Part III: 2D Display Technology and Operation

- Lecture 11 (Part III-1): Display interface and CRT
- Lecture 12 (Part III-2): Flat panel displays: LCD
- Lecture 13 (Part III-3): Flat panel displays: LCD (cont.), Plasma
- Lecture 14 (Part III-4): Flat panel displays (cont.), Projection displays
- Lecture 15 (Part III-5): Projection displays (cont.), Laser display,
- Lecture 16/17 (Part III-6): Other displays: color-enriched display and high dynamic range display
Types of Projection Displays

- **Category by size**
  - Spatially immersive displays
  - Cinema projectors
  - Digital projectors
  - Ultra-short throw projectors
  - Rear projection TV (*)
  - PICO projectors
  - Mini-projectors

- **Category by display technology**
  - Cinema film projectors (*)
  - CRT-based projection system (*)
  - HTPS LCD-based projection system
  - DLP-based projection system
  - LCoS-based projection system
  - Laser-based projection system

Three-Panel LCoS-based Projection System

- LCOS using slow TN LCs can only be designed for three-panel systems, while some fast-response LCoS displays can be used for one- or two-panel projection systems.
- The first 3-panel projection system based on LCoS was developed by IBM in 1998, which used a Philips color prism to separate and recombine colored beams.

With the Philips color prism, it is difficult to maintain the state of polarization adequately in a dichroic prism, resulting in poor system contrast.
LCoS Projection—3xPBS/X-Cube System

- It is an extension of the HTPS LCD projection system.
- The PBS can be: the conventional MacNeille prism type, 3M reflective type, or the wire-grid plate type.

![Diagram of LCoS Projection System](image)

LCoS—3 Panels with Retarder Stack Filters

- Retarder stack filters (RSF) selectively transform the polarization state of one or more color bands
  - [Sharp, G. D., 1998, 1999]
  - They are fabricated as a laminate of transparent stretched polymer retardation films (roughly 60um in thickness)
- Red/cyan RSF: transform linear polarized red light to the orthogonal polarization state, while leaving cyan light (Green+blue) unchanged
- Green/magenta RSF: transform linear polarized Green light to the orthogonal polarization state, while leaving Magenta light (red+blue) unchanged
- Red/blue RSF: transform linear polarized red light to the orthogonal polarization state, while leaving blue light unchanged

Chapter 6, Polarization engineering for LCD Projection, by Michael G. Robinson, Jianmin Chen, and Gary D. Sharp
LCoS—3 Panels with Retarder Stack Filters

- Retarder stack filters with MacNeille PBSs combine the polarizing/analyzing functions with the splitting and recombining of color.
- This design has improved compactness compared with the 3xPBS/X-cube architect.
- ColorQuad is one of the many LCOS projection systems based on this approach.

Field Sequential Single-Panel LCoS System

- This requires fast response LC, such as FLCoS.
- Single panel sequential color projectors have been commercialized by www.microdisplay.com.
  - Operating at ~500Hz field rate, with a reported contrast of 400:1.
  - Suitable for modest screen sizes ~40”-50”
  - The low cost made it competitive with direct-view TFT LCD and plasma.
LCoS Projectors—Advantages

- IC compatibility: LCoS fabrication is compatible with the standard IC technology.
- Cost-effective for high resolution: LCoS is much more amenable to high resolution than HTPS and DLP.
  - E.g. HD resolution (1920x1080) on a 0.7” panel and 1280x720 on a 0.5” panel
- Minimal screen door effect: >90% fill factor.
- Smooth picture: the pixel edges in LCoS tend to be smoother compared to the sharp edges of DMD.
- High contrast: compatible with DLP systems, with demonstrated contrast of 2000:1.
- High response speed: 4X faster compared to transmissive LCDs (<1ms LCoS has been achieved, FLCos is even faster).

LCOS Projectors—Disadvantages

- Lifetime: similar concern to HTPS, but have recently been improved, quoted 300,000 hours (~34 years) lifetime.
- Color break-up: in sequential color LCoS systems, similar rainbow effects to one-chip DLP.
- Complexity: LCoS-based optical system is more complex than DLP or HTPS system (accurate polarization control is the key).
DLP-Based Projection System

In general, the device tilt angle sets the maximum useful numerical aperture of the optical system at the device. This prevents overlap of the on-, flat-, and off-state pupils for contrast control.

One-Chip DLP Projectors

- Grayscale in DLP-based system are achieved using pulse width modulation.
- DLP operates fast enough to be able to achieve full color image using field-sequential color approach.
  - Capable of 16.7 million colors, 24-bits

Grayscale in DLP-based system are achieved using pulse width modulation. DLP operates fast enough to be able to achieve full color image using field-sequential color approach. Capable of 16.7 million colors, 24-bits.
Light Pipe in Illumination Engine

Advantages:
• Uniform black level due to uniform illumination angles
• Short overall length due to the use of the prism to separate illumination and projection in glass rather than air space.
• Shorter back working distance for projection lens
• Projection offset for keystone correction can be optimized for application to minimize field of projection lens.
• ...

Disadvantages:
• Additional costs, size, and weight of the prism
• TIR air-gap coatings have relatively high losses, 2% to 3% per surface.
• Telecentric designs have lower angles of illumination than non-telecentric illumination, which in general lowers contrast.
  • The higher the angle, the higher the contrast
  • Absolute black level is typically higher (worse) than nontelescopic architectures by up to 2X, due to the proximity of optical surfaces near the mirror device and the lower overall illumination angles.
• ...

One-Chip DLP Projectors—Telecentric Architecture

Telecentric systems are defined by locating the exit pupil of the illumination system (entrance pupil of the projection lens) at or near infinity from the device surface.
One-Chip DLP Projectors—Non-Telecentric Architecture

Advantages:
• Offset angle creates a larger angular separation between the illumination and projection path, yielding higher overall contrast.
• Fewer number of optical elements, lower cost and higher efficiency.
• …

Disadvantages
• Nonuniform angles of incidence of the illumination at the device produce non-uniformity.
• Vertical offset requirements increases as F/# decreases in order to physically separate illumination and projection optics.
• Projection lens elements on the screen side of the stop tend to become larger than those in telecentric case.
• The higher illumination angles distort the image of the integrator rod, creating more overall losses.
• …

The RGB color disc is replaced with Yellow and Magenta color disc.

The dichroic color-splitting prisms direct R continuously to one chip and G and B alternately to the second chip.
Three-Chip DLP Projectors

- Three chips, one for each primary color
- A set of dichroic color-splitting prisms splits the light by reflection into the primary colors and directs them to the appropriate DMD.
- The modulated light from each DMD travels back through the prisms, which act as combiners.
- Capable of more colors
  - up to 35 trillion

DLP Projector Comparison

- The choice of the three architectures depends on the intended application and is based on a tradeoff between light utilization efficiency, brightness, power dissipation, lamp technology, weight, volume, and cost.
- Single-chip: self-converged, lower cost, and best portability, but visible color artifacts (known as color break-up or rainbow effect).
  - Increasing field rate from 180HZ to 360HZ.
  - Many single-chip DLP projectors using six-segment color wheel.
- Two-chip: greater light efficiency, suited for applications requiring the longest lifetime lamps that may be spectrally deficient in the red.
- Three-chip: highest light efficiency, suited for applications requiring the brightest displays.
DLP Projectors

- Polarization independence
- DLP projectors overall have small package size (especially the single-chip design).
- High contrast ratio: The new generation DMD has an increased tilt angle (from 10deg to 12 deg), which significantly improve DLP system contrasts.
  - It is common to have 1000:1 contrast DLP system
- High aperture ratio: often >90%
  - DMD mirrors are suspended above the driving circuits.
  - The gap between mirrors is usually less than 1µm.
  - Minimal screen door effect in contrast to HTPS systems.
- Good reliability: Tests have shown that current DMD performance is not degraded after thousands of hours of operation under harsh environments.

Extra Information

- Video demonstration (www.dlp.com)


Rear Projection Television

- Microdisplay technology combined with a folded optical path yields a large-screen monitor significantly thinner than the CRT versions.

- This was once a popular method for achieving large-size TV.

Key components
- Microdisplay: DLP, LCoS
- Projection lens
- Folding mirrors
- Projection screen

Design formats
- Single fold
- Multiple folds

Ultra-thin reflective free-form RPTV
Rear Projection TV: Projection Screen

- Fresnel lens redirects lights onto the lenticular sheet.
- Lenticular sheet disperses light horizontally for horizontal perspectives.
- Dispersing layer further disperses light in vertical direction.
- Trade off between transparency and viewing angle.

![Diagram of Rear Projection TV](image)

Short-Throw Projector

- Ultra short working distance
- Off-axis system
- Multiple aspheric and free-form surfaces
- Need to be large field of view and low image skew and distortion

![Short-Throw Projector Images](images)
Short-Through Projector Design Examples

- Zheng et al., Displays, 2008
  - Zernike polynomials surfaces
  - F-number = 2.5 and field of view 130-degrees
  - MTF is over 60% at 100 lp/mm
  - distortion is less than 2%

Pocket Projector: Microdisplay Based

- Dell, M109S
  - DLP/LED based
- TI/Optoma, DLP PICO
  - DLP/LED based
- 3M, MPro
  - LCoS/LED based
Pocket Projector: Looking Inside

- TI/Optoma, DLP PICO
- 3M, MPro

- White light LED
- Fresnel lens
- Plastic PBS with optical power and proprietary MultiLayer Optical Film
- FLCOS with color filter
- Projection lens

Pocket Projector: Laser Based

- Microvision Inc., PicoP
  - Key components:
    - R,G,B laser module
    - MEMS
Examples of Compact Projection Lenses

Arc Lamp Vs. Alternative Light Sources

<table>
<thead>
<tr>
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<td>LED, Panel type SLM, raster scanning (near eye application) Laser: Panel type SLM, line type (OLV, GEMS), raster scanning</td>
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Lecture 15: Laser Displays

- Laser display technologies
  - Projection displays with laser sources
  - Laser-based raster scanning display
  - Laser-based Grating Electromechanical System

References

- G. Hollemann, "RGB lasers for laser projection displays," Proc. of SPIE.
Basic Laser Types Categorized by Lasing Media

- **Gas laser**: HeNe, CO2, Argon-ion, etc.
- **Solid state laser**: Ruby, Nd:YAG (neodymium-doped yttrium aluminum garnet), etc.
- **Fiber lasers**: Solid-state lasers or laser amplifiers where the light is guided due to the total internal reflection in a single mode optical fiber
- **Diode or semiconductor laser**: electronically pumped
  - Gallium arsenide (GaAs), Indium gallium nitride (InGaN), etc.
  - Commonly used in laser printers, CD/DVD players, etc.
- **Dye laser**: Organic dye dissolved in water, methanol, etc.
- **Other types**:
  - Chemical lasers
  - Excimer lasers
  - Bio laser
  - Free electron lasers...
Early Stage Laser Displays

- **Visulux laser projection system, in late 1980’s**
- **Key features**
  - Laser types: Argon-ion and dye lasers (gas and dye types)
  - Color:
    - G,B components are directly split from the laser source.
    - R component is produced by the dye laser pumped by the cyan wavelength of the Argon-ion laser.
  - Acousto-optic modulators
  - Scanning mechanism:
    - 48-facet polygon for the horizontal scan
    - Galvano-mirror for the vertical deflection
- **Disadvantages**
  - Large and high operational costs
  - 208V, 60Amp, ~19 KW power consumption
  - 4 gpm's of water cooling
- **Practical laser displays have to go with solid state laser or diode laser.**

Electronic Displays with Laser Sources

- **RGB lasers to replace lamps or other sources**
- **Gray level method**
- **Projection or scan mechanism**
  - Some laser displays adopt projection techniques where microdisplays are used as spatial light modulators.
  - Some laser-based displays adopt point-type raster scanning techniques using MEMS reflecting mirrors.
  - Other laser displays adopt line-type scanning techniques using line type diffraction optics arrays.
- **Screen: speckle reduction techniques**
Laser Sources

- Red laser diode: very common and well developed
- Blue laser diode: relatively new but attainable
  - Example: Indium gallium nitride (InGaN) laser at 445nm
- Green laser diode:
  - No commercially available “true” green laser diode till Nichia and OSRAM developed the 525 green diodes in 2010.
  - Before 2010, most green LD are generated by double frequency the infrared LD.

Green Laser Generation Via SHG

- Yb-doped fiber laser
  - Fiber laser pumped by infrared laser diode
  - Ytterbium (Yb) doped fiber laser lasing at 1064nm
  - High nonlinearity MgO:LiNbO3 (PPMgLN)
  - 1064nm laser is frequency-doubled and produces 532nm laser.
- Method commonly used in green laser pointers
  - Termed as diode-pumped solid-state laser (DPSS), or diode-pumped solid-state frequency-doubled laser (DPSSFD)

Figure 1. Schematic diagram of the green SHG laser unit

Figure 2. Photograph of the green SHG laser unit

Gray Level Method

- Direct modulation of laser
  - Quality and depth depend on how well the laser brightness can be controlled.

- Modulation of laser with other component
  - Such as acousto-optic modulator combined with pulse width modulation
    - Quality and depth depend on the temporal response and effectiveness of the modulator.
  - Spatial light modulators: such as LCoS, LCD, DLP

Laser Speckle

- It is a random intensity pattern formed by the interference of a set of wavefronts.
- Speckle types
  - Objective speckle: when laser light, which has been scattered off a rough surface, falls on another surface, it forms an “objective speckle pattern”.
  - Subjective speckle: When an image is formed of a rough surface which is illuminated by a laser beam, a speckle pattern is observed in the image plane; this is called a “subjective speckle”.
- Speckle is undesired in laser displays.

Objective speckle example: the speckle pattern formed when a laser beam was scattered from a plastic surface onto a wall.

Subjective speckle example: laser speckle on a digital camera image from a green laser pointer.
Speckle Example in Laser-based Projection Displays

Speckle Reduction Technique

- Consists of a rotating lens array made of lenticular lenses, and a rod integrator.
- Lens array rotates at high speed thus reduces the temporal coherence.
- Rod integrator further reduces coherence.
- Lens array has a low light loss of 3%

Speckle Reduction: results

- Suppression of speckle
- Less interference noises
- Uniform illumination

![Image](a) ![Image](b)

Figure 3. Projected images on screen with (a) conventional optics and (b) new illumination optics

![Image](a) ![Image](b)

Figure 4. Detected images of eye-like CCD camera with (a) conventional optics and (b) new illumination optics


Laser-based Projection System

- Laser wavelengths: 445nm LD, 640nm LD, 532nm LD-pumped SHG
- Three LCD panels for RGB primary colors
- Projection lens similar to conventional designs
- Compared to HTPS-AMLCD projectors, the major differences are light source and illumination

![Diagram](a) ![Diagram](b)

Laser-based Projection System: Prototype

- 52” rear projection display
- 0.7 inch 3LCD panels
- R: 640nm 2W/8W 25% efficiency
- G: 532nm 1.3W/28W 4% efficiency
- B: 445nm (InGaN) 1W/19W 5.2% efficiency
- Total power consumption of 50W
- Wide color gamut of 137% NTSC

Point-type Laser Raster Scanning Displays

- RGB laser diodes
- Microelectromechanical system (MEMS) scanner enables point-type raster scanning display.
  - Single axis, 2 scanner
  - Tow axis, 1 scanner

References:
Raster Scan Design – “Flying spot”

Raster Scanner: Two Mirrors in Series

- One mirror will have fast oscillation to scan horizontal direction.
- Second mirror will have slow scan for vertical direction.
- Because of this separation, the beam will not be perpendicular to the scan axis.
- When the beam is off the center of the second mirror, length of the scan line increases → PINCUSHION DISTORTION.
- Pincushion distortion can be electronically corrected by displaying the scan lines near top and bottom in fewer clock cycles.
Example- Samsung

- VGA (640x480)
- 60 fps
- 80 inch image size
- Horizontally scanned by a polygon scan mirror and vertically by a galvanometer.


Bi-Axial MEMS Raster Scanner by Fraunhofer

- Gimbal mount solves distortion problem
- Drawback is that it is a more complicated device.

Bi-Axial MEMS Scanner by Microvision

- Effective aperture 1mm
- Scan cone: 43.2 (H) x 24.3 (V) degrees (16:9)
- Housed with small magnets
- Magnetic field at approximately 45° to the scan axes
- A single composite drive signal
- Piezoresistive sensors provide scan mirror position feedback to maintain closed loop accuracy of the desired scan mirror motion.

Pocket Laser Projector

- PicoP, Microvision Inc.
- Key features
  - Use R,G,B diode lasers
  - No microdisplay device, no projection lens, no illumination optics
  - Pixels are generated by raster scanning the laser beam
Screen Size vs. Pixel Size

- Conventional projectors have a limited depth of field.
  - Pixel size increases significantly at defocus position to the designated focal distance (F/4 system for the purple curve).
  - Unsuitable for curved surface projection
- Laser-based raster scanning projector has infinite focus.
  - Pixel size increases linearly with the screen distance (size)
  - Ideal for projection on curved surfaces

Laser Modulation: Speed Matters

- Actual pixels are “portrayed” by laser modulation.
- Grey scale and contrast depend on accuracy of modulation.
- Laser modulation speed is proportional to the product of horizontal resolution, vertical resolution, and flicker free frequency.
  \[ f_{MOD} \approx 60 \text{Hz} \times P_x \times P_y \]
- Acoustic modulators are commonly used

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Modulation bandwidth (MHz)</th>
<th>Rise/fall time (ns)</th>
<th>Pixel duty time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD (480P), VGA</td>
<td>20</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>HD 720P</td>
<td>56</td>
<td>8.9</td>
<td>17.8</td>
</tr>
<tr>
<td>1080i</td>
<td>65</td>
<td>5.8</td>
<td>15.6</td>
</tr>
<tr>
<td>1080P</td>
<td>130</td>
<td>3.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Laser as Display Light Source: Pros and Cons

- **Pros**
  - Narrow bandwidth, highly saturated color
  - High intensity, high efficiency
  - Coherent light source ideal for diffraction, interference based displays
  - Directional source ideal for scanning displays
  - Long lifetime
  - Fast speed

- **Cons**
  - Interferences generate speckles

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Laser Vs. Conventional Display Technologies

Table 3: Comparison of display performances between conventional displays and MEMS-based raster scanning display.  
(X: bad, △: fair, O: good, @: excellent)

<table>
<thead>
<tr>
<th>Display Solutions</th>
<th>FPD</th>
<th>PJ display w/ arc lamp (panel type)</th>
<th>PJ display w/ LED (panel type)</th>
<th>PJ display w/ Laser (line type or scanning type)</th>
<th>Relevant feature of laser display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural color</td>
<td>△</td>
<td>△</td>
<td>O</td>
<td>@</td>
<td>NTSC 130%</td>
</tr>
<tr>
<td>Ultra high resolution</td>
<td>O</td>
<td>△</td>
<td>O</td>
<td>@</td>
<td>Point or line scan</td>
</tr>
<tr>
<td>Image artifact</td>
<td>△</td>
<td>△</td>
<td>O</td>
<td>@</td>
<td>Speckle</td>
</tr>
<tr>
<td>Small form factor</td>
<td>△</td>
<td>△</td>
<td>O</td>
<td>@</td>
<td>MEMS scanner w/ minimum optics</td>
</tr>
<tr>
<td>Cost-effective</td>
<td>X</td>
<td>△</td>
<td>O</td>
<td>@</td>
<td>MEMS scanner w/ minimum optics as long as cost of laser is reasonable</td>
</tr>
</tbody>
</table>

FPD – Flat panel display  
PJ – projection


Laser Display Obstacles

- Speckle
- Suitable green laser with high efficiency, high power and compact size
- Resolution
- Thermal management
  - Less efficient -> more heat
  - Intense heat generating component such as green laser should be taken care.
- The success of laser displays is highly dependent on the progress of
  - Laser diode technology
  - MEMS technology
To fully resolve the HDTV content (in 1920x1080 full color pixels), for a person at a distance of 2 meters from the TV, the pixel size needs to be as small as 0.6mm and the screen size needs to be as large as ~70” diagonal to match the approximately 1 minute of arc resolution.

- Projection displays: optically magnifying a small picture on a miniature display.
- Front-projection: viewer & projector on the same side of the screen.
- Rear projection: opposite sides.
- Projection displays offers an economical solution to large, high-resolution displays.

**Display Technology Vs. Size**

<table>
<thead>
<tr>
<th>Pixel count (Millions)</th>
<th>Size (inches)</th>
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<tbody>
<tr>
<td>UHD 4K, 3840x2160</td>
<td>50</td>
</tr>
<tr>
<td>UHD 8K, 7680x4320</td>
<td>150</td>
</tr>
<tr>
<td>HD 1080p, 1920x1080</td>
<td>150</td>
</tr>
<tr>
<td>720p, 1280x720</td>
<td>150</td>
</tr>
</tbody>
</table>

![Figure 1.1 Viewing geometry for direct-view HDTV](image1)

![Figure 1.2 Display technologies as a function of screen size and resolution](image2)
Christie TotalVIEW CAVE @ Discovery World in Milwaukee

DOME-Shaped Immersive Theater
Skyskan’s Definiti 8K Projection

http://www.skyskan.com/products/systems/projection/8k

8K Fulldome

This chart shows the proportional scale differences from 1080p (1920×1080 pixels) to 8K×8K fulldome video.
Immersive Video Wall

GE’s New Customer Experience Center: Pyrs LPD Video wall

Ultra Short-Throw Projector
Pocket and Mini-Projectors

PICO projectors

Smartphone with built-in pico projector