Laser Science and Laser Illuminated Projection

SMPTE Webcast
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Your Host

Joel E. Welch
Director of Education
SMPTE

Today’s Guest Speaker

Bill Beck
The Laser Guy
Barco
Goals of the Webcast

- Provide foundational concepts and terms by which to describe, understand and evaluate laser illuminated projectors (LIPs)
- Introduce and explain laser technology basics, laser engine architectures and LIP performance
- Introduce and define key figures of merit (FOM)
- Review current Image Quality and Operational FOMs
- Summarize current state of the art for RGB and BPP LIPs

Laser Webcast Outline

1. Introduction and Status
2. Laser Science
3. Laser Engine Architectures
4. Projector – Image Quality (IQ) Figures of Merit (FoM)
5. Projector – FoMs and 6P
6. Summary
7. Q&A
8. Glossary of Terms, Acronyms and Definitions
1. Introduction and Status

Introduction and Status

- **Commercial Laser Illuminated Projectors are here!**

  - High Brightness RGB LIPs deliver >60,000 DCI lumens
    - Premium Laser Format (PLF) theaters
    - Larger screen 3D conventional theater
  - Blue Pumped Phosphor LIPs do ~6,000 DCI lumens
    - Small theaters, typically with gain screens
Who is Selling Laser Illuminated Projectors?

- Integrated Single Projector
- Dual Projector
- Fiber Coupled Projector Head

BPP (Laser Phosphor)

2. Laser Science
What are Lasers?

Solid state components that

**CONVERT ELECTRICITY INTO LIGHT**

With very special Properties...

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How do Lasers differ from Xenon lamps?

- High Spatial Brightness – power emanates from a very small spot as a collimated beam and diverges (spreads slowly) i.e., low *étendue*

- Lasers produce **narrow wavelengths** or bands of color - 0.1 to 2 nm and are coherent, which causes interference and speckle

- Lasers have **very long lifetimes** - 10,000 to 100,000 hours - with little decline in brightness per hour of use

- Lasers have **high conversion efficiency** - overall Electrical to Optical (E to O); no excess or unwanted wavelengths to block

10-30+ %
How is a Laser Light Source different from a Xenon Lamp?

<table>
<thead>
<tr>
<th>Attribute</th>
<th>units</th>
<th>Laser</th>
<th>Xenon Lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>E to O Conversion</td>
<td></td>
<td>Stimulated emission</td>
<td>Gas discharge; short arc creates bright “spot”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High spatial brightness</td>
<td></td>
</tr>
<tr>
<td>Output pattern</td>
<td></td>
<td>Coherent; collimated to</td>
<td>Isotropic = all directions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>moderately divergent</td>
<td>Must be focused to spot</td>
</tr>
<tr>
<td>Spectral bandwidth</td>
<td>nm</td>
<td>“Narrow” - 0.01-2</td>
<td>“Wide” - 60 - 80/per RGB Primary</td>
</tr>
<tr>
<td>étendue</td>
<td>mm²-sr</td>
<td>Very small - 0.001-1</td>
<td>High relative to laser 4-20</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Hours to end of life</td>
<td>5,000 -100,000 to 80%</td>
<td>200 - 2000 to 50% power 500 - 1000 (typical)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30,000 Commercialized</td>
<td></td>
</tr>
<tr>
<td>System Efficiency</td>
<td>lumens / wall plug watt</td>
<td>5 - 8</td>
<td>2-6</td>
</tr>
</tbody>
</table>

Why use lasers?

- **BRIGHTER IMAGE** – low étendue output of lasers enables digital projector brightness levels 2-3 times that of Xenon lamps

- **BETTER IMAGE** – significant, demonstrated increases in uniformity, contrast ratio and color gamut and saturation

- **LONGER LIFETIME** – solid-state lasers hold the promise of NO LAMP CHANGES over 5-10 year life of projector

- **HIGHER EFFICIENCY** – lasers can reduce direct and indirect power consumption by 30-50%
### Laser Device - Figures of Merit (FOMs)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Figure of Merit</th>
<th>Unit of Measure</th>
<th>Range or Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Wavelength</td>
<td>Nanometers (nm)</td>
<td>400 to 700</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Full Width/Half Max</td>
<td>FWHM</td>
<td>0.1 to 3</td>
</tr>
<tr>
<td>Spectral Power Distribution</td>
<td>Spectral Curve</td>
<td>N/A</td>
<td>up to 30 nm</td>
</tr>
<tr>
<td>Output Power</td>
<td>Watts (CW equivalent)</td>
<td>Optical watts (W)</td>
<td>0.5 to 100+</td>
</tr>
<tr>
<td>Luminous Efficacy</td>
<td>Lumens per optical watt</td>
<td>lm/W</td>
<td>20 to 683 max</td>
</tr>
<tr>
<td>Electrical to Optical Efficiency</td>
<td>watts_{optical}/watts_{electrical}</td>
<td>%</td>
<td>3 to 30</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Hours until 20% down</td>
<td>hr</td>
<td>10,000 to 40,000</td>
</tr>
<tr>
<td>Roll-off rate</td>
<td>Power redux / khour</td>
<td>%</td>
<td>0.67 to 2.5</td>
</tr>
<tr>
<td>Beam Quality</td>
<td>Divergence; roundness</td>
<td>Mrad; °; %</td>
<td>“0” to 35°</td>
</tr>
</tbody>
</table>

### Laser types

- **Diodes (LD) – single emitter (SE)**
  - Edge emitters
  - Surface emitters (SEL; VCSEL;)
- **Diodes – multiple emitter (ME)**
  - Bars or lines of edge emitters (Pumps; Stacks)
  - Arrays of surface emitting lasers
  - Aggregations of SE or ME into a beam or fiber
- **“Doubled” Diode modules (SHG = Second Harmonic Generation)**
  - Diodes with SHG crystals/devices double frequency CHANGES the **COLOR**
Lasers used for Projection

- **Diodes (LD) – single emitter (SE)**
  - Edge emitters
  - Surface emitters (SEL; VCSEL)

- **RED** 635 – 660 nm
  - mW – 2W Continuous Wave = CW
  - 10-25% Wall Plug Efficiency = WPE
  - Moderate cost/W

- **GREEN** 510 - 530 nm (in development)
  - mW to 1 W CW
  - Low % WPE
  - High cost/W

- **BLUE** 440 - 470 nm
  - 1-3 W CW
  - 10-30% WPE
  - Low cost/W

- **“Doubled Diode” modules (SHG)**
  - Infrared diode, array or bar
  - Second Harmonic Generation
  - 1064nm => 532nm
  - 930nm => 465nm
  - mW – 3W (CW)
  - 5 - 8% WPE

- **Diode pumped SS and FL - IR + SHG modules**
  - Infrared 808nm array or bar pumps laser crystal => 1064nm
  - Crystal doubles frequency (SHG) 1064nm => 532nm
  - mW – 100W (CW)
  - 8 – 17% WPE
### RGB Laser Wavelength Options

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength (nm – FWHM)</th>
<th>Device Type</th>
<th>Watts per Device</th>
<th>Lumens Per watt</th>
<th>Lumens per Device</th>
<th>E to O % Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED</td>
<td>657 - 1</td>
<td>Diode</td>
<td>0.5 - 2</td>
<td>50</td>
<td>50 - 100</td>
<td>10 - 20 (est.)</td>
</tr>
<tr>
<td>RED</td>
<td>638 - 1</td>
<td>Diode: Bar</td>
<td>0.5 - 16</td>
<td>131</td>
<td>131 - 2096</td>
<td>10 - 30</td>
</tr>
<tr>
<td>RED</td>
<td>615 - 8</td>
<td>DPSS + OPO</td>
<td>10</td>
<td>301</td>
<td>3010</td>
<td>5</td>
</tr>
<tr>
<td>GREEN</td>
<td>550 - 0.1</td>
<td>VCSEL SHG</td>
<td>2</td>
<td>679</td>
<td>1358</td>
<td>3 - 4</td>
</tr>
<tr>
<td>GREEN</td>
<td>546 - 12</td>
<td>DPSS wide spectrum</td>
<td>20 - 50</td>
<td>671</td>
<td>&gt;30,000</td>
<td>8 - 10</td>
</tr>
<tr>
<td>GREEN</td>
<td>532 - 0.1</td>
<td>DPSS, VCSEL, FL + SHG</td>
<td>2 - 100</td>
<td>603</td>
<td>&gt;60,000</td>
<td>5 - 17</td>
</tr>
<tr>
<td>GREEN</td>
<td>525 - 2</td>
<td>Diode</td>
<td>1</td>
<td>542</td>
<td>542</td>
<td>8 - 12</td>
</tr>
<tr>
<td>BLUE</td>
<td>465 - 2</td>
<td>Diode</td>
<td>1.2</td>
<td>50</td>
<td>60</td>
<td>18 - 22</td>
</tr>
<tr>
<td>BLUE</td>
<td>445 - 2</td>
<td>Diode</td>
<td>3.5</td>
<td>20</td>
<td>60</td>
<td>20 - 24</td>
</tr>
</tbody>
</table>


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### Why RGB Wavelengths Matter...

**Lumens per Laser Watt – P3 vs. Rec. 2020**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>P3</th>
<th>Rec. 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>635</td>
<td>201</td>
<td>12,267</td>
</tr>
<tr>
<td>545</td>
<td>669</td>
<td>43,361</td>
</tr>
<tr>
<td>465</td>
<td>50</td>
<td>2,728</td>
</tr>
<tr>
<td>RGB</td>
<td>366</td>
<td>50,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>P3</th>
<th>Rec. 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>630</td>
<td>181</td>
<td>14,752</td>
</tr>
<tr>
<td>532</td>
<td>603</td>
<td>42,108</td>
</tr>
<tr>
<td>615</td>
<td>367</td>
<td>3,128</td>
</tr>
<tr>
<td>RGB</td>
<td>288</td>
<td>60,000</td>
</tr>
</tbody>
</table>
Primary Selection vs. Gamut

- Narrowband primaries “on locus”
- Wider gamut and more saturated
- But higher speckle and OMF
- Longer Reds and shorter Blues are commercially available
- Shorter Green adds Magenta but cuts Yellow saturation
- Wider gamut primaries reduce luminous efficacy (lm/watt)

Primary Selection vs. Luminous Efficacy

- Luminous Efficacy = White balanced lumens / RGB watt
- Ideal is to use “native” laser primaries:
  - Rec 709: 613/550/463 nm = 362 lm/W
  - DCI P3: 615/545/465 nm = 366 lm/W
  - Rec 2020: 630/532/467 nm = 288 lm/W
- Readily available lasers: 640/532/445 nm
  - Rec 709: Raw 249 lm/W Correction reduces lm/W
  - DCI P3: Raw 261 lm/W Correction reduces lm/W
  - Rec 2020: Raw 261 lm/W Very slight reduction in lm/W
3. Laser Engine Architectures

Laser Projector Architectures

Direct Scanned laser Projection

- Laser beam
- Direct laser light projected on the screen
- Eye-Safety hazards
- Image quality challenges
- Not used in front projection applications

Laser Illuminated Projection

- Blue laser Pumped Phosphor
- Direct laser light + laser pumped phosphor
- Limited brightness

RGB Laser

- Direct RGB laser light for High Brightness
- Up to 6,000lm DCI
- 60,000 lm

Barco
Visibly yours
Lasers in the BOX or out of the BOX?

Integrated
- Simple
- Safe
- Efficiency - ~ 10-15% higher

Fiber Coupled
- Complex
- Remote source
- Modular

RGB Architectures

Free Space Aggregation

Fiber Coupled
RGB Power Quantification

- Assume Native DCI P3 Primaries 615/545/465
- Generates 366 white balanced lumens per RGB laser watt
  60,000 lumens out = ~165 RGB laser watts to the screen

- Assume readily available lasers 640/532/445
- Generates only 261 white balanced lumens per RGB laser watt
  60,000 lumens out = ~230 RGB laser watts out – after color correction

Now assume ~33% projector throughput (after laser input)

~700 RGB watt input required or around 200+ devices

BPP Architectures
Image Quality - Figures of Merit (FOMs)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Figure of Merit</th>
<th>Unit of Measure</th>
<th>Range or Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>White Balanced Lumens</td>
<td>lm</td>
<td>6,000 – 60,000</td>
</tr>
<tr>
<td>Sequential Contrast</td>
<td>Peak White : Full Black</td>
<td>Ratio</td>
<td>2000 - 3000:1</td>
</tr>
<tr>
<td>Speckle Contrast Ratio</td>
<td>SCR = S.D./mean</td>
<td>%</td>
<td>~2 - 20</td>
</tr>
<tr>
<td>Luminance Uniformity</td>
<td>Min / Max (Center)</td>
<td>%</td>
<td>90 - 95</td>
</tr>
<tr>
<td>Color Uniformity</td>
<td>Delta x,y</td>
<td>0.00x</td>
<td>Meets DCI</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1000 pixels wide</td>
<td>K</td>
<td>1 - 4</td>
</tr>
<tr>
<td>Color Space (Gamut)</td>
<td>Primary points</td>
<td>x,y</td>
<td>P3; Rec. 2020</td>
</tr>
<tr>
<td>3D systems</td>
<td></td>
<td></td>
<td>Supports all types</td>
</tr>
<tr>
<td>Stereo Contrast Ratio (6P)</td>
<td>Correct eye/incorrect</td>
<td>Ratio</td>
<td>700-1000:1</td>
</tr>
</tbody>
</table>
What is speckle?

You know it when you see it...

- Speckle is an interference pattern image artifact that occurs when highly coherent, narrow band light is used.

- Figure of merit is “Speckle Contrast Ratio” (SCR%)
  \[ SCR\% = \frac{\text{Standard deviation of measured pixel intensity}}{\text{mean pixel intensity}} \]

- Though objectively measureable, level of offensiveness is subjective.
- Content, observer, visual acuity, position, screen type all impact speckle.

Single line vs. Multi/Wide-band Primaries

Narrow band RGB laser “lines” FWHM ≤ 1 nm
- Simple modeling and supply chain … but
- Massive Speckle
- Potential for “Observer Metameric Failure” (OMF)

Multiple RGB lines per primary - n x FWHM ≤ 1 nm
- Wavelength options depend on physics and availability
- Little impact on speckle if narrowband
- Unknown impact on OMF

Spectrally broadened RGB bands FWHM 10 - 40 nm
- Replicates incoherent white light
- Low speckle and OMF
- Hard to achieve with available lasers
Primary selection vs. Speckle Contrast Ratio (SCR)

- Benchmark is Xenon illumination – Incoherent and Lambertian
  - RGB pass bands for DCinema installed base ~60 nm wide
  - System f# ~2.4 (fast) to maximize angle and usable lamp output
  - SCR for Xenon ~ 1% - hard to measure
- Single wavelength, narrow line (~0.1 nm) RGB primaries SCR ~20%
  - UNWATCHABLE in Green and Red; speckle noticeable even in Blue
- Multiple emitters of the same wavelength – some reduction in SCR%
- Multiple wavelengths of different wavelengths further reduces speckle
- 6 primary 3D engines help reduce speckle further

Contrast Ratio / High Dynamic Range (HDR)

- Current DCI spec: 2000:1
- LIPs at 2300 - 3000:1
- All movies are mastered for this spec contrast level!
  - Post production reference projectors about 2000-2300:1
  - If cinema contrast is much higher -> artifact visibility
- Laser + redesigned projector optics can achieve 10,000:1
- Will require additional HDR DCP (Digital Cinema Package)
- Higher contrast typically results in
  - Lower optical efficiency
  - More speckle
5. Projector FOMs

How lasers reduce Operating Costs

- Longer lifetime at full power - > 30,000 hours vs. 500 hours
  
  - *Eliminates 60 or more lamp changes vs. 6 kW Lamp Projector*

- Higher projector OPTICAL throughput

- Higher wall plug efficiency - 5 - 6 lm/WPW vs. 2 - 5 for Xenon
  
  - *Lower Power Consumption*
**Light Source Lifetime Comparisons**

- **Xenon lamps**
  - 6.5 kW lamps (500 hrs @ 50% of initial brightness)
  - Blue Phosphor Projector (20k hours at 50% of initial brightness)

- **RGB Laser Projector**
  - 30k hours @ 80% initial brightness

- **RGB Laser Projector Eliminates 60 or more Xenon Lamp Replacements**

**Xenon vs. Laser Efficiency Comparison**

<table>
<thead>
<tr>
<th></th>
<th>Initial Brightness</th>
<th>Average Brightness</th>
<th>System Power Consumption</th>
<th>Efficiency (lm/W)</th>
<th>Consumption (W/klm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barco Xenon DP4K-32B</strong></td>
<td>33,000 lm</td>
<td>@75% = 24,750 lm</td>
<td>7.5 kW</td>
<td>3.3 lm/W</td>
<td>303 W/klm</td>
</tr>
<tr>
<td><strong>Barco Laser DP4K-60L</strong></td>
<td>60,000 lm</td>
<td>@90% = 54,000 lm</td>
<td>10 kW</td>
<td>5.4 lm/W</td>
<td>185 W/klm</td>
</tr>
</tbody>
</table>

**Laser DP4K-60L has:**
- **64% better efficiency**
- **39% lower power consumption**
What is 6 Primary or “6P” 3D?

- With lasers, it’s possible to use 6 RGB Primaries for Color3D separation (=6P)
- Single and dual projection architectures possible (active and passive)
- In both cases, the image quality and brightness are much better than with Lamp Based Dolby or Infitec Wheels and Polarization systems.

Laser 6 Primary Architectures

- Single 6P solution
- Dual, 3P + 3P solution
6. Summary and Conclusions

- Laser Illuminate Projectors are here NOW

- Lasers DO provide consistent, higher brightness, contrast, uniformity

- Lasers DO provide substantial operating cost saving

- Laser Illuminated Cinema performance already exceeds Xenon illuminated digital projectors
Questions & Answers

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