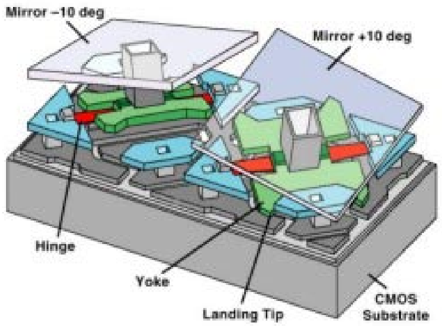


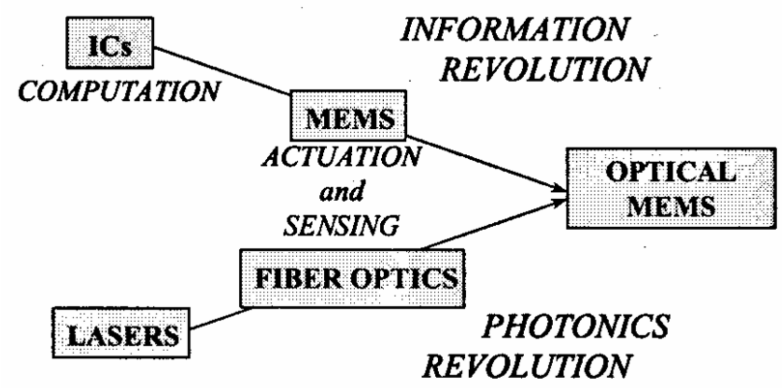
Optical MEMS

Fundamentals of Micromachining

Dr. Bruce Gale

With special thanks to Dr. Michael McShane

Integrating Technologies



Micro-Optics

- Driven by communications industry
  - Couplers, demultiplexers, switches, routers, etc.
  - Display technology
- Mostly *elements*, not complete systems
  - Thin-films
  - MEMS devices
  - Gratings
  - Lasers

Categories of Optical MEMS

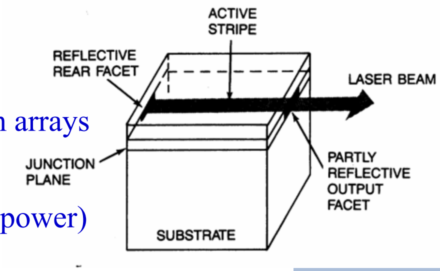
- Sources
- Waveguide Optics
- Free-Space Optics
- Transmissive Optics
- Reflective Optics
- Diffractive Optics
- Interference-Mode
- Detectors

Sources

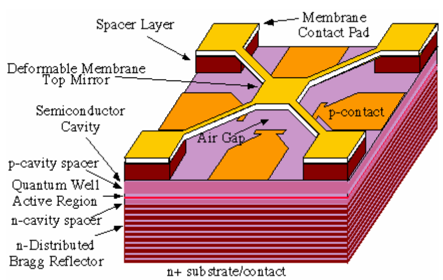
- Thermal Emitters
- Semiconductor Devices
  - LEDs
  - Laser Diodes
    - Edge-Emitting
    - VCSELs
  - Note that these devices using microfabrication techniques, but are not considered MEMS
  - Easily integrated
- Polymer Emitters

Semiconductor Lasers

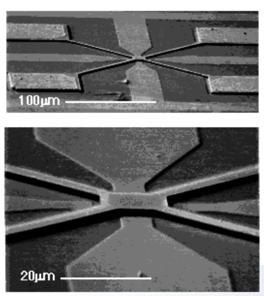
- Pumping usually with DC current (low power)
- Many wavelengths available
- Raw beams are elliptical/wedge shaped, astigmatic
- Compact, low input power
- Optical Power
  - 0.1-5mW typical
  - HP (to 100 W) available in arrays
- Cost
  - \$15-\$10,000 (goes ~ with power)

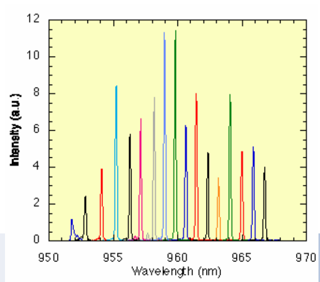


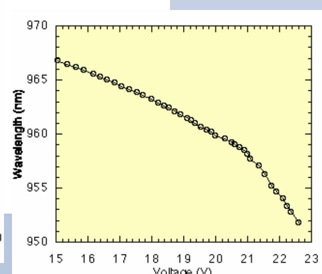
Micro-Lasers



- VCSEL
  - Vertical-Cavity Surface-Emitting Laser
- Tunable through mirror displacement





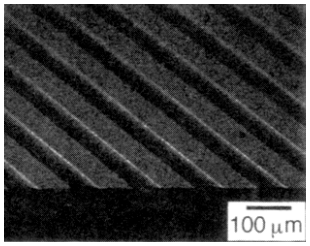


Waveguide Optics

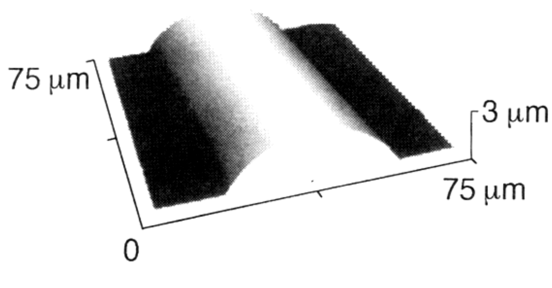
- Planar Waveguides
- Mixers and Switches
- Fiber Alignment

Waveguides

Waveguides: electromagnetic radiation "guided" via total internal reflection
($n_{clad}<n_{core}$)

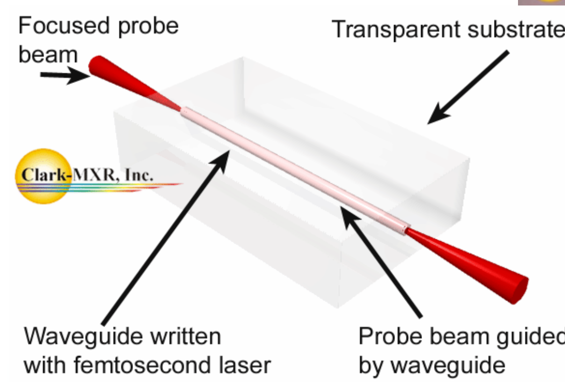


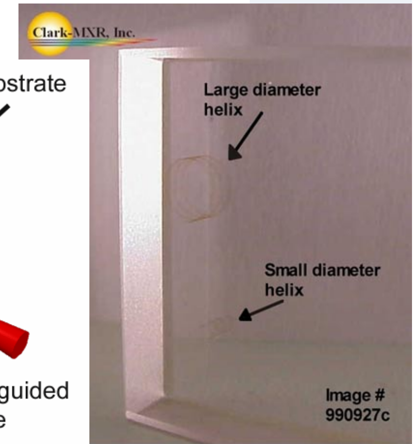
SAM-patterned PMMA waveguides



Ultrafast Laser-written Guides

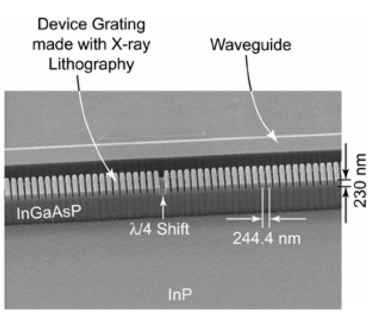
Laser induces local Δn

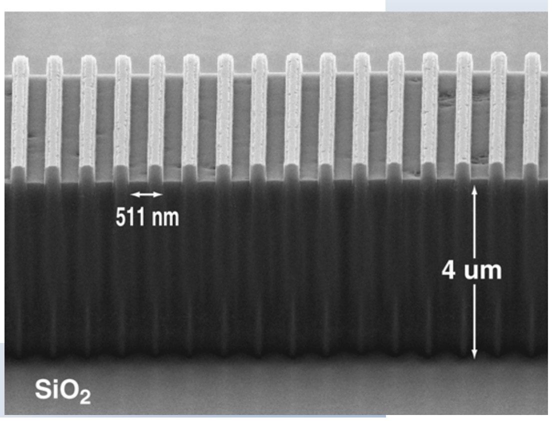




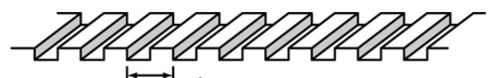
Integrated Bragg Gratings

Bragg Grating: Periodic variation in *n* results in selective reflection of wavelengths

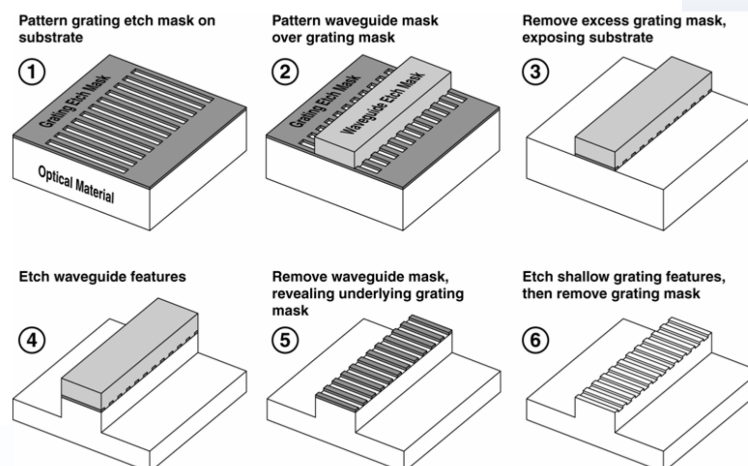




Bragg Gratings

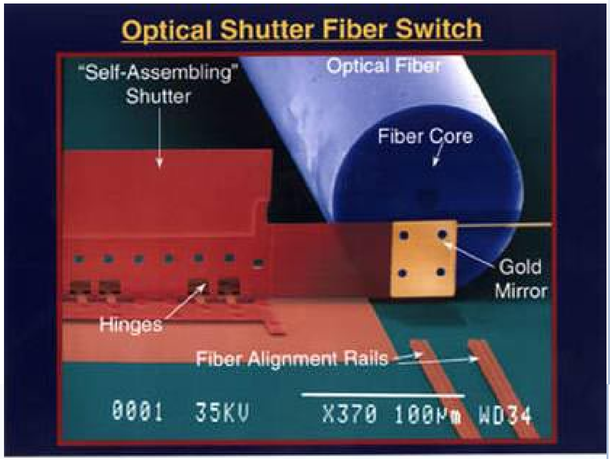


$$\Lambda = \frac{\lambda_0}{2n_{eff}} = 215 - 530 \text{ nm}$$

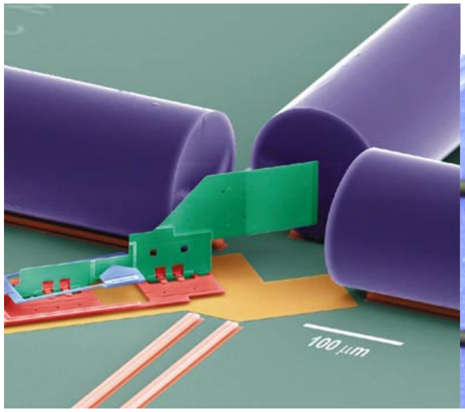


MEMS Optical Switches

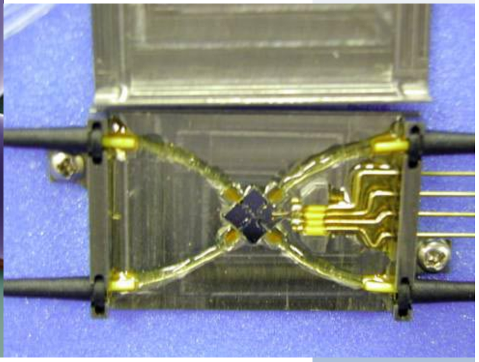
- BIG business
- Lots of investment for communications



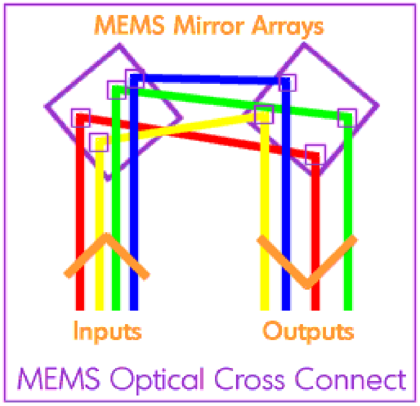
MEMS Optical Switches

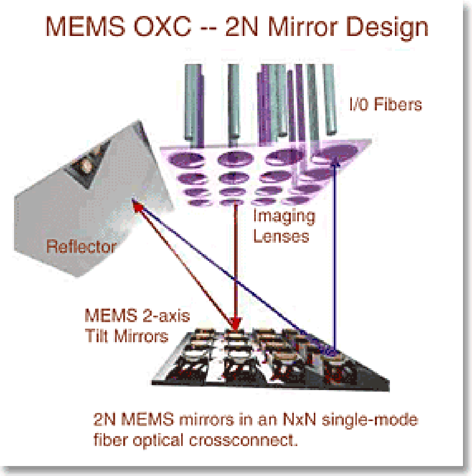


Packaged switch

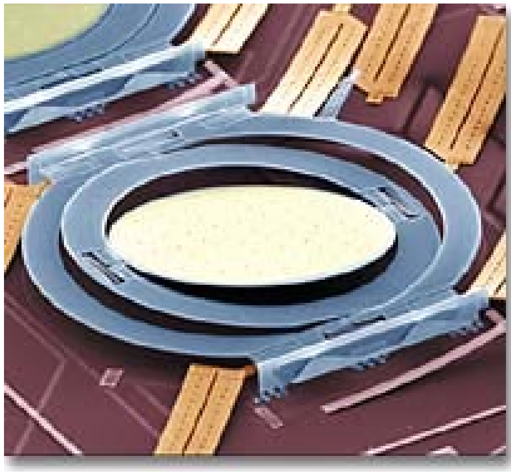


Arrays of Mirrors for Switching





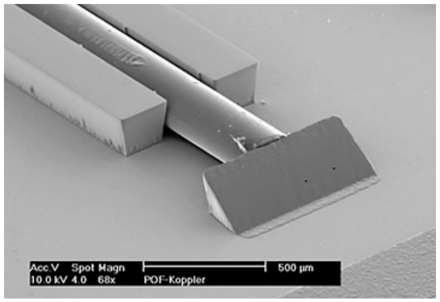
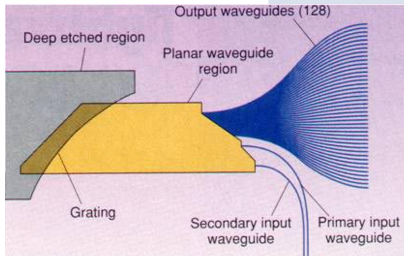
Arrays of Mirrors for Switching



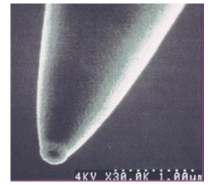
Motion in all directions

Optical Interconnects

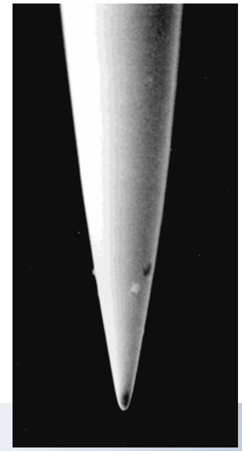
- Fiber-space connections via prism
- Fiber-fiber coupling (multiplexing)

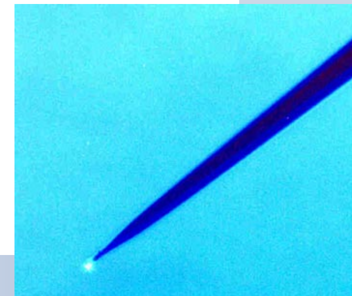
Submicron Fiber Probes



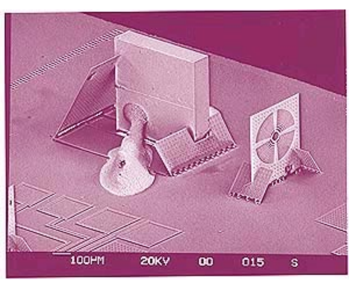
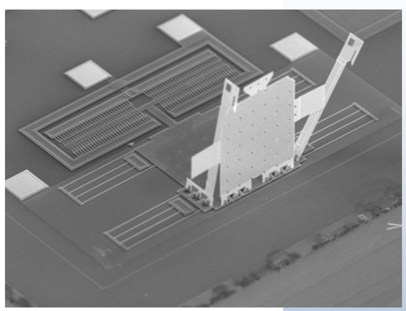
Sensor Tips



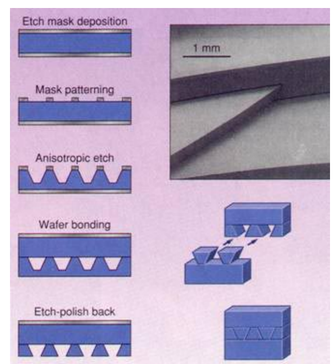
Metal-coated tips for near-field scanning microscopy (NSOM)

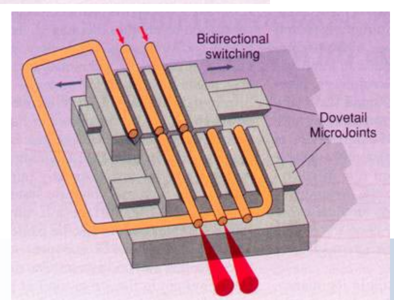


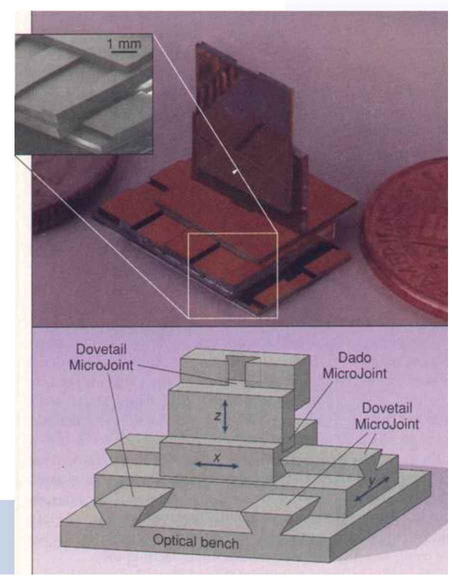
Free-space Micro-optics

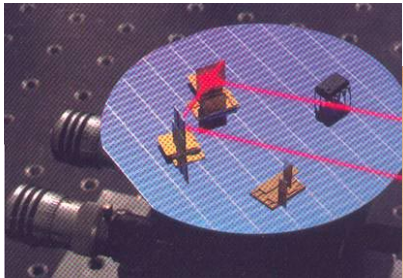
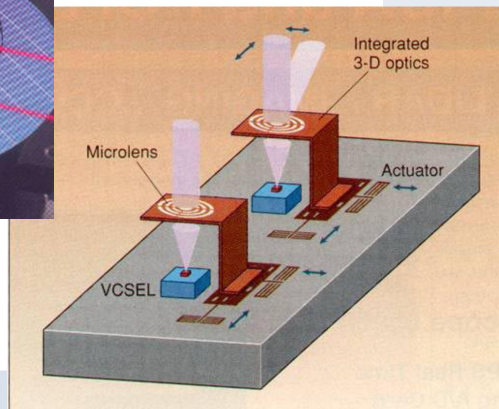

"Microjoinery"







Micro-optical benches

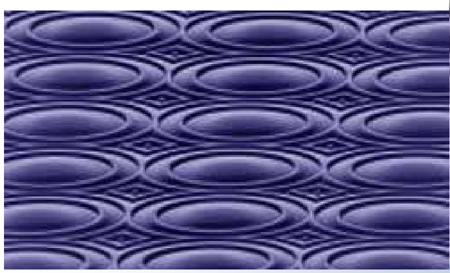
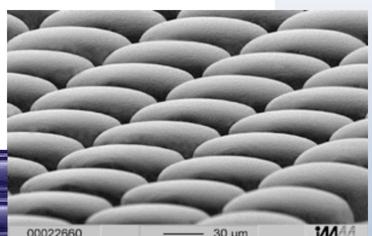



Transmissive Devices

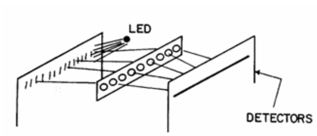
- Refractive Microlenses
- Filters
- Beamsplitters
- Prisms
- Apertures
- Shutters/Choppers

Microlenses

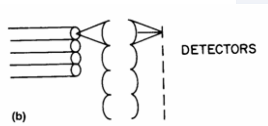
- AKA Lenslets

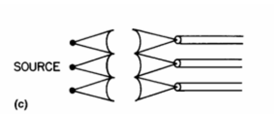
Applications of Refractive Optics



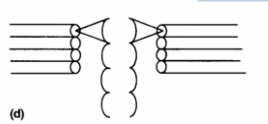
One-to-one imaging of document



Point imaging

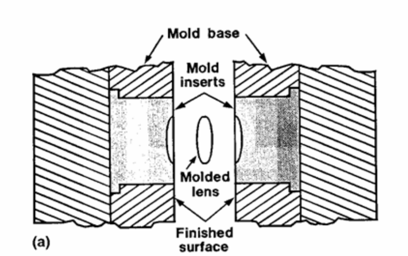


Source-to-fiber array



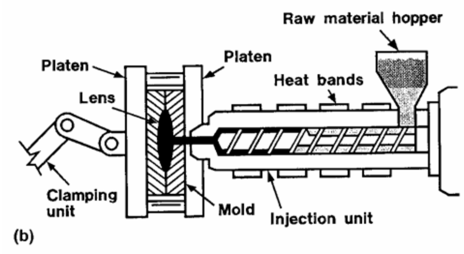
Collimation/reimaging

Extrusion Molding of Optics

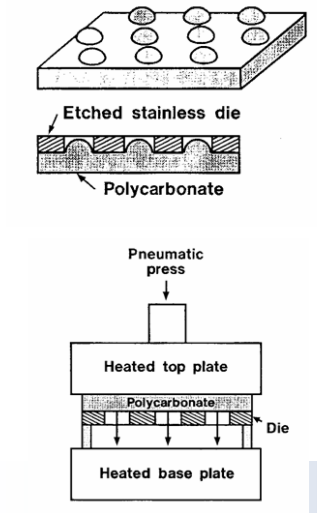


Same as macro-analog

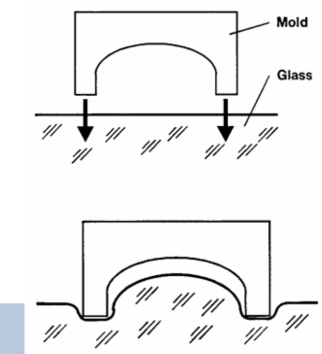
Diamond-turned mold (expensive)



Hot Pressing/Contactless Molding



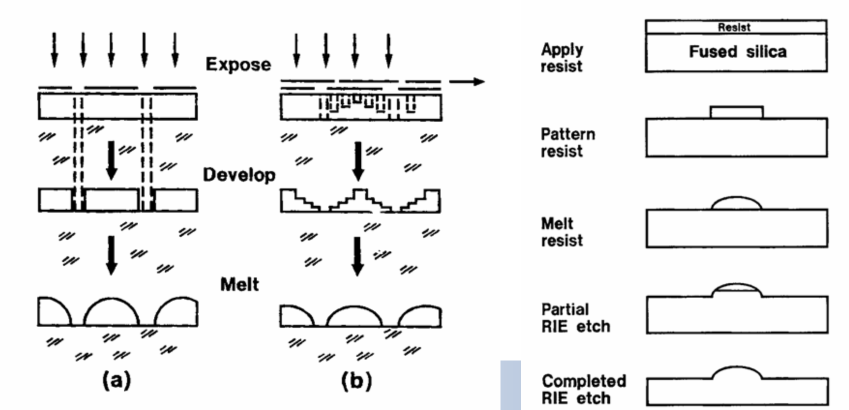
Materials:
polycarbonate, PMMA, polystyrene
glass



Photoresist-Based

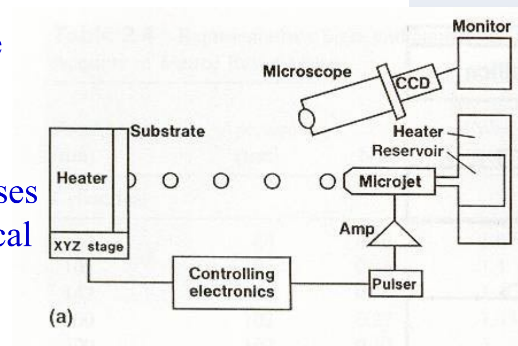
$$R_c = (n-1)f = \frac{D}{4L}$$

D=diameter (5-750µm)
L=resist thickness (up to 50µm)

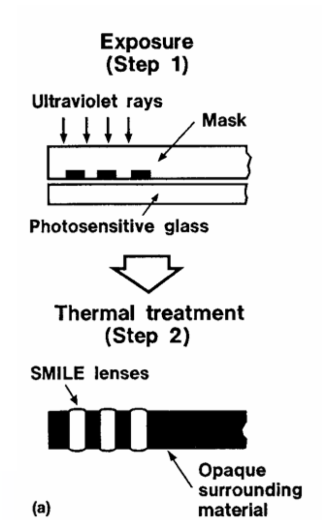


Microdispensing

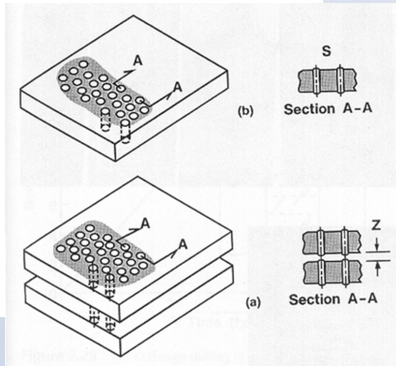
- Microjet directs droplets to substrate
- Liquid solidifies on contact
- Surface tension causes formation of spherical surface
- 25-100µm diameter



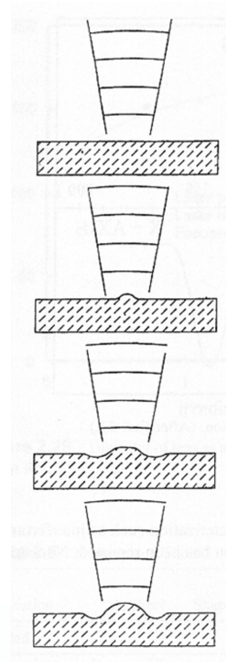
Photosensitive Glass

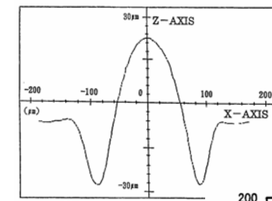


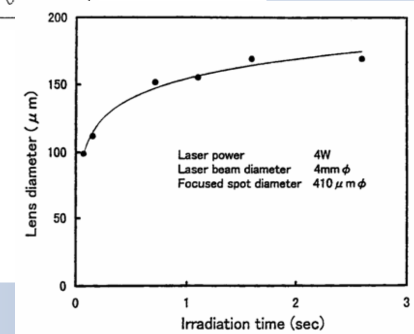
Exposed glass densifies and squeezes soft (unexposed) glass → spherical extrema
80-1000μm diameter



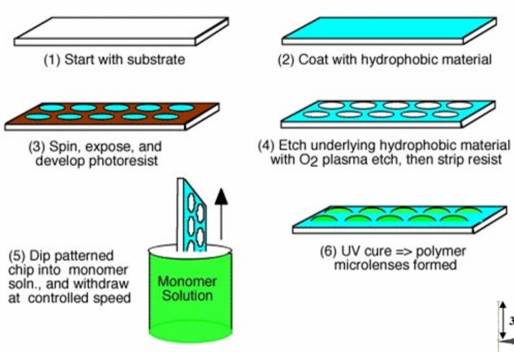
Laser Heating

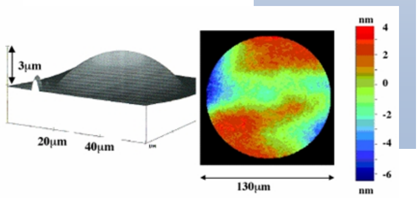






Biomimetic Lens Growth





2-500μm diameters
Highly spherical
Other shapes also possible

Comparison of Microlenses

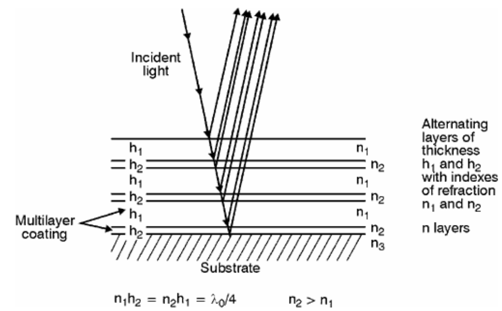
Fabrication	Asphere	Shapes	Array	FL (μm)	Diameter (mm)	Packing/ Geometry
Molded						
Plastic	Y	Any	Y	>100	>0.1	100%/any
Glass	Y	Any	N	>500	>2*	—
Contactless	N	Any†	Y		>0.1	80%/any
Resist						
As is	N	Circle	Y			
Etched	N	Circle	Y			
Microjet	N	Circle	Y		0.08–1	80%/any
Photosens glass	N	Any†	Y	>200	0.08–1	80%/any
Laser	N	Circle	Y	>100	>0.1	?/any

*Depends on radius of curvature of cutting tool.
†The surface figure is dependent on the boundary curve.

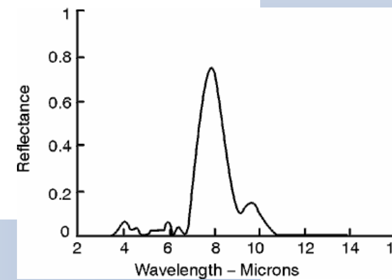
Reflective Optics

- Reflection Coatings
  - Si
  - Metals
  - Multilayer Dielectrics
- Mirrors
  - Single
  - Arrays

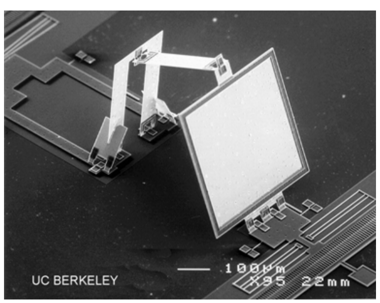
Multilayer Dielectrics

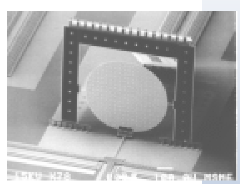


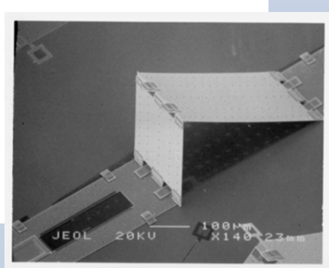
Sequential deposition of materials
Sputtering
Molecular beam epitaxy
Self-assembly



Mirrors

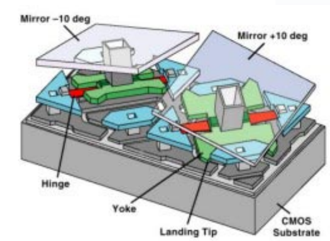


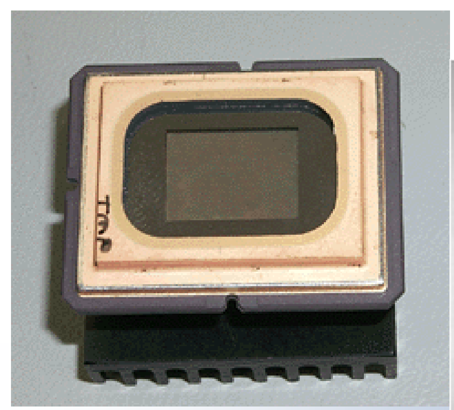


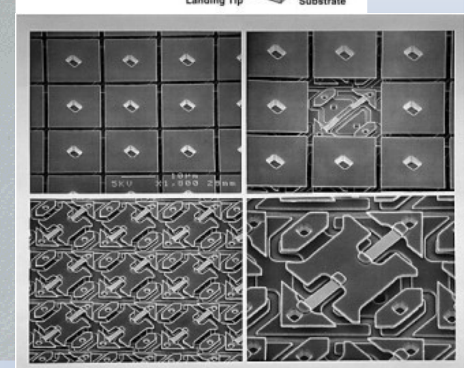


Digital Mirror Displays

- Big push for small, lightweight, flexible displays
- Texas Instruments DMD







Tunable Filters

http://dmtwww.epfl.ch/ims/micsys/projects/porsi/GLammel_porous_Si.ram

Porous Silicon Reflector

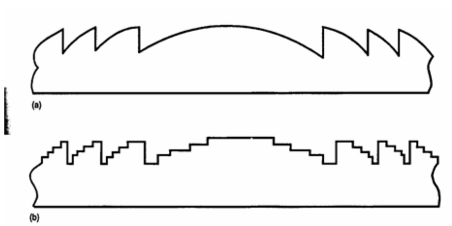
1100 µm x 1850 µm x 30 µm..

Au tracks on Si_3N_4 used for thermal bimorph arms

Diffractive Optics

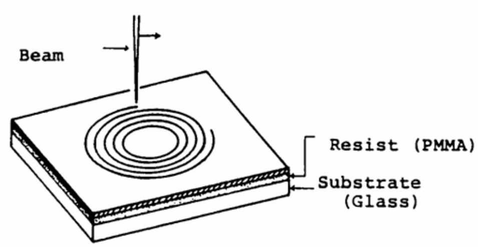
- Microlenses
- Fresnel Zone Plates
- Gratings

Direct Writing



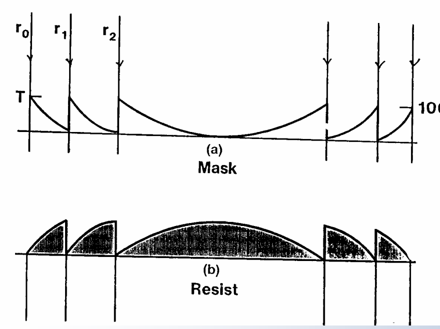
Approximate the phase of a spherical lens with a diffracting surface: use Fresnel-like structures or "binary optics"

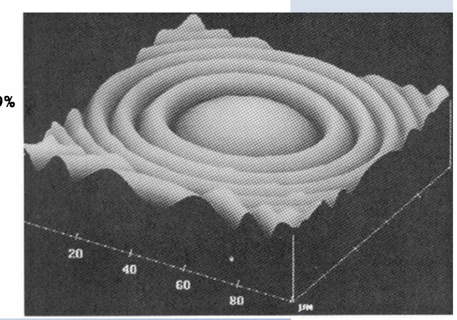
•Micro-Fresnel lenses require gray-scale exposure and resist with linear response
•Option 1=Direct-write (beam patterning)



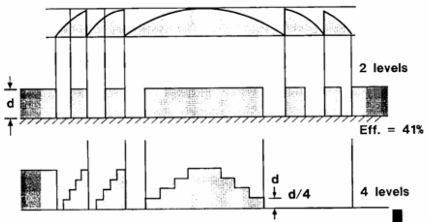
Gray-Scale Patterning

•Gray-scale masks produced with e-beam writing



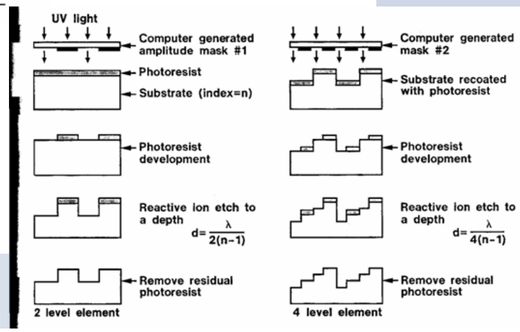


Multilevel Patterning



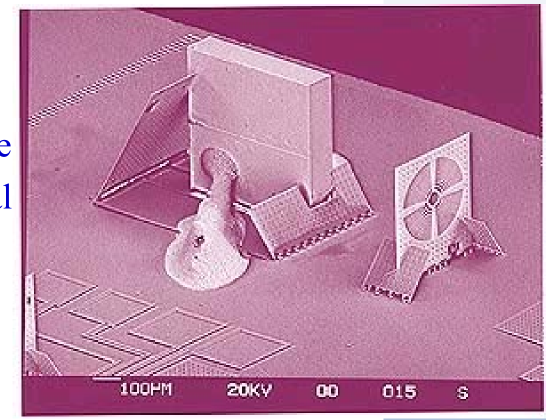
•"Digitize" the surface
•Diffraction efficiency ~ # of levels (N)
•Eff(N)=$|\text{sinc}(\pi/N)|^2$ (%)

•Sequential exposures and etching steps employed
•Each subsequent step has increasing resolution
•Each step produces $d/4$
•# masks = $\log_2(N)$

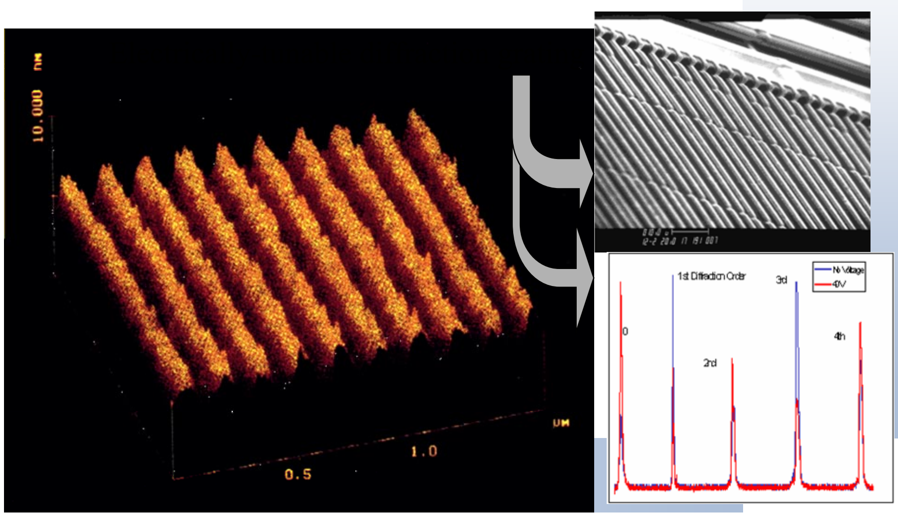


Zone plate lens

- Varying fuctions
  - Collimation
  - Focusing
  - Beam Steering
- Fabricated in-plane
- Elevated to vertical



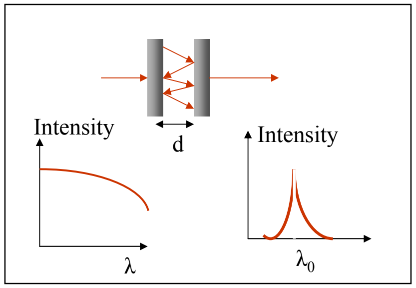
Gratings

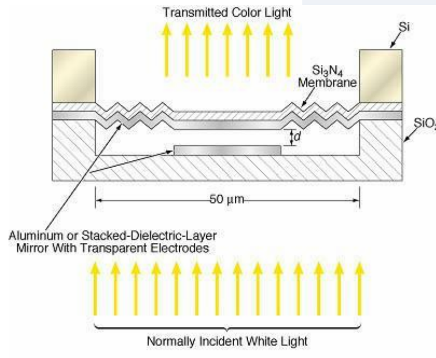


Interference-Mode Devices

- Fabry-Perot Interometers
- Mach-Zehnder Interferometers
- Michelson Interferometers

Fabry-Perot Interferometer





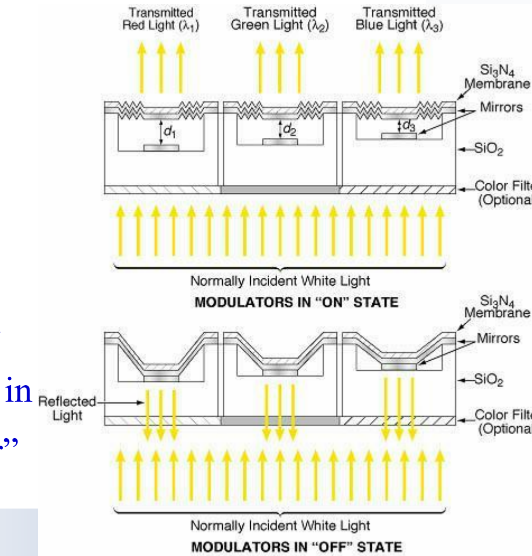
•Change in optical pathlength:
•Refractive index (n)
•Cavity length (d)

•Changes resonance wavelength (wavelength at which constructive interference occurs)

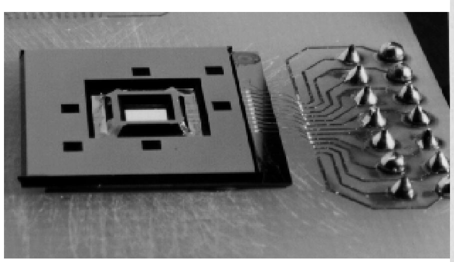
$$\text{Phase shift} \quad \phi = \frac{2\pi nd}{\lambda}$$

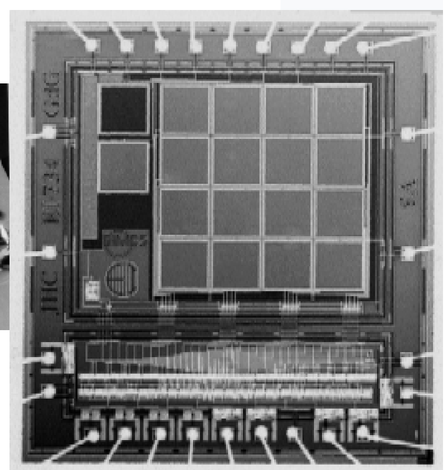
Fabry-Perot Interferometer

- Actuation moves membrane
- Movement alters optical pathlength
- Results in change in transmitted “color”



Fabry-Perot Array

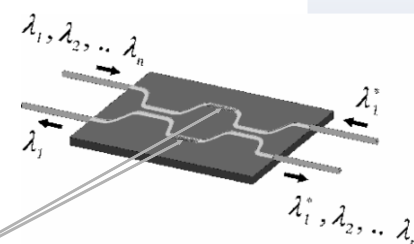




•Arrays used to cover broader spectral regions
•Required due to periodicity of interference

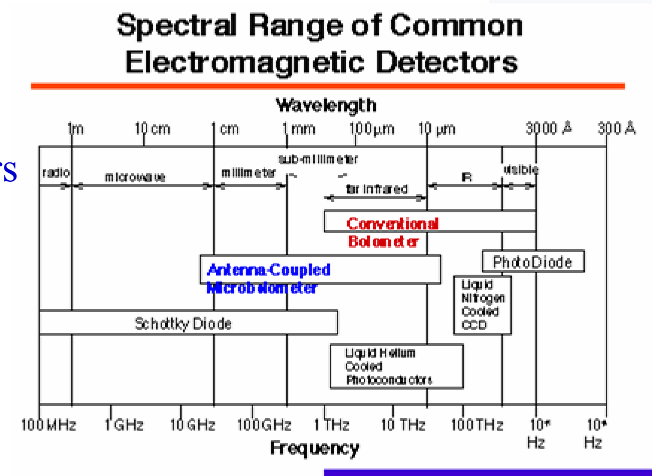
Waveguide Interferometers

- Optical couplers in regions of waveguide contact
- Coupling depends on relative phase of waves arriving at coupler
- Changes in “arms” produce changes in output fringes



Detectors

- Photodiodes
- µ-bolometers

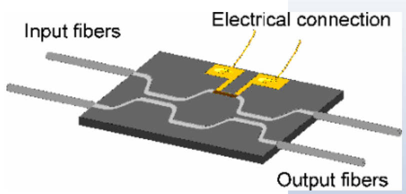


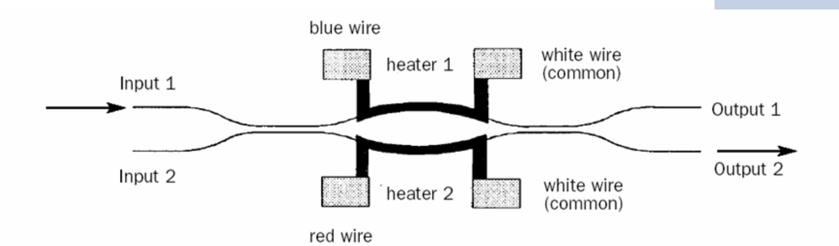
Applications

- Switches
- Spectrometers
- Scanners
- Displays

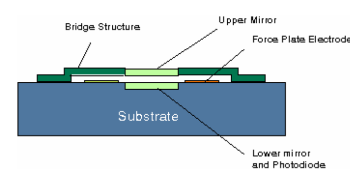
Switches

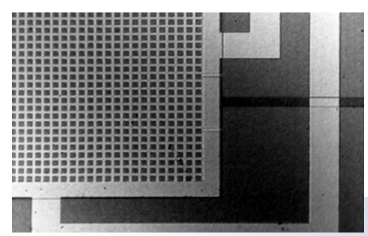
- Temperature change causes change in refractive index
- Interference between waves at coupler altered

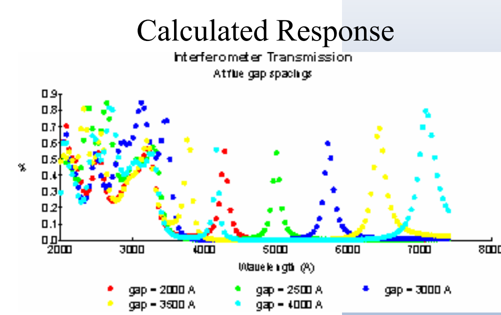




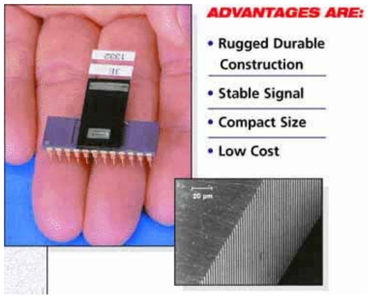
Fabry-Perot Spectrometers

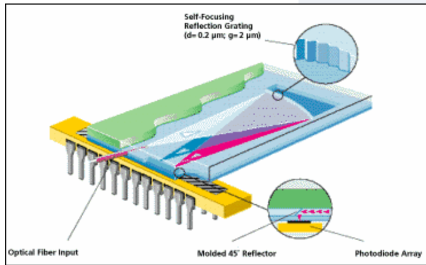




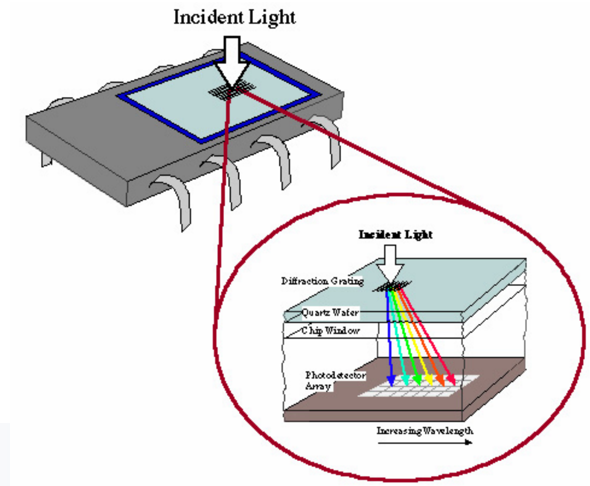


Dispersive MicroSpectrometers



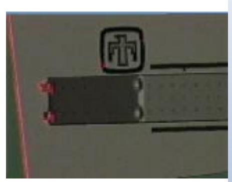


Dispersive MicroSpectrometers



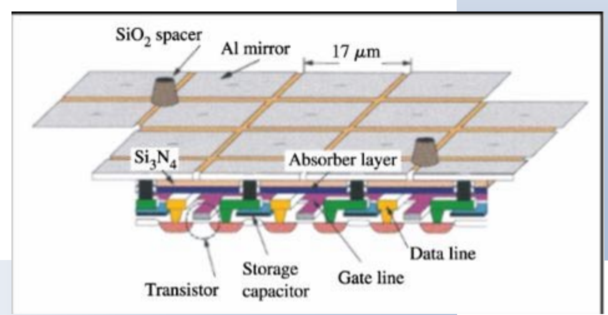
Micromirror Scanners

- Function: Beam-steering
- Applications
  - Code-reading
  - Imaging
  - Motion detection
  - Precision Machining

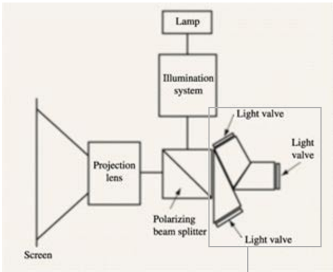


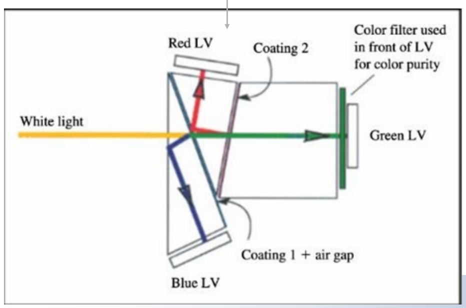
Spatial Light Modulators

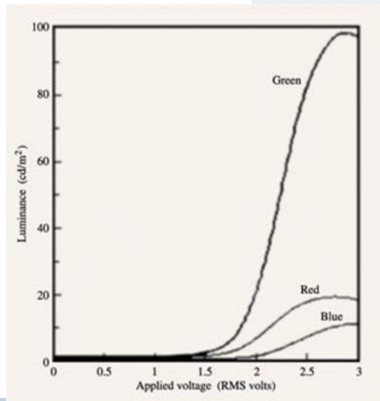
- Active Matrix Displays: Reflective Light Valves
  - Efficiently map R-G-B onto screen
- SiO2 spacers define liquid crystal cell gap



Modulator Properties







References

- *Microoptics Technology*, Borelli
- *Optics & MEMS*, Walker and Nagel
- Fundamentals of Microfabrication
- Many, many, many WWW sites