Lasers, Lamps, or Phosphors – Choices for the Future of Digital Cinema

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Abstract

The first generation of digital-cinema projectors has now been deployed into the majority of movie theaters around the world. The illumination technology used for that first generation was xenon lamps. When that choice was made xenon was the only viable technology that could achieve digital cinema's goals. Today, cinema has a new set of challenges and a new set of technologies to choose from. Now that laser and laser-phosphor are mainstream illumination technologies cinema-projection engineers have an entirely new set of design decisions to make.

Author Keywords

Projection; digital cinema; DCI; illumination; xenon; laser; RGB laser; laser phosphor; LaPh; P3; Rec.2020; 3D; 6P; SCR.

1. Introduction

On June 19, 2000 digital cinema hit its first major milestone. Star Wars Episode I: The Phantom menace was publically shown using early prototypes of Texas Instruments' DLP™ Cinema projectors on two screens; one near New York and the other near Los Angeles. Although those prototypes were still somewhat crude compared to the projectors in use today, they successfully demonstrated that digital projection was a viable alternative to film exhibition.

The economic advantages of digital for exhibition had been obvious for a long time. A typical major movie release from Hollywood could open on over 3,000 screens. Each one of those screens needed a physical film print that could cost several thousand dollars. Consequently, distribution costs for a single film ran easily into millions of dollars.

In contrast a digital movie could be stored on a portable hard drive costing less than $100, and the hard drive could be reused for multiple releases. However, not everything is about the money. The movie-going experience still has to be better than what can be seen in the home. Otherwise who would attend?

In order to ensure high presentation quality, the Digital Cinema Initiative (DCI) was formed in March 2002 by a coalition of Hollywood studios with a mandate to establish industry standards for digital cinema [1]. Their goal was to match the quality of existing film standards. The following overall specifications were determined to be necessary:

- A nominal brightness of 48cd/m^2.
- A nominal sequential contrast of 2,000:1.
- An ANSI contrast of 150:1.
- A color space known as P3 exceeding Rec.709 that could reproduce more of the colors captured by film.
- A minimum resolution exceeding HD.
- A white point of (x=0.314, y=0.351) to match the typical white point of open-gate film.

Reliability was the remaining requirement. The exhibitors were accustomed to mechanical film projectors that could be expected to last from a minimum of ten years to as many as thirty. They had an expectation that any digital projector they bought to replace mechanical ones would have a similar life.

2. Xenon Lamps

In the early 2000's as the projection equipment manufacturers began to design products to meet the DCI requirements, there were extremely limited options for the light source. Assuming a typical screen gain of 1.8, achieving 48cd/m^2 on a screen 50 feet (~15m) wide requires over 10,000 lumens. Achieving the same luminance on a screen 65 feet (20m) wide requires nearly 20,000 lumens. The sheer light output required of the projector made LED lighting unfeasible. Laser and laser-phosphor were far too immature as illumination technologies to consider. That left xenon and mercury-vapor lamps.

However, mercury-vapor lamps tend to be red deficient. In contrast, xenon has a relatively flat spectrum. In addition, multi-kilowatt xenon bulbs were already in widespread use in the cinema industry as the lighting source for film projectors (where they replaced carbon arc lamps). Mercury-vapor lamps were (and still are) limited to hundreds of watts. The choice was obvious.

However, while xenon lamps provided an excellent solution for the Hollywood studios, film exhibitors had other concerns. Unfortunately, xenon bulbs have a relatively short life span and as they age they get dimmer. They are also susceptible to flicker. Both of these problems can impact the audience's enjoyment of the movie. Eventually the lamp will fail and will need to be replaced.

The xenon gas inside the lamps is at extreme pressure, particularly during operation (typically ranging from four to over ten atmospheres), which makes them an explosive hazard. Safely replacing a lamp requires specially-trained personnel wearing protective clothing and a face shield. In any given theater a certain number of spare lamps will have to be pre-purchased and on hand for quick replacement.

In addition, of all the illumination technologies used in digital projectors, xenon lamps are typically the least efficient electrically and require a higher level of forced-air cooling, which consumes additional power. All of these considerations lead to an ongoing cost of ownership for theatre owners.

3. Laser-Phosphor Light Sources

Laser Phosphor (LaPh) is a newer option for a projection light source that has begun to find a place in digital cinema. LaPh is a solid-state technology that relies on a combination of low-cost blue lasers and ceramic phosphors to generate the required red, green, and blue light. Typically, in LaPh systems the blue channel is provided by blue laser diodes.

Such lasers operating at 465nm are readily available. This wavelength of blue light is very close to the DCI P3 blue primary and makes a very natural choice. A second set of blue lasers, typically 445nm are used in parallel as the pump for a yellow-emitting YAG phosphor. The output of the phosphor has a broad spectrum which can be filtered using dichroics to generate the required red and green primaries.

The major benefit promised for LaPh systems is a reduction in the total cost of ownership (TCO). As a solid-state technology, LaPh illumination systems are predicted to have very long operational lifetimes; as much as 30,000 hours to half brightness (although

DCI-compliant LaPh projectors in cinemas haven't been operating long enough yet to confirm this). The light source will not need to be constantly replaced as does a lamp. In addition, LaPh systems are typically more energy efficient than Xenon. This should also help to reduce the cost of ownership by reducing electricity bills. Another benefit of the long operational life is that the on-screen brightness is more stable, reducing only gradually over time.

However, in a good many theatres a lower TCO is not necessarily realizable. For the most common theatre sizes the TCO for xenon can actually be lower than for LaPh, primarily because of economies of scale for the most popular xenon lamps.

For example, a 20,000lm xenon projector using a 3kW lamp that is changed every 1,900 hours of use (at end of lamp warranty) will use nominally 16 lamps over 30,000 hours of "on" time. A cost analysis shows that the TCO of a comparable LaPh projector operating over the same time period is about 25% higher.

Over a service life of ten years an LaPh projector will also need to have its light source replaced anywhere from one to three times, adding to the TCO.

One possible benefit from using LaPh can come from a reduction in cooling requirements. LaPh-based projectors typically generate less heat than xenon-based projectors, which means less noise from forced-air extraction. Hence, "boothless" installations in which the projector is located in the theatre with the audience may be somewhat easier to accomplish. Such installations can reduce the cost of new theatre builds by reducing the amount of real estate required, which is especially valuable in emerging markets.

4. Challenges for Laser Phosphor

The first big challenge of designing a projector based on LaPh for the cinema market is achieving the requisite color space. While the blue channel is inherently within specifications, the yellow phosphors that are commercially available are very broad band. Although the resulting colorimetry may be acceptable for commercial applications where the Rec.709 color space is adequate, cinema demands the much more challenging P3 color space. To achieve this, a notch filter is required to remove much of the yellow light from the system. This has a direct, negative impact on the brightness and efficiency of the projector.

The next challenge in using LaPh as a light source is red deficiency. After dichroic filtering has been applied the intensity of the red light relative to green and blue can be low. The DCI requirements specify the color temperature of a full field white to be (x=0.314, y=0.351). In order to support this, manufacturers may need to rely on a "Red Boost." A red light source, typically direct-emitting red laser diodes, can be added to the red channel. Although this approach requires fewer red lasers than a "pure" (red, green and blue) laser solution would, it adds a substantial amount of cost and complexity to the design.

The ultimate limits on the use of LaPh in digital cinema are étendue and phosphor quenching. Most cinema projectors are built around TI's DLP™ technology, which is constrained to operate at light-path focal ratios no lower than about 2.5. At smaller f-numbers the contrast ratio will become unacceptable.

Phosphor is a lambertian emitter. Due to étendue considerations there is a maximum spot size on the phosphor wheel from which light can be captured and coupled onto the DLP device (also known as a DMD). Phosphors are also subject to a phenomenon known as quenching. The efficiency of a phosphor's ability to convert blue light to yellow light is limited by its temperature. As the energy density of the pump laser increases to 50W/mm^2 the conversion efficiency can drop by approximately 15%. At 100W/mm^2 efficiency can be reduced by 30%. See Figure 1. Even with improved cooling techniques there will still be a significant efficiency loss [2].

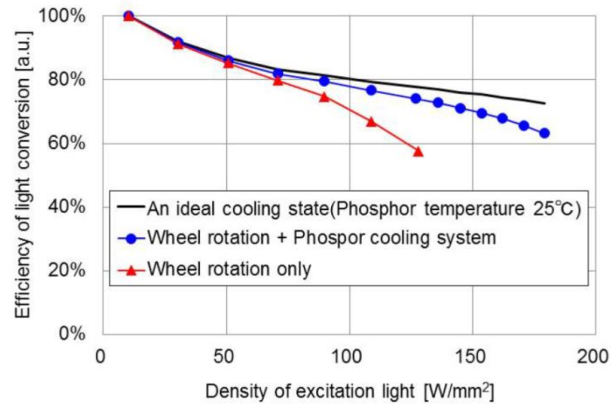

Figure 1. The dependence of laser-phosphor light-conversion efficiency on excitation density (from [2]).

One practical consideration for theatre owners is screen size. The light source in a typical LaPh projector is not expected to be replaced before 30,000 hours, at which time the light output has dropped 50%. Hence, if DCI-mandated on-screen luminance levels are to be maintained over that entire time, the screen must be sized as if the projector outputs half as much light as initially specified, with the projector running at much less than full power most of the time.

For example, a 20,000lm LaPh-based projector that when new could fill a screen 20m (65 feet) wide (assuming a screen gain of 1.8) should be treated as if it outputs only 10,000lm, restricting the screen to no larger than 14m (46 feet) wide. A similar analysis must be done with lamp-based projectors but the theater owner has the option to change a lamp after much less than a 50% drop (20% is considered best practice), meaning a much higher average light output. Consequently, LaPh is best suited to smaller screens.

5. RGB-Laser Technology

Laser projectors have been eagerly anticipated almost from the moment the first visible-light laser was created in 1960. Projectors that use lasers to directly create calligraphic (vector) images appeared on the scene as early as the 1970's and were typically used to give laser-light shows in planetariums. However, it is only recently that projectors that use lasers as light sources have begun to be deployed into cinemas and other large-venue applications (e.g., theme-park rides). Only within the last few years have the associated costs fallen enough to make a "pure" (red, green and blue) laser-illuminated projector economically feasible.

The greatest technical advantage that lasers bring is their extremely small étendue. A single laser diode can supply from one to five watts of optical power, which is woefully insufficient to light up a screen. However, because the étendue is so small it is possible to place large numbers of devices in parallel (see Table 1). This has enabled cinema projectors in excess of 65,000 lumens, almost double the brightest xenon-based projectors available.

The small étendue leads to a second advantage of RGB-laser illumination for projection. The étendue of a spatial light modulator such as a DMD is inversely proportional to the square of its f-number. Historically, DLP cinema has targeted an f-number of about 2.5 in order to maximize the étendue of the imager and therefore maximize the brightness achievable with a Xenon lamp. However, this has always come with a cost. The system contrast ratio is a function of f-number. As we decrease the numerical f-number to increase brightness, the contrast ratio decreases accordingly.

Table 1. Maximum number of devices in the étendue of a 4K DMD for different laser-diode wavelengths

Color Channel	Wavelength (nm)	Power (W)	Max. No. of Devices	Max. Achievable Lumens
Red #1	639	16	25	50,000
Red #2	657	12	233	139,000
Red #3	657	13	46	30,000
Green #1	547	3.1	400	836,000
Green #2	520	7	93	316,000
Blue	465	23	93	108,000

With a laser-based system there is the freedom to increase the f-number to 4.0 or even higher, providing a better contrast ratio while still coupling in enough light to maintain high brightness. The current state of the art for Xenon-based DLP Cinema projectors is a sequential (on/off) contrast ratio of around 2,000:1. With laser-based systems this can be increased to >5,000:1.

Another advantage that lasers bring to cinema is a greatly expanded color gamut. Recent televisions and monitors (e.g., models using quantum dots) are capable of reproducing colors well outside the P3 color space. Full reproduction of the Rec.2020 gamut defined for ultra-high definition (UHD) television is the ultimate goal but will be difficult to achieve. Nevertheless, the proliferation of such "Wide Color Gamut" displays will drive the creation of content in the Rec.2020 color space. Lasers, being essentially monochromatic, easily allow a projector to be designed to achieve the full Rec.2020 color gamut, thereby enabling faithful exhibition of that content in theatres.

High Dynamic Range (HDR) is another emerging display technology that is of increasing relevance. Recently, Christie teamed up with Dolby to create a projector for use in Dolby Vision™ theaters. This new projector has a contrast ratio that is in excess of 1,000,000:1 while more than doubling the screen brightness to 108cd/m^2. This feat was made possible by the étendue advantage offered by lasers.

As a solid-state technology, lasers are expected to have a very long operational life. Specifically, Christie's laser-projection systems for cinemas are designed to maintain 80% of their initial brightness for 30,000 hours, which corresponds, for example, to eight hours operation per day for ten years. This eliminates all lamp-replacement costs. When combined with increased electrical efficiency, the reduction in total cost of ownership can make a compelling case for RGB-laser illumination over xenon.

6. The Laser Advantage for 3D

One of the benefits of the digital-cinema rollout has been the reintroduction of 3D technology in movie theaters. This has become a major source of revenue and a key feature that has differentiated cinema from the home-viewing experience, especially given the failure of 3D to catch on in the home.

Figure 2. Christie's CP42LH RGB-laser-illuminated DLP Cinema projector with full-size laser module rack.

In most theaters 3D has been achieved by adding a switchable polarizer in front of the projector in combination with a "silver" screen and passive 3D glasses for the audience. The drawback to this approach is efficiency: at least 65% of the source light and typically closer to 85% is lost to the polarizer and to the glasses. When coupled with aged lamps that are no longer at their initial brightness, the effect is a very dim image. In one study of screens in China it was found that images could be as dim as ~1cd/m^2, with nearly half of the 170 theatres surveyed below 10cd/m^2 [3].

This has led to numerous audience complaints as well as difficulty convincing customers that 3D is something worth a higher ticket price. At such dim levels of light colors are washed out and image detail is lost. With the much higher light levels available to an RGB-laser-illuminated projector the 3D presentation can be restored to the 48cd/m^2 luminance that was always intended.

The use of lasers also enables an alternative approach to 3D known as "6P" (six primaries). In this approach, typically two projectors are used; one for left-eye images and one for right-eye images. Each projector uses a different set of non-overlapping wavelengths. This is feasible due to the fact that lasers are effectively monochromatic and provide a very tightly controlled spectrum. The audience is then issued a set of glasses with dichroic filters. This provides several benefits.

The first benefit is the elimination of the need for a "silver" screen. Polarized 3D requires a screen that preserves the polarization of light that hits it. Such a screen typically uses flecks of aluminum embedded in a binding agent for the front surface. This gives the screen a metallic silver sheen. It also introduces a problem known as "sparkle," in which the metallic reflections impart a distracting texture to the image. A 6P system, on the other hand, can use a traditional white screen which has a much more pleasing appearance.

Another major benefit of 6P is reduced crosstalk. Ideally each eye of the 3D glasses will reject 100% of the light intended for the opposite eye. In reality this is difficult to achieve using polarized light and leads to some of each image "leaking" into the other. For a typical silver screen a Stereo Contrast Ratio (SCR) of 100:1 can be expected for circular polarization, and 160:1 for linear polarization [4]. Wavelength separation is a more robust technology that generally has lower crosstalk. With 6P, SCRs over 1,000:1 have been measured [5], with recent advances in coatings now achieving in excess of 2,000:1.

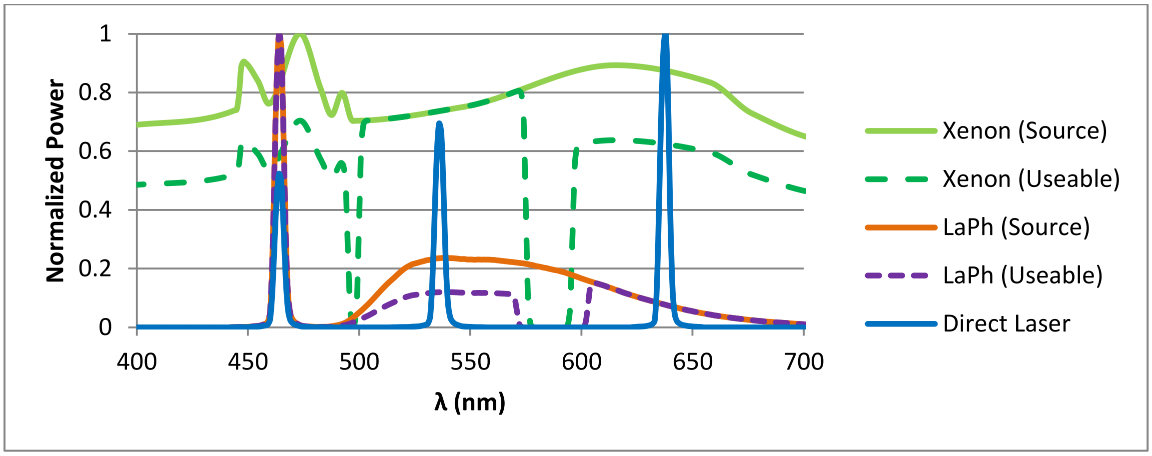

Figure 3. Comparing the spectra of three projector light sources and of images using those light sources.

7. Challenges for RGB-Laser Illumination

The biggest drawback to the widespread use of RGB lasers in cinema continues to be cost. Despite the tremendous advances in the last few years laser projection continues to be a premium product. As sales volumes increase economies of scale will help drive costs down. Further innovation is also expected to continue improving the wall-plug efficiency of RGB-laser projectors.

RGB-laser projection also needs to deal with the problem of speckle, which is a visual artifact similar in appearance to the above-discussed "sparkle," and which is a consequence of the coherent nature of laser light. A number of techniques both internal and external to the projector have succeeded in minimizing speckle to an acceptable level. However, some of these techniques, such as screen vibration, can add additional costs to the installation.

One potential problem introduced into theaters by RGB lasers, or rather by the monochromatic Rec.2020 color primaries they can reproduce, is observer metameric failure. The response of cone receptors in the human eye will vary between individuals. Narrow-band light sources reduce the number of wavelengths that these variations can be averaged over. This makes it less likely that two individuals will perceive the colors on the screen exactly the same way. How much of an issue this will be in practice for movie exhibition is an unresolved question. A multi-primary system with lasers at additional wavelengths is one possible solution, should one be required.

8. Comparing Optical Efficiencies

Figure 3 shows normalized power spectra for xenon, LaPh and direct (RGB) laser light sources (solid lines) along with the spectrum that appears on screen in each case (dashed lines).

Xenon lamps supply a large amount of yellow light (570nm to 600nm). In order to achieve the P3 primaries for red and green a yellow notch filter must be added to the system. The system must then be color balanced to achieve DCI white (x=0.314, y=0.351). Since xenon has an excess of blue and red light some of that light must be discarded. This reduces the efficiency of the system significantly.

LaPh systems also require a yellow notch filter. These systems are red deficient so there is a need to discard green light to meet the white balance. The blue channel is independent and typically composed of a large number of discrete laser emitters. This allows the projector to be designed with exactly the correct amount of blue light. Combined, this allows LaPh to be much more efficient than xenon. If red boost is used then the green light no longer needs to be discarded, increasing efficiency even further.

In the case of direct Laser all three colors are monochromatic and independent. There is no need for notch filters and the correct amount of power per channel can be chosen optimally. This gives the best efficiency possible.

9. Conclusion

When digital cinema began, xenon was the only practical choice as a light source that could provide the light levels necessary for large theatre screens as well as much of the color gamut offered by film. Today, however, laser-phosphor and particularly RGB lasers have become viable alternatives for a number of reasons. Both technologies eliminate frequent lamp changes while RGB lasers can also provide light levels far in excess of what is possible with xenon as well as a greatly expanded color space.

At the moment the higher cost of RGB-laser illumination limits its use to Premium Large Format theatres. As the cost of lasers continues to come down it is fully expected that RGB-laser projection will become comparable in cost to xenon- and laser-phosphor based projection. When that day arrives the other advantages of RGB-laser projection will make it the preferred cinema solution and the obvious best choice.

10. References

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