Updated for Public Release– 12/2/22 - Bill Beck, LIPA Communications

Title: **Types of Laser Illuminated Projectors (LIPs) – Evolution, Tradeoffs and Trends**

Introduction

This article will present the historical challenges and efforts that have made laser illuminated projectors a practical reality. Most early developments were singular, prototype projects with R&D level components. Two distinct technical approaches emerged - one focusing on niche and premium Digital Cinema applications; the other on broader applications - more cost-constrained, lower lumen models, designed primarily to eliminate the need for lamp changes.

Initially, these two "tracks" were initially independent in both their goals and architectures. However, as laser illumination became more practical, it became apparent that both approaches, "pure" RGB laser and BLUE Laser "pumped" phosphor (BPP), (an outgrowth of the LED Lighting world), could be combined or "hybridized". By 5 or 6 years ago, LIPs had matured substantially. Both of the original approaches and other developments have evolved to the point where specific product requirements could be met with optimized *combinations* of both highly developed Laser illumination technologies.

LIPA members take great pride in the progress that has been made through their individual efforts and the evolution of the industry as a whole. At this point, it is important to acknowledge that solid-state illumination is now the technology of choice and that numerous adaptations have enabled an incredibly wide range of product features, benefits, performance improvements and new capabilities - at all price points.

Historical Background

More than ten years have passed since the commercial introduction of Laser Illuminated Projectors, or "LIPs". The two applications that drove initial commercialization resulted in differing approaches to early LIP design. Digital or DCinema, defined to the last detail by Hollywood's Digital Cinema Initiative (DCI) required standards-based image quality (IQ) and consistency. Higher volume, "lamp-less" projectors, leveraged rapidly growing BLUE laser production volumes and consequent breakthrough cost reductions.

Both application segments had general requirements for commercialization: extremely **high performance** for DCinema; vs. **balance of performance vs. cost** for BLUE laser "pumped" phosphor (BPP) designs. Target performance for DCinema meant "perfect", bright images - first time, every time - as good or better than the global DC28.0 Digital Cinema specification required.

Early *non-cinema* LIPs offered existing performance but *without the need for lamp changes,* addressing one of the key pain points for the use of projectors in various settings (meeting rooms, class rooms, conference halls, etc.) And with longer light source life, more *consistent* performance over time.

Laser-illuminated projection has improved and changed greatly over the last 10-15 years. In this article, we will review the "why" and "how" these developments have progressed, review the attributes and applications of each type of LIP and predict what additional developments could emerge in the future.

Early Development

The early development of LIPs (2000's) was initially slow, complex, and for Digital Cinema, constrained by a large set of unique requirements. Lamp-illuminated digital projectors operate by **spectrally** filtering broadband or "White" light into RED, GREEN and BLUE primary light, and then **spatially** modulating each primary's intensity - **sequentially** in 1-chip systems; **simultaneously** in 3-chip systems. Whether the "spatial light modulator" (SLM) chips are Digital Micro-mirror Device (DMD) type, Liquid Cristal Display (LCD) or Liquid Crystal on Silicon (LCoS), they all modulate the intensity of RGB input light for each individual picture element or pixel in the frame.

Laser Illuminated (digital) Projectors, utilize intense light beams from RED, GREEN, and BLUE lasers or the light emitted from Blue laser excited Phosphors in place of RGB-filtered lamp light. The unique challenge for LIPs - in fact the primary impetus for the founding of LIPA, was the onerous regulation of any projector containing a laser light source. But before any efforts would be made to rationalize regulation, LIP developers had to see a path to threshold commercial product performance – outstanding image quality and/or acceptably low selling price.

First Big Challenge - "No good lasers…at any price"

Early on, few kinds of RED, GREEN or BLUE lasers were available. Each color device typically came from **different suppliers**, many of which were not interested in the projection application. Available high power Laser sources were manufactured in low volumes, resulting in **high cost**. Each Laser "color" required different material systems or complex architectures; **had low** Electrical to Optical "E to O" conversion efficiencies and often, **insufficient lifetimes**. Putting together RGB prototypes was therefore extremely complex, challenging…and costly.

One of the breakthrough developments for Laser illuminated projectors, was the increasing availability of Blue Laser Diodes. Huge investments in LED lighting fueled the co-development of Blue LEDs and companion "Yellow" Phosphors that together produced "White" light for the lighting industry. The same Gallium-Nitride (GaN) materials used in LEDs could make Blue Lasers in the volumes and at the price points required for small, inexpensive, "lamp-less" digital projectors. Early versions of Blue Laser-pumped Phosphor (BPP) and Blue Laser+BPP+LED hybrid projectors were first introduced by Casio, an early LIPA member.

The Laser-LED hybrid design had some limitations, such as deficient RED output, resulting in limited overall lumen output due to limited luminance and coupling of divergent RED LED output. Current LIPA member, Appotronics, pioneered BLUE laser-pumped phosphor illumination technology starting in 2007. Instead of using LEDs for supplementary color light, Appotronics "dug into the recipes of phosphor materials" and committed to a pure *Laser*-Phosphor solution.

There was still a significant challenge for laser-phosphor sources. Due to the quenching phenomenon of phosphor materials, the maximum achievable luminance level quickly hit a practical limit of around 3000lm (at that time). Appotronics continued to focus on the R&D of laser phosphor light sources. Its rotating phosphor material solution solved the quenching (saturation) problem and successfully drove the laser phosphor illumination solution to tens of thousands of lumens, using a single phosphor "wheel". Today Laser Phosphor technology supports 50,000lm (non-cinema) projectors.

Second Big Challenge – Regulatory hurdles and the founding of LIPA – 2011

The early regulatory environment for "Laser projectors" was controlled initially by the US FDA-CDRH and was based on the already strict regulation of Laser Light Shows (LLS), mandated in the 1970s. This existing regulatory hurdle and uncertainty around any new LIP regulations continued to discourage investment and development.

RGB Laser supply chains were just not there yet for commercial systems - until a number of forward-looking developers, manufacturers and key End-Users "stepped up" and **founded LIPA in May of 2011**. [ed. Note: LIPA founding members were Barco, Christie Digital, Dolby, IMAX, Laser Light Engines, NEC Displays, Sony, and Ushio/NECSEL.]

LIPA's founding mission was to provide a single industry voice to help "rationalize" the regulation of laser *illuminated* projectors. Instead of risking time and resources to address the FDA as individual companies, members created LIPA to provide informed and unified guidance for regulatory change. Although it took a substantial, pooled investment over a number of years, LIPA, the FDA and the IEC together, created a new regulatory *category* for LIPs and a framework to provide the growing user community with the confidence to adopt and use this versatile new solid-state illumination technology.

Development accelerated and after an extensive series of performance validation and safety tests, Hollywood "blessed" RGB Laser Digital Cinema image quality and regulatory bodies provided installation and operation guidelines via "Variances" to the exlisting LLS regulations.

In 2014, RGB LIPs for high-end DCinema and Premium theaters were commercially launched and installed by Barco, Christie, NEC, IMAX and Dolby, all founding members of LIPA.

Photo: Early Barco DPK-60L (60,000lm) RGB Laser and chillers for laser cooling and temperature control. Barco is a LIPA member.

<u>The Race to Address the Vast "Middle Market"</u>

During the early adopter period, proponents of the two emerging Laser light generating architectures, RGB and BPP, began a "technology race". High brightness [up to 60,000lm] RGB for DCinema "flagship" LIPs were sold on the bases of outstanding, consistent image quality and previously unachievable brightness levels.

The rapid adoption of the Blue Laser-Pumped Phosphor approach enabled lower cost, lower brightness, [up to ~3000lm], "lamp-less" projector designs. This new category of projector was actually introduced to the market before the first Cinema LIPs were installed. These smaller LIPs offered the attractive advantage of "**never needing a lamp change**", with good image quality for much higher unit volume applications.

The race for the vast, high value, Total Addressable Market (TAM) "middle" was first driven by growing unit volumes of BPP models and their BLUE laser diode light sources - and highly engineered cost reductions of RGB DCinema projectors. Both of these advances were spearheaded by LIPA members. Every year, lower brightness RGB models "proved in" commercially at ever lower price points. BLUE Laser volumes exploded, phosphor technology improved as noted above, and BPP models proliferated. At much higher and ever-increasing lumen levels, they eventually began competing at the same high brightness levels as RGB technology (5,000lm and up) - **RGB** with a **maximum brightness and image quality lead** and lower Total Cost of Ownership (TCO) vs. traditional Xenon Arc Lamp illuminated Cinema projectors - and **BPP** with **competitive price positions.**

The Fusion of RGB and Laser Phosphor Architectures

Currently, RGB + BPP LIP light source architectures are combined to optimize the benefits of higher performance and lower cost over a wide range of brightness and performance categories. Many of LIPA's members have contributed to this broad-based LIPA evolution.

The Laser light source utilizes a new light source architecture combining RGB lasers and phosphors where three peaks of RGB lasers and the broad-band yellow phosphor spectrum are added together. The RGB+Phosphor (ALPD 4.0) based projector can deliver as much as 60 klm light on the screen

As this development race played out, both brightness/image quality and cost/value expectations evolved beyond the binary choice of RGB or BPP, respectively. Specialization, product differentiation and refinement progressed rapidly as customers began demanding models with a varied mix of unique selling points (USPs).

Product Development "Value Vectors"

Today, nearly every projector maker offers one or more LIP models in their product range. Some have even committed to develop and sell *only* Laser (illuminated) product lines. Driven by the accelerating development of Laser and related technologies, combined with intense competition, now over 50% of new projector sales by revenue are LIPs. And the "value vectors" enabled by new architectures, larger and more diversified supply chains and application-optimized designs are proliferating.

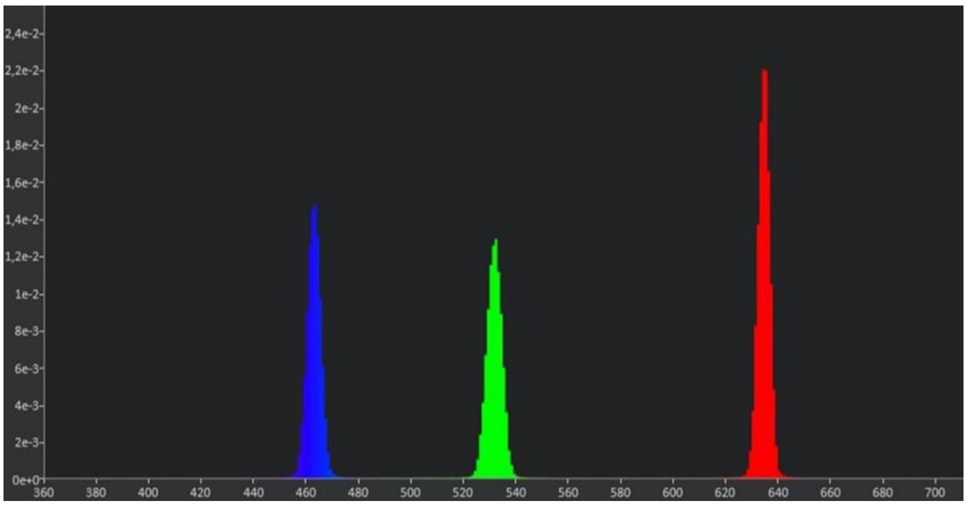
What are these value vectors and how do different types of lasers and optical architectures enable them?

- **Image Quality (IQ)**
  - Higher brightness levels
  - Outstanding spatial and temporal uniformity
  - Higher Contrast and Dynamic Range (HDR)
  - Wider Color Gamut (WCG)
  - Increased color saturation
  - Increased Color fidelity and matching between multiple projectors over time
  - “Zero" Laser Speckle on matte screens and reduced speckle on silver/high gain screens
- **Acquisition Cost** reduction
- **Maintenance** reduction/elimination
- **Total Cost of Ownership (TCO)** reduction
- **Light source lifetime** Increase and slower brightness roll-off
- **Power efficiency** [White-balanced lumens / wall plug (electrical) watt] Increase
- **Thermal management** - e.g., air vs. liquid cooling; increased cooling power efficiency and cost reduction
- **Size and Weight** reduction
- **Ambient Noise** reduction
- **“Low-touch operation”** - Ease of adjustment/maintenance/repair
- **Remote location of Laser engines** - “Off-Board Illumination”; “Light Farms”
- **Special capabilities** - 3D, RGB+IR, multi-projector blending
- **Range of Interchangeable lenses**

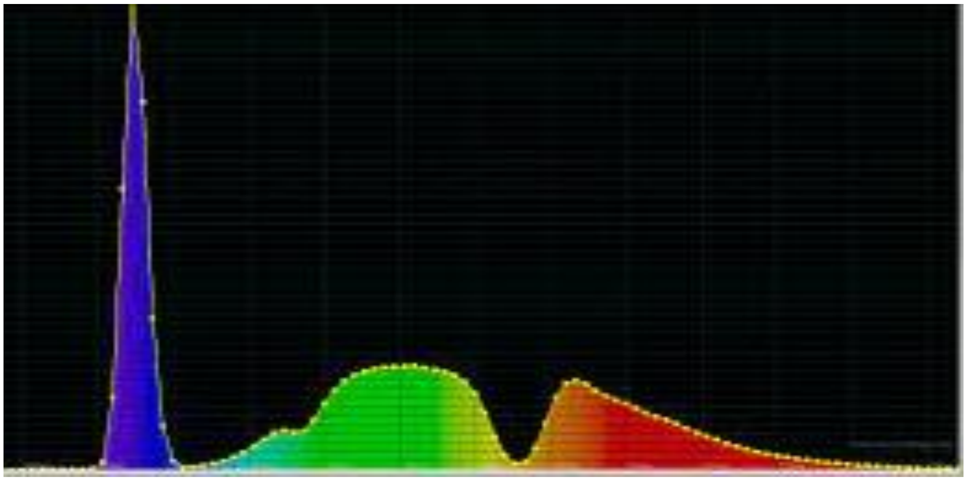
All these value vectors and design goals require optimized combinations of Laser types and have driven a proliferation of light source architectures and projector designs.

Laser Light Source and Projector Architectures

RGB = **RED, GREEN, BLUE** - The simplest combination of laser "primaries", one for each additive primary color needed to create all the colors of a given color gamut. This architecture uses the direct output of Laser diodes, typically in narrow bands of RED, GREEN and BLUE. Variants of this architecture have been developed to reduce laser speckle and for spectral separation 3D projection. See below for a typical RGB output spectrum.



BPP = **BLUE** Laser-Pumped ("Yellow") Phosphor was one of the first and simplest "Hybrid" La-Ph architecture - low cost – but relatively low lumen output. High-*energy and power* BLUE Laser photons pump a phosphor that produces broadband light output from **GREEN** to **RED**, "centered" on YELLOW, which unfortunately, must be filtered out (blocked), reducing overall phosphor conversion efficiency (luminous efficacy) to *useable* GREEN and RED. Note the spectral "notch" where the YELLOW phosphor light has been blocked and discarded.



New LIP Light Source Architectures

Many new and nuanced hybrids have evolved from these two original architectures; designed to compensate for remaining wavelength "gaps" in available laser devices and to provide incremental improvements in performance and/or needed cost reductions. Other new architectures have achieved a desired performance requirement or capability enabled by new laser types.

The first new hybrid to emerge was **BPP** + **RED**, at first incorporating **RED LEDs** This improved projector color but was still limited in overall lumen output.

More recently, RED laser diodes were added to medium lumen, BPP Cinema designs. The Red output of the "Yellow" Phosphor emission rolls off at *longer* wavelengths, limiting total "white balanced" (WB) lumens, **RED** saturation and color gamut that a **BPP**-only LIP could produce. By adding **RED** laser diodes, a small BoM cost increase delivers a large visual and value **increase in overall White Balanced (WB) Lumens**, greater RED saturation and **wider color gamut**.

Photo: Sharp/NEC Displays - Red Laser + Blue Laser + Green Phosphor DCinema projector. NEC is a LIPA founding member.

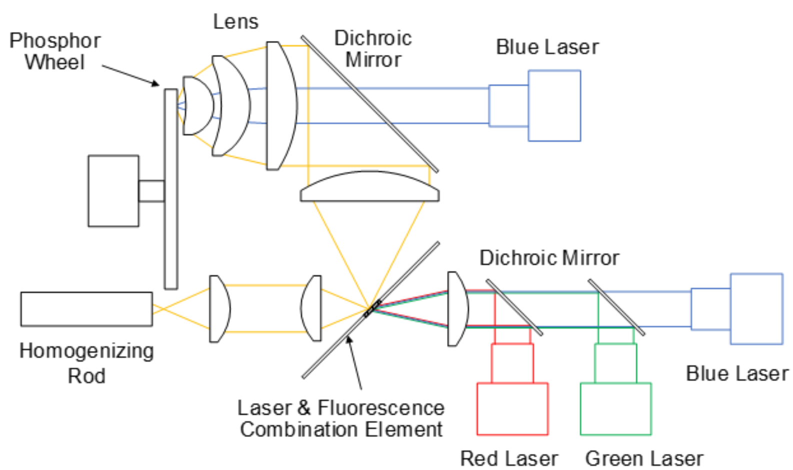
The next step in source optimization came at the short wavelength end of the Phosphor output spectral curve. As phosphor green output rolls off at *shorter* wavelengths, GREEN laser diodes, (which have the opposite problem, power roll-off at longer wavelengths), can be added to efficiently increase the lumen output of the “hybrid” green primary “band”.

Increased Lumen Output at Lower Cost

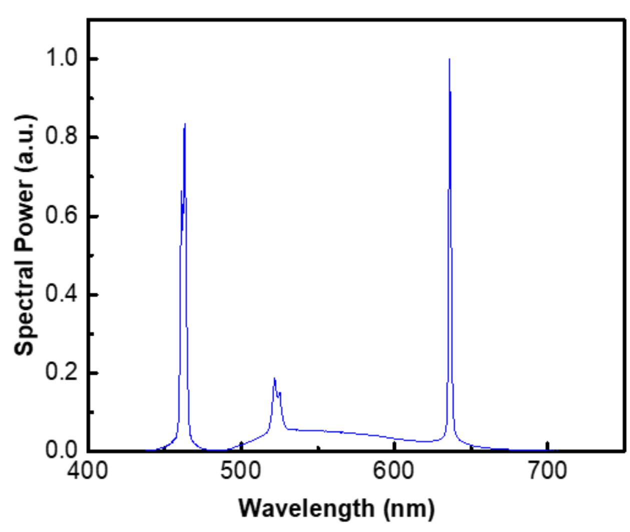
One approach to increase *overall* lumen output at lower cost is to combine the lumen output of a low cost **BPP** engine with that of a small but optimized set of **RGB** Lasers. **BPP** output can be limited by the saturation effect leading to the necessity to cool the phosphor wheel; the much larger output étendue of the phosphor output; the “notch out” (yellow filtered) part of spectrum to meet wide gamut requirement or all three. Adding low *étendue* and “wider gamut” diodes at compensating wavelengths can increase white balanced lumens and/or enable a wider gamut output.

The RGB+Phosphor (Appotronics ALPD 4.0) architecture is different from either one of the two base technologies, RGB or BPP. As shown in the below figure, it combines the light from both the RGB lasers and the blue laser-pumped phosphor. It solves the problem of phosphor’s limited color gamut, limited efficiency, and RED deficiency. It still has a cost advantage compared to direct lasers because the majority of RED and GREEN light still comes from cost-effective phosphor output.

It also mitigates the laser speckle problem of pure narrowband RGB lasers because as shown in the below spectrum figure, phosphor light contributes both Red and Green, while the RED and GREEN Laser's two peaks are added on top of yellow phosphor's wide spectrum.



The architecture of ALPD®4.0 light source.



Normalized spectra of ALPD 4.0 light source

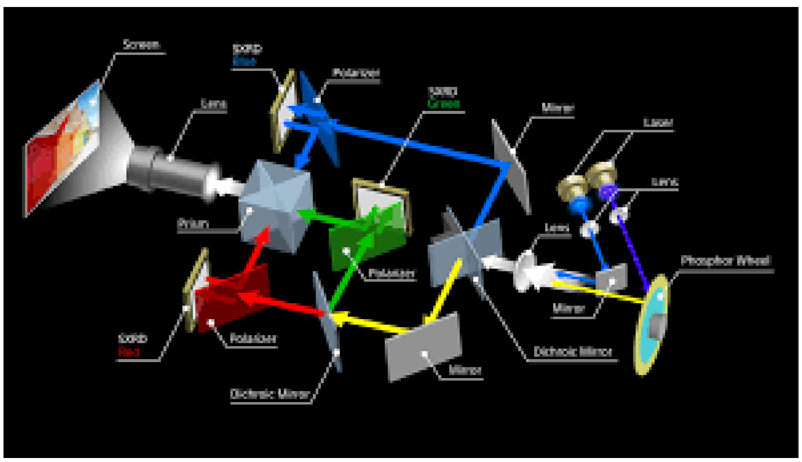
Laser Speckle Reduction

The laser speckle produced by a narrowband **RGB** architecture can be mitigated by combining broad-band phosphor light with the **RGB** Laser sources. This approach is now widely used in BPP-based projectors to both achieve higher overall lumen output and to reduce laser speckle, especially for use with high gain/silver 3D screens, where perceived Laser speckle is more pronounced.

Improving Color

The addition of RED Lasers and GREEN Lasers can dramatically increase color gamut and color saturation with a small increase in BoM cost. As the RGB + Phosphor technology integrates the advantages of both RGB and BPP, achieving high WB lumen output, wide Gamut and speckle free performance.

Major improvements in image quality, color gamut, WB Lumen output and speckle reduction can all be achieved with optimized source *hybrids*. As more laser and phosphor types become available, additional improvements are possible.



BLUE Laser-Pumped Phosphor schematic (Courtesy of SONY)

Unfortunately, the peak output of the phosphor is in the Yellow band, which needs to be blocked by a filter, reducing overall efficiency. Note the use of different Blue wavelengths for the BLUE primary and for Yellow phosphor pumping. With the availability of higher power BLUE diodes, the same wavelength can now be used for both phosphor pumping and the BLUE primary.

The novel architecture of the RGB+Phosphor design enables much wider color gamut compared with light sources that only use blue lasers and yellow phosphors. Therefore, the DCI-P3 color Gamut can be achieved without using a notch filter, which increases the efficiency passing through the 3DMD projector engine. The elimination of the notch filter largely reduces the spectrum loss compared to the xenon lamp and previous architectures. Meanwhile, RGB lasers enable more freedom to adjust the luminance contribution from each primary color, therefore the **efficiency of white balancing can be improved to around 98%.**

Barco DP2K-36BLP laser phosphor retrofit DC projector adopts notch filter free design thanks to RGB+Phosphor (ALPD 4.0) design.

Laser-enabled Features, Benefits and Capabilities

Listed below are specific ***Laser-enabled*** LIP features, benefits and capabilities. As one would expect, they are being developed for special applications and specific performance requirements.

Ultra-high Brightness –

- **DCinema** LIPs first "proved-in" for very large screen DCinema applications where maximum attendance would support their higher acquisition cost. Maximum lumen output was limited by SLM chip *area*, chip and optics cooling, **RGB** wavelength selection, optical train and lens design. Initially, output reached an upper limit of about 60klm, but this has been surpassed by enhanced chip cooling, optimum RGB Primary wavelength selection and other custom modifications. **RGB** laser projectors now produce brightness levels in excess of 75,000lm. Some of the largest screens, such as Premium Large Format

(PLF) or branded premium theaters are equipped with *dual* (or quad) high brightness **RGB** laser projectors.

- **Non-Cinema** - “banks” of high brightness, no lamp change LIPs are expanding the growing field of “projection mapping”, providing breathtaking creative effects on a wide variety of architectural and natural “canvases”. The long-lifetime of the Laser illumination sources now enables cost-effective, *permanent*, multi-projector mapping installations. Below is one of the world’s largest mapping projects at the Hoover Dam on the Nevada-Arizona border.

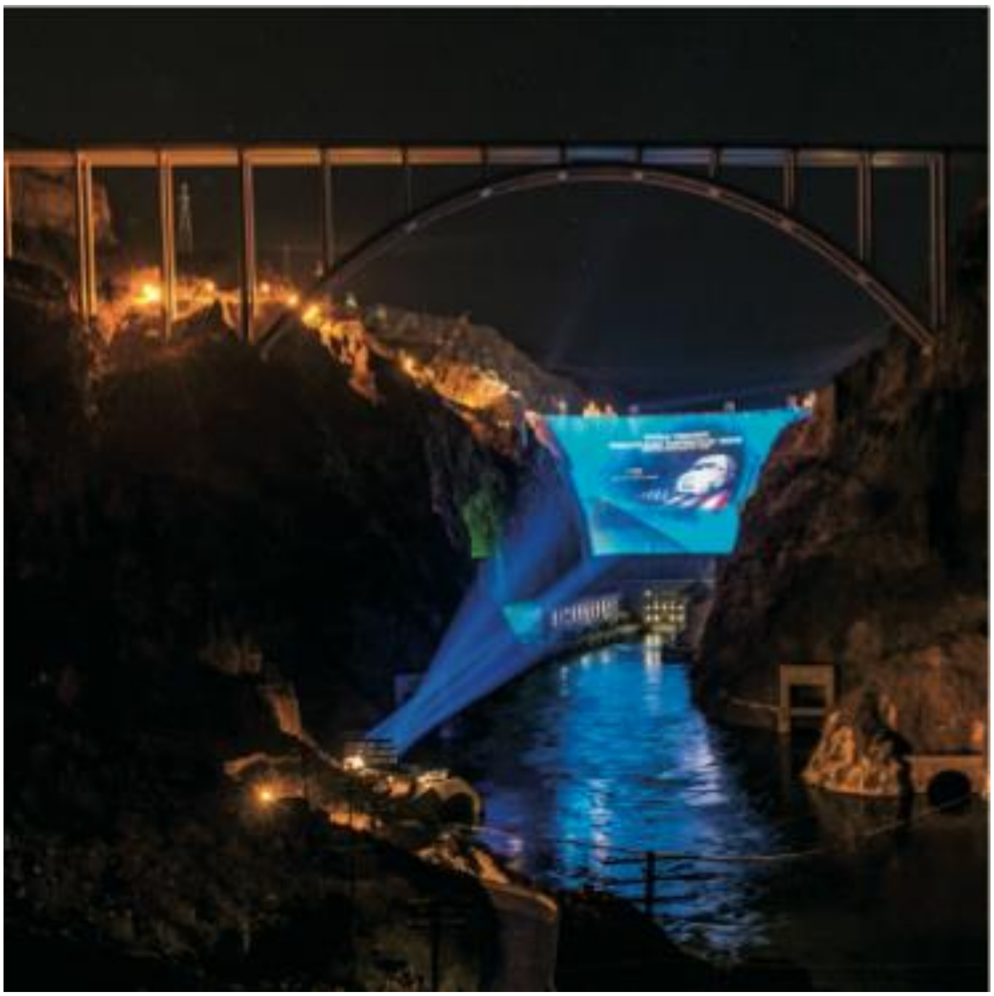
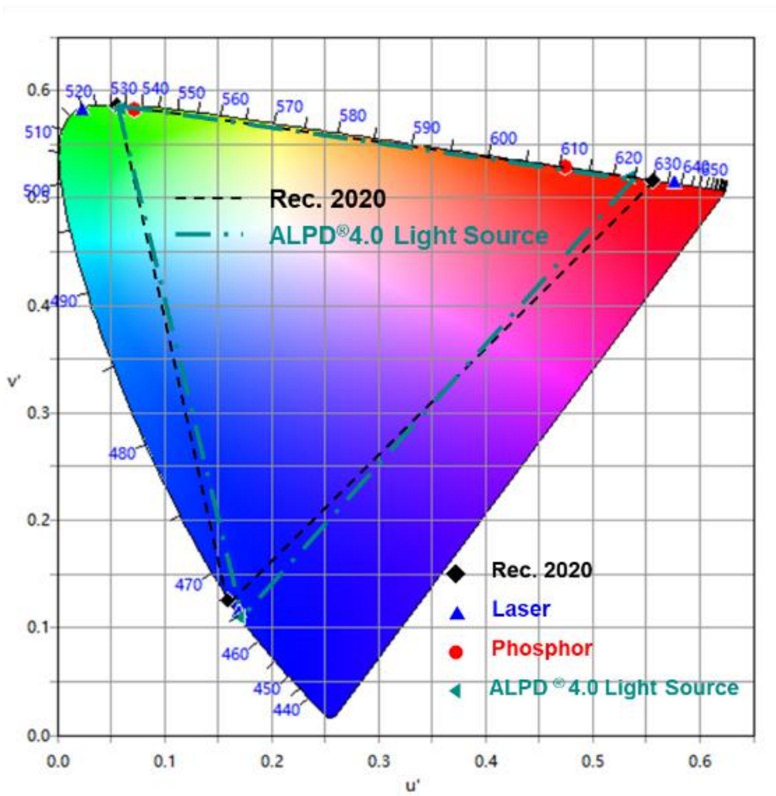


Photo of Barco Laser Projection Mapping event – 60 Projectors; 1.17 million Lumens; 2,500’ throw; 420,000 sq. ft. surface 4,592 x 2,048 pixels

Wide Color Gamut – REC. 2020 or "near-REC. 2020" Color Gamut can be easily achieved and is actually *enabled* by RGB Laser technology. Given that longer RED and shorter GREEN wavelengths are both readily available, *native* REC. 2020 is technically and commercially feasible. However, as these Wide Gamut primary wavelengths have lower luminous efficacy (lm/W), they are less energy efficient than REC. 709 or DCI P3 Laser color Gamuts.

The RGB+Phosphor (ALPD 4.0) light source in a 3DLP projector can achieve a wide color gamut, overlapping 98.5% of REC. 2020 as shown in Figure X. The source spectrum can be adjusted by direct modulating the four independent groups of diode lasers (Red, Green, Blue lasers and phosphor-excitation Blue lasers). The figure below shows the RGB primary color coordinates of direct lasers and phosphor light in CIE 1976 chromaticity diagram. Since the laser light and phosphor light have different color coordinates, a varying color gamut can be achieved with different luminance ratios of them.



The color gamut of our latest RGB+Phosphor (ALPD4.0) laser phosphor light source.

High Dynamic Range (HDR) – LIPs can enable Higher Dynamic Range in two ways: "the brute force approach", which takes advantage of the ultra-high brightness capability of LIPs, combined with second level of modulation to achieve much blacker "blacks". These systems are complex and expensive but represent "The Best" in Premium and Premium Large Format, or PLF Cinema presentation. The other approach is via "global" (or local "sector") dimming of the laser illumination itself. The capability to modulate the native illumination of the laser sources directly, though prohibited by the DCI Specification, is being well exploited outside of the Cinema application

Several branded, dual-RGB laser projector systems are extending the dynamic range and contrast performance of PLF Cinema presentation. They use a two-stage modulator approach, a "brute force" approach that requires very high light input which can only be provided by laser illumination.

Photo: Christie-built dual projector DOLBY HDR Cinema Projection system. Christie is a LIPA founding member

In 2021, DCI ratified and published an HDR Specification that will stimulate more content production and wider availability of this higher image quality technology.

Barco Light Steering provides another approach to HDR by directing additional light to the brightest parts of a frame. It is a promising and more efficient approach to increase dynamic range. This technology continues to be developed and has a promising future now that the DCI specification is complete.

Polarization modulation/phase control is new Laser-enabled SLM capability that is being developed. It has yet to be fully exploited for use in advanced HDR or other systems.

Brighter, efficient 3D – Ten years ago, 3D was one of the primary accelerators of the rapid introduction of LIPs into Cinema exhibition, primarily to offset the loss of brightness that all 3D systems incur. Though 3D may be less popular in Cinema today, the advantages of laser illumination, in particular RGB/R'G'B', 6 Primary, (so-called "6P") systems vastly improved the quality of 3D Cinema and other 3D visualization/simulation applications. The biggest benefit of "spectral separation" 3D comes from the elimination of the need for a "silver", polarization preserving screen. Dual projector systems, which enable full time output from both projectors, each with slightly different RGB Laser primary wavelengths, vastly increase the brightness of the image. [Ed. Note: This year, the Cinema world will see the sequel to the legendary Avatar, by James Cameron, a huge driver for 3D and LIPs, then and now.]

Spectral separation 3D systems have numerous high-end applications outside of Cinema. Amazingly high-quality 3D for visualization and simulation is one of the off-shoot capabilities of specialized LIPs. The combination of sophisticated multi-spectral filtering glasses with well-designed multi-primary (more than one RGB band per eye) laser sources enable super bright images with very low 3D cross talk. The narrowband RGB laser sources are easily filtered with no spectral overlap. Speckle is reduced as these multi-primary systems produce more "spectrally diverse", i.e., wider bandwidth light).

Laser Rear Projection "wall" for Auto Design/Visualization

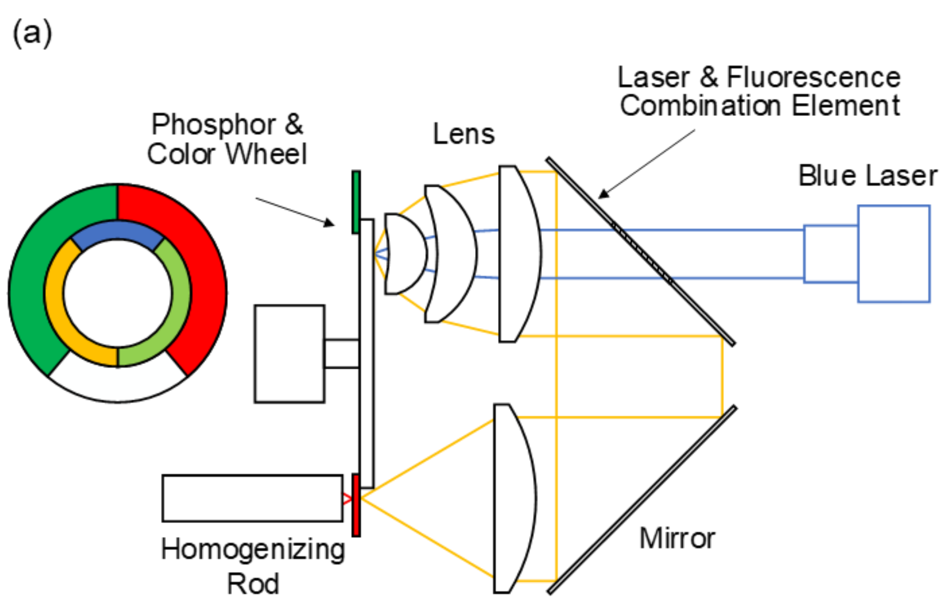
Laser Rear-Projection Video walls – RP LIPs are used as the building blocks for the most advanced large-scale video walls. In these applications, color saturation, color uniformity and spatial brightness uniformity are taken to the max *and* are provided by extremely efficient, long lifetime *Laser light sources*. In these systems, image quality and uniformity are enhanced, while dramatically reducing power consumption, maintenance and *down-time for calibration or light source replacement.*

Photo courtesy of Barco, LIPA founding member - RGB Laser ODLS-721

Multi-LIP applications - LIPs can produce more uniform brightness across the frame, a benefit that was initially not valued by the Cinema community until it became clear that with an inherently "flat" illumination source, no power or bit depth was wasted to achieve required uniformity (typically achieved via compensation by the SLMs). Brightness and color uniformity are now highly valued in Cinema, but are absolutely essential for any edge-blended, multi-projector application, such as control rooms, simulation, dome projection, mapping, etc. The combination of native color and brightness uniformity with better overall efficiency has taken all these applications to higher levels of brightness and performance. Recently, the elimination of the need for lamp changes has enabled *permanent* large scale, multi-projector mapping installations.

Ultra-Short Throw "UST" Laser TV - Laser illumination is not just for big screen applications. By 2013, Laser-Phosphor technology from LIPA member Appotronics enabled a new category of Projection TV "turned inside out".

LG's two-piece Hecto Laser TV consists of an Ultra-Short-Throw (UST) projector and specialized 100-inch screen debuted at CES2013. Hecto TV (powered by Appotronics' ALPD2.0 technology) was the first mass-production Laser TV that "placed the corner stone" for this new TV category.



The architecture of Appotronics's ALPD®2.0 laser phosphor light source

More recently, the combination of “4K” high resolution SLM chips, wider gamut RGB laser engines and ultra-short throw projection lenses have brought new life to “Laser (rear projection) TV” - but “without the box”. This application is extremely popular in the Far East and enables big screen TV images that do not require the big screen - or the shipping and installation costs - and can easily be moved from one room to another.

Photo: Epson UST 4K Laser TV – (Note: white screen required for projection on stone or colored walls) Epson is a LIPA member

Laser-enabled size/weight reduction – Increases in power per laser diode as well as the ***integration of multiple Laser “dies” or “facets” per package*** have enabled substantial reductions in the size and weight of high brightness projectors. 50+klm used to require “washing machine-size” beasts, but now are available in smaller form factors. This model includes 3 chip 4K resolution, 50,000lm and by augmenting its BPP architecture with longer wavelength Red Lasers, it comes close to wide gamut Rec. 2020.

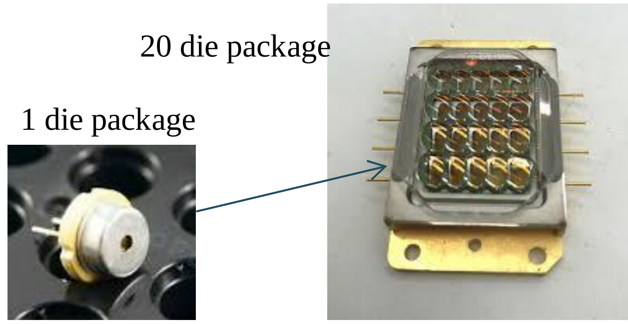
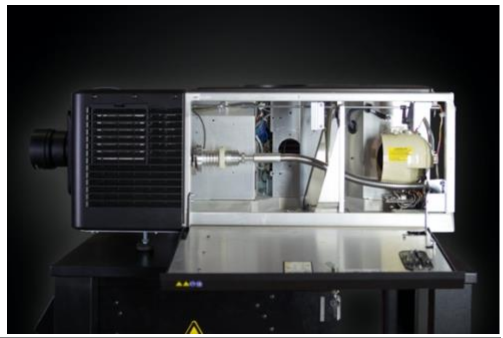


Photo: Panasonic 50,000lm; 3chip; 4K BPP+RED wide gamut laser projector @<320L volume

Remote Laser Engine projectors - “Off-board” or “Remote Source” Illumination is uniquely enabled by very low <u>étendue</u> laser sources, which in turn enable efficient laser power coupling into large core optical fibers. The ability to couple 10s or 100s of watts of Laser optical power is enabling practical short and medium distance laser illumination and “delivery” to a remote projection head. A few niche systems have been available for some time. Early systems were sold mainly for retrofitting older lamp-based digital Cinema projectors with higher image quality and much longer lifetime Laser illumination.

This application is beginning to see growing interest in both Cinema and non-cinema markets and may ultimately lead to the convergence of LIPs with “controllable Lighting”. One application that has yet to be commercially achieved is the concept of a “Light Farm”. That is, a large, centralized RGB Laser light source or bank of Laser engines that powers an entire multiplex or theme park attraction. Although technically and commercially challenging, this could be achieved as some of the missing ultra-high-power, fiber-coupled sources and appropriate regulatory structures are developed. In the meantime, the separation of the laser engine from the projection head enables much smaller, quieter, and cooler light/image delivery for multiple projector applications.

Images of two Remote Illumination systems offered by LIPA members are shown below.



Cinemeccanica – LUX Remote fiber delivery System

Cinemeccanica is a LIPA member

Digital Projection – Satellite MLS Modular Laser System
Digital Projection is a LIPA member

<u>Conclusions</u>

- The broadening development of Laser Illuminated Projection has addressed large enough markets for **continued Laser technology investment** and for projection design teams to move well beyond “meeting basic image quality specs”

- **Reducing Acquisition Cost** continues to be a driver in nearly all categories - suggesting ongoing opportunity for improved laser sources with higher power and longer lifetimes at lower per laser watt prices
- **RGB and Laser Phosphor "Hybrids" will continue to evolve** and coexist, addressing more product requirement segments as they develop and improve.
- The **Gallium-Nitride (GaN) Blue laser/Blue LED supply chain still dwarfs that of Red and Green Lasers**; cost/volume and efficiency/lifetime advantages continue to favor BLUE + Phosphor and Hybrids for all but the highest performance and/or fiber delivered designs
- **Physics continues to limit the availability and performance of longer wavelength GREEN and shorter wavelength RED diodes**, further driving the clever use of hybrid engines.
- **Off-Board Illumination is becoming feasible at distances up to 500 meters** and will emerge as a new application-enabling technology. However, new regulatory challenges will emerge. Large "Light Farm" systems will require laser sources with better beam quality and much higher power per delivery fiber.

****

GLOSSARY OF TERMS AND ACRONYMS

- **LIP** = Laser Illuminated Projector; a projector where all or some of the light projected is produced by one or more lasers, laser diodes or laser modules
- **LIPA** = Laser Illuminated Projector Association; founded in May of 2011 by a group of projector suppliers, manufacturers, and users to facilitate regulatory changes and accelerate the adoption of LIPs. See: www.LIPAinfo.org
- **DCI** = Digital Cinema Initiative – a group established to set and manage specifications for the global conversion from film to "digital" i.e., file-based Cinema capture, storage, distribution, projection and anti-piracy
- **DCinema** = Digital Cinema per DCI 28.0 specifications; originally used to distinguish between traditional film-based Cinema; as of this writing, essentially all Cinema is DCinema so often the specialized term is not used

- **BLUE Laser** = A laser, laser diode or laser module that emits visible light wavelengths that a human sees as Blue; ~440-470nm
- **BPP** = BLUE laser "pumped" or "excited phosphor; a hybrid Laser + Phosphor architecture that uses high *energy* Blue light to excite a phosphor material, typically on a rotating wheel that transmits or reflects emitted broadband light ranging from Green to Yellow to Red. The broadband light emitted off of the surface of the wheel is filtered to the desired output spectrum; often the Yellow light is blocked leaving the GREEN and RED primaries. Additional Blue laser light provides the BLUE Laser primary illumination for the SLMs and ultimately, the projected image.
- **Lamp-less projector** = Term describing projectors with solid-state Laser, BPP, LED or Hybrid light sources. The term is meant to convey the benefit of "never" needing a lamp change. As no solid-state Laser, BPP or LED light sources have infinite lifetimes, at some point they also must be replaced. But in many cases, Laser light sources are now available that can last as long as the projector.
- **"White" light** (WL)= broad band light containing all wavelengths in the visible range such as light from the sun or lamps or bulbs such as Xenon Arc or High-Pressure Mercury that produce "all visible colors" and can be easily filtered to approximate sunlight. This term is also used to describe the combination of narrowband (laser or LED) RED, GREEN and BLUE or RGB light that appears to a human as White when projected on a white screen. Technically, this light is actually RGB when separated into its spectral components or measured by a spectrometer. Note that there are infinite combinations of RGB that produce white light from a digital projector. For this reason, there is a range of "white" colors or white points available. The white point is typically specified for various color spaces.
- **RGB or RED, GREEN and BLUE primary light** = the three primary colors, which when additively combined, produce all the colors of a color space or gamut bounded by the triangle from the net colorpoint of each primary. RGB primaries may be produced discretely by individual lasers or laser module; as combinations of multiple laser wavelengths or bands or by filtering Red, Green and Blue bands or spectra from a broadband White Light source such as a Xenon lamp in a Cinema projector.

- **Spatial Light Modulator (SLM)** = a multi-pixel transmissive or reflective chip that transmits or reflects illumination light proportionally to an input signal per pixel and time period. Most projectors use either DMD - Digital Micromirror Devices or LCD – Liquid Crystal Display devices. Pixels are arranged in rectangles with the wider dimension (#of columns) noted in K or 1000 columns. A 4K Cinema SLM has 4,096 columns (4K in Computer Science). Modulation of amplitude, brightness per pixel, can be directly modulated in the analog domain or indirectly via pulse width modulation in the digital time domain.
- **Digital Micro-Mirror Device (DMD)** = Spatial Light Modulator chip type that incorporates a moveable micro-mirror for each pixel or picture element of the total frame. The mirror has an "on" state, that is, a position where it reflects the maximum amount of input illumination to the projection lens optics. In the "off" state, it diverts the light of that pixel to a beam "dump" that blocks and absorbs it as waste heat. The length of time the mirror is in the on state per frame time determines the perceived brightness of the pixel for that frame. TI's DMDs are extremely reliable and their pixel mirrors can operate at extremely high levels of input Laser light, making them well suited for DCinema and other high brightness LIP applications.
- **Liquid Cristal Display (LCD)** = SLM type that utilizes a specialized organic chemical that transmits or blocks light proportional to an applied signal. LCD chips or "panels" have been designed to operate in transmissive mode but for higher illumination levels, a special type of LCD panel called LCoS or Liquid Cristal on Silicon is mounted on a highly reflective Silicon substrate which enables the incident light to pass through the pixel "valve" twice thereby providing a higher dynamic range and backside cooling of the chip.
- **Liquid Crystal on Silicon (LCoS)** = A dual pass LCD design where the illumination light passes through the Liquid Crystal "valve", reflects off the silicon **substrate** and passes through the pixel valve again. Key benefits of the LCoS Design are that it can achieve a higher dynamic range and it can be cooled from the backside and mounted on combining prisms on the front side enabling very compact architectures.
- **Picture element or pixel** = discrete piece of an image projected on the screen. The frame consists of n x m rows and columns of individually projectable picture elements. Each pixel consists of modulated RGB light for each frame period. The mix of RGB amplitudes determines both the color

and brightness of the pixel. The digital video signal determine the amplitude of the projected mix of RGB light per pixel per frame.

- **"E to O" conversion efficiencies** = Electrical to Optical conversion efficiency It is the % of input electrical watts that a device, module or system outputs as Light power in optical watts. As both metrics are of power in units of watts, they can be compared. Note however that optical power in watts is not the same as perceived brightness, which is a function of wavelength (color) of the optical power. Green light appears the brightest for a given optical power, then Red with Blue providing very little brightness. E to O efficiency metrics enable comparison of like devices. Examples: a Blue diode with 30% E to O is more efficient than one with 12% efficiency. RGB engine efficiency is a complex interaction of device efficiencies, primary wavelengths, required cooling, power supply design and beam quality. Engine efficiency *correlates* with Projector efficiency but is not the same.
- **Laser projectors** = Originally this meant Laser Light Show (LLS) equipment that projected high power, collimated laser beams defining lines, images and other effects on dust or moisture in the air. The term Laser Illuminated Projectors or LIPS was established by LIPA to distinguish the developing product category from the older and far more hazardous LLS category that was severely regulated by the FDA. Ten years later, the adoption of Laser Illuminated Projectors has made it the dominant category and the term has been simplified to Laser Projector by most users. LIPA continues to use the term Laser Illuminated Projector to stress the extremely low level of hazard presented by all but the highest brightness LIPs relative to the projected Laser beams in a Laser Light Show.
- **US FDA-CDRH** = United States Food and Drug Administration-Center for Diseases and Radiological Health; one of the first government agencies to regulate the use of Lasers in commerce in the 1970s. Longstanding regulations have existed to control the use of high-power, Laser Light Show systems. LIPA started its mission to rationalize FDA LIP regulations after individual manufacturers banded together to present a unified voice in the regulation of LIPs. The FDA is a US agency. The International Electrotechnical Commission (IEC) regulates LIPs on an international basis
- **Laser Light Shows (LLS)** = A laser light show is a system or device that projects "raw" high power, collimated light beams, which preserve the intensity of the laser output over vast distances. The emergence of these

early entertainment systems in the 1970s triggered the early regulatory regime controlled by the US-FDA. LLS systems are still tightly regulated, requiring registration, Variances, that is, a license to operate a specific product in a controlled way with trained personnel and other safety measures. NOT the same as a LIP, which incorporates lasers to produce the output but that converts it to a divergent beam as it exits the projection lens, rapidly reducing the hazard as the viewer moves away from the lens.

- **RGB Laser** = LIP or laser module consisting of ONLY Red, Green and Blue laser light sources. NOT a hybrid with phosphor, lamp or LED sources. Some call this design "pure" laser or "true" laser to differentiate it from hybrid types.
- **Blue Laser Diodes** = Solid-State, Electro-Optic device that converts electrical energy into Blue light (440-470nm). Laser chips or "dies" are packaged in single or multi-die formats. The output of the chip is NOT well collimated and is often lensed to focus the output to a desired geometry-often but not always a circular spot. The Gallium-Nitride (GaN/AlGaN) material system produces BLUE and GREEN primary light output.
- **LED lighting** = A class of Solid-State Illumination (SSI) analogous to LIPs where the illumination is produced either by RGB Light Emitting Diodes (LEDs) or Blue LED pumped "yellow" phosphors to produce "white light". The huge investment in LED lighting boosted the volume of Blue Lasers and the application of BPP architectures for LIPs. LEDs are used in projection but as the output of LEDs diverges rapidly (is not collimated like laser output), the amount of light that can be focused on the SLM is severely limited.
- **Gallium-Nitride (GaN)** = Gallium-Nitride is a semiconductor material system used to produce UV, Blue and Green LEDs and Lasers. It is a mature technology; produces efficient, long-life devices available in a range of discrete wavelengths and continues to increase in terms of output power per die. UV and short wavelength Blue came first with continuous progress in terms of power per device, efficiency, lifetime, and longer wavelength output into the GREEN band. However, as wavelength increases, efficiencies, power per device and lifetime generally decrease.
- **BPP + RED** = Laser Light Source architecture that combines the output of BLUE Lasers, Blue Laser-Pumped Phosphors and RED lasers to provide RED,

GREEN and BLUE light to 3 chip or sequential, 1 chip Spatial Light Modulators. RED lasers are added to compensate for the low and less saturated Red light output from the phosphor.

- **UST** = Ultra-Short Throw Lens or TV design. Special variant of a projector that projects the image up steeply to the rear, on a very close wall or screen. Similar to a projection TV "in reverse" - without the enclosed screen. Viewer typically cannot come between the lens and the screen, an added safety feature for UST-TVs with laser light sources.
- **Solid-State Illumination** = Lighting or illumination systems comprised of semiconductor-based, "solid-state" light emitting devices, such as Laser Diodes (LDs) or Light Emitting Diodes (LEDs), as opposed to lamps such as incandescent or gas discharge.
- **White Balanced (WB) Lumens=** The maximum lumen output of a LIP that is calibrated to produce required White Point and in the case of DCinema, the specified RED, GREEN, and BLUE color points to assure maximum color saturation and specified color gamut
- ***Étendue*=** the optical metric that describes the "extent" of light-source in terms of its geometry. It is the combination (product) of the source cross-sectional area and its divergence in solid angle (steradians). The metric is normally expressed in mm^2-sr. The optics of the projector may have a variety of component *étendues*, but the smallest *étendue* component limits the maximum amount of light that can be transmitted through the projector. For example, the etendue of the mixing rod may be 10, but if the *étendue* of the SLM is 8, then some of the coupled laser light from the mixing rod will not be transmitted through the SLM chip. The collimated output of a laser beam can be *2-4 orders of magnitude* smaller than the input etendue of a mixing rod and downstream chips and optics, huge increases in coupled light are possible. This is one of the underlying benefits of using Laser illumination. In fact, the amount of laser power that can be optically coupled into Digital projector is limited only by the ability to cool the chips, prisms, and optics as even a small percentage loss leaves a lot of heat in components.
- **Laser Speckle=** An image quality defect created by static or dynamic interference patterns produced by the coherent output of a laser. This pattern was initially a "show-stopper" for early Laser projector demos as it

was seen as a unacceptable “step backwards” in image quality, producing a shimmery, “speckled” pattern where solid color should be. Lots of engineering went into solving this problem. In general, multiple discrete lasers, beam angles, polarization states and wavelengths are the key to minimizing speckle. Of these, **the spectral width of the “band” is the best way to minimize speckle**. This is why the combination of broadband phosphor emission and narrow band RGB Laser diode light is so effective. Wider bandwidth “hybrid” RGB primaries effectively **eliminate speckle**. However, they also reduce color saturation and increase the *étendue* of the light output from the hybrid engine, limiting the total amount of light that can be coupled into and through the projector.

END Final Public Release Version - BB – 12/2/22