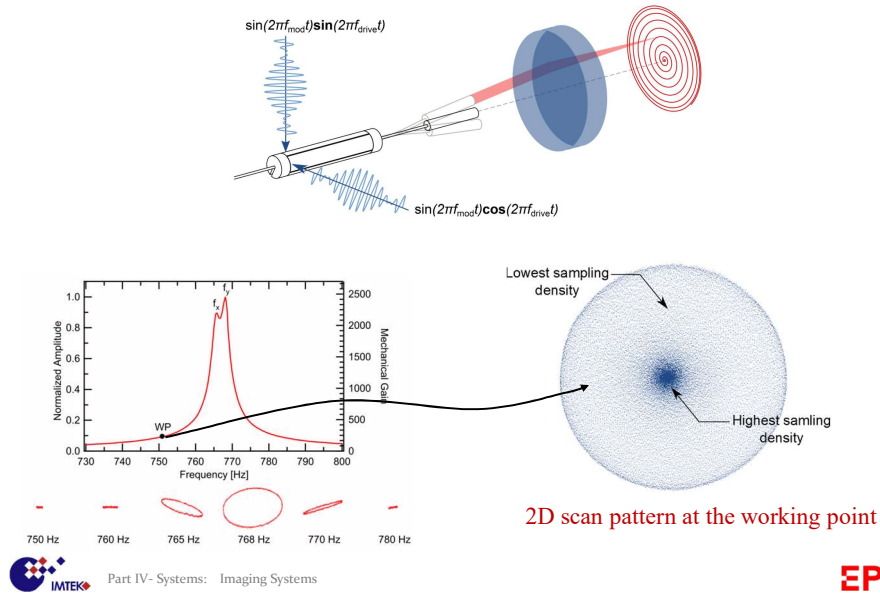
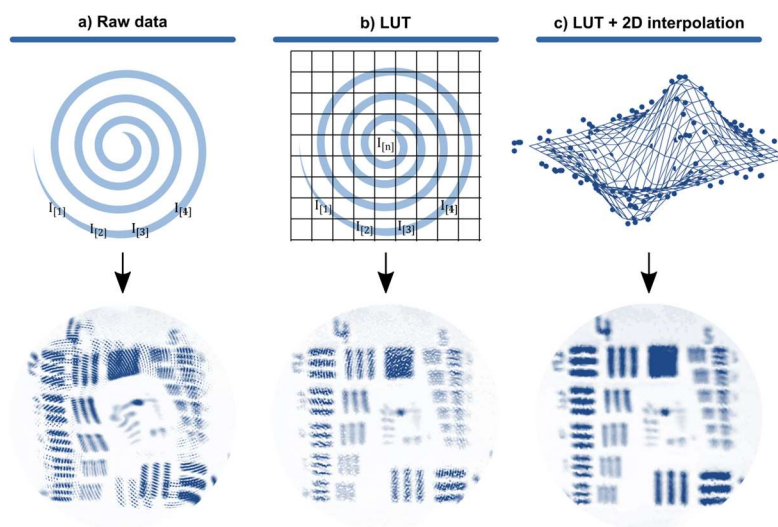


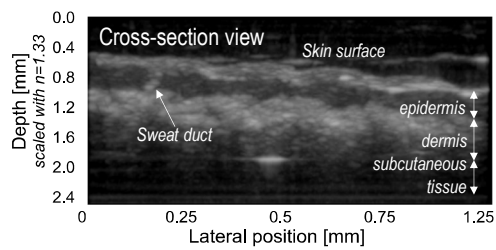
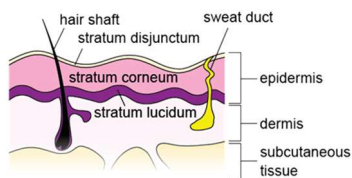
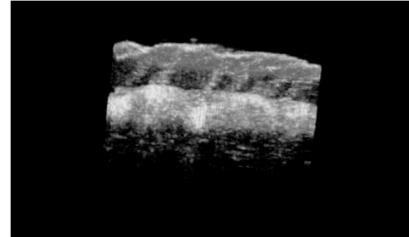
Image Acquisition and Distortion Correction



Vilches et al 2017 J. Micromech. Microeng. 27 105015

OCT Imaging Results

- SS-OCT parameters
 - ❑ Insight Photonics akinetic source
 - ❑ 142 KHz A-scan rate
 - ❑ 4 volumes/second
 - ❑ 32 nm bandwidth @ 1.34 μm
 - 25.4 μm axial resolution in air
 - ❑ 3.3 mW optical power
 - ❑ 82 dB SnR
- Sample: Human fingertip



MOEMS FOR CAMERA MODULES

MOEMS in Digital Cameras

➤ Zoom and autofocus systems

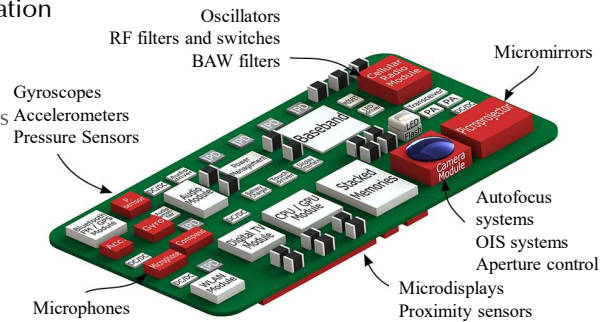
- ❑ Translating lenses
- ❑ Tunable-focus lenses

➤ Optical Image Stabilization

- ❑ Tunable lenses

➤ Aperture adjustment

- ❑ Microfluidic solutions
- ❑ Mechanical shutters



MEMS and MOEMS in modern smartphones

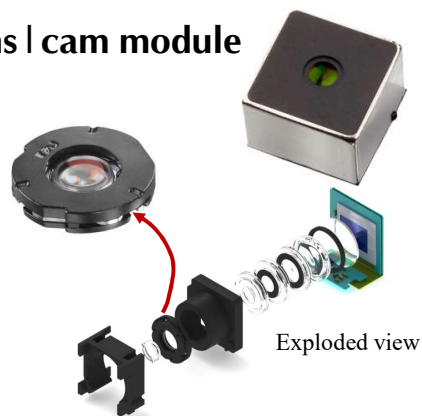


Part IV- Systems: Imaging Systems

EPFL

invensas – mems | cam module

- Integrated MEMS autofocus camera
- Vertical comb actuates polymer lens
- Camera specs:
 - Resolution 8MP
 - Pixel Size $1.4 \mu\text{m} \times 1.4 \mu\text{m}$
 - Relative Aperture (f#) f/2.4
 - Focusing Range 10 cm to ∞
 - Module Height 5.35 mm (COB)
- Autofocus specs:
 - Operating Voltage: 2.8 – 4.5 V
 - Power Consumption: 0.2 mW / 0.45 mW
 - Current: 80 μA
 - Settling Time: <10 ms (typical)
 - Travel: 100 μm (min)
 - Repeatability: $\pm 1 \mu\text{m}$ (nom)



Part IV- Systems: Imaging Systems

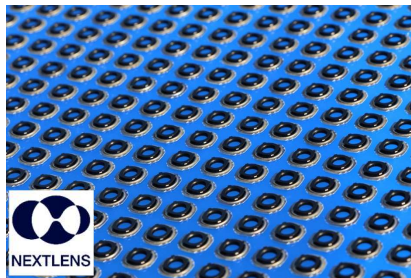
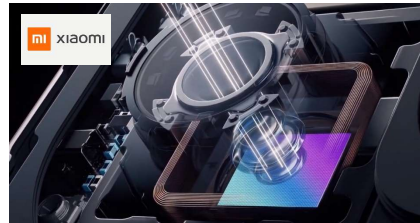
352

Micro-605: Optical MEMS and Micro-Optics

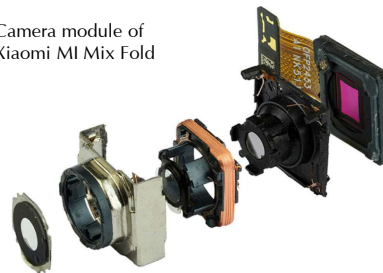
EPFL

Nextlens/Optotune Tunable Lenses

- First commercial smartphone camera with a liquid-tunable lens
- Optotune technology
- Magnetic actuation
- < 5 ms response time
- Wafer-level lens manufacturing

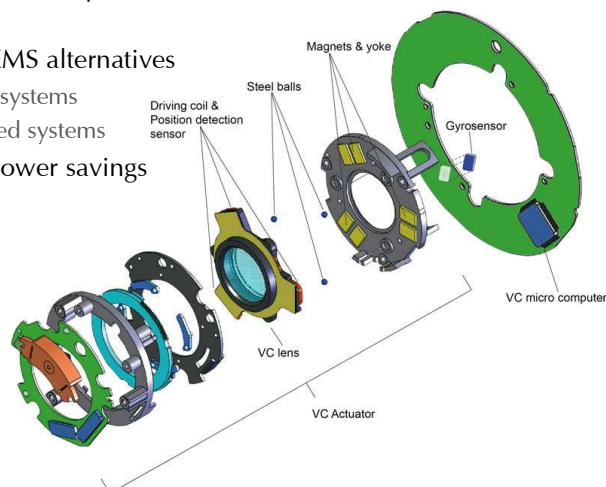


Camera module of
Xiaomi MI Mix Fold



Optical Image Stabilization (OIS)

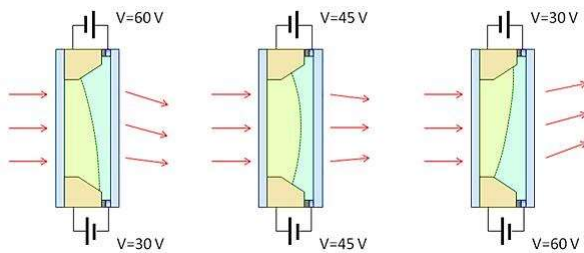
- Reduction of image blurring due to “shaking hands”
- Miniaturize systems for smartphones
 - Voice-coil actuators
- New generation MOEMS alternatives
 - Tunable lens based systems
 - MEMS platform based systems
- Order of magnitude power savings
- Enhanced speed
- Enhanced precision



Varioptic OIS – Shaking the Lens

- Varioptic is a developer of electrowetting based tunable lenses
- Quad-electrode lens for two-axis image stabilization
- Achieves auto-focus AND optical image stabilization
- Applications
 - mobile photography in medium light (indoors, at dusk...)
 - mobile video
 - mobile data capture

varioptic



Part IV- Systems: Imaging Systems

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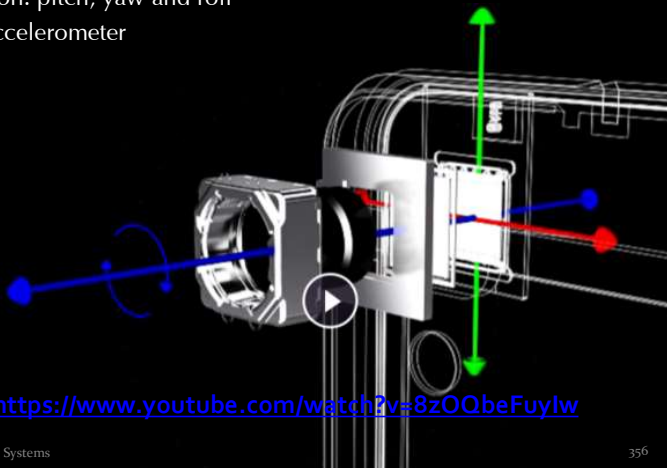
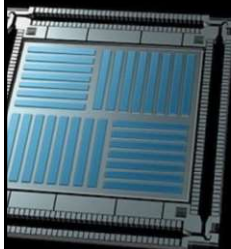
Micro-605: Optical MEMS and Micro-Optics

EPFL

MEMSDrive OIS – Shaking the Sensor

- Up to 5 axes moving the image sensor
- MEMS platform with comb actuators
- Features:
 - ❑ 3 Axis stabilization: pitch, yaw and roll
 - ❑ Built-in 2 Axis accelerometer

 MEMSDrive



<https://www.youtube.com/watch?v=8zOObeFuyIw>

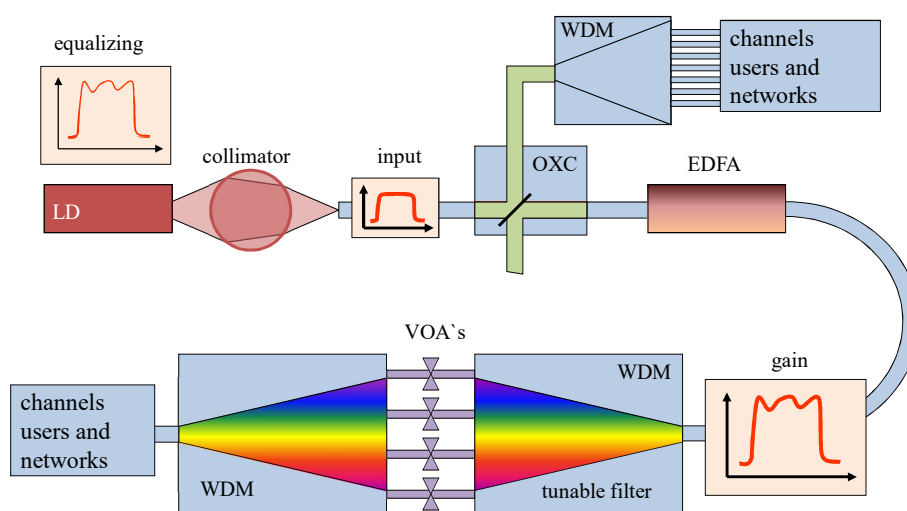


Part IV- System Imaging Systems

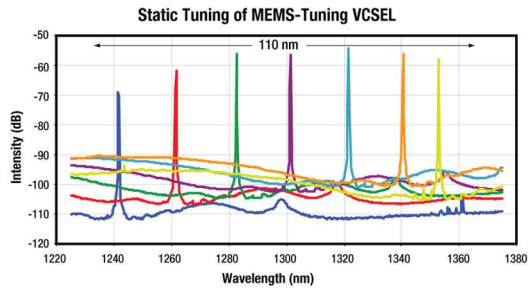
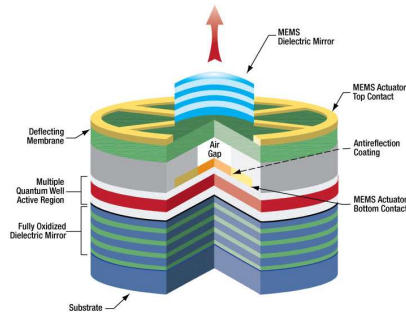
356

MOEMS FOR TELECOM

MOEMS in a Telecom Network

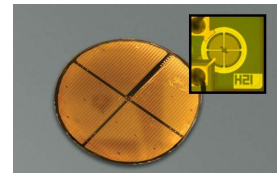


Thorlabs MEMS Tunable VCSEL



- MIT spin-off technology
- Developed for OCT @ 1300/1040 nm
- >100 nm tuning with 400 KHz
- ~25 mW output power
- > 1 m coherence length

THORLABS



Part IV- Systems: Telecommunications

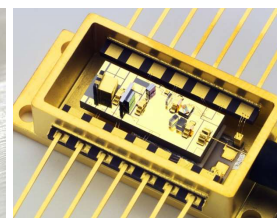
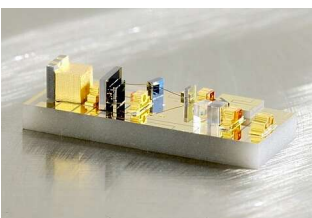
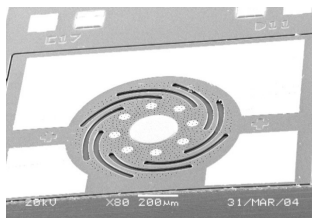
359

Micro-605: Optical MEMS and Micro-Optics

EPFL

Axsun Tunable Laser System

- MEMS Tunable Fabry-Perot Filter with an SLED
- Up to 100KHz sweep rate with >100 tuning at 1.06 μm
- Micro-Optical toolbox and automated assembly
- Applications
 - Telecommunication
 - Optical Coherence Tomography
 - Spectroscopy



AXSUN
a Volcano company

<http://www.axsun.com>



Part IV- Systems: Telecommunications

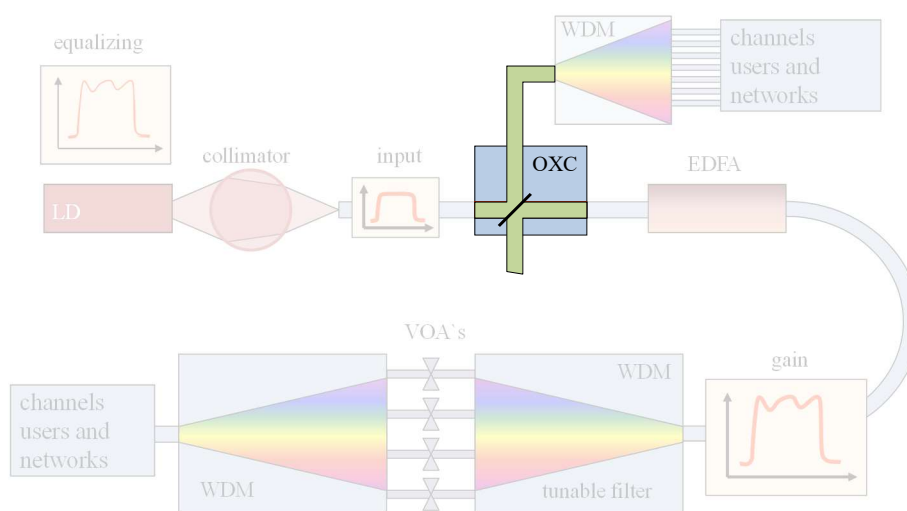
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Micro-605: Optical MEMS and Micro-Optics

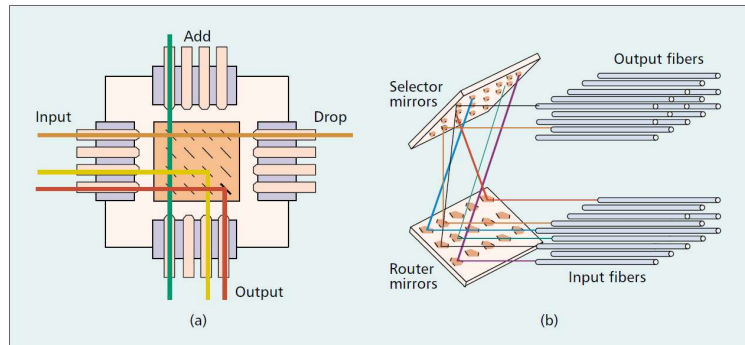
EPFL

OPTICAL SWITCHING

Optical Cross-Connects



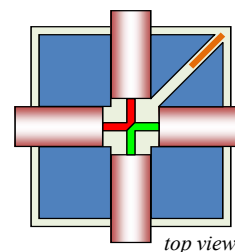
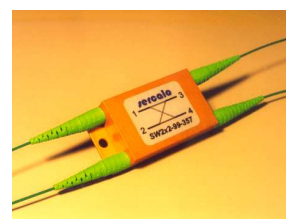
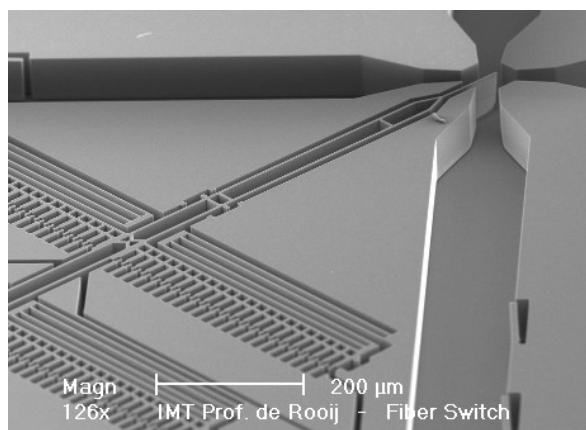
Optical Switches



- Faster than conventional optical-electrical-optical switching
- No signal bandwidth limitation
- Comes in three variants:
 - Small lensless switches
 - Sharing $1 \times N$ fiber switches
 - Optical cross-connects ($N \times N$)



Sercalo 2x2 Switch

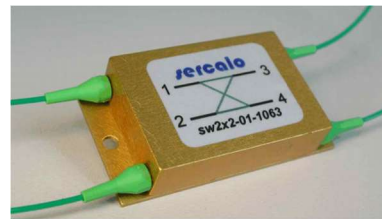
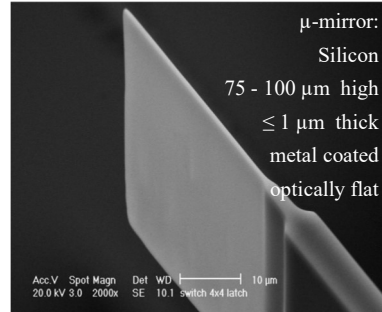


- IMT – University of Neuchatel Spin-Off
- Single mode fibers with self-alignment grooves



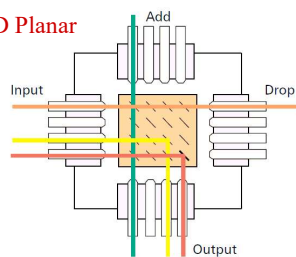
Sercalo 2x2 Switch

- Broad wavelength range 1.2 – 1.6 μm
- High repeatability < 0.002 dB
- Fast response time < 1 ms
- High cycling rate > 500 Hz
- Small insertion loss < 0.9 dB
- Low Crosstalk < 50 dB
- PDL < 0.1 dB
- Ext. operation at 5V
- 500 T-cycles (-40°C to 85°C)
- 9760h life test (85°C, 80 Hz)
- Telcordia GR 1221 qualified



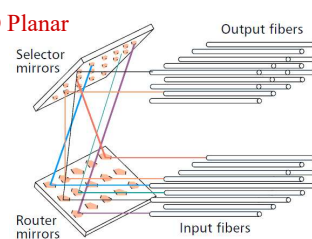
MxN Optical Switch (XConnect) Architectures

2D Planar



- Based on vertically “flap” mirrors
- Incompatibility with large matrices
 - Chip area becomes too large
- Collimating/focusing optics for fibers
- Self aligned fibers through v-grooves
- Sercalo, OMM, etc.

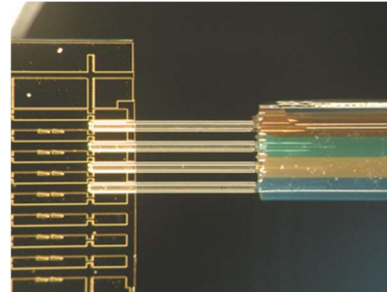
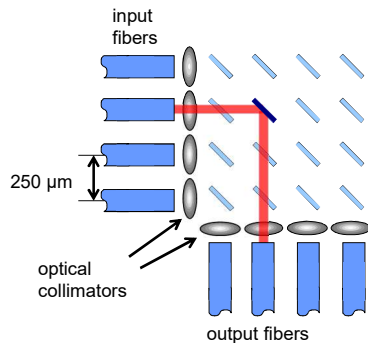
3D Planar



- Based on 2D biaxial mirror arrays
- More suitable to large fiber count switches
 - 512 x 512 demonstrated
 - Complicated alignment and assembly
- Collimating/focusing optics for fibers
- Lucent, JDSU, Fujitsu, Calient, etc.



Sercalo 2D MEMS OXC Array

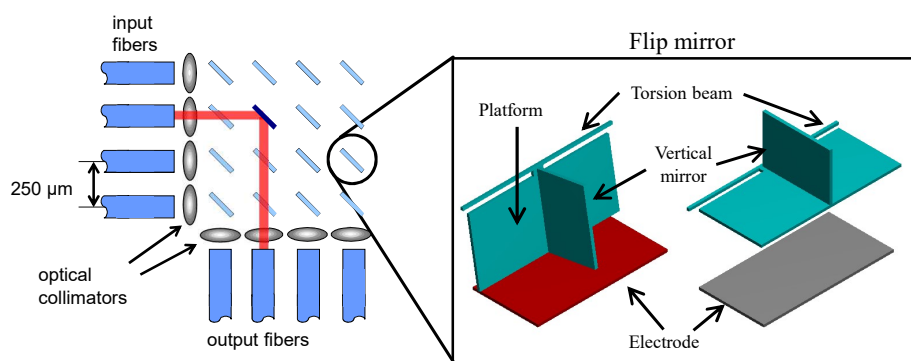


sercalo
microtechnology ltd

- DRIE silicon bulk micromachining
- Mirrors pitch = fiber pitch of fiber ribbons ($= 250 \mu\text{m}$)
- Novel compact optical collimators (patent pending)
- Flip mirrors on platforms with torsion hinges
- Electrostatic actuation with bottom electrodes (separate chip)
- Chip based on silicon bulk micromachining (DRIE)



Sercalo 2D MEMS OXC Array

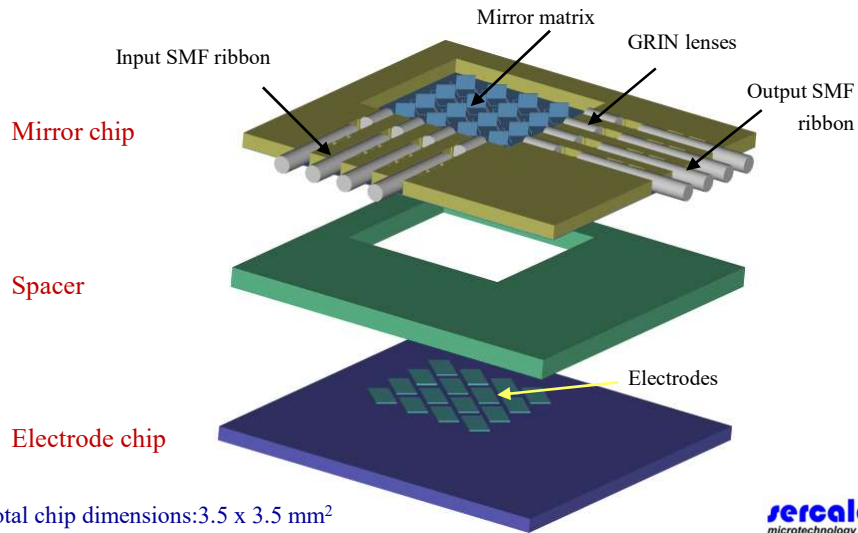


- Pitch of mirrors = pitch of fiber ribbons ($250 \mu\text{m}$)
- Novel GRIN lenses for coupling efficiency at small foot print
- Flip mirrors with torsion hinges and bottom electrodes
- Mirror chip: silicon bulk micromachining (DRIE)
- Electrodes on separate chip

sercalo
microtechnology ltd



Sercalo OXC Array



Part IV- Systems: Telecommunications

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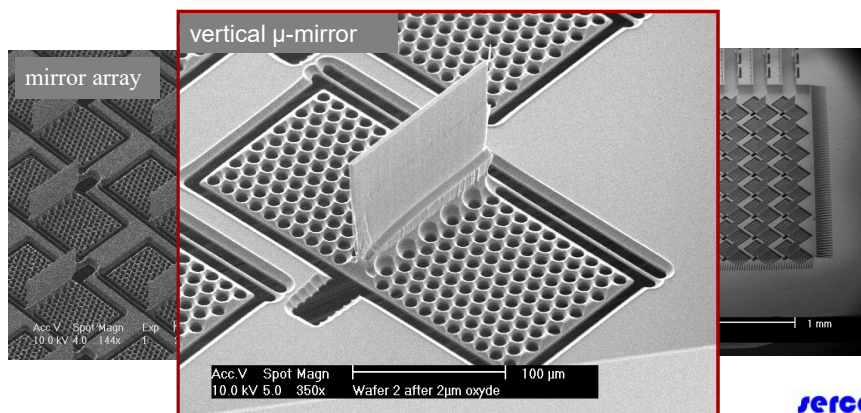
Micro-605: Optical MEMS and Micro-Optics

sercalo
microtechnology ltd

EPFL

Sercalo 2D MEMS 8x8 Switch – Array Detail

- Vertical mirrors (100 μm) on platforms
- Torsion hinges < 1 μm
- Perforated platform to reduce weight and drag



Part IV- Systems: Telecommunications

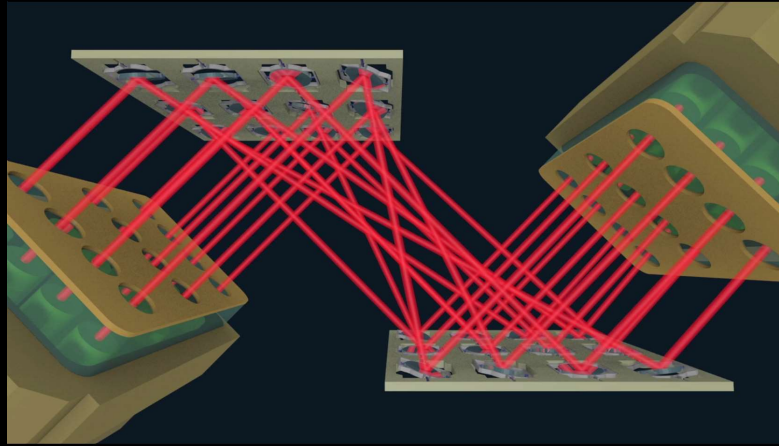
370

Micro-605: Optical MEMS and Micro-Optics

sercalo
microtechnology ltd

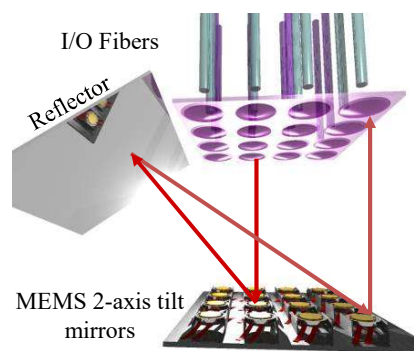
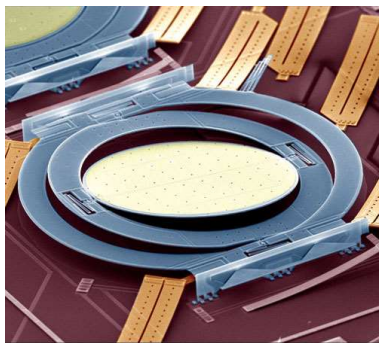
EPFL

3D MxN Optical Xconnect - Concept



Lucent Free-Space OXC I

- Lucent Technologies
 - 3D switch
 - Large scale switching
 - Hundreds of channels possible
 - Large device



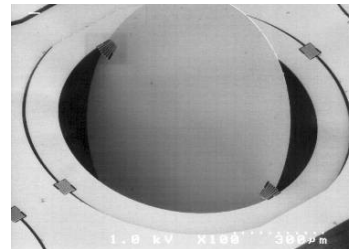
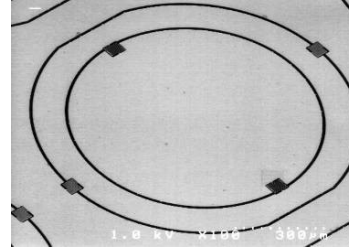
Source: Courtesy Lucent Technologies

Alcatel-Lucent 



Lucent Free-Space OXC II

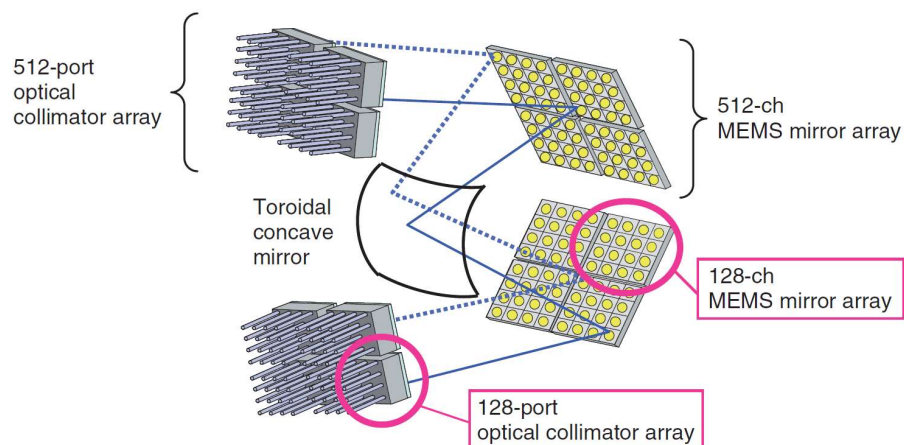
- Lucent Technologies
 - SOI mirrors
 - Reliable single crystal silicon hinges



Source: Courtesy Lucent Technologies



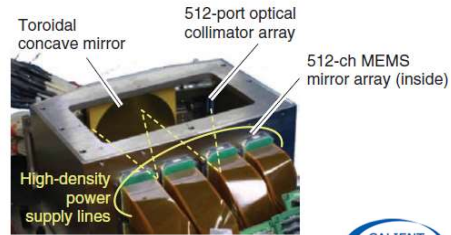
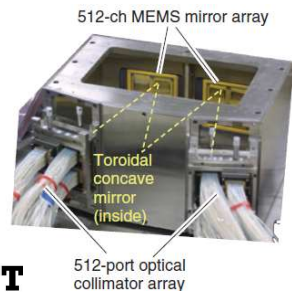
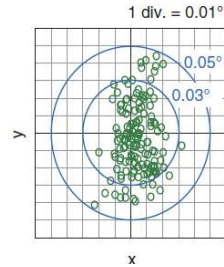
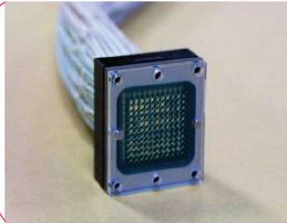
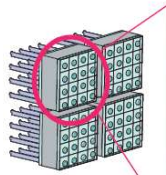
Calient 3D Optical Switch



512 × 512 Port 3D MEMS Optical Switch Module with Toroidal Concave Mirror, NTT Technical Review 10 (11) 2012.



Calient/NTT 3D Optical Switch



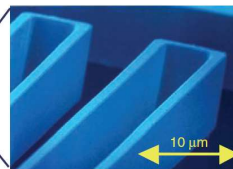
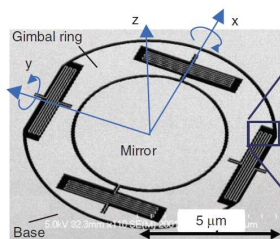
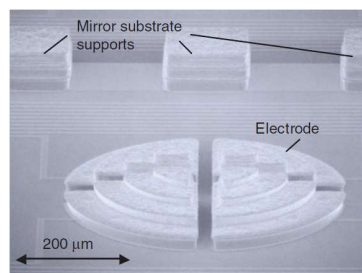
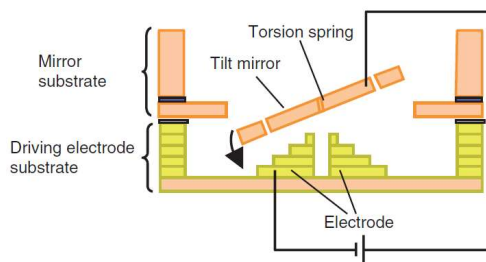
Part IV- Systems: Telecommunications

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Micro-605: Optical MEMS and Micro-Optics



Calient/NTT: MEMS Mirror



"High-yield Fabrication Methods for MEMS Tilt Mirror Array for Optical Switches," NTT Technical Review 5(10), 1(2007)



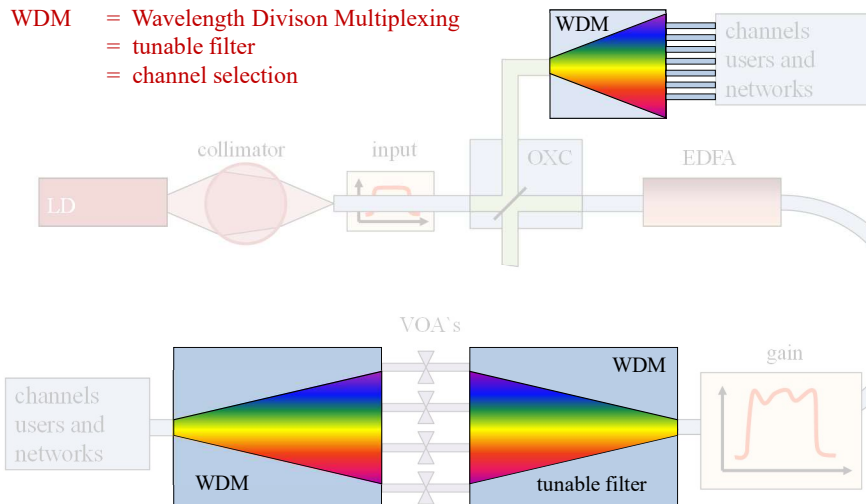
Part IV- Systems: Telecommunications

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Micro-605: Optical MEMS and Micro-Optics



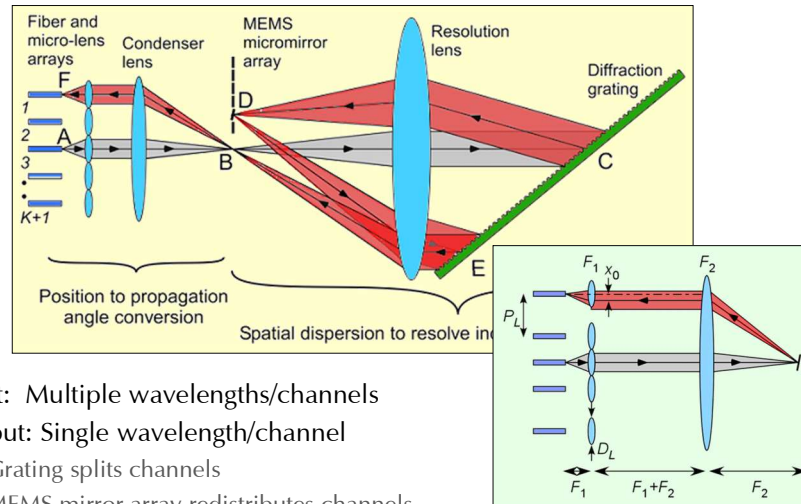
Wavelength Selective Switches



WSS Implementation

- Applications
 - Multiplexers and Demultiplexers
 - Add/Drop multiplexers
- General elements of a free space optical WSS
 - Fiber array and microlens array (MLA) for input and output;
 - beam shaping of collimated light from MLA via anamorphic optics (cylinders or prisms);
 - Birefringent crystals and waveplates if needed
 - a diffraction grating used in reflection or transmission or an AWG
 - switching engine

Wavelength Selective Switches



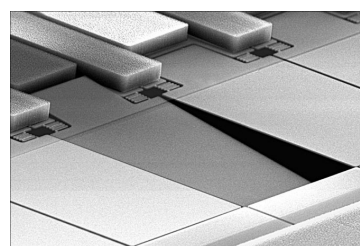
- Input: Multiple wavelengths/channels
- Output: Single wavelength/channel
 - Grating splits channels
 - MEMS mirror array redistributes channels

Source: Journal of Lightwave Technology, Vol. 23, Issue 4, pp. 1620-

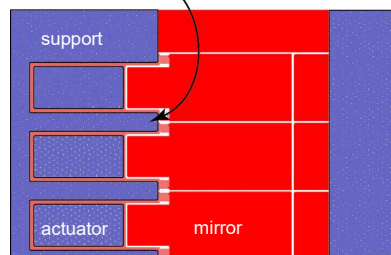
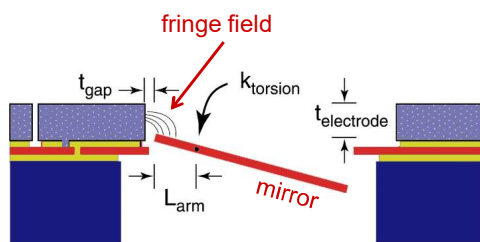


Lucent Technologies MEMS WSS

- One-axis tilt
- Bulk+surface micromachining:
 - SOI + poly-Si (10 μ m) + DRIE
 - Poly-Si: in-situ CVD doped
- Vertical / out-of-plane actuator
 - „Fringe-field-actuated“



electrical shield and mechanical support



Sources: Journal of Lightwave Technology, Vol. 23, Issue 4, pp. 1620, <http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1240141&isnumber=27805>

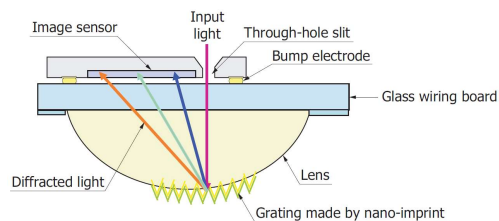
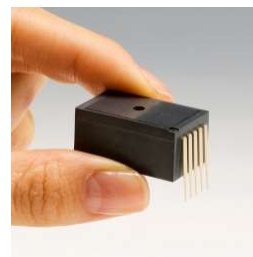


MOEMS SPECTROMETERS



Hamamatsu Compact Spectrometer

- MS Series
- CMOS integrated Si sensor array
- Specifications
 - Thumb size: $27.6 \times 16.8 \times 13$ mm
 - Weight: 9 g
 - Spectral response range: 640 to 1050 nm
 - Spectral resolution: 20 nm
- Target Applications
 - Color monitoring for printers
 - Color control in displays
 - Component analysis

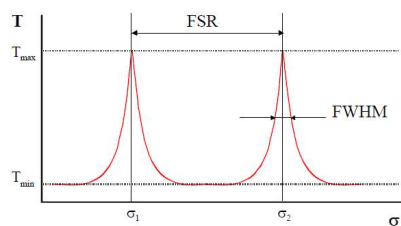
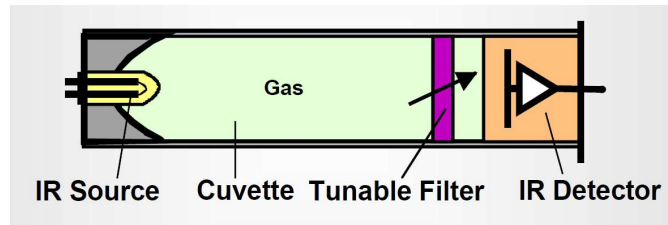


HAMAMATSU
PHOTON IS OUR BUSINESS

http://www.hamamatsu.com/resources/pdf/ssd/c10988ma-01_etc_kacc1169e07.pdf



Fabry-Perot Spectrometer



Zentralwellenlänge: $\lambda_m = \frac{2nd \cos \theta}{m}$ $\sigma_m = \frac{m}{2nd \cos \theta}$

Halbwertsbreite: $FWHM = \frac{1}{2nd \cos \theta} \left(\frac{1-R}{\pi \sqrt{R}} \right)$

Freier Spektralbereich: $FSR = \frac{1}{2nd \cos \theta}$

Reflektions-Finesse: $\tilde{F}_R = \frac{FSR}{FWHM} = \frac{\pi \sqrt{R}}{1-R}$

<http://www.infratec.de/en/sensor-division/publications.html>



Part IV- Systems: Advanced Instrumentation

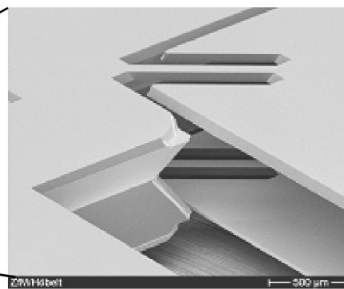
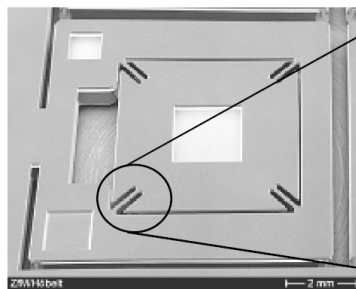
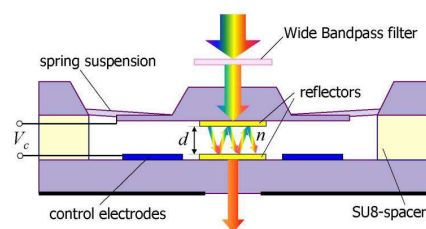
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Micro-605: Optical MEMS and Micro-Optics



InfraTec Fabry-Perot Spectrometer

- For the spectral range of 3-5μm
- Based on a pyroelectric detector
- Similar systems by
 - Axsun Systems



http://www.infratec.de/fileadmin/downloads/pdf/Paper_DSS6.pdf



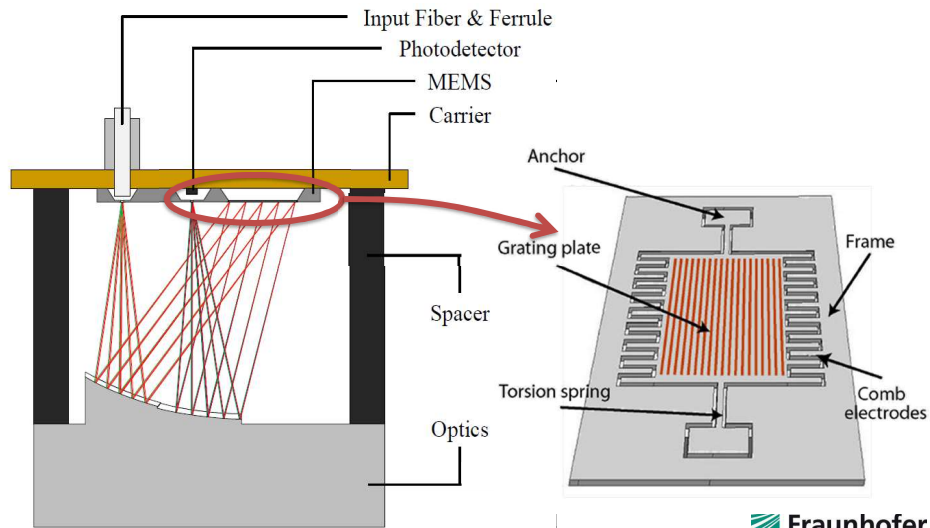
Part IV- Systems:

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Micro-605: Optical MEMS and Micro-Optics



Fraunhofer Grating Spectrometer



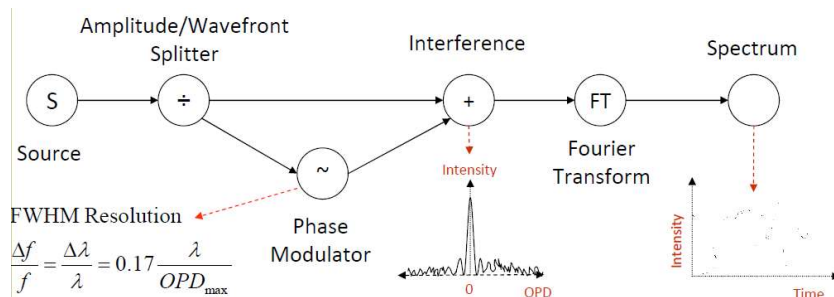
Fraunhofer Grating Spectrometer

- Hybrid Integration
 - Optics substrate
 - Precision machining of aluminum
 - Two tilted mirrors
- MEMS device
 - SOI substrate
 - Grating with comb drive and two optical slits
- System
 - 15 x 10 x 14 mm
 - 0.95-1.9 μm range
 - 9 nm resolution



Fourier Transform Spectroscopy

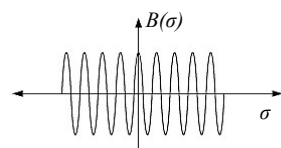
- Throughput Advantage
- Multiplexing Advantage
- Single Detector Measurement



FTS: Interferogram vs. Spectrum

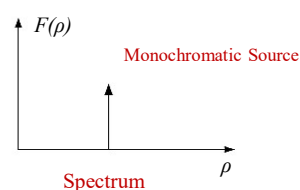
$$F(\rho) = \int_{-\infty}^{\infty} B(\sigma) \cos(2\pi\sigma\rho) d\sigma \quad (W)$$

$$B(\sigma) = \int_{-\infty}^{\infty} F(\rho) \cos(2\pi\sigma\rho) d\rho \quad (W/cm^{-1})$$

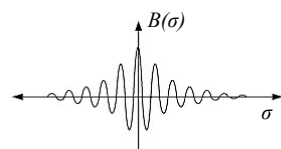


Interferogram

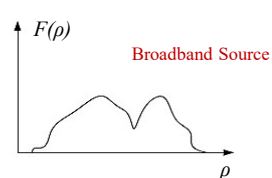
Fourier Transform



Spectrum



Fourier Transform

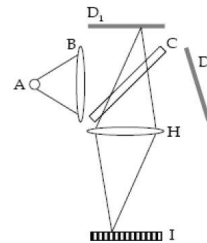
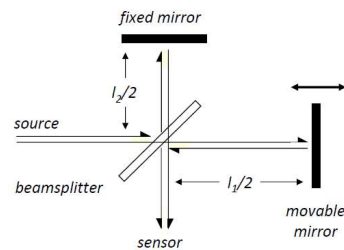


Wiener-Khinchin theorem:

The autocorrelation function of a wide-sense-stationary random process has a spectral decomposition given by the power spectrum of that process

FTS with Amplitude Splitting

Michelson Interferometer



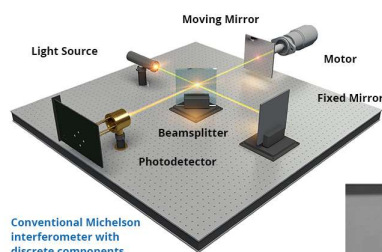
Scanning configuration

Stationary configuration

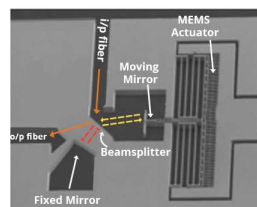
- FTS with Michelson Interferometer
 - Moving mirror and a single detector
 - Static but tilted mirror and a line detector
- Former for IR, latter for visible applications due to detector costs



Si-Ware NeoSpectra FTIR Technology



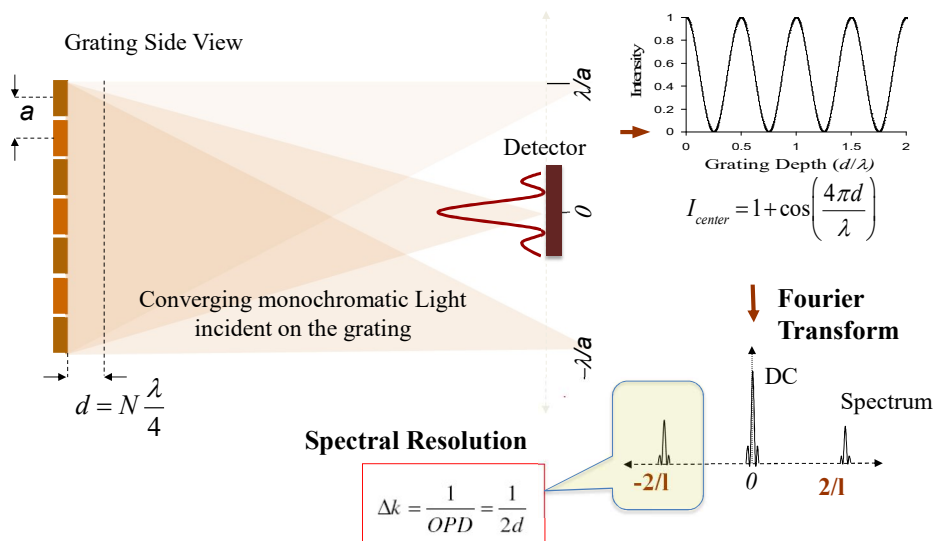
Conventional Michelson Interferometer with discrete components



Monolithic Michelson interferometer chip enable by SIMOST

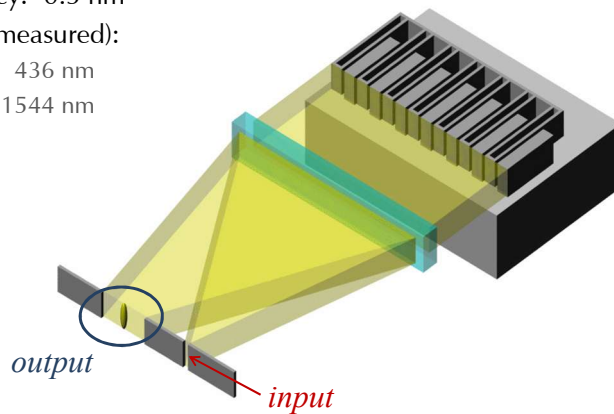


FTS: Lamellar Grating Interferometry



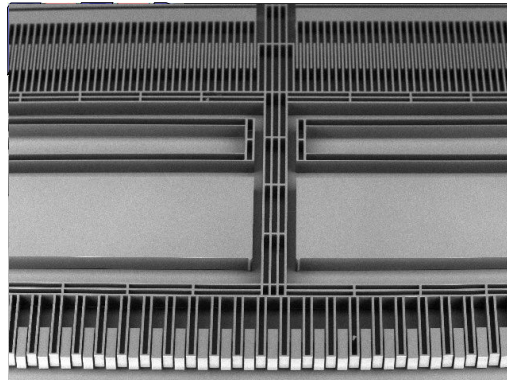
IMT –Lamellar Grating Interferometer

- Optics: Lamellar Grating
- MEMS: SOI / DRIE comb drives in push-pull configuration
- Maximum optical path difference (OPD) = 226 μm
- Wavelength accuracy: 0.5 nm
- Optical resolution (measured):
 - 1.2 nm @ $\lambda = 436 \text{ nm}$
 - 13 nm @ $\lambda = 1544 \text{ nm}$



AROptix – MEMS FTS

- IMT Spin-off
- Fourier-Transform based (FTS)
- Grating height/ Grating period: 75 μm / 90 μm
- Chip dimensions:
 - 7 x 8 mm
- Maximum OPD: 226 μm
- Illuminated periods: 32
- Long wavelength range:
 - 0.5 – 2.6 μm
- Resolution:
 - 0.7 (VIS) to 27 nm (NIR)
- Fast, modular, small
- Optical fiber input



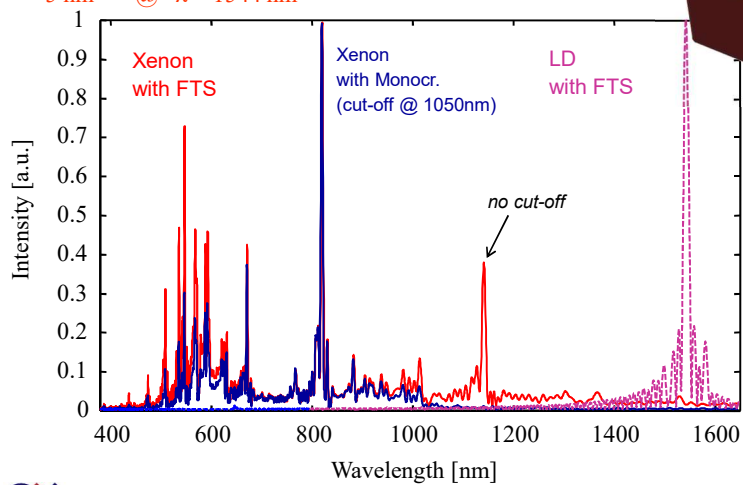
AROptix – MEMS FTS

Optical resolution (measured):

- 0.5 nm @ $\lambda = 436$ nm
- 5 nm @ $\lambda = 1544$ nm

Measurement speed:

- 2 ms



InGaAs detector:
380 nm – 1700 nm
Au coating on grating

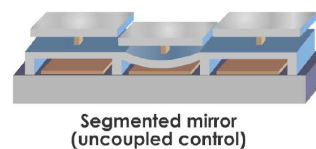
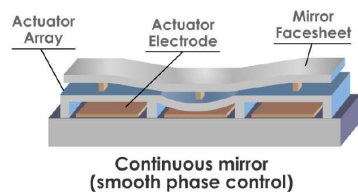
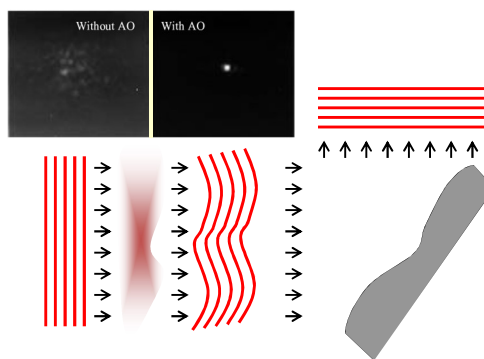


ADAPTIVE OPTICS



Adaptive Optics – Basics

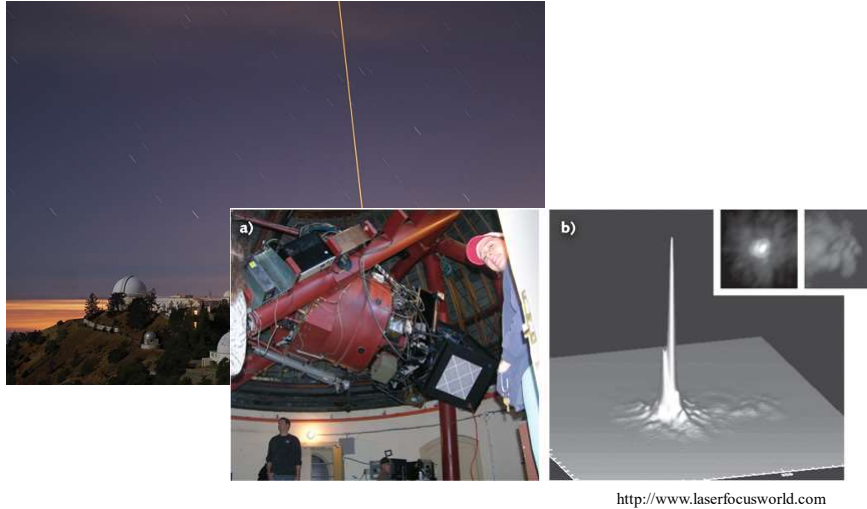
- Image correction
 - Astronomy
 - Laser communication
 - Ophthalmoscopy
- Wavefront deformed
 - e.g. by air turbulences
- Wavefront correction
- Deformable MEMS mirrors
- Lick Observatory uses MEMS



Credit: Boston Micromachines Corp.

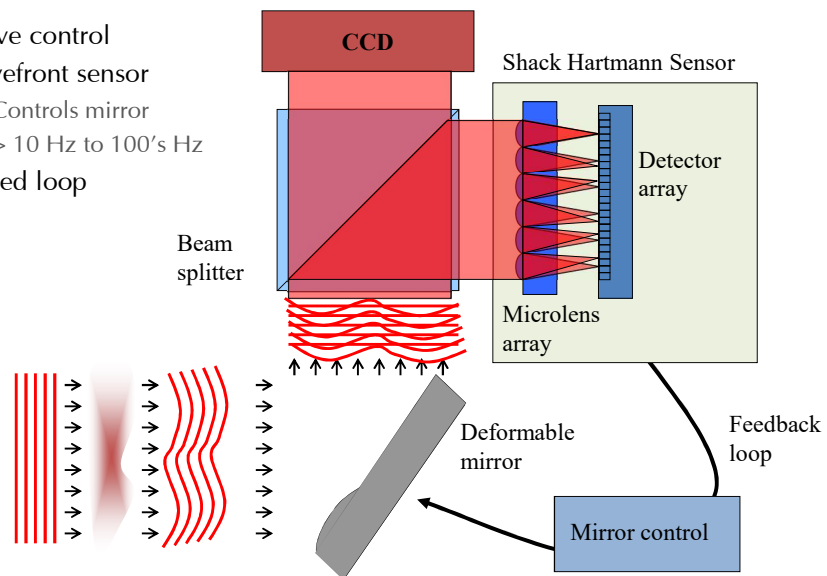


Adaptive Optics – Turbulence Monitoring



Adaptive Optics – Concept

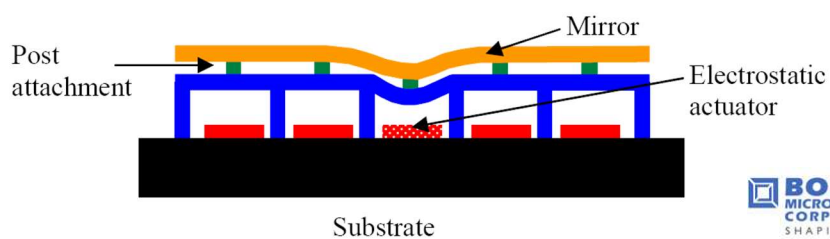
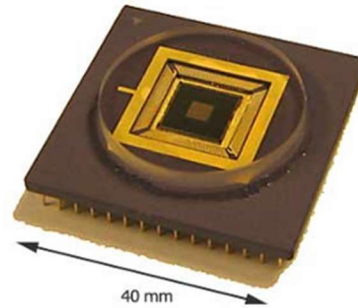
- Active control
- Wavefront sensor
 - Controls mirror
 - > 10 Hz to 100's Hz
- Closed loop



MEMS Adaptive Optics Mirrors

- **Boston Micromachining**

- Surface micromachining
- Thin membrane on posts
- Electrostatic actuation
- Voltage ≥ 200 V
- Up to 1000 actuators
- Stroke: ≤ 3.5 μm
- Complex electronics



BOSTON
MICROMACHINES
CORPORATION
SHAPING LIGHT



Part IV- Systems: Advanced Instrumentation

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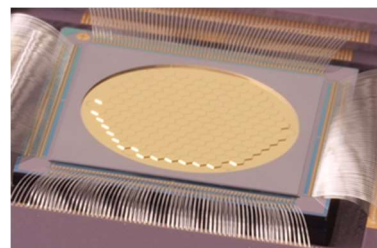
Micro-605: Optical MEMS and Micro-Optics

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MEMS Adaptive Optics Mirrors

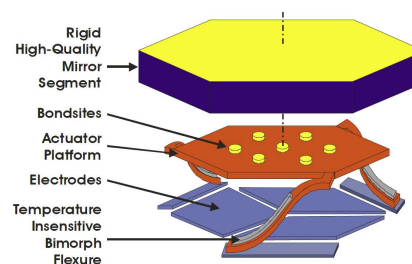
- **Iris AO**

- Actuators: Surface micromachined
- Mirrors: Bulk micromachined
- Wafer level bonding process
- Segmented mirrors
- Electrostatic actuation
- Stroke: 7.6 μm



- **PTT489 Deformable Mirror™**

- 489 actuator, 163 segments
- Stroke: 5 or 8 μm
- Tilt Angle: ± 4 or ± 6.4 mrad
- Surface Flatness: < 20 nm rms
- Inscribed Aperture: 7.7 mm
- Mechanical Response: < 200 μs



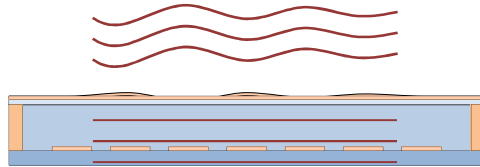
Part IV- Systems: Advanced Instrumentation

400

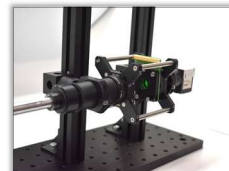
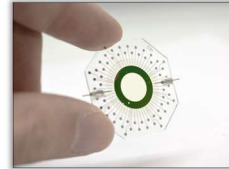
Micro-605: Optical MEMS and Micro-Optics

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Phaseform Deformable Phase Plate

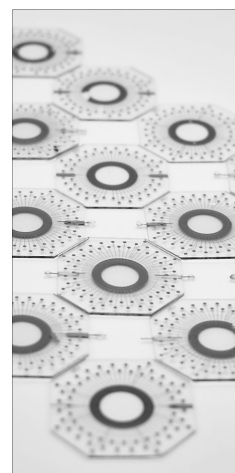


$$\Phi(x, y) = \frac{2\pi}{\lambda} d(x, y) (n_{\text{liquid}} - n_{\text{air}})$$



Phaseform Deformable Phase Plate

- Performance figures
 - Clear aperture: 10 mm
 - Thickness: 0.85 mm
 - Actuator count: 63
 - Stroke: $\pm 4 \mu\text{m}$ OPD (defocus)
 - Initial flatness: $<0.25 \mu\text{m}$ RMS
 - Best flat: $<20 \text{ nm}$ RMS
 - Max Zernike mode: 7th radial order ($\sim\lambda$)
 - Transmission eff.: $>85\%$ ($0.35\text{-}1.2\mu\text{m}$)
 - **Switching speed: $<100 \text{ ms}$**
 - Damage threshold: $>5 \text{ W}$ (collimated)
- Applications
 - Microscopy
 - Ophthalmology
 - Laser machining

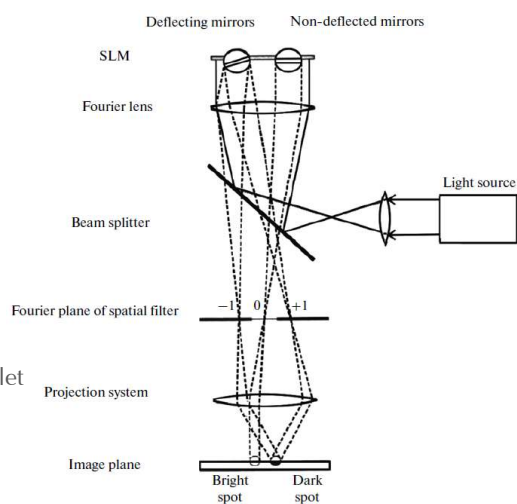


MASKLESS LITHOGRAPHY



Optical Maskless Lithography

- Programmable “mask”
 - Vs. permanent photomask
- No cost for prototype masks
 - Vs. \$ millions per set
- Instant mask production
 - Vs. weeks to months per set
- Requirements:
 - High resolution
 - Fast addressing
 - High reliability
 - High reflectivity in deep ultraviolet (DUV), e.g. $\lambda = 257\text{nm}$
 - Stroke typ. $\lambda / 2$, $\sim 130\text{ nm}$

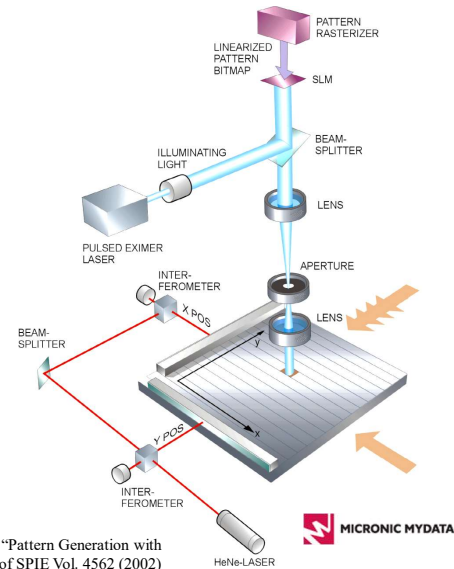
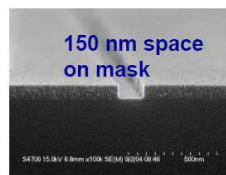


Belokopytov and Ryzhkova, Russian Microelectronics vol. 40 no. 6 2011



Micronic OML System

- Partially coherent diffractive imaging
- Pulsed excimer laser coincides with a fully loaded new pattern on the SLM
- A stepper with a programmable reflective mask and 200X reduction
- Quick and cost effective production of 65 nm and 45 nm node reticles
- Interconnect layers



Sandström, et al. Micronic Laser Systems. "Pattern Generation with SLM Imaging". Proceedings of SPIE Vol. 4562 (2002)



Part IV- Systems: Advanced Instrumentation

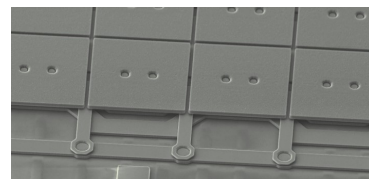
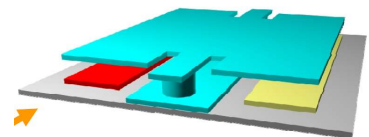
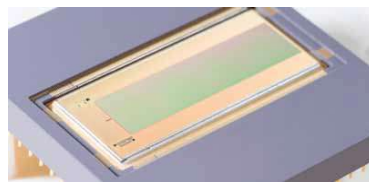
405

Micro-605: Optical MEMS and Micro-Optics

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Micronic OML System

- 1D Tilting mirror array
- Fabricated by Fraunhofer IPMS
- Surface micromachined
- CMOS Backplane
- SLM Specifications
 - Matrix size: 2048×512 mirrors
 - Pixel size: $16 \times 16 \mu\text{m}$
 - Frame rate: 2 kHz
 - Mirror edge deflection: 0 - 180 nm
 - Wavelength 248 nm
 - Average beam power: 40 mW
 - Data voltage: 0 - 25.5 V analogue



MICRONIC MYDATA

Fraunhofer IPMS



Part IV- Systems: Advanced Instrumentation

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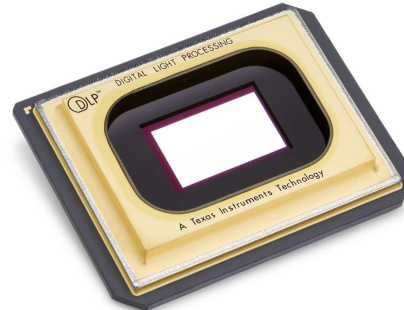
Micro-605: Optical MEMS and Micro-Optics

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www.ipms.fraunhofer.de/content/dam/ipms/common/products/SLM/cbm-e.pdf

DLP Based OML Systems

- Applications
 - UV-Setters for printing
 - PCB manufacturing
 - UV sensitive polymer patterning
 - Biopatterning
- Companies
 - BasysPrint
 - Dai Nippon Printing
 - Hitachi Via Mechanics
 - FujiFilm
 - ...



basysPrint

Hitachi Via Mechanics, Ltd.

DNP
Dai Nippon Printing Co., Ltd.

FUJIFILM



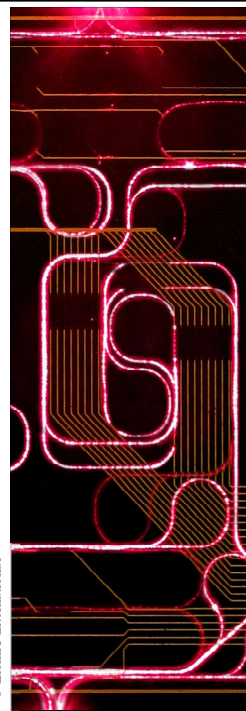
PART V

EMERGING TOPICS



Current Trends in MOEMS

- Today MOEMS is an established technology:
 - Well-understood fundamentals
 - Countless commercial applications
 - Standard foundry processes
- To where is the field heading?
 - New manufacturing platforms
 - Rapid prototyping
 - Photonic integrated circuits
 - New applications
 - LIDAR and remote sensing
 - Endomicroscopy
 - Adaptive optics
 - Mobile Imaging (zoom optics)



RAPID PROTOTYPING OF MOEMS

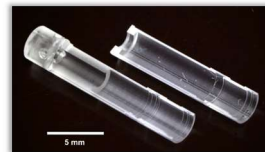
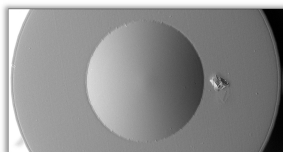


Part V- Emerging Topics

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Rapid Prototyping of Micro-optics and MOEMS

- Motivation
 - How can we cut down design cycle time?
 - How to realize low-volume, high-complexity devices?
 - Can we manufacture optical surfaces and actuators monolithically?
- Most promising methods are
 - Two-photon polymerization
 - Selective laser etching



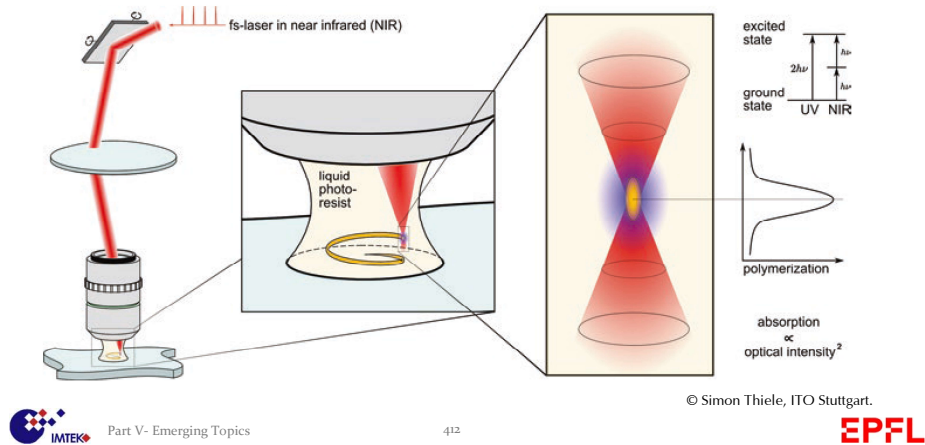
Part V- Emerging Topics

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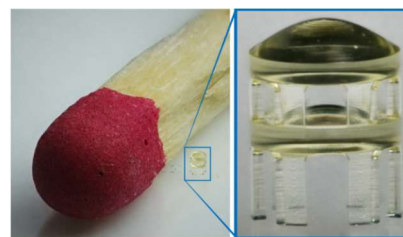
3D Printing by 2PP

- Based on 3D scanning of a focal spot
- Overlapping of neighbouring voxels can lead to < 10 nm surface roughness
- Limited in maximum sample dimensions

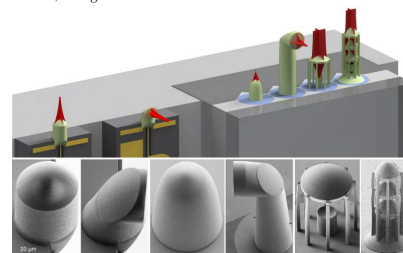


3D Printing by 2PP

- Voxel size depends on NA
 - 63X objective: $0.2 \times 0.2 \times 0.7 \mu\text{m}$
 - 20X objective: $0.6 \times 0.6 \times 5 \mu\text{m}$
- Optical quality surfaces possible by process optimization
 - Free-form optics
 - Complex optical surfaces
- Emerging actuator concepts
 - EM actuation via magnetic liquids
 - Electrostatic actuators



© ITO, Stuttgart



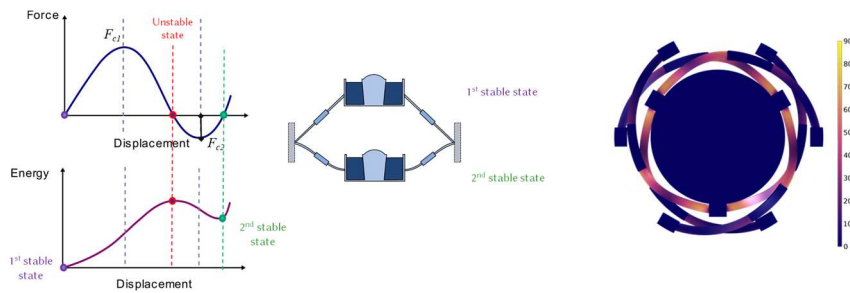
© Vanguard Photonics

microlight3D

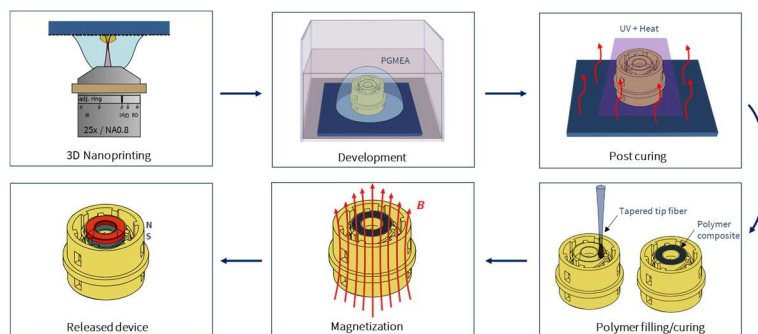
upnano

nano scribe

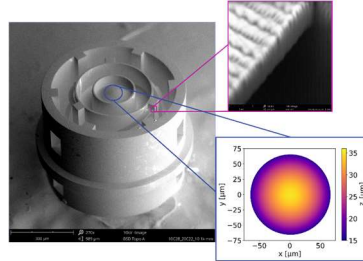
3D printed magnetic lens witch



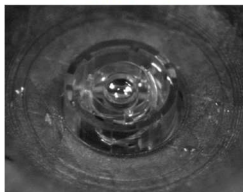
3D printed magnetic lens switch



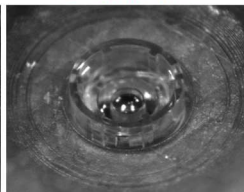
3D printed magnetic lens switch



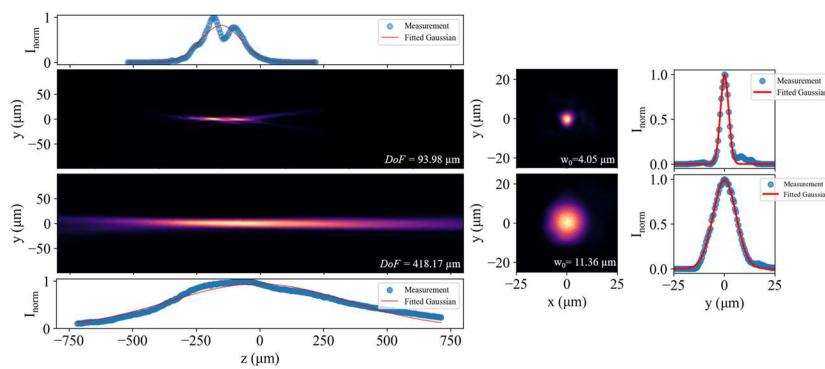
1st stable state



2nd stable state



3D printed magnetic lens switch



PHOTONIC INTEGRATED CIRCUITS



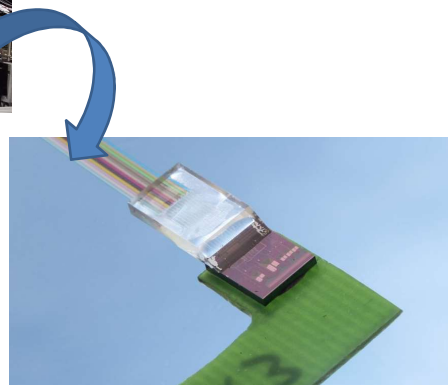
Part V- Emerging Topics

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From Discrete Components to Chip-Scale Optics



Journal of Instrumentation 14(11):P11025-P11025

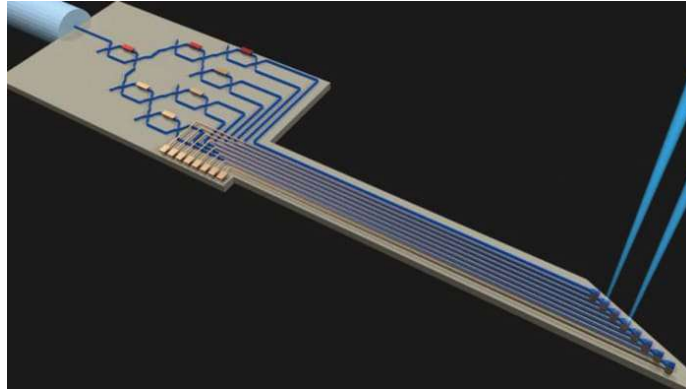


Part V- Emerging Topics

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PICs: Enhanced Functionality

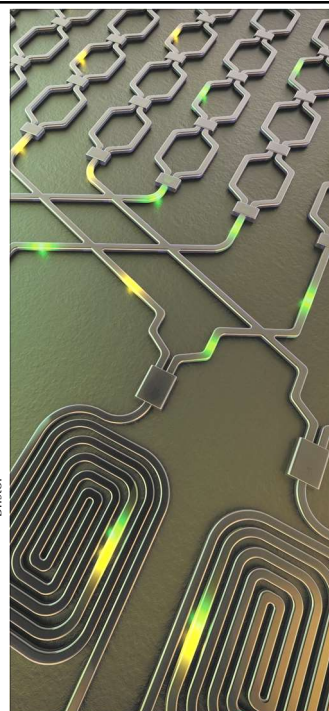


Implantable nanophotonic probe based on an optical switch array for optogenetic neural stimulation. (Credit: Aseema Mohanty/Columbia Engineering)

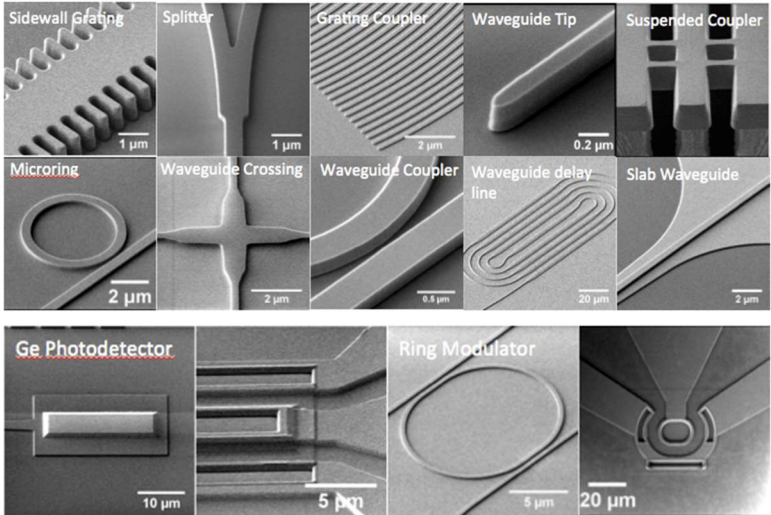
Building Blocks of PIC Platforms

- Passive devices
 - Waveguides/couplers
 - Optical switches and interconnects
 - Filters, multiplexers & demultiplexers
 - Dispersion compensators
 - Variable optical attenuators
 - Isolators and circulators
 - Delay lines
- Active devices
 - Modulators
 - Amplifiers
 - Lasers and LEDs
 - Detectors
 - Wavelength and mode converters

Xiaogang Qiang/University of Bristol

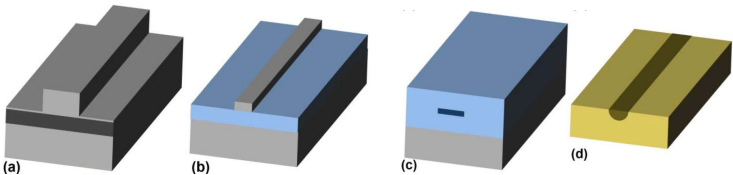


Sample Foundry Process



Different PIC Platforms

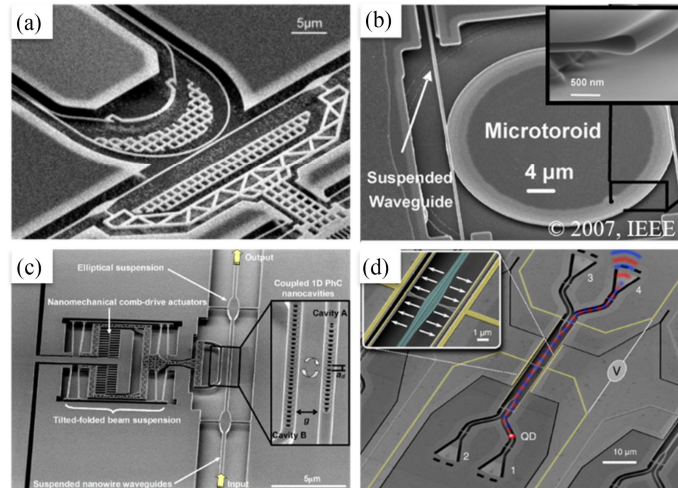
Platform	Wavelength range (nm)	Light Source	Detection	Modulation Method	Modulation Speed /MHZ	propagation loss (dB/cm)	Applications
Si ₃ N ₄ ^c	400-4000	External	External	Thermal / Piezoresistive	~0.001 / 1	~0.1-10	Telecom, LIDAR, OCT
Silicon ^b	1100-9900	External	Integrated	Plasma dispersion	~10000	~0.5-2	Telecom, LIDAR, Spectroscopy
InP ^a	1300-1600	Integrated	Integrated	Electro-absorption	~10000	~2	Telecom, LIDAR
LiNbO ₃ ^d	400-5000	External	External	Electro-optic	~100000	~0.1	Telecom



IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS), 2018, pp. 8-13,



Optical MEMS for PICs: Couplers



IEEE JSTQE, vol. 26, no. 2, 2020

(a) Opt. Express, vol. 21, no. 19, pp. 22034–22042, 2013.
 (b) IEEE JSTQE, vol. 13, no. 2, pp. 202–208, Mar./Apr. 2007.
 (c) Opt. Lett., vol. 35, no. 15, pp. 2517–2519, Aug. 2010.
 (d) Optica, vol. 6, no. 4, pp. 524–530, Apr. 2019.

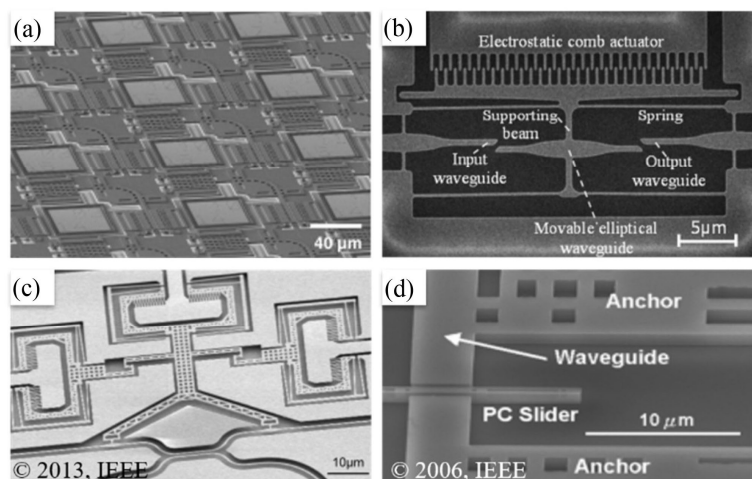
424



Part V- Emerging Topics

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Optical MEMS for PICs: Switches



IEEE JSTQE, vol. 26, no. 2, 2020

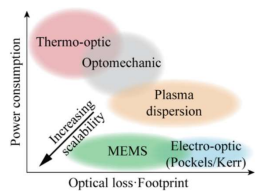
(a) Optica, vol. 6, no. 4, pp. 490–494, Apr. 2019..
 (b) Appl. Phys. Lett., vol. 92, no. 10, Mar. 2008, Art. no. 101110.
 (c) IEEE Photon. Technol. Lett., vol. 25, no. 7, pp. 675–677, Apr. 2013.
 (d) JSTQE vol. 18, no. 2, pp. 358–360, Jan. 2006..



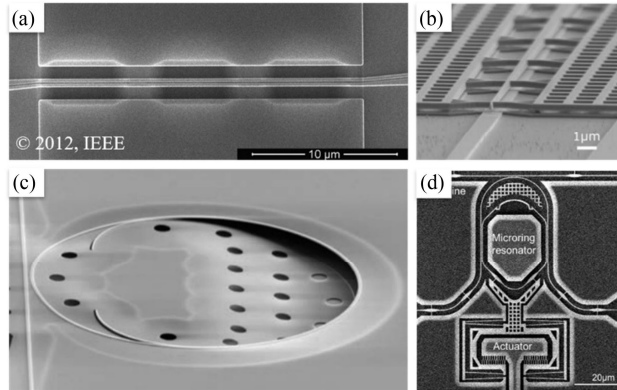
Part V- Emerging Topics

EPFL

Optical MEMS for PICs: Phase Shifters



IEEE JSTQE, vol. 26, no. 2,
2020



- (a) IEEE Photon. J., vol. 4, no. 3, pp. 779–788, Jun. 2012.
- (b) Proc. Eur. Conf. Integr. Opt., Gent, Belgium, 2019, p. F.A2.4.
- (c) Opt. Lett., vol. 40, no. 15, pp. 3556–3559, 2015.
- (d) IEEE Photon. Technol. Lett., vol. 18, no. 2, pp. 358–360, Jan. 2006.



Part V- Emerging Topics

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MEMS LIGHT DETECTION AND RANGING

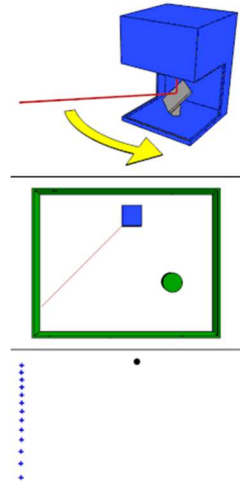


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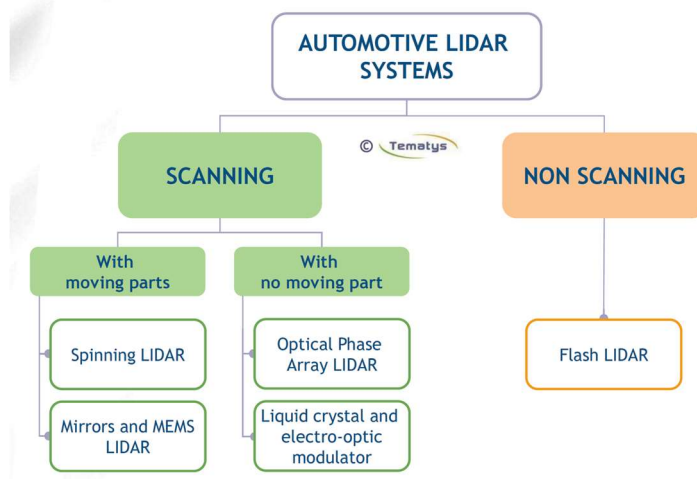
Light Detection and Ranging

- Active sensors for 3D environmental mapping
- First uses in atmospheric research and geo surveys
- Huge boost due to autonomous driving
- Automotive LIDARs typically
 - Use NIR/SWIR light (0.8-1.55 μm wavelength),
 - Feature laser illumination,
 - Limited by eye-safety concerns,
 - Use some type of avalanche photo-diode,
 - Literally count photons.
- Compared to RADAR, LIDAR has
 - Has higher spatial resolution,
 - Lower range due to atmospheric effects such as
 - Absorption,
 - Scattering.

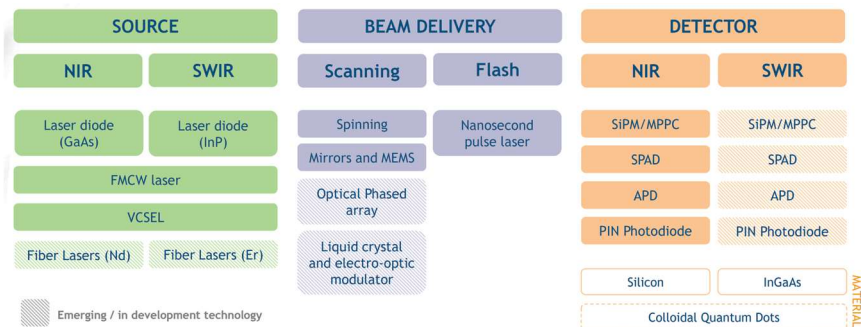


Source: Wikipedia

The Contemporary LIDAR Landscape



The Contemporary LIDAR Landscape



© Tematys



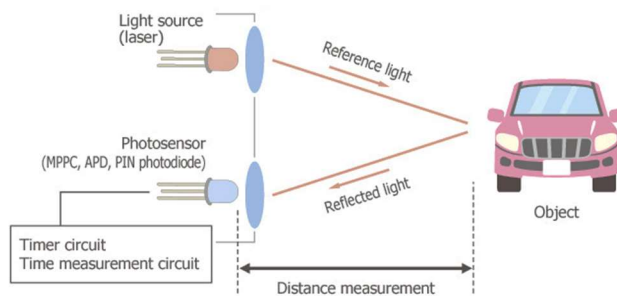
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Time-of-Flight (ToF) LIDAR

- Dominates current automotive LIDAR market due to simple structure and signal processing methods
- Uses pulsed laser sources
- Laser power is limited by eye-safety
- Can be effected by sunlight and other LIDARs
- Can be scanning or non-scanning (FLASH)



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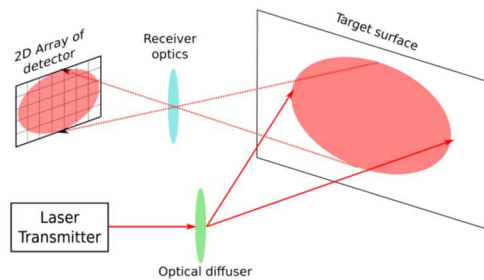
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Time-of-Flight Flash LIDAR

- Flood illumination + detector array
 - Avoids moving parts (truly *solid-state*)
 - Avoids motion artifacts
- SPAD or APD arrays
 - Each pixel measures a ToF
- Limited in range (typically <100 m) and FoV
- Potentially very low-cost



128 x 32 Geiger-mode Avalanche Photodiode



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MEMS LIDAR

- High speed scanning at a lower cost w.r.t. spinning LIDARs
- Cost-effective due to batch manufacturing
- Spatial resolution limited due to mirror sizes
- Approaches to 3D imaging
 - Single laser + 2D scanning
 - Multiple lasers + 1D scanning



© Blickfeld

intel REALSENSE TECHNOLOGY



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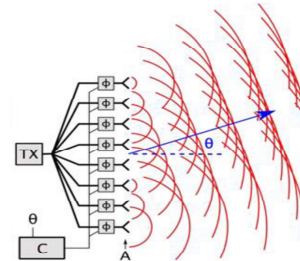
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LIDAR with Optical Phased Arrays

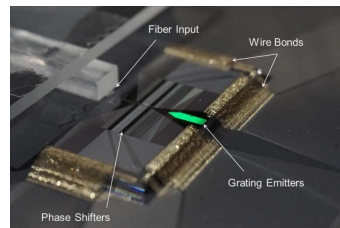
- Scanning with no moving parts
 - Robust and low-cost
- Based on PIC technology
 - Every emitter is phase controlled
- 1D & 2D scanning variants
- Limited in spatial resolution
- Recently commercialized



QUANERGY OPA
Solid-state LIDAR



© Quanergy



Credit: Steven Miller, Columbia Engineering.



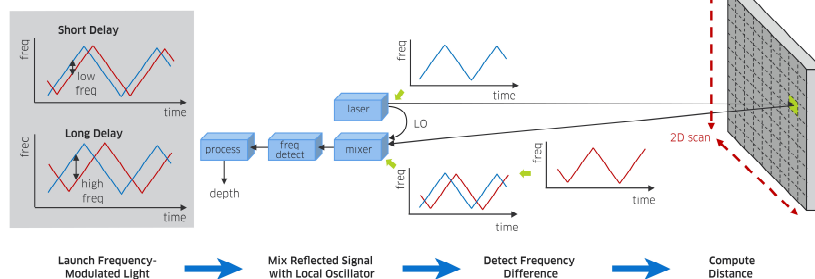
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FMCW (Coherent) LIDAR

- **F**requency **M**odulated **C**ontinuous **W**ave
- Light source is not pulsed
- Coherent detection: Return signal is interfered with the local oscillator
- Can measure distance & velocity
- Virtually immune to ambient light
- Complex hardware and software



Launch Frequency-Modulated Light

Mix Reflected Signal with Local Oscillator

Detect Frequency Difference

Compute Distance

Source: Lumentum White Paper



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FMCW (Coherent) LIDAR: Distance & Velocity

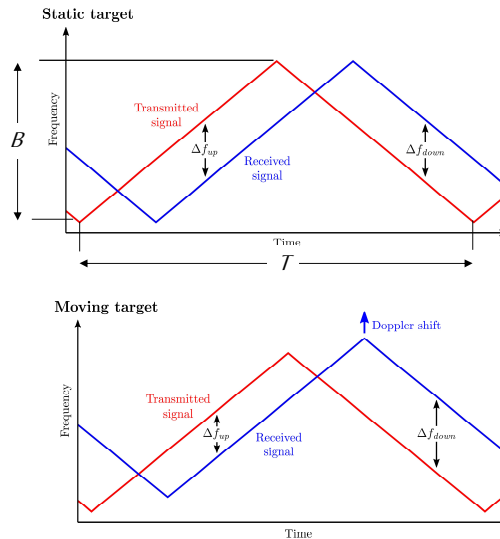
- Triangular modulation of the laser frequency
- Full-sweep at every measurement location

Distance of the object

$$d = \frac{c(\Delta f_{up} + \Delta f_{down})B}{4T}$$

Velocity of the object

$$v = \frac{\lambda(\Delta f_{up} - \Delta f_{down})}{4}$$



AY Piggot, arXiv:2011.05313v1, 2020



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Acknowledgements

Prof. Hans Peter Herzig
Dr. Wilfried Noell
 Prof. Hans Zappe – IMTEK
 Prof. Hakan Ürey – Koç University



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Micro-605: Optical MEMS and Micro-Optics

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