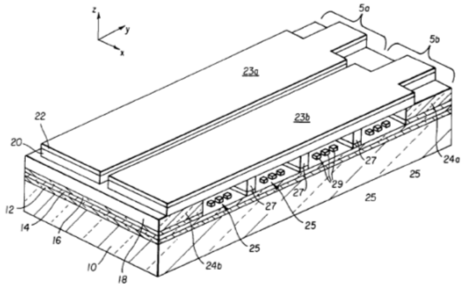
The Institute of Optics Colloquium,
University of Rochester, April 20, 2009.

Grating Electromechanical Systems (GEMS), Laser Displays, and Related Doodles



Marek W. Kowarz*

Infotonics Technology Center

***Major portions of this work were performed when the author was with Eastman Kodak Company.**

GEMS Technology: Timeline and Milestones

Grating ElectroMechanical System

2000

2001

2002

2003

2004

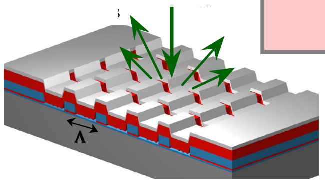
2005

2006

2007

2008

Invention of GEMS Device



1st Operational GEMS Device

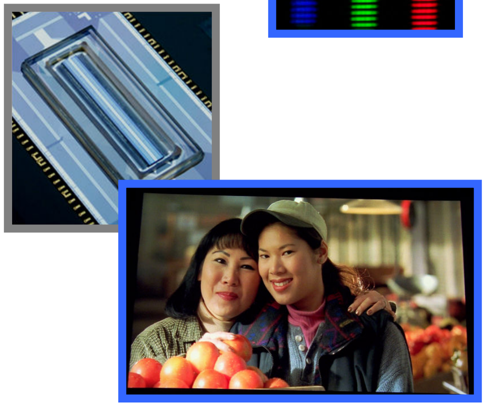
Monochrome Display 256 X 455

RGB Laser Display 256 X 455

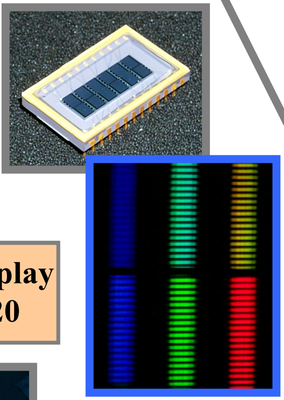
Base Device Patent (6,307,663)

Base Display Patent (6,411,425)

Sapphire Display 1080 X 1920



Spectral Imager 6-Band Demo



XGA Display Evaluation Kit

Spectral Imager Device & System

ITC

Kodak

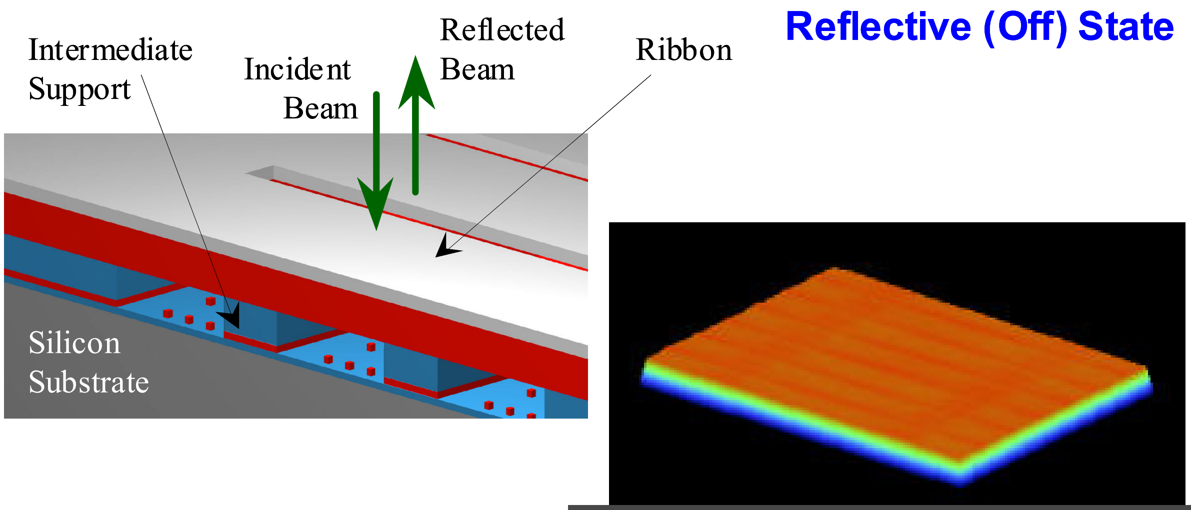
GEMS Display Project

ITT

GEMS Project

GEMS Device

Reflective (Off) State

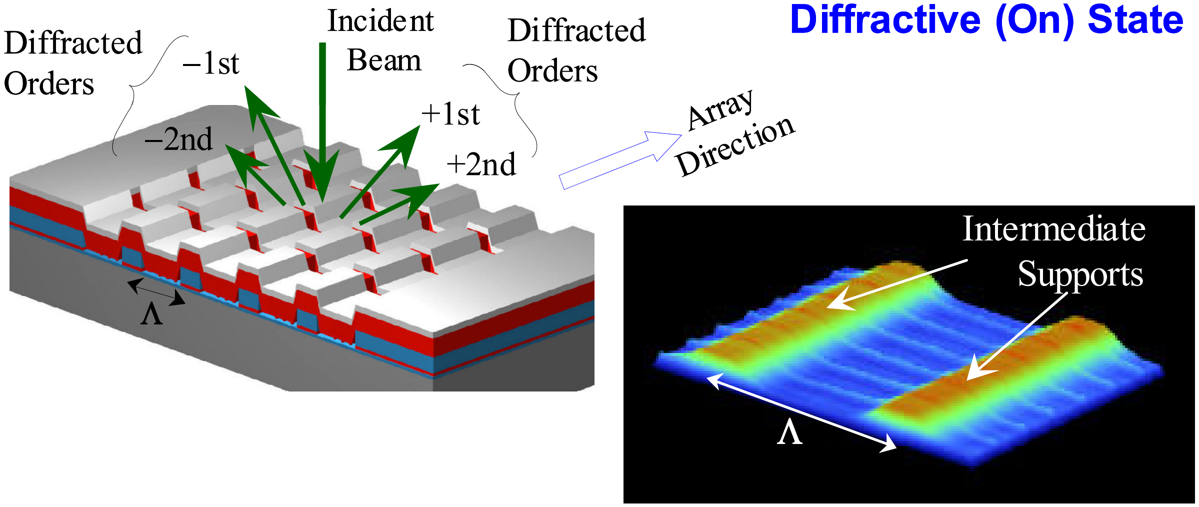


Typical Dimensions

Grating period = 15 to 50 μm

Actuation depth = 150 to 200 nm

Diffractive (On) State



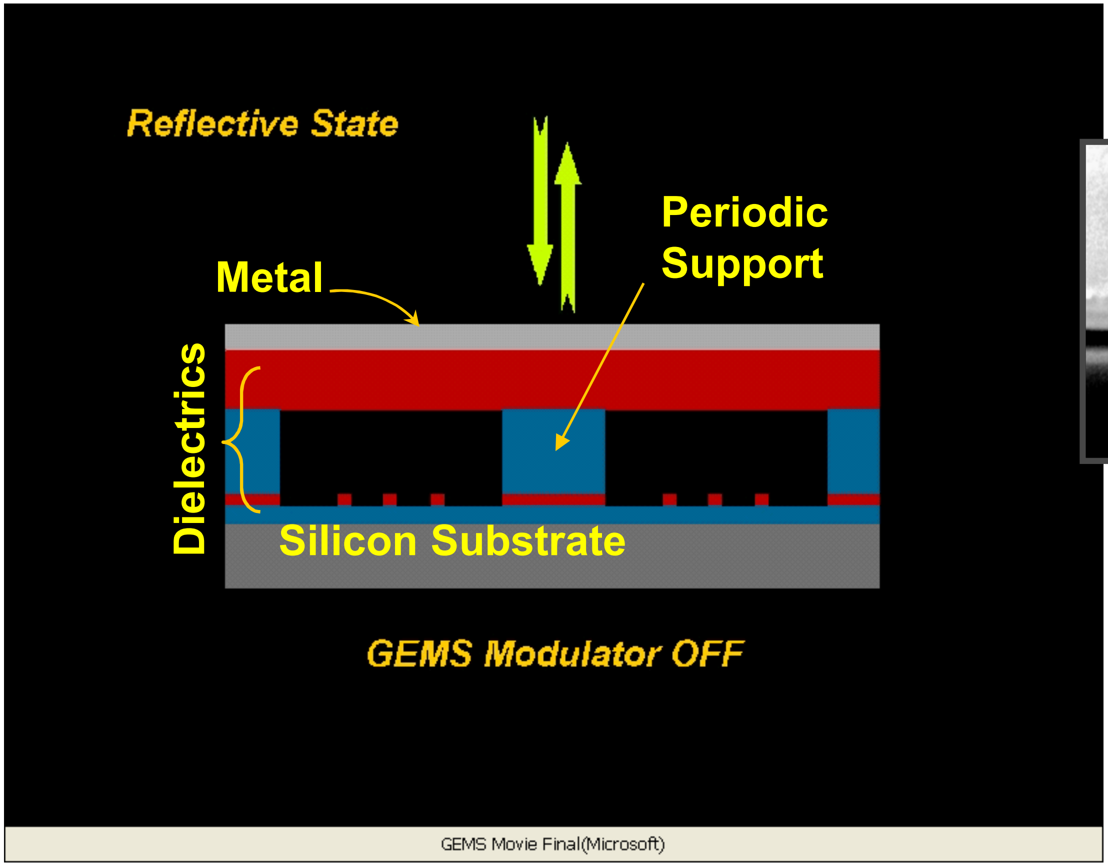
Device Features

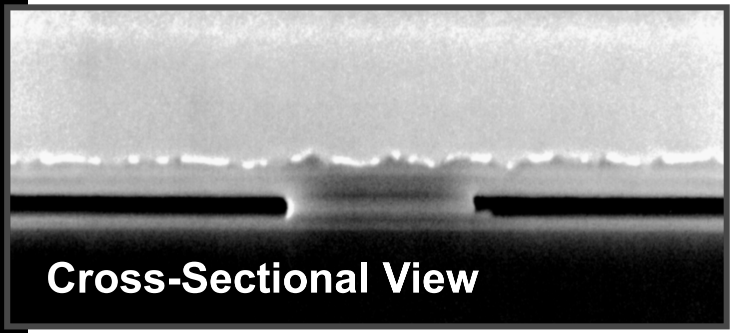
Very wide active area
⊥ grating (Λ) direction
Digital operation
>2000:1 contrast
>60% multiorder efficiency

GEMS Device Structure and Operation

Grating ElectroMechanical System

The GEMS device consists of a linear array of pixels with electromechanical ribbons suspended above a hidden grating



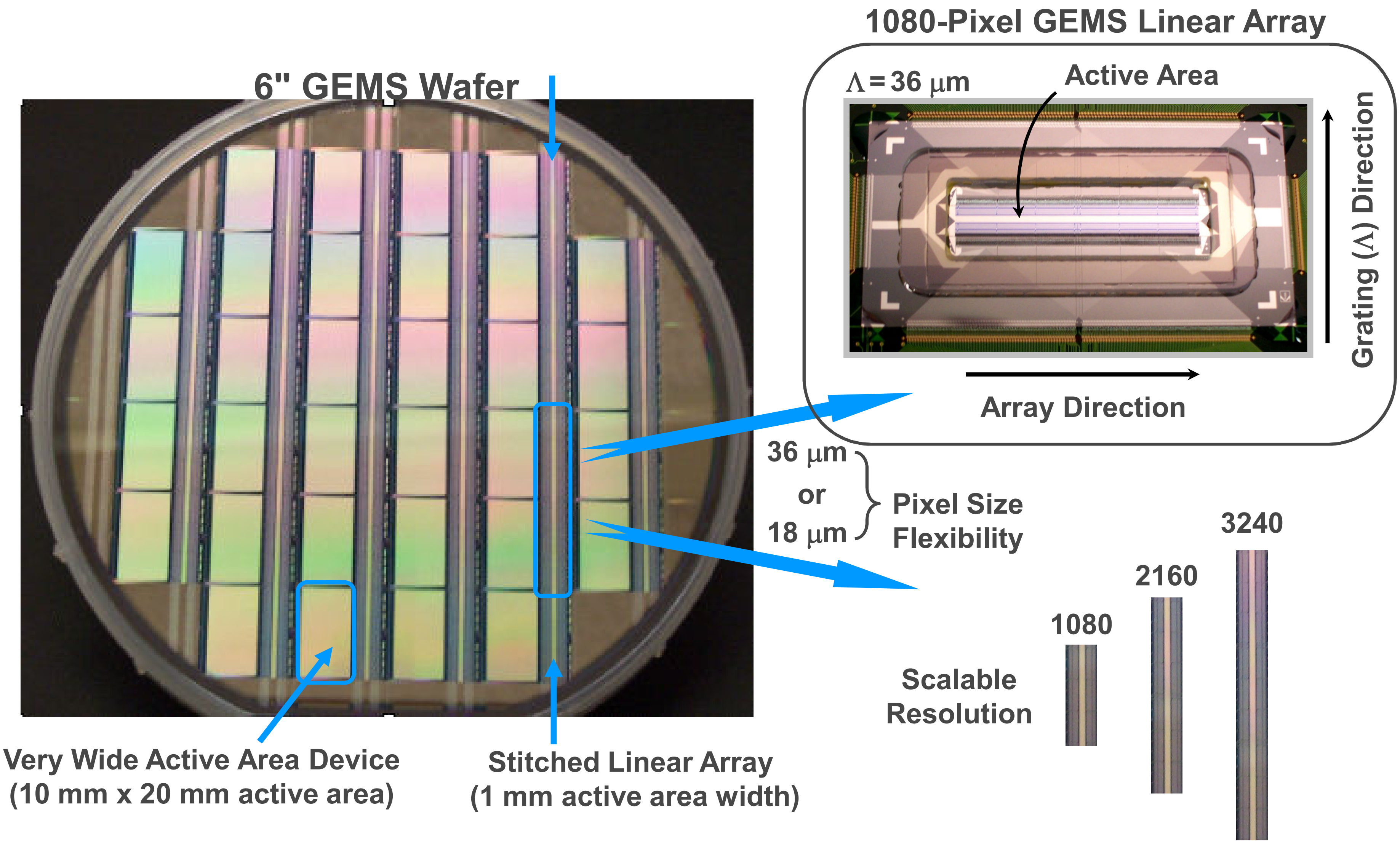


Typically

Pitch = 15 to 50 μm

Actuation Depth = 150 to 200 nm

GEMS Device Wafer



6" GEMS Wafer

1080-Pixel GEMS Linear Array

Λ = 36 μm

Active Area

Grating (Λ) Direction

Array Direction

36 μm
or
18 μm

Pixel Size Flexibility

Scalable Resolution

1080

2160

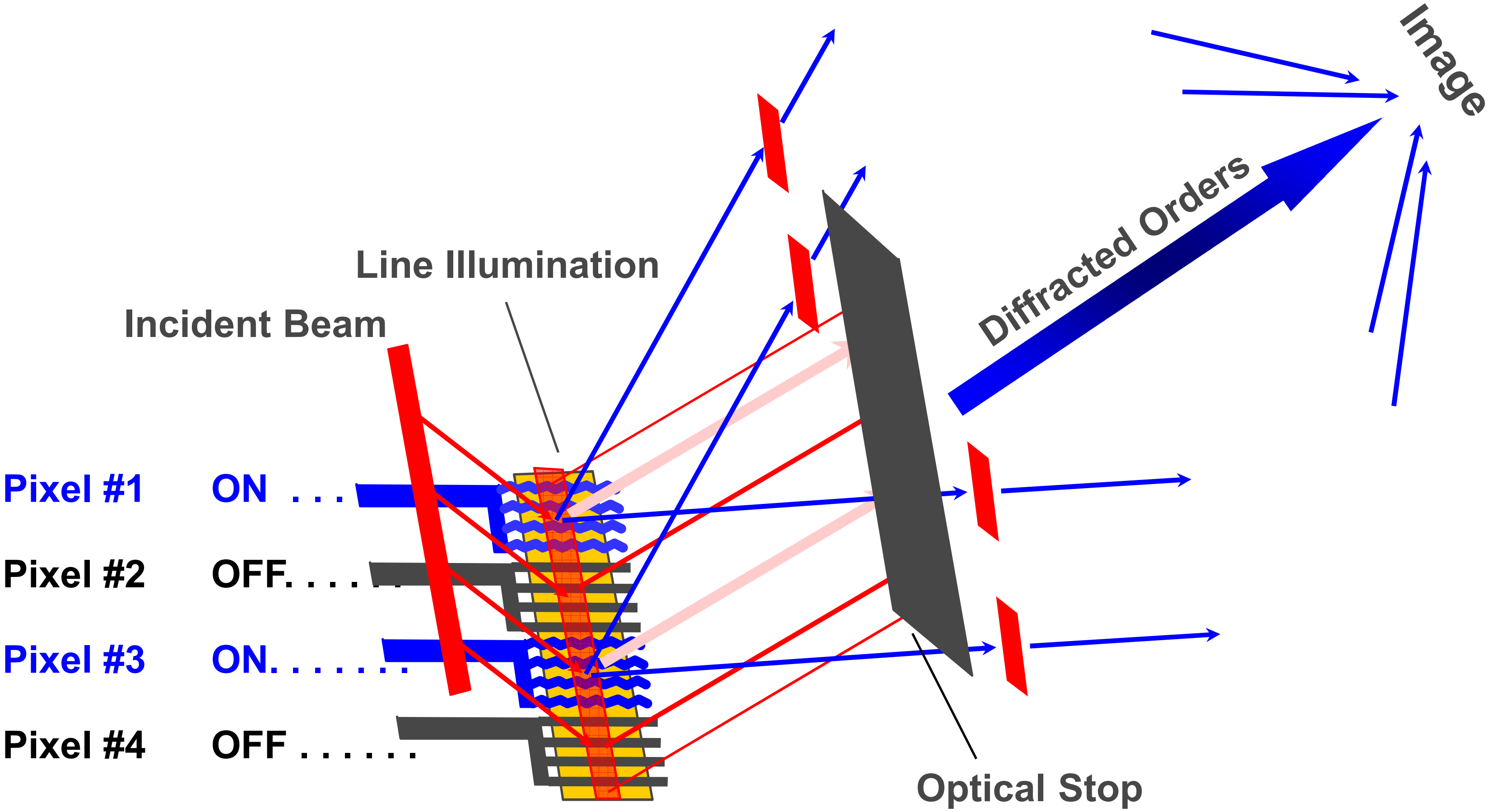
3240

Very Wide Active Area Device
(10 mm x 20 mm active area)

Stitched Linear Array
(1 mm active area width)

Optical System Principles

- OFF pixels reflect light, which is blocked by an optical stop
- ON pixels diffract light and the diffractive orders are collected to form a line image

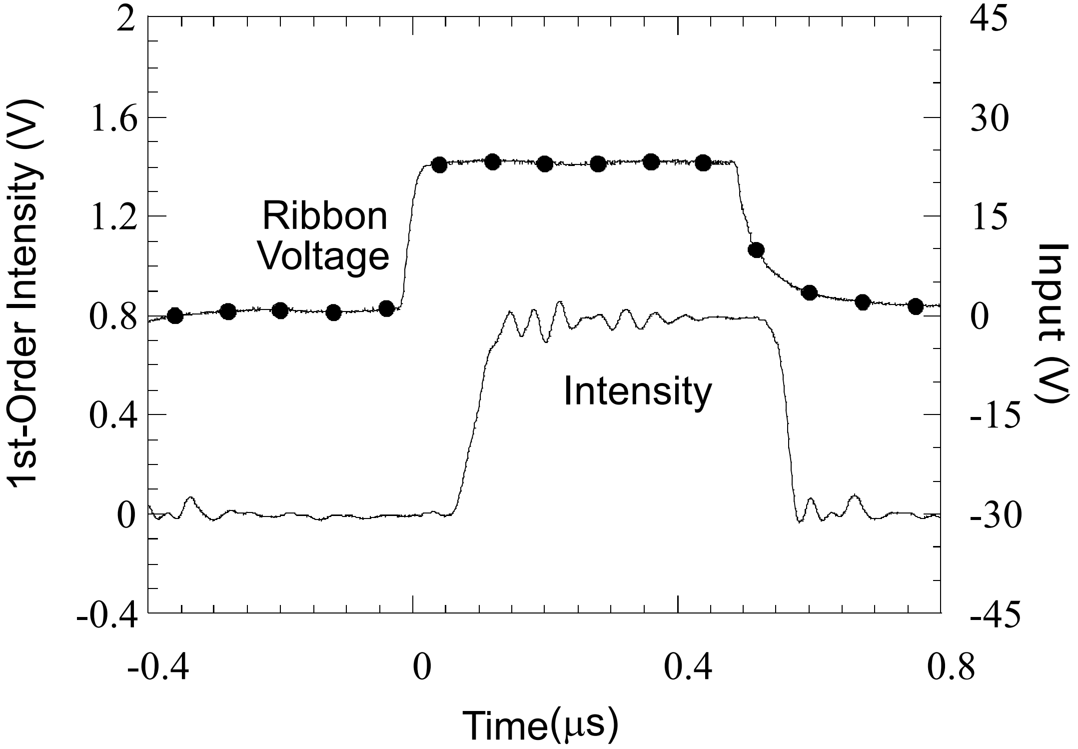


GEMS Device High-Speed Response

The fast switching speeds of the GEMS device enable a 2D display with a 1D linear array

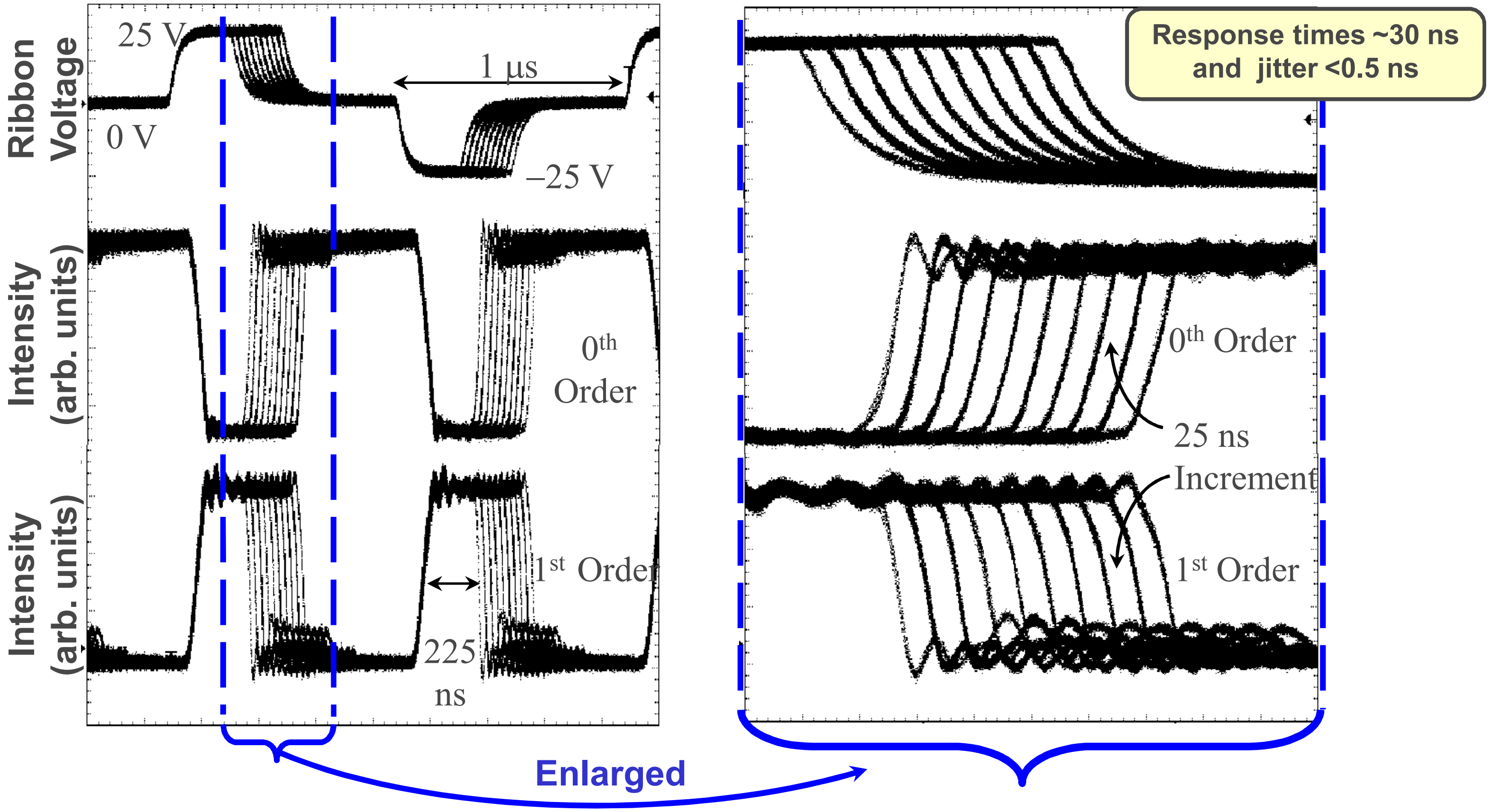
~30 nanosecond digital operation

Response to High-Speed Input Signal



PWM Gray Scale Generation

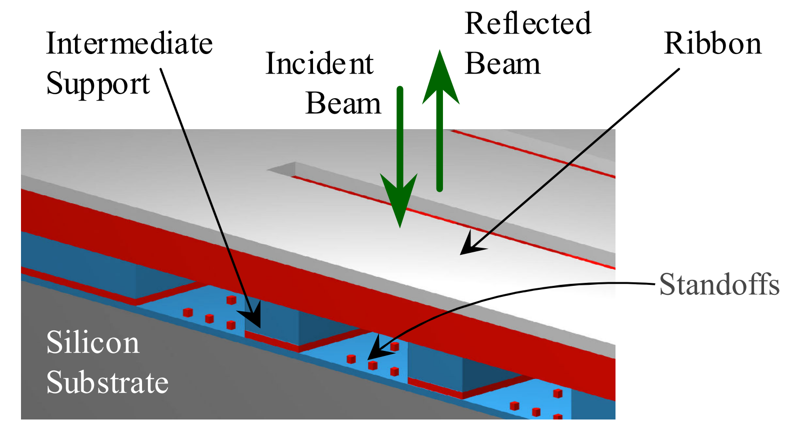
The fast switching speeds allow for the generation of gray scale through pulse width modulation (PWM)



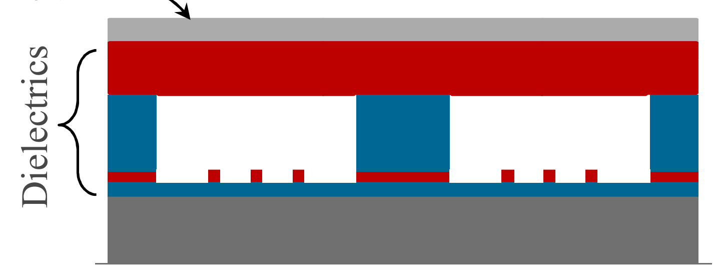
Example of Response to Random PWM Data Stream

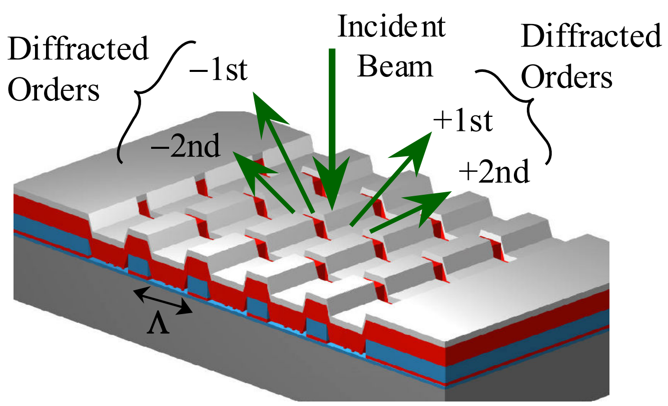
Response times ~30 ns and jitter <0.5 ns

Opto-Electromechanical Device Model

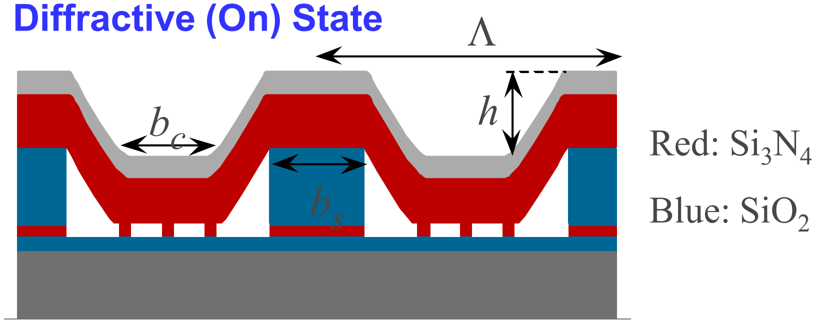


Reflective (Off) State





Diffractive (On) State



- GEMS period (Λ)
- Support width (b_S)
- Channel depth (h)
- Ribbon width
- Ribbon gap
- Ribbon dielectric thickness
- Ribbon metal reflector
- Standoff separation
- Standoff height

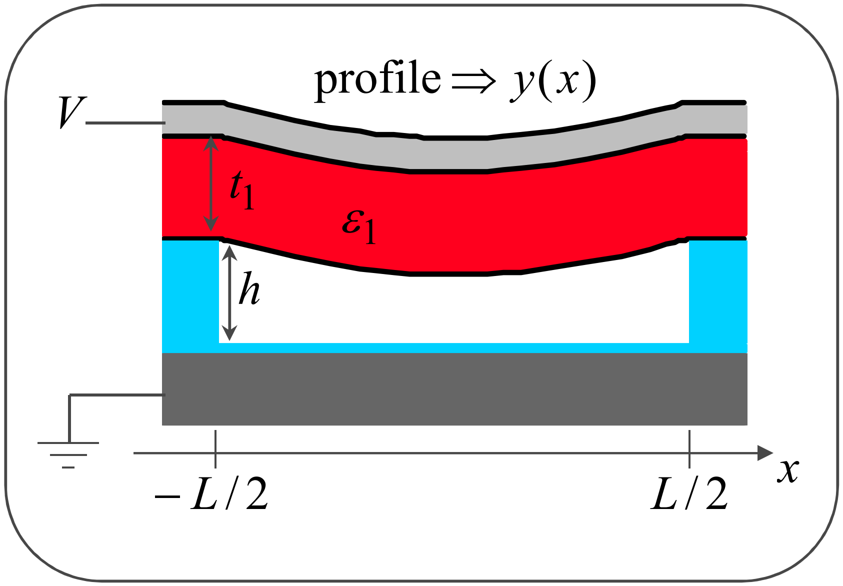
Opto-Electromechanical Model

1. Pull-down & operating voltage
2. Ribbon profile
3. Diffraction efficiency

Stress-Limit Ribbon Deformation Model

Stressed ribbon differential equation:

$$\overbrace{\cancel{EI\frac{d^4y}{dx^4}}}^{\text{bending}} - \overbrace{Sw\frac{d^2y}{dx^2}}^{\text{tension}} = \overbrace{\frac{\varepsilon_o w V^2}{2(t-y)^2}}^{\text{electrostatic attraction}}$$



where

ε_o ⇒ permittivity of free space

ε_q ⇒ relative permittivity of qth layer

σ_n ⇒ stress of nth layer

L ⇒ ribbon length, w ⇒ ribbon width

$S = \sum_n \sigma_n t_n$ ⇒ tensile force per unit width

$t = h + \sum_q \frac{t_q}{\varepsilon_q}$ ⇒ effective electrostatic gap

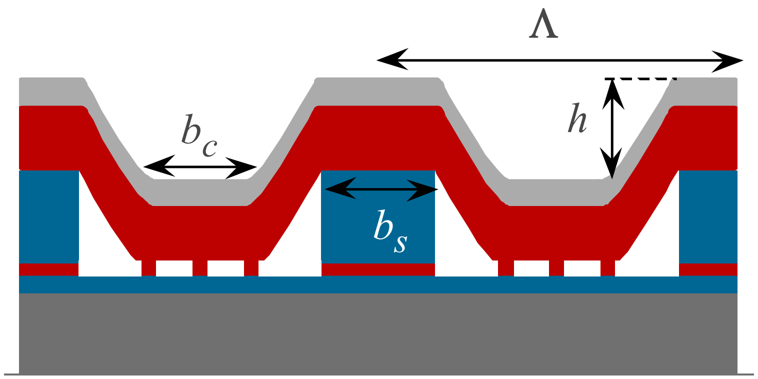
Analytical solution for ribbon profile and critical voltages

Device Model: Critical Voltages, Contact Length & Efficiency

Pull-down voltage: $$V_{PD} = \frac{1.673}{L}\sqrt{\frac{St^3}{\varepsilon_o}}$$

Release voltage: $$V_{RL} = \frac{2}{L}\sqrt{\frac{S}{\varepsilon_o}}\left[\sqrt{(t-h)th} + (t-h)^{3/2}\ln\left(\frac{\sqrt{t}+\sqrt{h}}{\sqrt{t-h}}\right)\right]$$

Contact length: $$b_c = L\,(1 - V_{RL}/V) \quad @\ \text{operating voltage}\ V$$



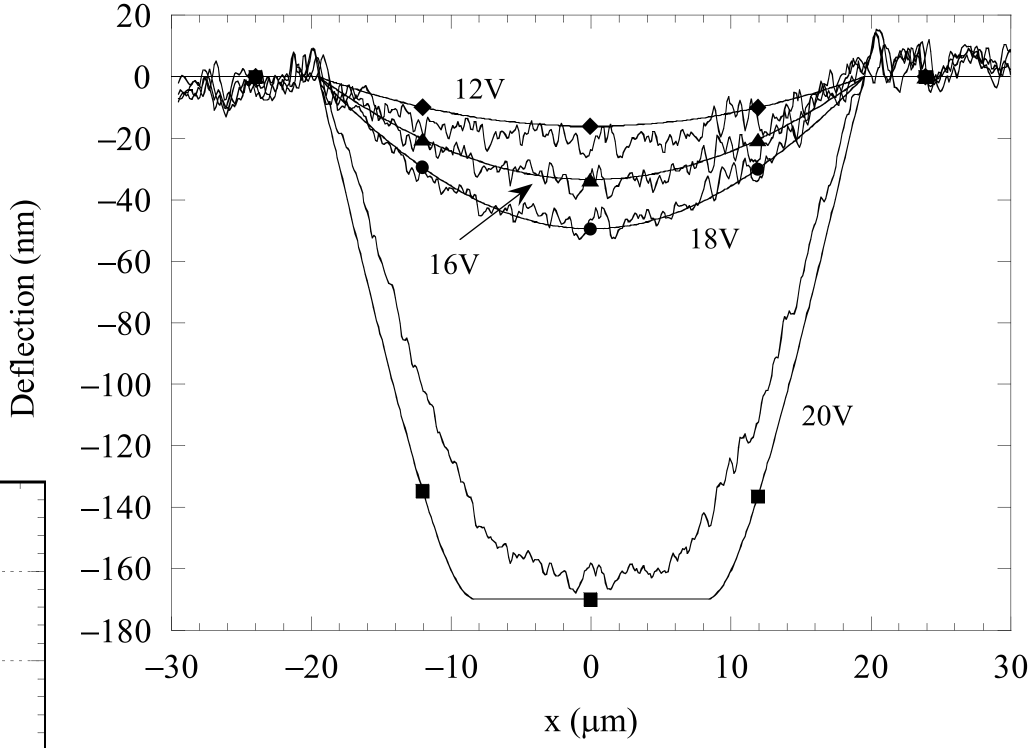
Nearly trapezoidal grating profile

Diffraction Efficiency:

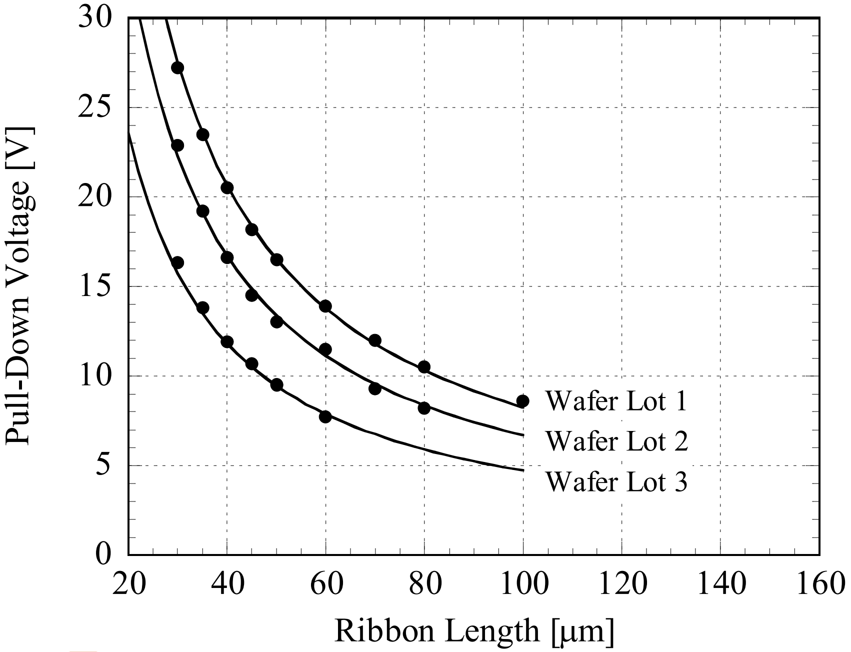
$$\eta_m = \left|\frac{1}{\Lambda}\int_0^{\Lambda} e^{i4\pi y(x)/\lambda}\, e^{-i2\pi m x/\Lambda}\, dx\right|^2$$

Stress-Limit Model Versus Experiment

Ribbon Shape (AFM)



Pull-Down Voltage

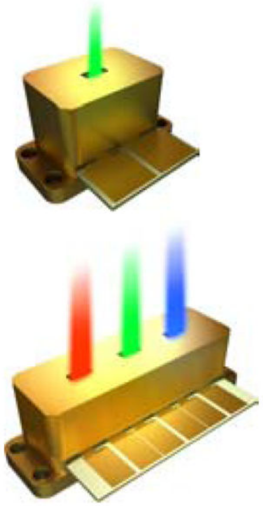


Laser Display

RGB Display Lasers (early 2000s)

New RGB laser generator (2nd generation) made by JENOPTIK LDT.
Photo: JENOPTIK LDT

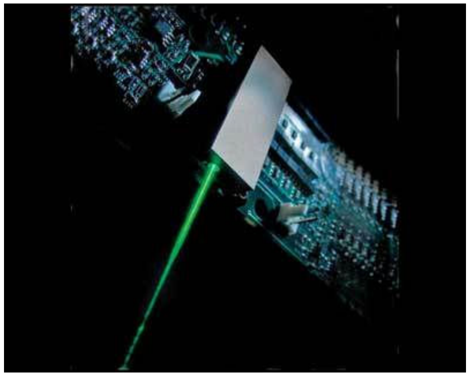
Compact RGB Display Lasers (now)



Novalux Necsel
(now Necsel)

Multi-Watt

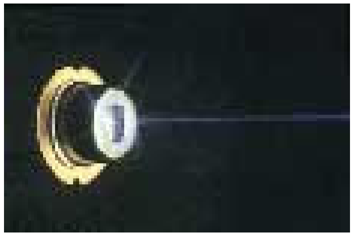
Corning Green Laser
(waveguide SHG)



100–300 mW

Nichia Blue Laser Diode

50 mW–1 W



And many others
in development
(OSRAM, Mitsubishi, …)

Laser Projection Display

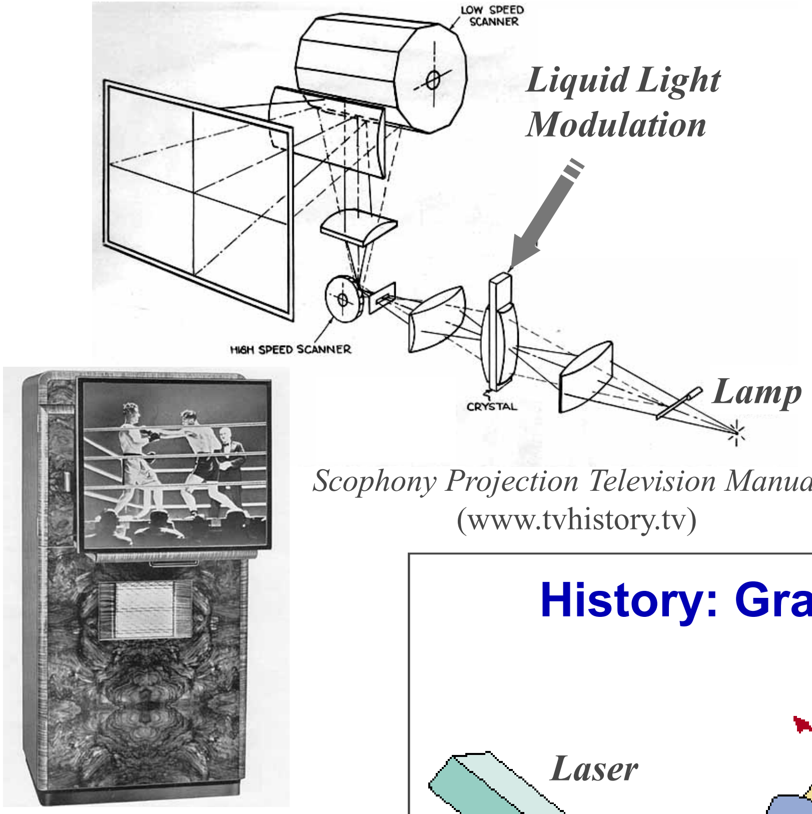
- Realization of low-cost, high-power RGB lasers enables
  - Projected images with large-screen diagonal (front or rear)
  - Color with extreme saturation, when desirable
  - Light source having long lifetime
  - Low cost per diagonal inch
  - Efficient use of light
  - High energy efficiency
  - Compact, lightweight systems

- A low-cost, high-performance light modulator is also required

Modulator Options

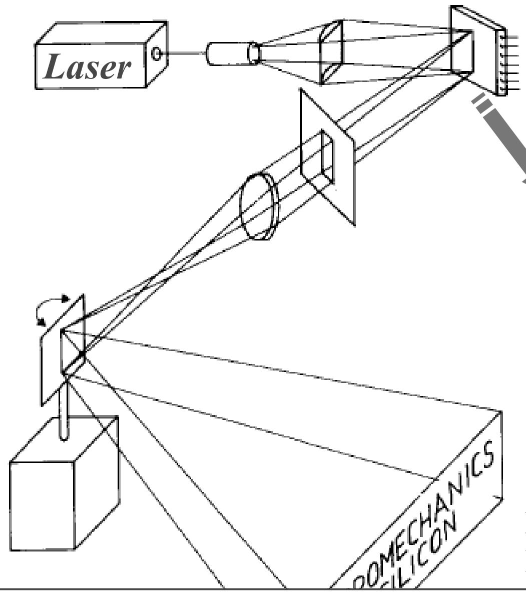
- 2D Spatial Light Modulator and no scanner – e.g., DMD
  - Example: Mitsubishi Laservue TV (see laservuetv.com)
  - Challenging to achieve full HD resolution without artifacts at low cost
- No Spatial Light Modulator and 2D laser scanner – e.g., MEMS raster scanner with direct diode modulation
  - Example: Microvision pico-projector (see www.microvision.com)
  - Low-cost solution
  - Full HD challenged by scanner resolution and laser modulation speed
  - Difficulties with speckle reduction and laser power scalability
- 1D Spatial Light Modulator and 1D scanner
  - Resolution is easily scalable
  - Excellent image quality
  - Low-cost solution at high resolution

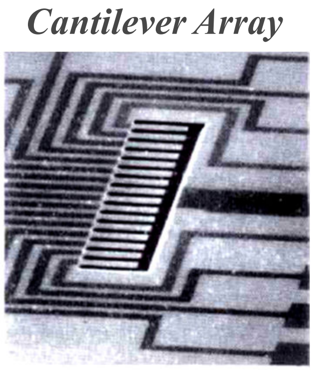
History: Scophony (1938)



Scophony Projection Television Manual
(www.tvhistory.tv)

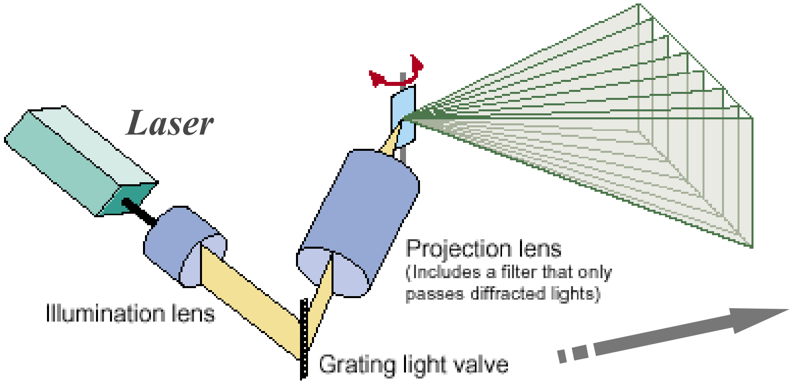
History: MEMS Cantilevers (1978)

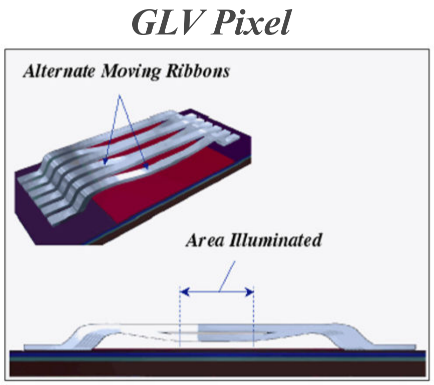




K. E. Petersen, IEEE Trans. Electron Devices 25 (1978)

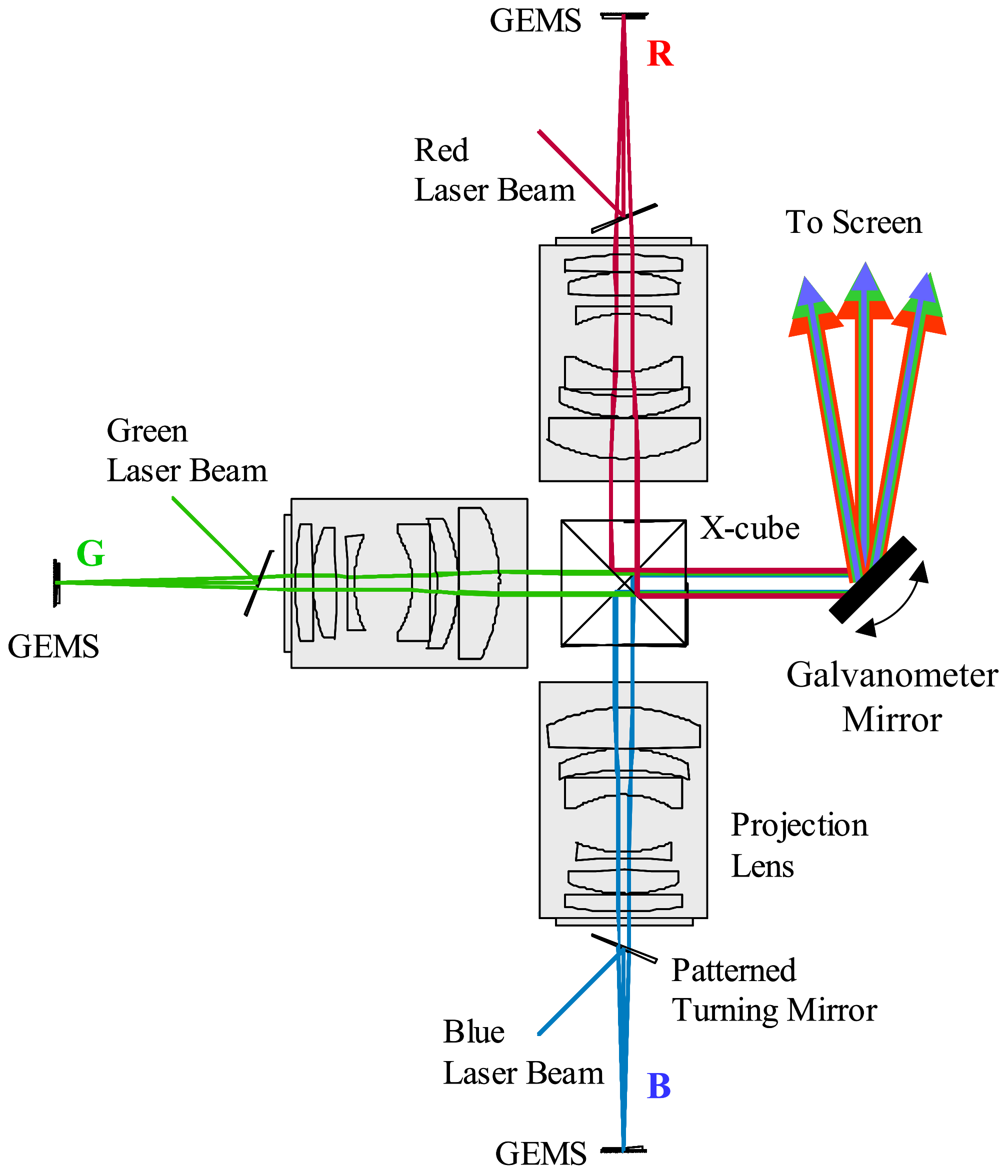
History: Grating Light Valve (1992 – Present)





Grating Light Valve Display Device, (Sony Corporation, 2002)
D. Corbin et al., *Grating Light Valve and Vehicle Displays*, (www.siliconlight.com)

Three-Chip Front-Projection Laser Display Prototype



Screen

Resolution	**1920 (H)** **1080 (V)**
Frame Rate	**60 Hz**
Screen Size	**115 inch**
Native Bit Depth	**11 bit/color (PWM)**
System Contrast	
Frame-sequential	**>1500:1**
ANSI Checkerboard	**>250:1**

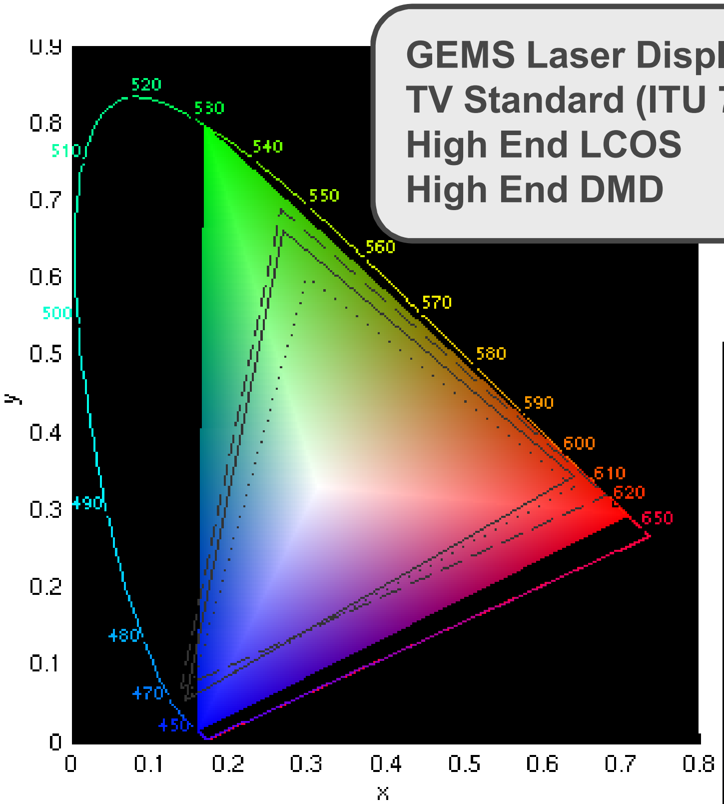
GEMS Front-Projection Prototype: Photograph of Scene from Scanned Motion Picture Film

Image Color Setting: Natural Mode

ITC Infotonics Technology Center

Kodak

Color Gamut



GEMS Laser Display	**(color filled)**
TV Standard (ITU 709)	**(dotted)**
High End LCOS	**(solid)**
High End DMD	**(dashed)**

Photograph of Computer-Generated Imagery

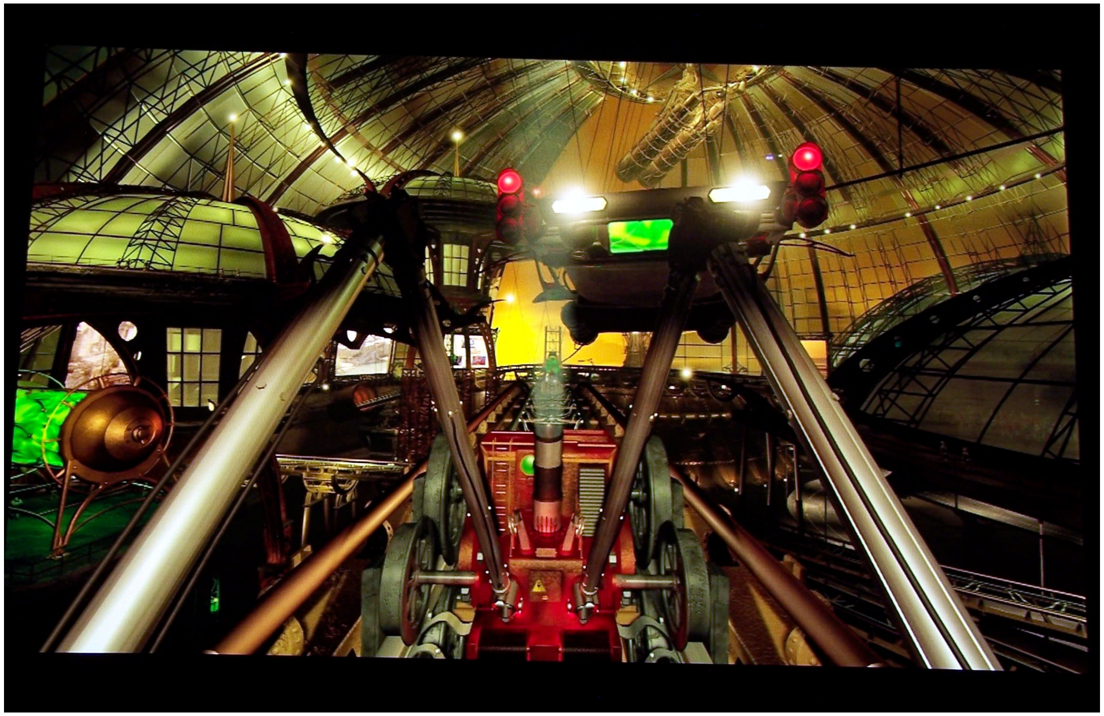
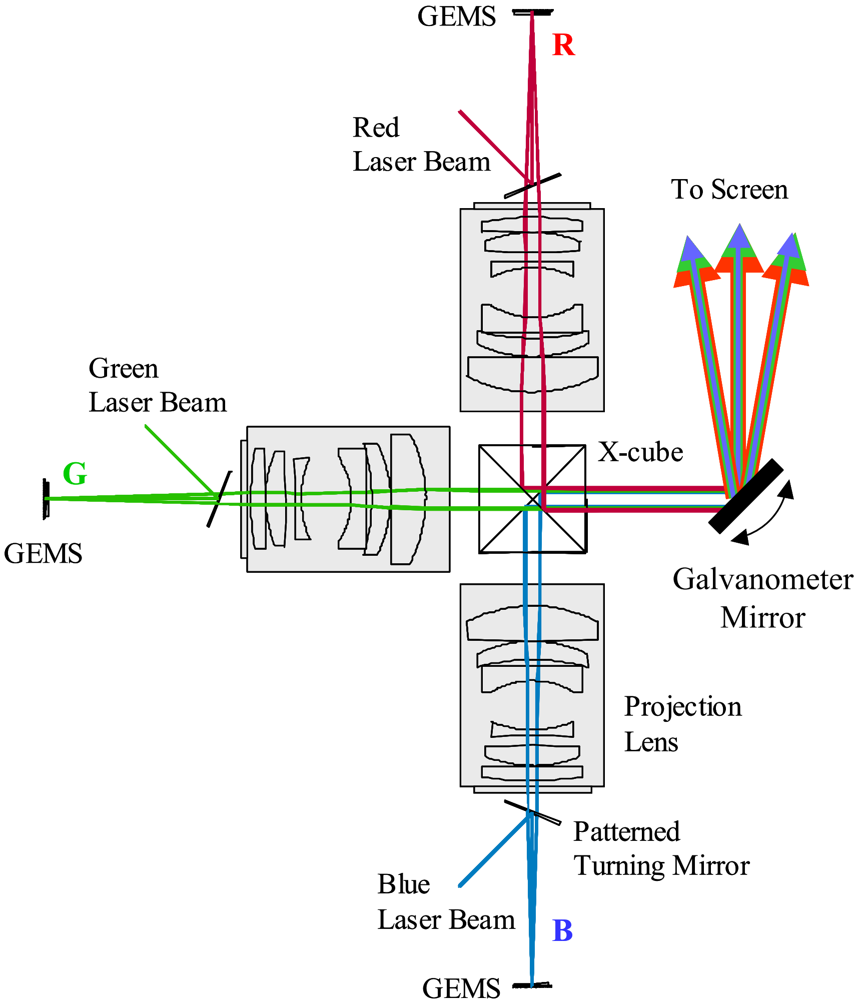
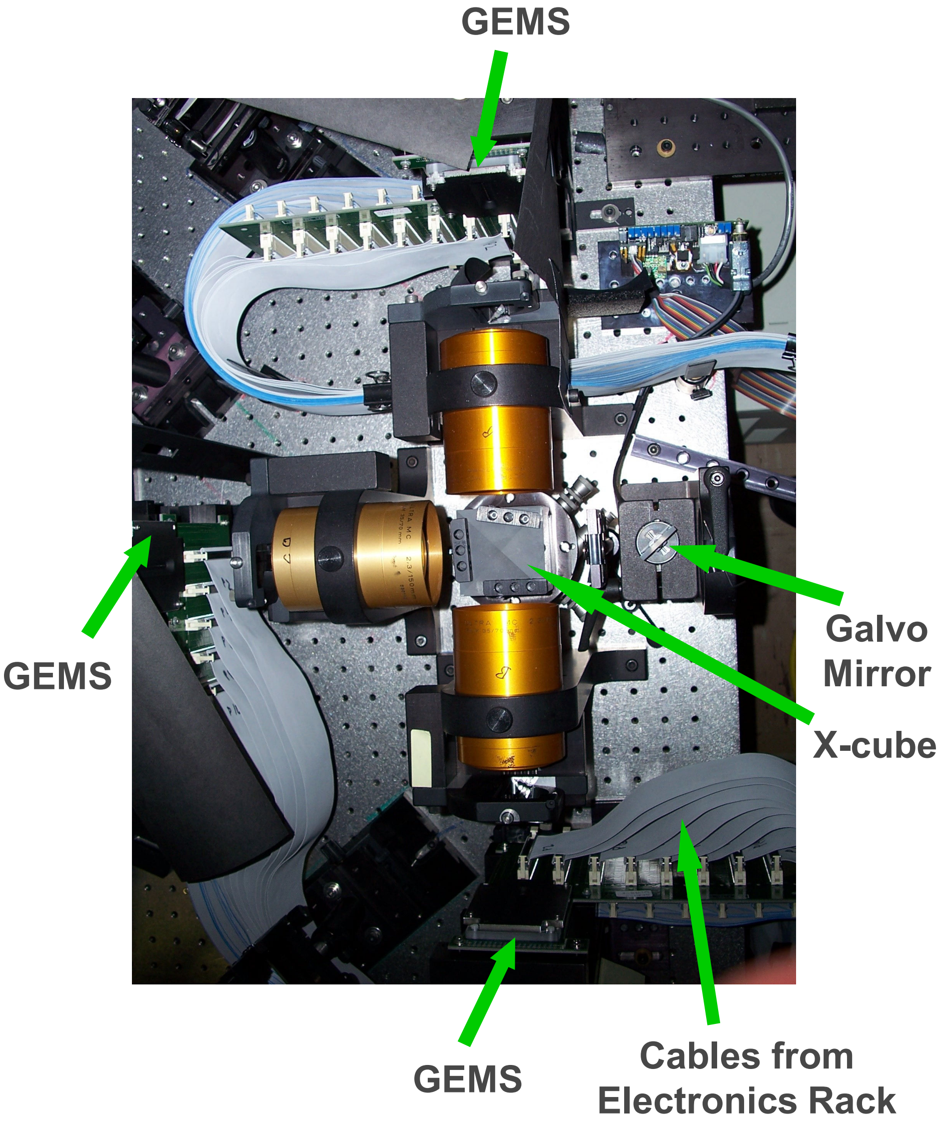


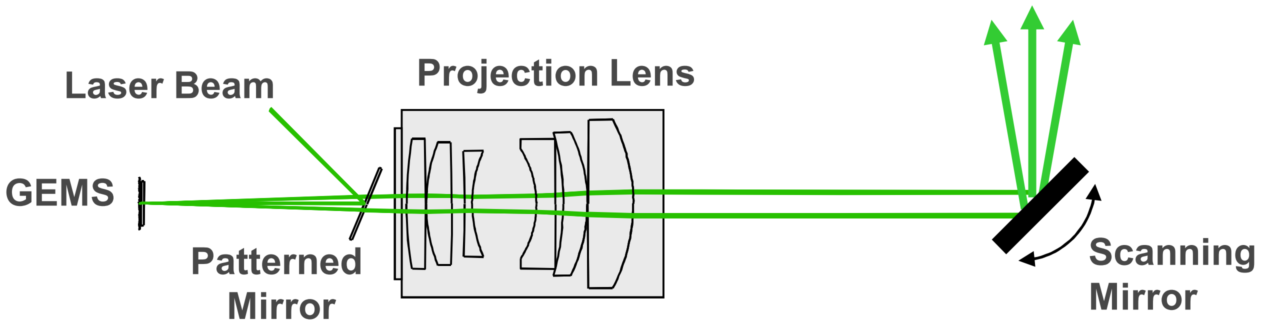
Image Color Setting: Full Gamut Mode

Three-Chip Front-Projection Laser Display Prototype

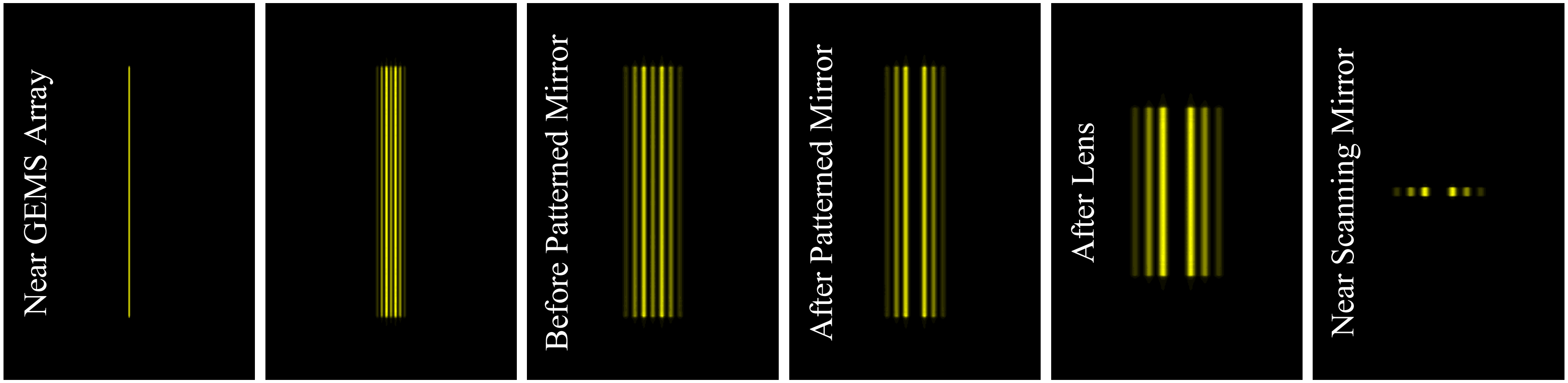




Propagation of Diffracted Light Beams

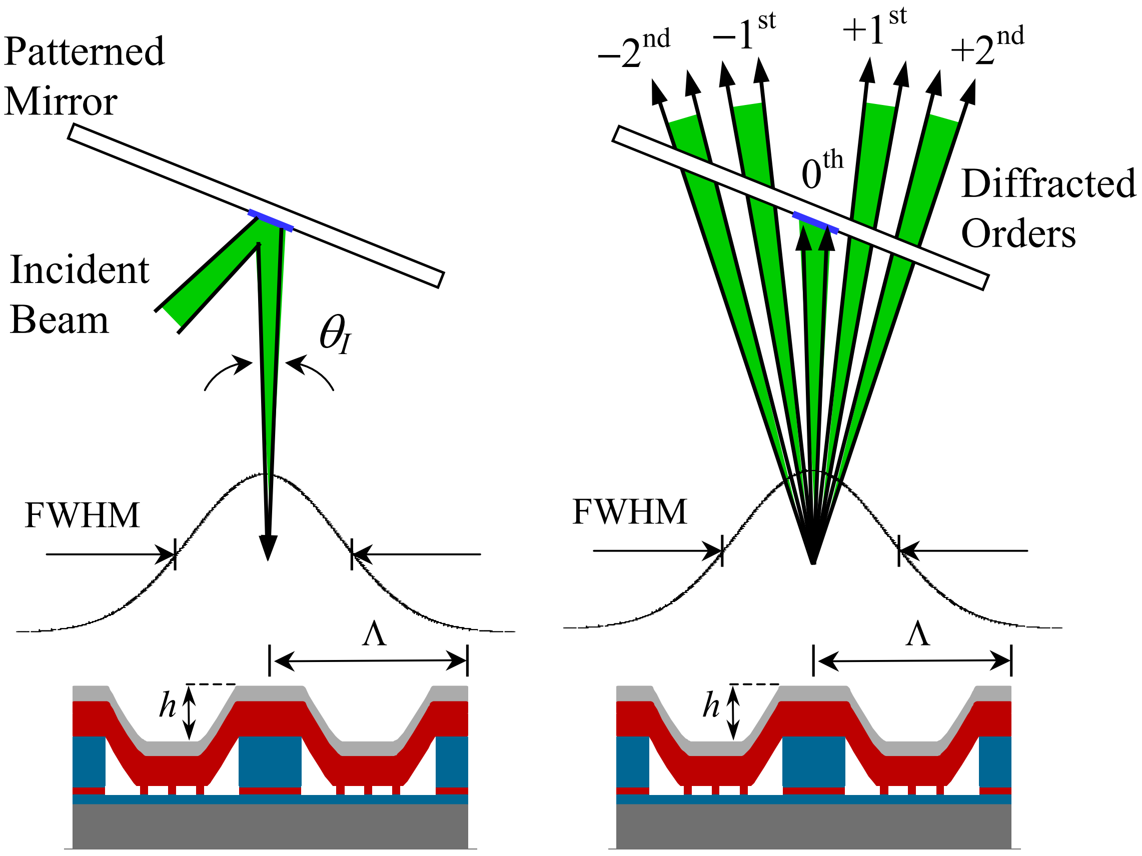


Light Propagation Model



- Perpendicular orientation of GEMS grating period enables
  - (a) Diffracted beams to be separated throughout system (except at image plane)
  - (b) On-axis illumination path before projection lens
  - (c) Collection of multiple diffracted beams with relatively small projection lens
- Small scanning mirror is placed near Fourier transform plane of projection lens

Separation of Diffracted Orders

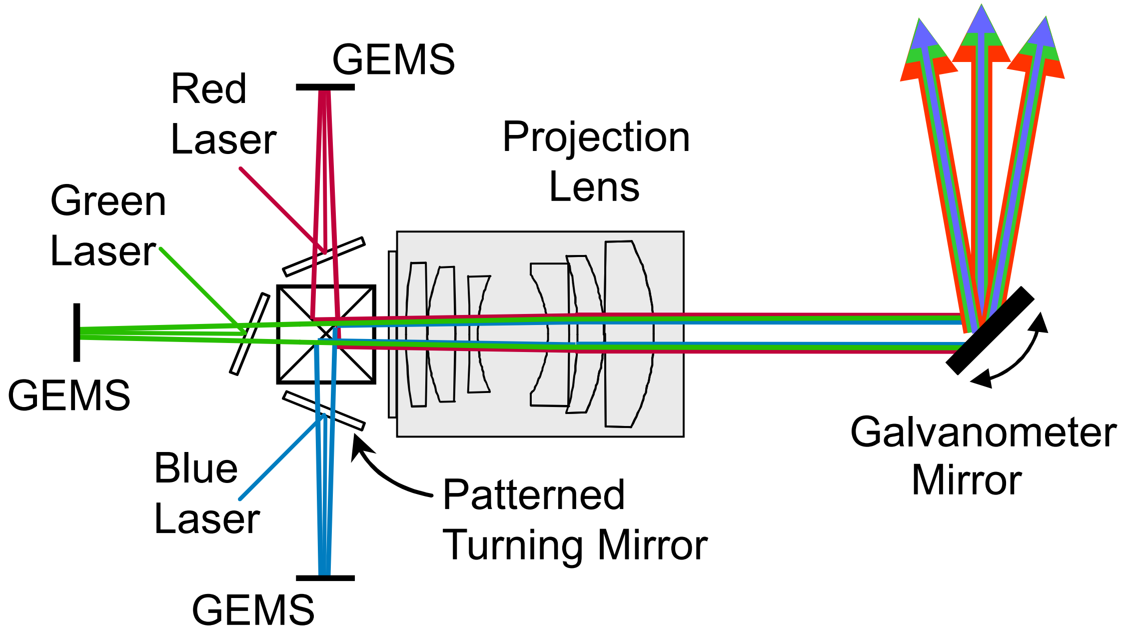


To separate diffracted orders: sin $\theta_I < \lambda/\Lambda$

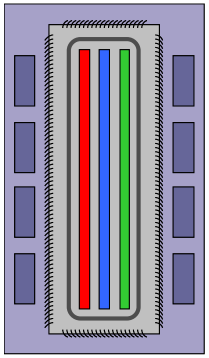
For a Gaussian laser beam: FWHM $\approx$ 0.55 $\lambda/\sin(\theta_I/2)$

Therefore, FWHM > 1.1 Λ [In practice FWHM $\approx$ 1.5 Λ]

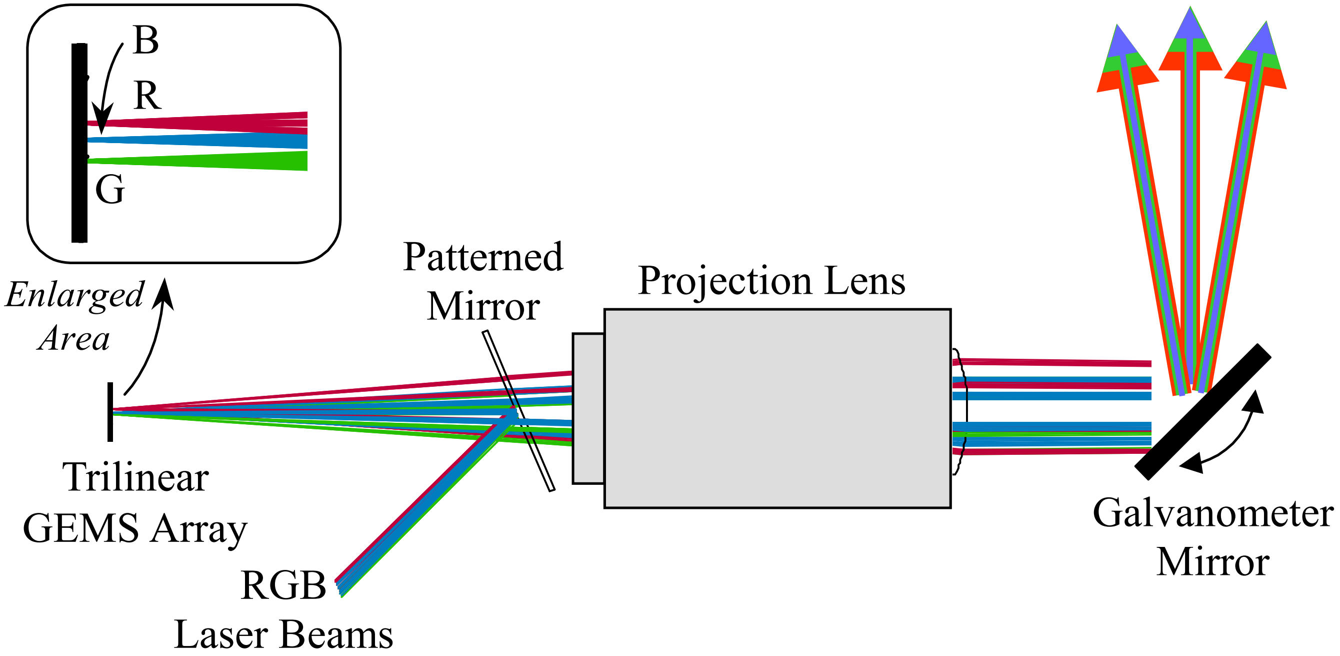
Laser Projector Architecture 1: Three-Chip System



Laser Projector Architecture 2: Multilinear Array System



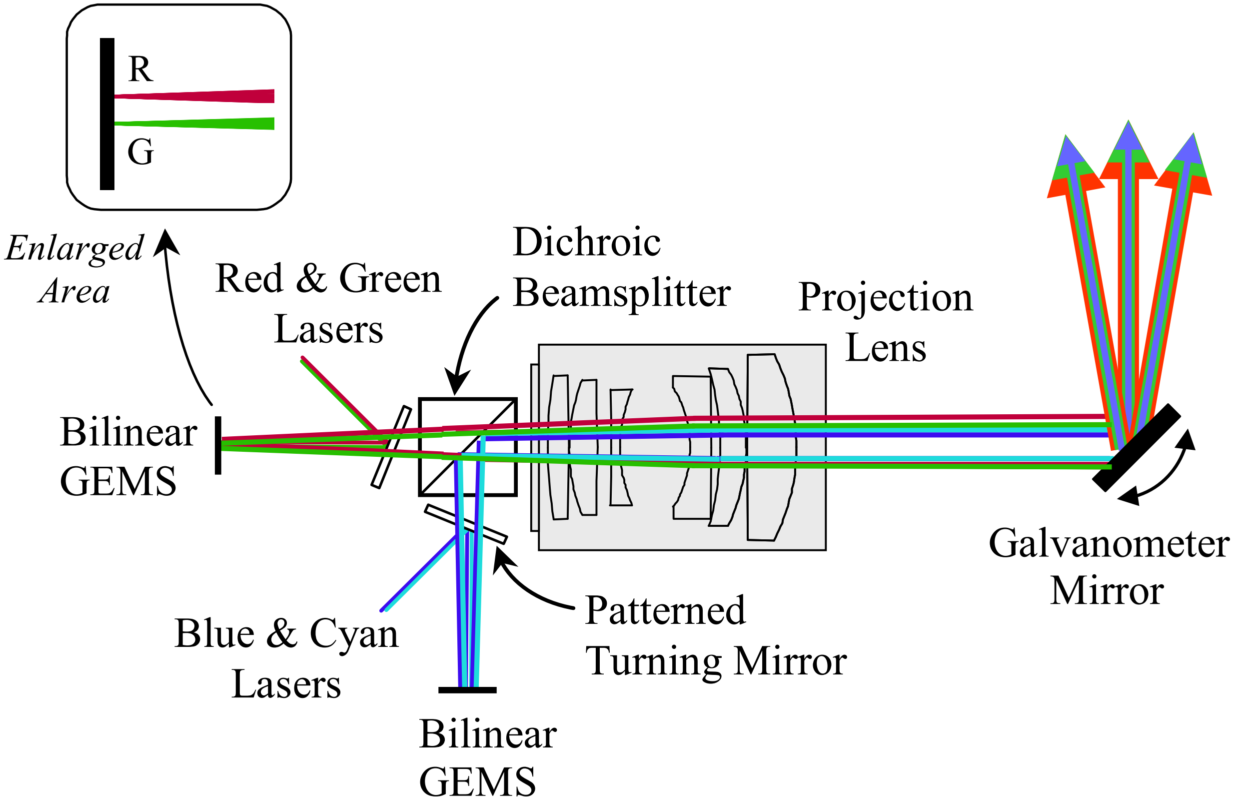
Trilinear Array
(front view)



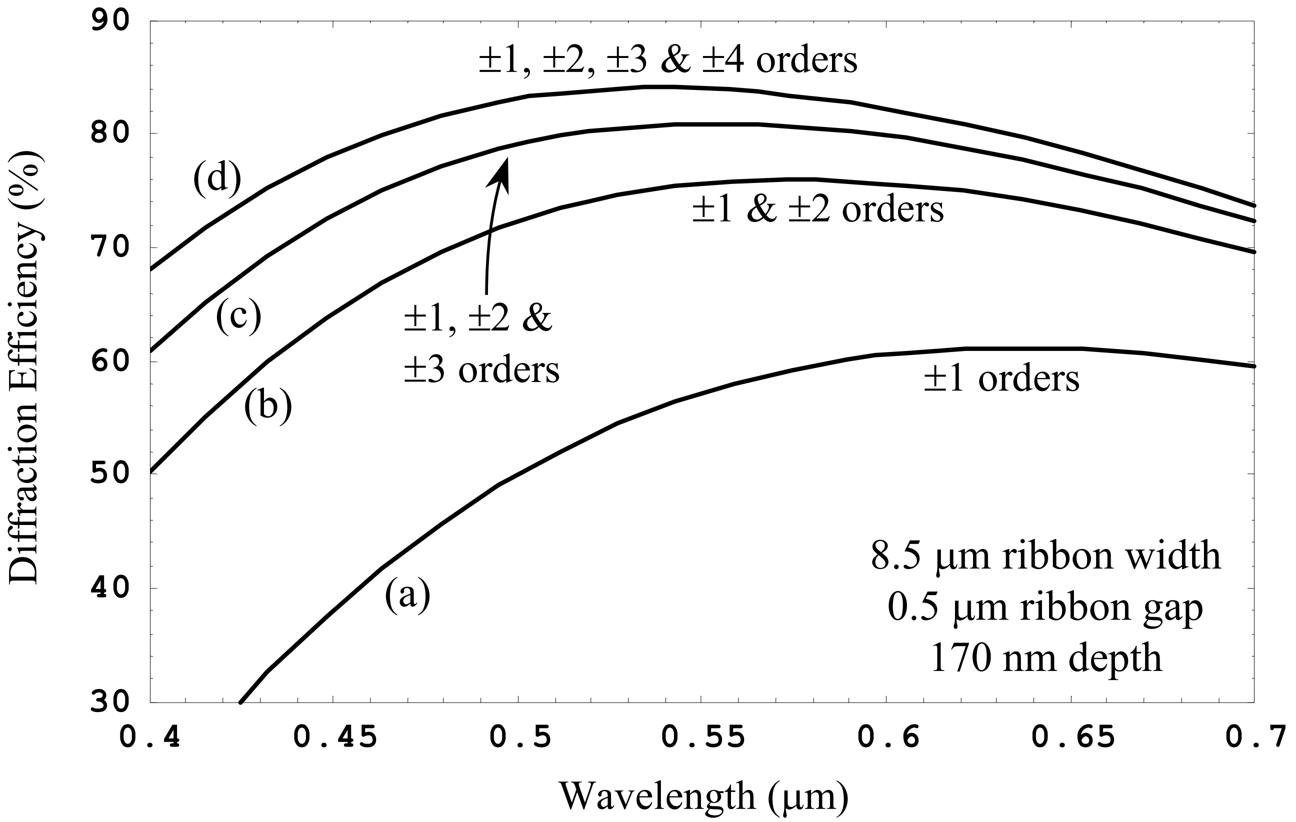
Combines advantages of three-chip architecture with those of single-chip architecture

- **Simple optical architecture**
- **Maximum laser power utilization and brightness**
- **Best image quality**

Laser Projector Architecture 3:
Four-Color System with Two Bilinear GEMS Arrays

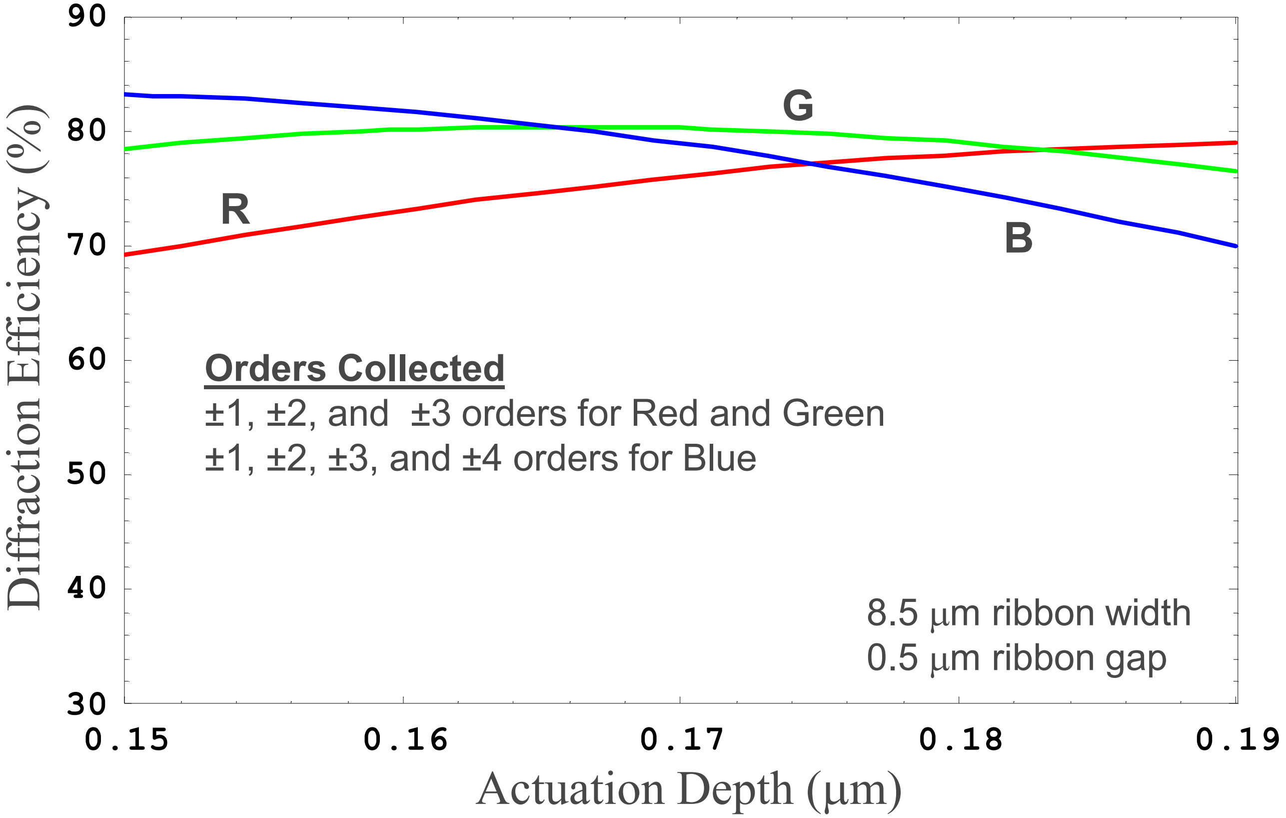


GEMS Device Efficiency Model



Optimized GEMS System Collects:	4 or 6 orders for Red (curve b or c)
	6 orders for Green (curve c)
	6 or 8 orders for Blue (curve c or d)

Device Efficiency Model for RGB System



Efficient GEMS device can be fabricated using the same design for all three colors

Note: RGB wavelengths are 630 nm, 530 nm, and 450 nm for model

GEMS Laser Projection System

Performance	Demo	Ultimate
Vertical Resolution **(device pixels)**	1080	2K – 4K
Horizontal Resolution **(scan)**	1920	4K – 8K
Frame Rate	60 Hz	60 Hz
Display Bit Depth **(per color)**	11 bit	>11 bit native
System Contrast **(ANSI)**	250:1	>500:1
System Contrast **(frame-sequential)**	1500:1	>5000:1
Data Stream Content	interlaced	progressive

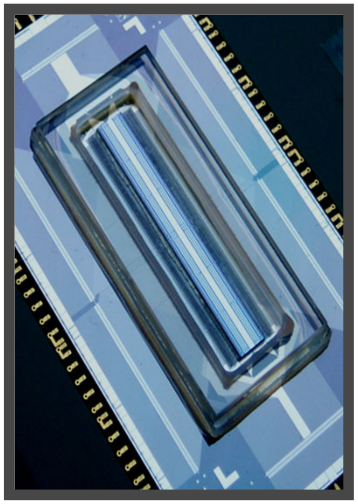
Technology Benefits

High Image Quality

- Laser primaries for wide color gamut with bright, saturated colors
- Extremely high and scalable resolution for sharp, crisp images
- High native bit depth for billions of noise-free colors per pixel
- Reduced pixelization
- No motion artifacts

Simple GEMS-Based Design

- Alignment and defect tolerant design
- Digital operation
- Compact optical components
- Low-cost modulator and optics



Extendable System

- Easily scalable linear array
- Programmable aspect ratio
- Flexible frame rate

System Architecture Options

- Single chip or three chip
- Multilinear arrays for high performance at low cost

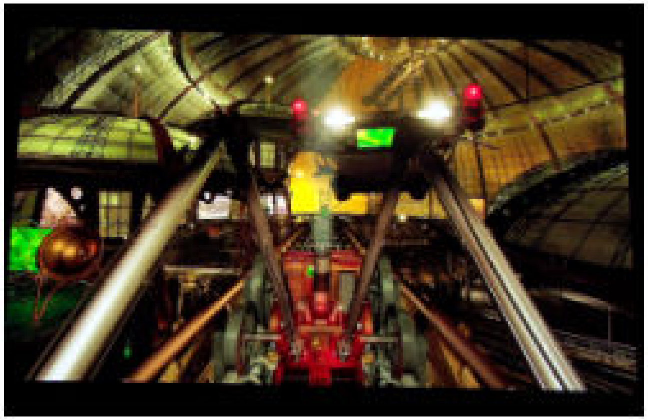
Potential Applications

GEMS Laser Display

- Front projection
- Rear projection laser TV
- Data visualization and simulation
- Command and control
- Panoramic workstations
- Heads-up displays
- Mobile projectors

Other Systems

- Laser printing
- Maskless lithography
- Light modulation
- Programmable spectral imaging
- …



Flight Training Simulator

PROGRAMMABLE SPECTRAL IMAGING

Multispectral Imaging: Introduction

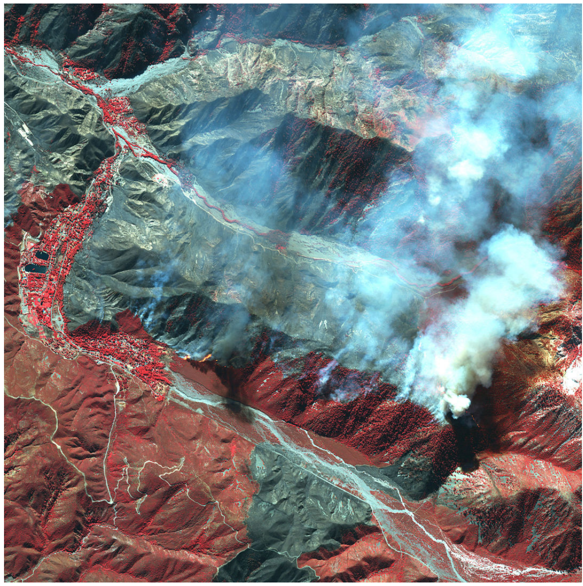
Multispectral imaging systems are used in a variety of applications where conventional RGB imaging does not adequately reveal spectral features of interest.

- *Application areas: remote sensing, medical, and biological imaging, …*

For example, the 4-band multispectral image below shows vegetation regions (false red) that are not visible in the natural color image.


DigitalGlobe

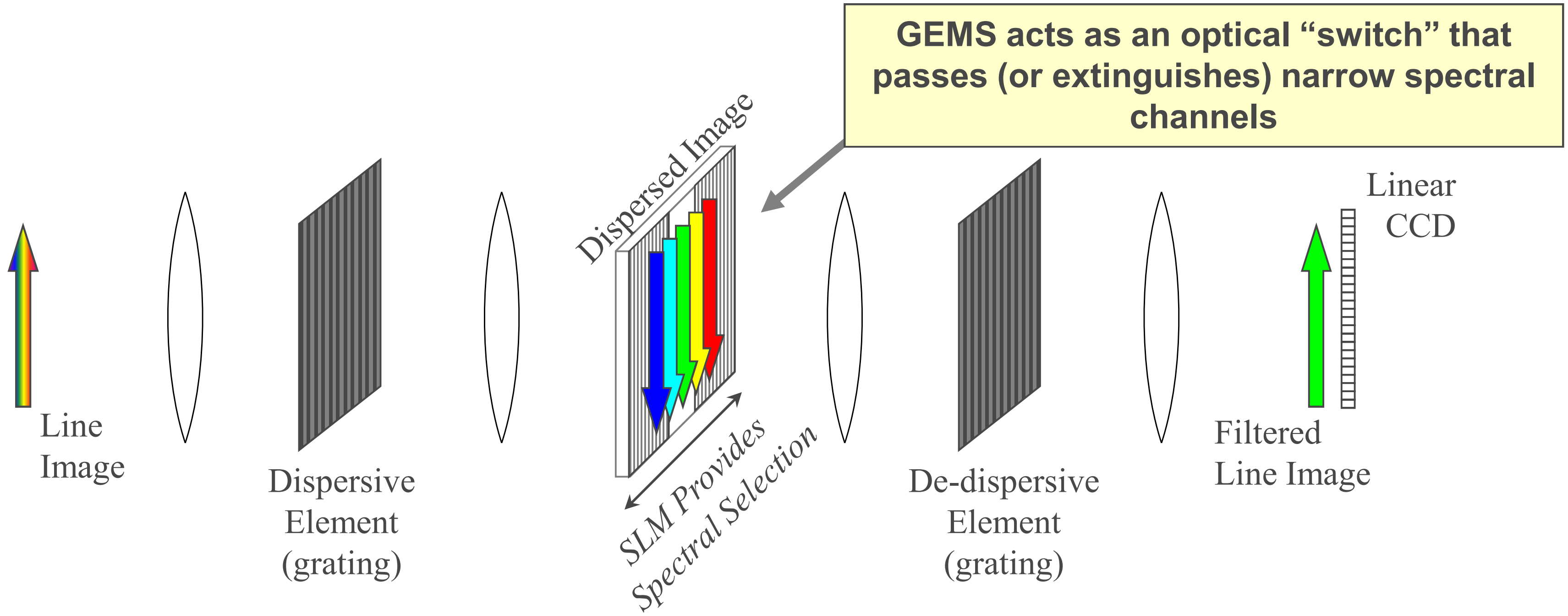
3-Band Natural Color Image of Forest Fire


DigitalGlobe

4-Band Image of Forest Fire with False Color Infrared

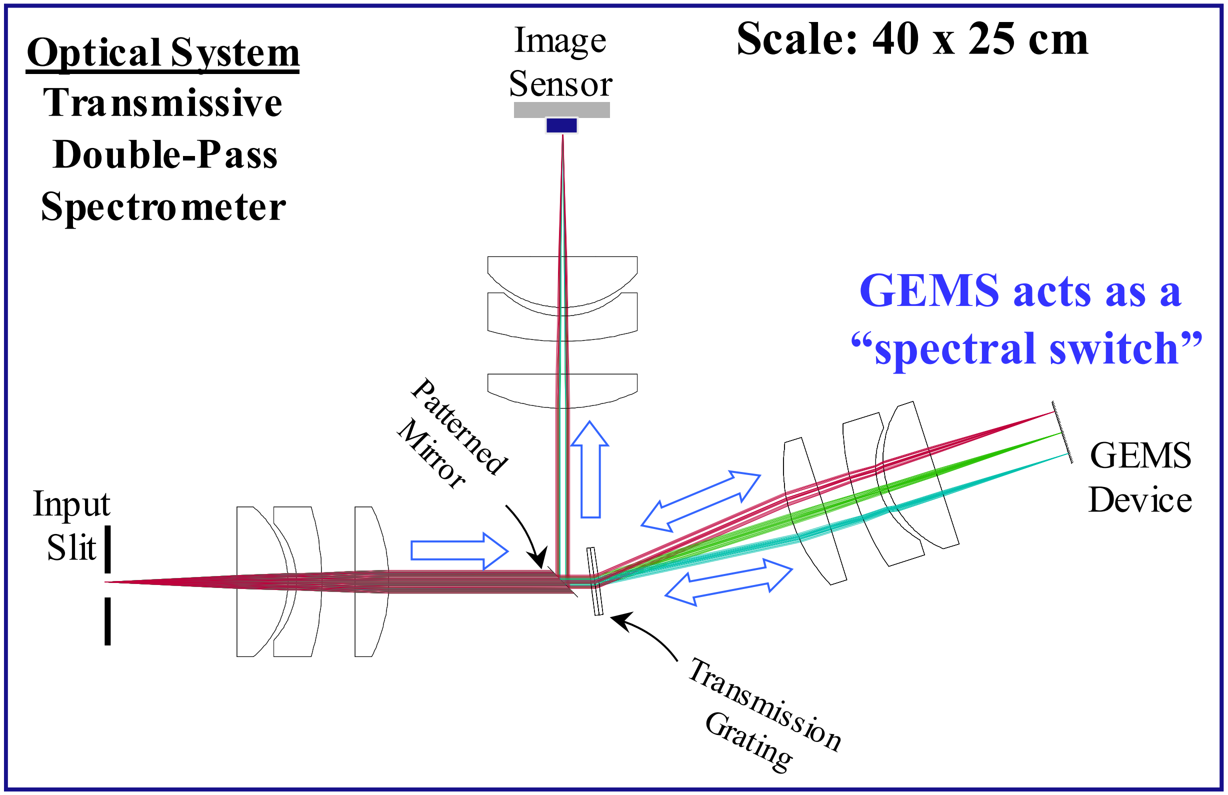
Challenge: Create an imaging system with a programmable spectral transmission function that provides high-resolution line-scanned imaging.

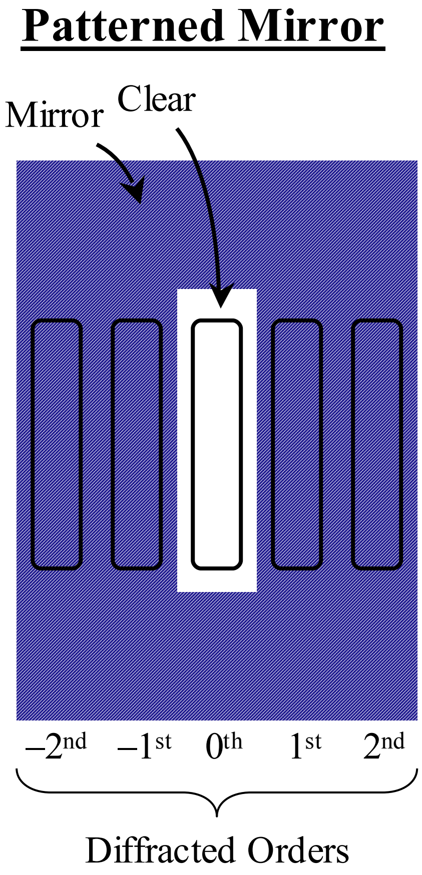
System Concept


GEMS acts as an optical "switch" that passes (or extinguishes) narrow spectral channels

- Spectral band selection approach:
  - Line image dispersed by a grating onto a **Spatial Light Modulator** (SLM)
  - Electronic control of SLM provides selection of wavelength bands for imaging
  - Selected bands are de-dispersed and re-imaged on a detector array
- 2D image is captured by line scanning across object of interest

GEMS-Based Programmable Spectral Imager

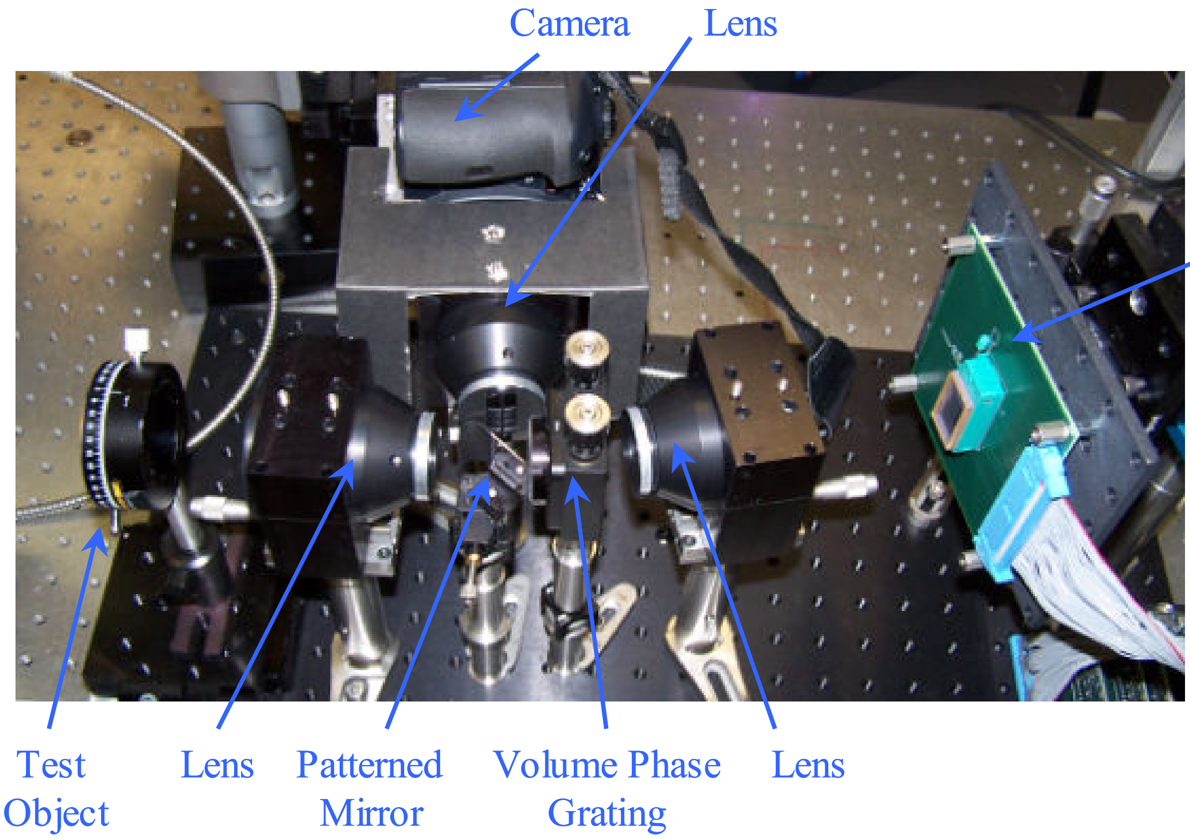


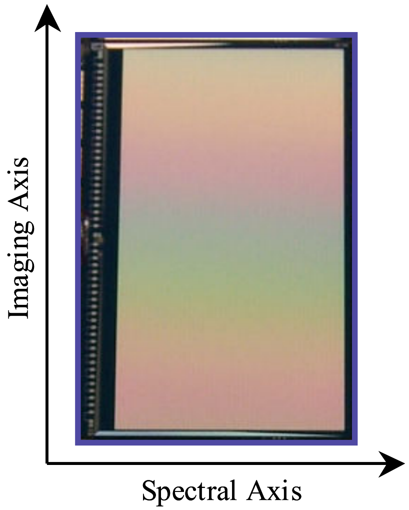


Key Features

- High-speed spectral tuning
- Excellent image quality
- 32 spectral bands (current configuration)
  - 450–566 nm: 12 bands with ~10 nm bandwidth
  - 566–634 nm: 14 bands with ~5 nm bandwidth
  - 634–692 nm: 6 bands with ~10 nm bandwidth

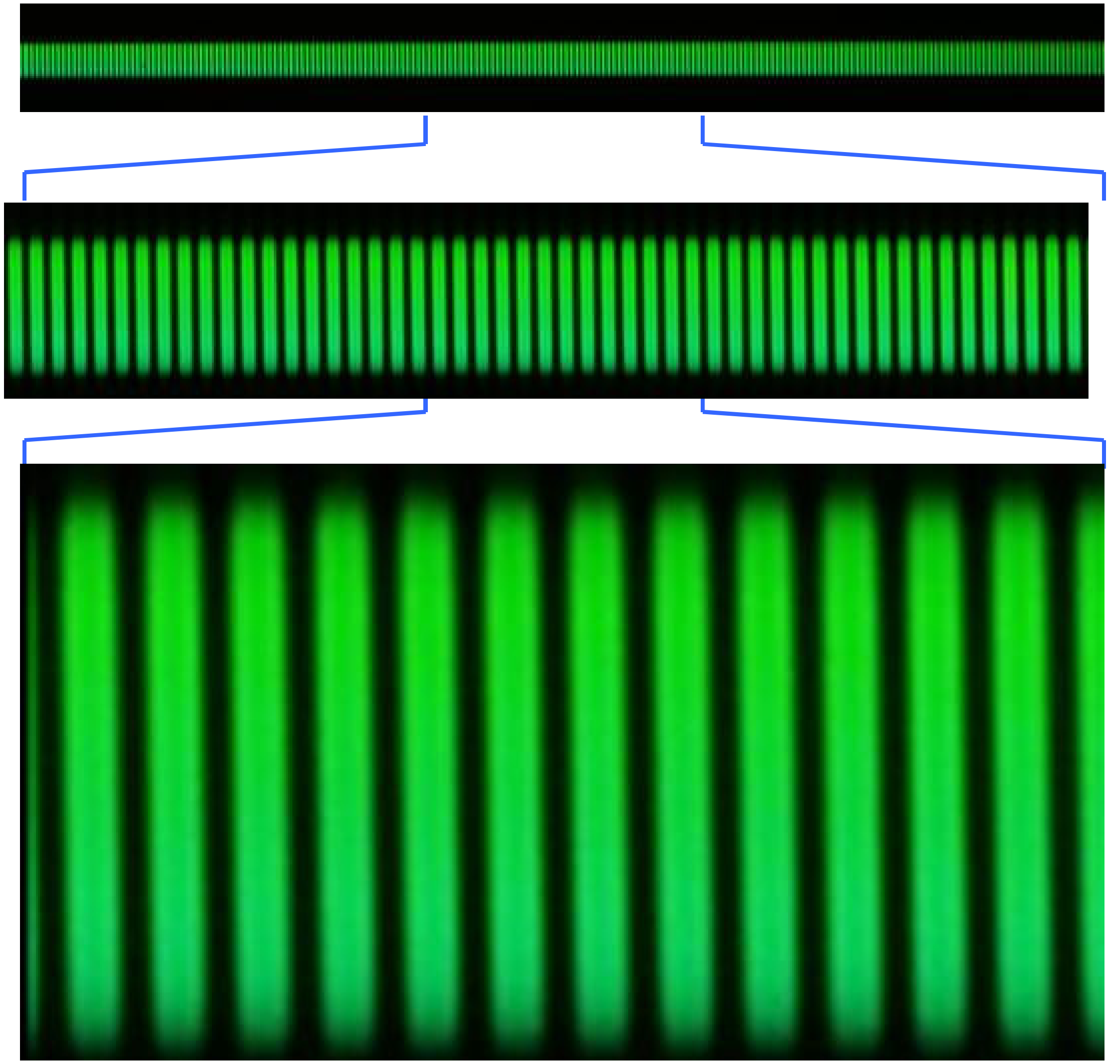
Spectral Imager Breadboard





Active Area: 10.8 mm x 19.44 mm

Breadboard Image Quality



Entire Image
(17 mm of 19.44 mm)

Enlarged 4X

Enlarged 16X

Test Object
Ronchi ruling (12 lp/mm)

Camera
Olympus E-1 (5 megapix)

Spectral Selection with Slide Translation

Red Band
(20 nm)

Green Band
(20 nm)

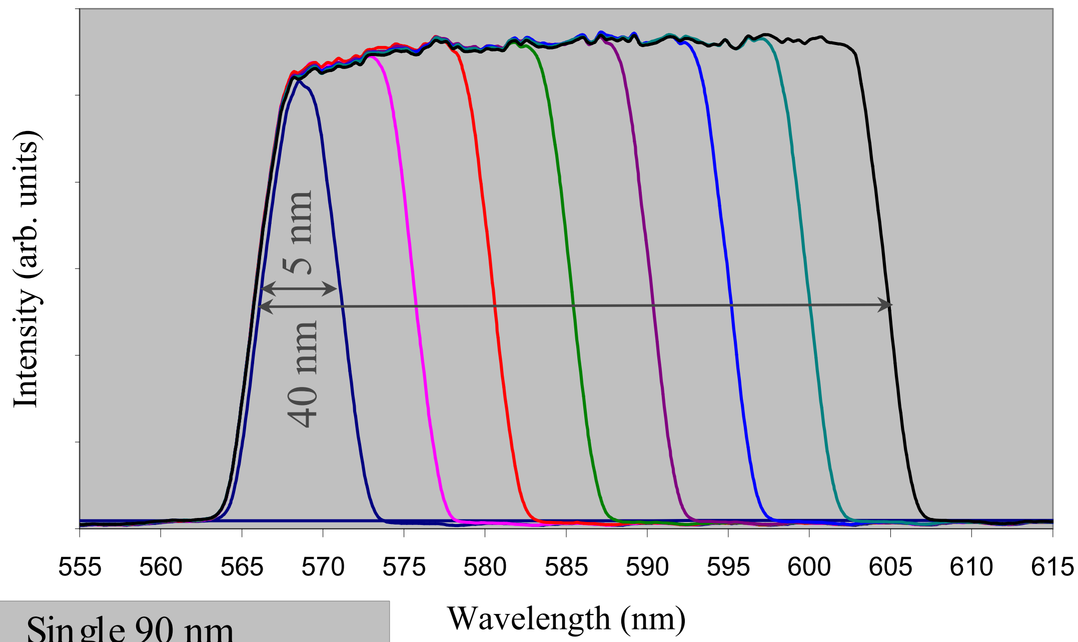
All Bands

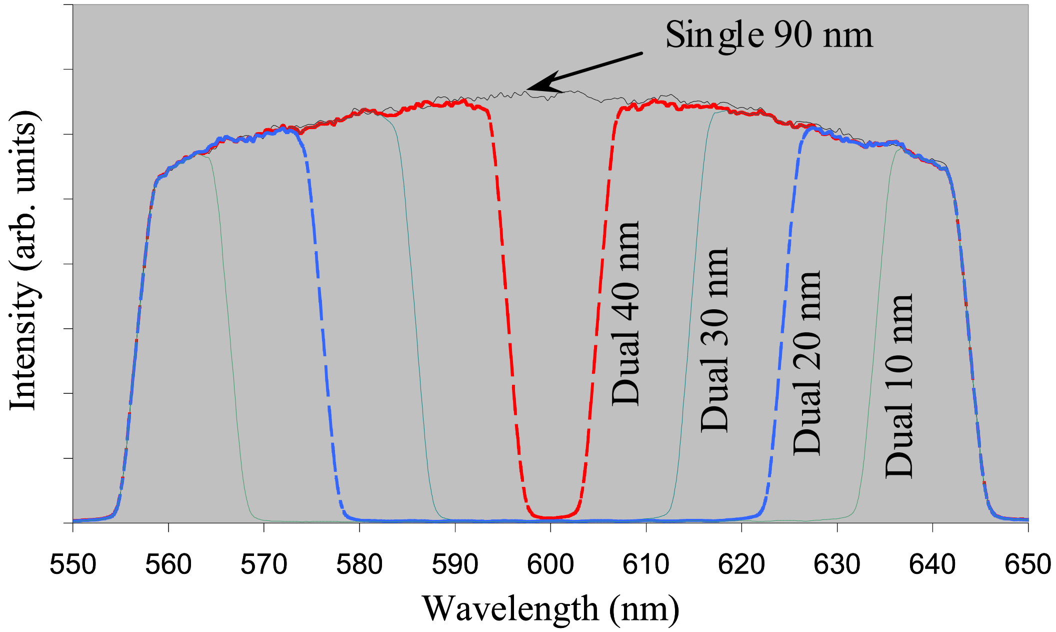
Blue Band
(20 nm)

Red & Blue Bands
(20 nm each)

Fully Programmable Spectral Bands

Programmable Bandwidth





Multiple Programmable Spectral Bands

An Interesting Combination…

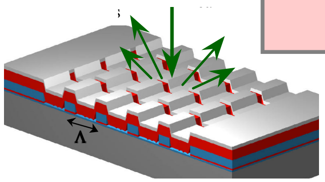
Programmable Spectral Imaging and Broad Gamut Display Both with GEMS-based Systems

GEMS Technology: Timeline and Milestones

Grating ElectroMechanical System

2000 2001 2002 2003 2004 2005 2006 2007 2008

Invention of GEMS Device



1st Operational GEMS Device

Monochrome Display 256 X 455

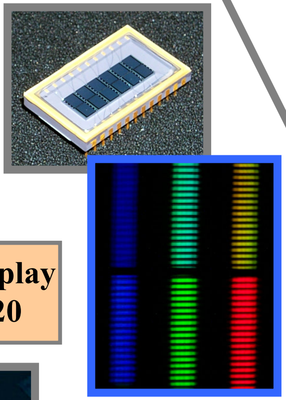
RGB Laser Display 256 X 455

Base Device Patent (6,307,663)

Base Display Patent (6,411,425)

Sapphire Display 1080 X 1920

Spectral Imager 6-Band Demo



XGA Display Evaluation Kit

Spectral Imager Device & System

ITC

Kodak

GEMS Display Project

ITT

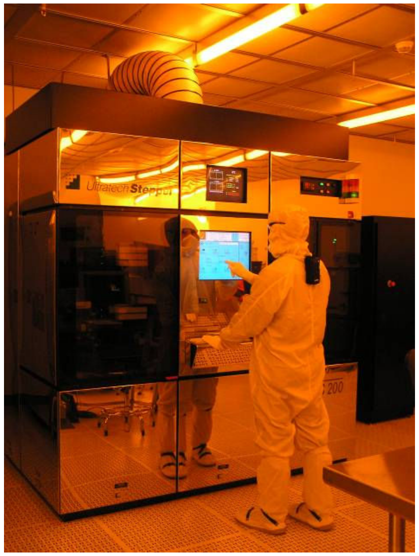
GEMS Project

ITC MEMS Wafer Fab

Ultratech Nano160
(1X projection; backside alignment)

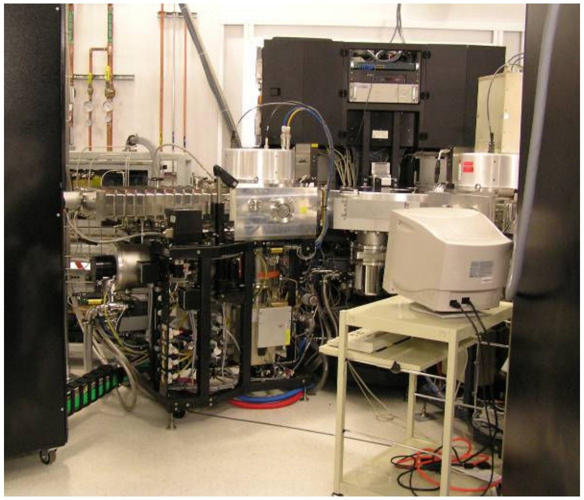
TEL Mark VII Coat/ Develop Track

LPCVD and Atmospheric Furnace Processes



Ultratech XLS Stepper
(4X projection; 0.35 µm resolution)

Chemical-Mechanical Polishing and Grinding



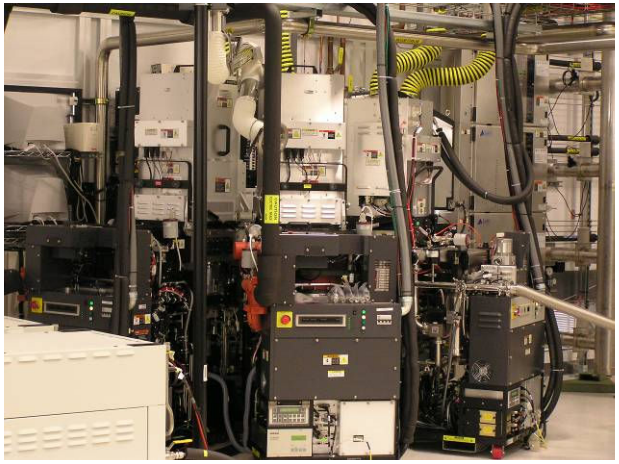
Veeco 3-Chamber Sputter Tool

ITC MEMS Wafer Fab

Leybold Reactive Evaporator for Optical Glasses

Xactix XeF2 Sacrificial Etch

STS Si Deep RIE

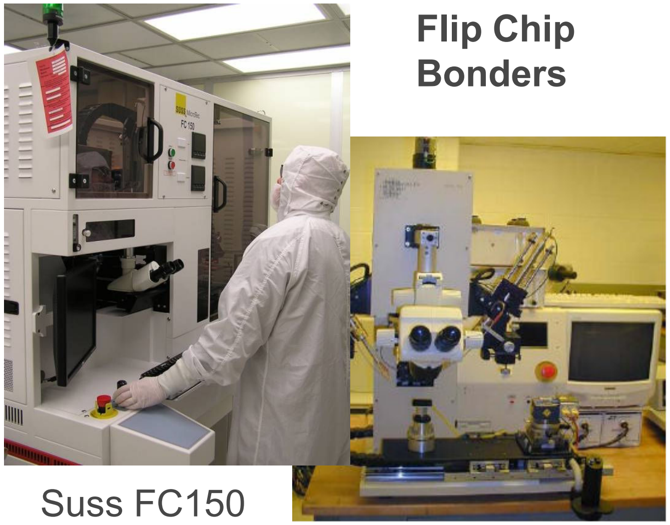


LAM Alliance Cluster Tool

ITC MEMS Packaging

Suss ABC200 Automated Wafer Bond Cluster

Flip Chip Bonders



Suss FC150

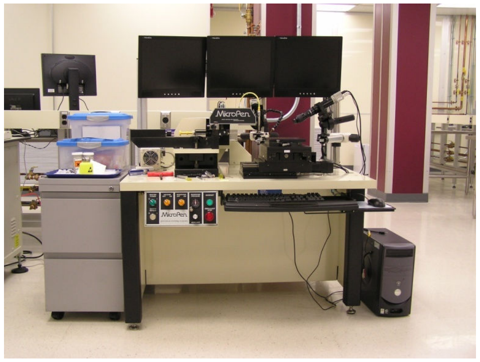
SEC 860 Omnibonder

Plating Bench

ADT 7200 Automated Dicing Saw

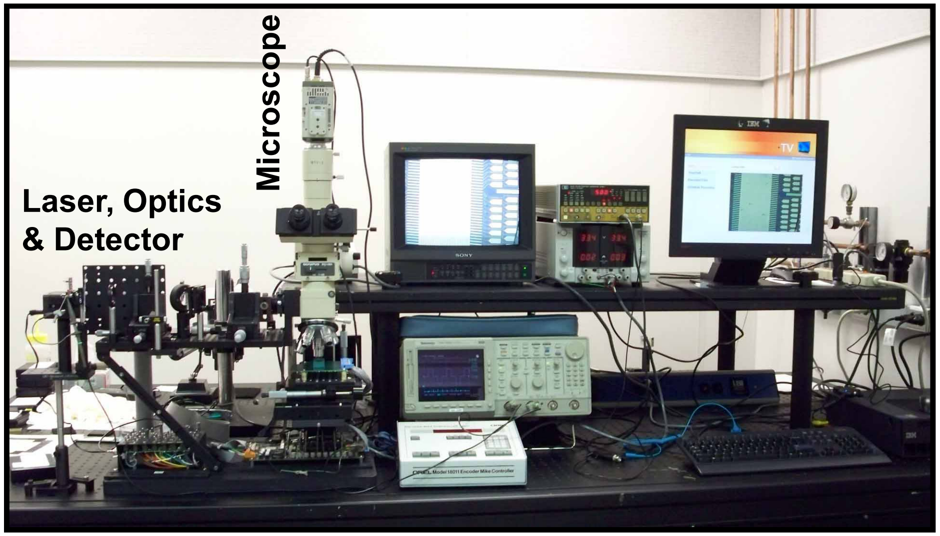
Asymtek Automated Fluid Dispensing system

Ohmcraft Micropen



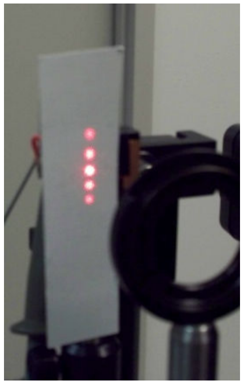
Hesse & Knipps Automated Wedge Wirebonder

ITC Laser Microscopy System for GEMS Device Screening

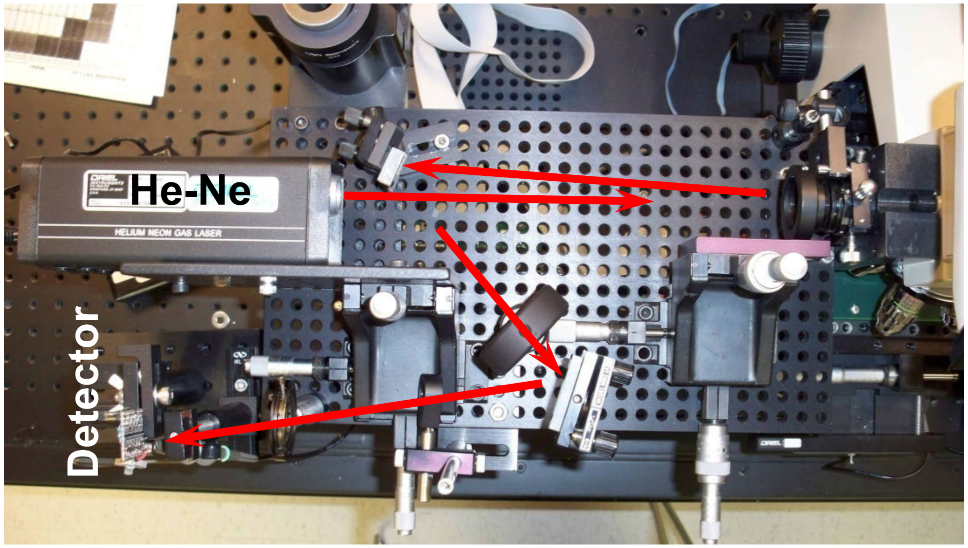


- Custom-modified high-quality microscope with laser probe beam for initial device screening
- System is configured to measure GEMS diffracted orders
- Provides feedback on device fabrication & packaging processes

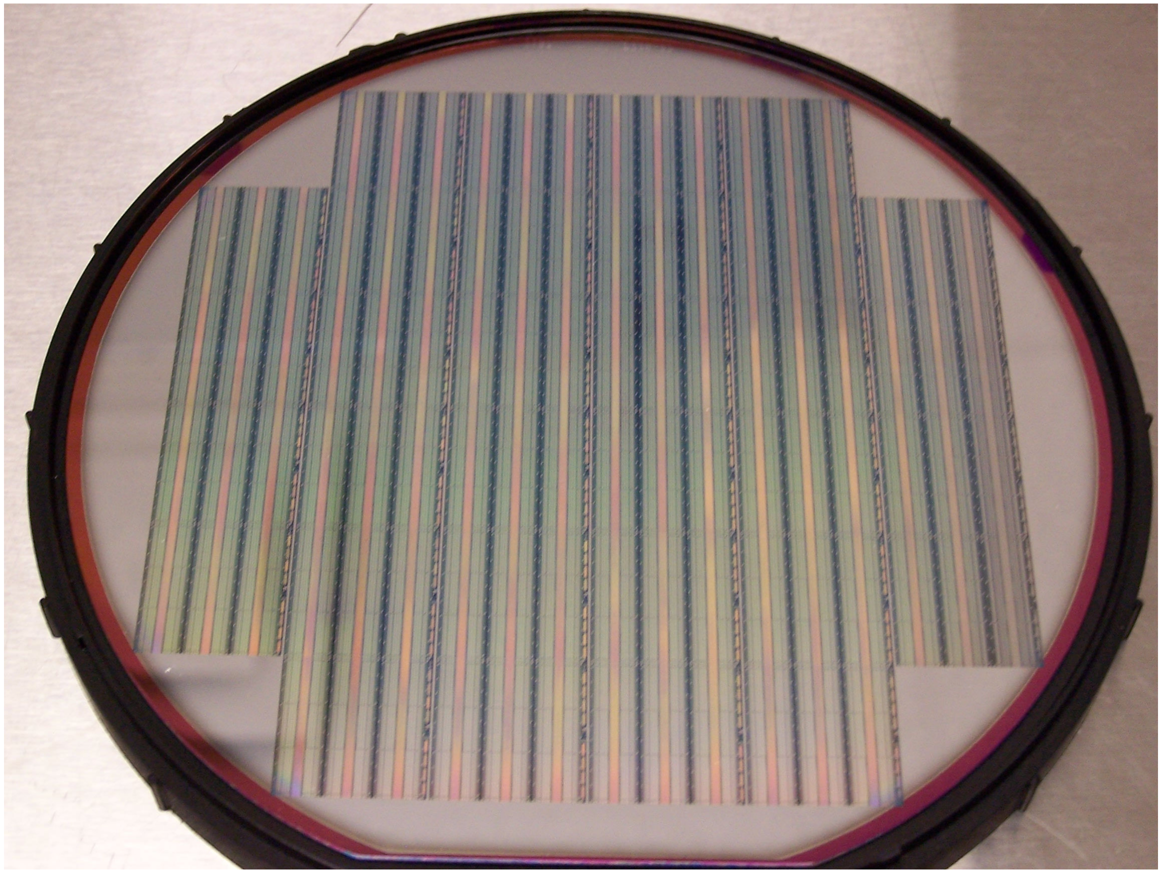
GEMS Diffracted Orders Near Detector



Laser, Optics & Detector



GEMS Wafer from ITC



Thank You !

e-mail: marek.kowarz@itcmems.com
website: www.itcmems.com

References

1) M. W. Kowarz, J. C. Brazas and J. G. Phalen, “Conformal Grating Electromechanical Systems (GEMS) for High-Speed Digital Light Modulation,” IEEE 15th International MEMS Conference Digest, pgs. 568-573 (2002).

2) J. D. Newman, M. W. Kowarz, J. G. Phalen, P. P. Lee and A. D. Cropper, “MEMS Programmable Spectral Imaging System for Remote Sensing,” Spaceborne Sensors III, SPIE Proc. Vol. 6220, pgs. 53-61 (2006).

3) M. W. Kowarz, J. G. Phalen and C. J. Johnson, “Line-Scanned Laser Display Architectures Based on GEMS Technology: From Three-Lens Three-Chip Systems to Low-Cost Optically Efficient Trilinear Systems,” SID Symposium Digest, Vol. 37, pgs. 1908-1911 (2006).

4) J. Agostinelli, M. W. Kowarz, D. Stauffer, T. Madden, and J. G. Phalen, “GEMS: A Simple Light Modulator for High-Performance Laser Projection Display,” ITE/SID 13th International Display Workshops (IDW’06), pgs. 1579-1582 (2006).