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

- Invention of GEMS Device
- 1st Operational GEMS Device
- Base Device Patent (6,307,663)
- Spectral Imager 6-Band Demo
- XGA Display Evaluation Kit
- Monochrome Display Patent (6,411,425)
- RGB Laser Display 256 x 455
- Sapphire Display 1080 x 1920
- Spectral Imager Device & System

**Timeline:**
- 2000
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008

**Partners:**
- ITC
- Kodak
- ITT
GEMS Device

Device Features

- Very wide active area
- \( \perp \) grating (\( \Lambda \)) direction
- Digital operation
- >2000:1 contrast
- >60% multiorder efficiency

Typical Dimensions

- Grating period = 15 to 50 \( \mu m \)
- Actuation depth = 150 to 200 nm
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

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

Stitched Linear Array (1 mm active area width)

1080-Pixel GEMS Linear Array

\[ \Lambda = 36 \text{ \( \mu \)m} \]

Active Area

Array Direction

Grating (\( \Lambda \)) Direction

36 \( \mu \)m

or

18 \( \mu \)m

Pixel Size Flexibility

Scalable Resolution

1080

2160

3240

ITC

Kodak
**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
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

PWM Gray Scale Generation
**Opto-Electromechanical Device Model**

Reflective (Off) State:
- Intermediate Support
- Incident Beam
- Reflected Beam
- Ribbon
- Standoffs
- Silicon Substrate
- Metal
- Dielectrics

Diffractive (On) State:
- Incident Beam
- Diffracted Orders
  - +1st
  - −1st
  - +2nd
  - −2nd

**Opto-Electromechanical Model**

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

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

Red: Si_3N_4
Blue: SiO_2
Stress-Limit Ribbon Deformation Model

Stressed ribbon differential equation:

\[ EV \frac{d^4 y}{dx^4} - Sw \frac{d^2 y}{dx^2} = \frac{\varepsilon_o w V^2}{2(t-y)^2} \]

where:

- \( \varepsilon_o \) ⇒ permittivity of free space
- \( \varepsilon_q \) ⇒ relative permittivity of \( q \)th layer
- \( \sigma_n \) ⇒ stress of \( n \)th layer
- \( L \) ⇒ ribbon length, \( w \) ⇒ ribbon width
- \( t \) ⇒ thickness of outer layer
- \( h \) ⇒ effective electrostatic gap
- \( S \) ⇒ tensile force per unit width

Analytical solution for ribbon profile and critical voltages
**Device Model: Critical Voltages, Contact Length & Efficiency**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ V_{PD} = \frac{1.673}{L} \sqrt{\frac{S t^3}{\varepsilon_o}} ]</td>
<td>Pull-down voltage:</td>
</tr>
<tr>
<td>[ 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] ]</td>
<td>Release voltage:</td>
</tr>
<tr>
<td>[ b_c = L \left( 1 - \frac{V_{RL}}{V} \right) ]</td>
<td>Contact length:</td>
</tr>
</tbody>
</table>

Contact length: \( b_c = L \left( 1 - \frac{V_{RL}}{V} \right) \) at operating voltage \( V \)

**Diffraction Efficiency:**

\[
\eta_m = \left| \frac{1}{\Lambda} \int_0^\Lambda e^{i \frac{4 \pi y(x)}{\lambda}} e^{-i \frac{2 \pi nx}{\Lambda}} \, dx \right|^2
\]

Nearly trapezoidal grating profile

[Diagram of nearly trapezoidal grating profile]
Stress-Limit Model Versus Experiment
Laser Display
RGB Display Lasers (early 2000s)
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)

History: MEMS Cantilevers (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

- 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
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

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: \( \sin \theta_i < \frac{\lambda}{\Lambda} \)

For a Gaussian laser beam: \( \text{FWHM} \approx 0.55 \frac{\lambda}{\sin(\theta_i/2)} \)

Therefore, \( \text{FWHM} > 1.1 \Lambda \) \[\text{[In practice FWHM} \approx 1.5 \Lambda\]
Laser Projector Architecture 1: Three-Chip System
Laser Projector Architecture 2: Multilinear Array System

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)

Diffraction Efficiency (%) vs. Wavelength (μm)

8.5 μm ribbon width
0.5 μm ribbon gap
170 nm depth
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

<table>
<thead>
<tr>
<th>Performance</th>
<th>Demo</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Resolution (device pixels)</td>
<td>1080</td>
<td>2K – 4K</td>
</tr>
<tr>
<td>Horizontal Resolution (scan)</td>
<td>1920</td>
<td>4K – 8K</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>60 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Display Bit Depth (per color)</td>
<td>11 bit</td>
<td>&gt;11 bit native</td>
</tr>
<tr>
<td>System Contrast (ANSI)</td>
<td>250:1</td>
<td>&gt;500:1</td>
</tr>
<tr>
<td>System Contrast (frame-sequential)</td>
<td>1500:1</td>
<td>&gt;5000:1</td>
</tr>
<tr>
<td>Data Stream Content</td>
<td>interlaced</td>
<td>progressive</td>
</tr>
</tbody>
</table>
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.

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

GEMS acts as a “spectral switch”
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)

Red Band (20 nm)  Green Band (20 nm)

Red & Blue Bands (20 nm each)  Blue Band (20 nm)
Fully Programmable Spectral Bands

Programmable Bandwidth

Multiple Programmable Spectral Bands

Single 90 nm

Dual 40 nm

Dual 30 nm

Dual 20 nm

Dual 10 nm
An Interesting Combination…

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

Veeco 3-Chamber Sputter Tool

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

Chemical-Mechanical Polishing and Grinding
ITC MEMS Packaging

Suss ABC200 Automated Wafer Bond Cluster

Asymtek Automated Fluid Dispensing system

Flip Chip Bonders

Suss FC150

SEC 860 Omnibonder

Plating Bench

ADT 7200 Automated Dicing Saw

Ohmcraft Micropen

Hesse & Knipps Automated Wedge Wirebonder

ITC MEMS Packaging
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

Laser, Optics & Detector

GEMS Diffracted Orders Near Detector
GEMS Wafer from ITC
Thank You!

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


