PRJ5-2
Invited

Progress on Laser Phosphor Light Source Technology

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Keywords: Projection display, laser phosphor light source, Rec. 2020, high efficiency

ABSTRACT

In recent years, the laser phosphor is becoming a mainstream light source technology in the industry of projection display. In this paper, we first review the development of different light source technologies used in projectors. Thereafter, we review the evolution of our laser phosphor technology and then present its latest progress-RGB laser phosphor.

1 INTRODUCTION

Over the past century, projection display systems have been well developed and widely used in many areas, including the cinema, education, business, and home theater. Researchers and engineers are still working to further improve the performance of projection systems, in the aspects of the lifetime, brightness, energy efficiency, color gamut, display contrast ratio, and cost. Among various components, the light source is quite essential to the system performance, and thus becomes a popular topic in the development of projection displays. The light source technology has been developed from the lamp, light emitting diode (LED) to the latest direct laser and laser phosphor technologies.

1.1 Lamp Light Source

The lamp light source for modern projectors has been developed since the 20th century, and the most commonly used lamps are xenon and high-pressure mercury lamps. However, lamps have some drawbacks, including limited lifetime (500-3500 hours), UV and IR irradiation, relatively low efficiency, safety risk due to high pressure, large Etendue value and cannot be instantly turned on and off [1]. Motivations to overcome these drawbacks lead to the development of long lifetime and high efficiency solid state light sources.

1.2 LED Light Source

LEDs have low cost, very long lifetime, and good color performance. Many attempts have been made to use LEDs in projectors in recent decades. However, LEDs are still suffering from some limitations. A significant one is the efficiency droop, referring to the efficiency reduction under a high input current density, which limits the achievable luminous flux of an LED chip. Meanwhile, LED light sources have Lambertian emitting patterns, resulting in large Etendue values. Therefore, they are not suitable for Etendue-limited high lumen applications, such as large-venue and digital cinema projectors.

1.3 Direct Laser Light Source

Direct laser projection displays have been continuously studied since 1960, when the first visible-light laser was invented. Laser diodes have narrow spectrum bandwidths and can achieve the largest possible color gamut Rec. 2020 [1]. Laser diodes can maintain their performance under a high-power density up to 25 kW/cm^2, while LEDs usually have an obvious efficiency drop at 10 W/cm^2 [2]. Thirdly, lasers can have extremely small Etendues, allowing the placement of a large number of laser diodes in parallel to achieve higher luminance. Finally, RGB laser-based projectors are cost effective benefitting from their high efficiency and long lifetime.

However, there are still limitations for direct laser light sources, which hinder their widely adoption in projector products, including the limited wavelength, the 'Green Gap' of semiconductor materials leading to the low efficiency and high cost of green lasers, and the thermal sensitivity of red laser materials. Another limitation of the direct laser projection display is the speckle noise, referring to the non-uniform display artifact on the screen generated by the coherent but dephased light interfering with each other. For the highly coherent laser lights, speckle noise can be quite severe and lead to poor display quality. The speckle contrast is commonly used to evaluate speckle noise, which is defined as the ratio of the standard deviation to the mean value of the fluctuated intensity [3]. To reduce the speckle noise, various method are applied based on the principle to generate uncorrelated speckle patterns in the spatial or time dimensions, such as introducing the incident angle diversity and so on. Besides, other methods introducing randomness to smooth the noise are also applied, such as vibrating the screen. However, these techniques with moving parts introduce new problems, including system efficiency reduction, system initial and maintenance cost increase, and extra reliability risk.

1.4 Laser Phosphor Light Source

Laser phosphor light sources are another type of solid-state light sources that typically utilize the combination of economical blue lasers and robust ceramic phosphors to generate the red and green lights cost-effectively. Laser phosphor light sources can overcome some problems of pure-LED or pure-laser light sources and have found various applications for projection displays.

Firstly, a phosphor is a wavelength conversion material, which absorbs efficient blue light and emits green, yellow or red light with high efficiency and low cost. Therefore, the laser phosphor technique can solve the 'Green Gap' problem of green lasers. Secondly, the laser phosphor technique utilizes a high-power-density blue laser light as the exciting source, providing a high luminance output. Thirdly, a blue laser can excite phosphor in a small region and provides a low Etendue value. Fourthly, a phosphor light commonly shows negligible speckle noise since it generates non-coherent light from spontaneous emission. Thus, phosphor light system have no demand of speckle reduction techniques. Finally, the total cost of ownership of laser phosphor light sources is quite competitive compared to traditional lamps.

However, there are still some challenges for laser phosphor sources. Firstly, the luminescence saturation limits the maximum luminance level. One solution can be applying phosphor materials on a rotating wheel. As thermal and optical energy spreads along the circumference of the wheel, the saturation threshold is increased. Secondly, most commercially-available highly-efficient phosphor materials have broad spectral bands, and are hard to achieve wide color gamut for high-end applications, such as DCI-P3 and Rec.2020. Thirdly, the red phosphors are currently suffering more on efficiency drop compared with green and yellow emission phosphors.

Appotronics has been dedicated to the research on laser phosphor technology and promoting its industrial application since 2007. Many companies also joined the effort to continuously develop laser phosphor light sources. In recent ten years, various designs have been proposed and introduced to the market. Casio introduced an LED/laser/phosphor hybrid light source in 2010, which is called Green Slim. This design solves the limited luminance and efficiency of green LED, but still suffers from the deficient red-light content of red LED. Texas Instruments (TI) also proposed its design of a laser phosphor light source in 2011. In the design, a blue laser is applied to excite the yellow phosphor on the phosphor wheel to generate yellow light. Meanwhile, a rotational color filter is applied to filter the phosphor light into R/G/B/Y primary colors in a time-sequential manner. The design can have the potential to achieve a high luminance output. However, the system architecture is relatively complicated. Meanwhile, the separate structure of two wheels demands two motors and requires precise synchronization between them, which further increases the system cost.

2 The Evolution of ALPD® Laser Phosphor Technology

Appotronics proposed an idea of using a blue light emitting semiconductor device (including lasers and LEDs) exciting a multiple-phosphor segment wheel technology in 2007 [4], namely the first-generation ALPD® technology. Thereafter, the ALPD® technology has been evolved for several generations and has achieved several breakthroughs in terms of the luminance, efficiency and color gamut.

The schematic structure of our first-generation (ALPD®1.0) laser phosphor light source is shown in Fig. 1(a). The light emitting from the blue laser is incident on a transmissive rotating wheel, which is composed of R/G/B/Y four segments. The wheel has a sandwich structure, with a blue-pass filter on the left, a phosphor film in the middle and a corresponding color purification filter on the right. Each segment can have its own phosphor and color purification filter. The B segment has a scattering diffuser film. This architecture had many advantages, including the compact size, least number of components, low total cost of ownership, low speckle noise, high efficiency and desirable color gamut.

However, this architecture has limited luminance scalability due to low thermal conductivity of transparent materials. Under the laser irradiation with high optical density, the phosphors, especially red phosphors, are affected by thermal quenching and optical power saturation. As shown in Fig. 1(b), with the excitation power density increasing, the red phosphor suffers from the most significant efficiency drop. Therefore, ALPD®1.0 light source is preferred to be used in applications with output flux below 3000 lumens.

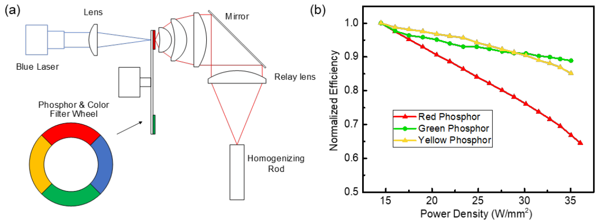

Fig. 1 (a) Architecture of ALPD®1.0 light source. (b) Normalized energy efficiency of phosphors versus the incident power density.

To overcome the luminance limitation of ALPD®1.0 architecture, ALPD®2.0 products was developed in 2013 with two main improvements, as shown in Fig. 2(a). Firstly, it utilizes a reflective phosphor wheel with the phosphor layers coated on a reflective metallic or ceramic substrate, whose good thermal conductivity can improve the thermal dissipation efficiency of the excited phosphor. Secondly, instead of directly filtering the Lambertian phosphorous light upon excitation, this design first collects the Lambertian light using an optical lens group and relays its magnified image onto the corresponding color filter mounted on the opposite side of the motor with smaller beam angle. This design can avoid trapping reflected light inside the color wheel and increase the filter efficiency. This design makes it feasible to filter red lights from excited yellow phosphors with higher light conversion efficiency and better thermal stability than pure red phosphors. Therefore, ALPD®2.0 laser phosphor light source offers much higher luminance than ALPD®1.0, enabling its application of high-end and high-lumen digital cinema projectors. Meanwhile, the novel in-plane structure of phosphor layers and color filters ensures the compact dimensions of the light source.

Besides the multi-segment color wheel in a single or double spatial light modulators (SLMs) projection system, ALPD®2.0 architecture can also utilize a single yellow phosphor segment in the triple SLM projection system, as shown in Fig. 2(b). To achieve the DCI-P3 color space, a notch filter is applied accompanied with the dichroic filters inside the Philips prism to purify the three primary colors, the situations of which are similar for both laser phosphor and xenon lamp light sources. Fig. 2(b) shows the normalized spectrum of laser phosphor light source and xenon lamp light sources with and without the filters.

The notch filter of ALPD®2.0 light source still introduces some light loss. Meanwhile, the red deficiency of yellow phosphors leads to the loss of extra green light to ensure white balancing for DCI compliant projectors. The overall efficiency of the spectrum usage of an ALPD®2.0 light source is 58.4% in a 3DMD DCI cinema projector. Therefore, it is still challenging and not economic to achieve significantly higher output than 18,000 lumens with the ALPD®2.0 light source (0.98” 3DMD, F/2.5 projection lens).

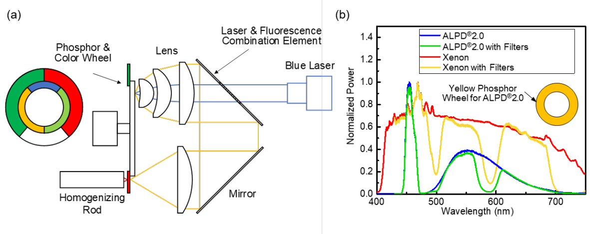

Fig. 2 Architecture (a) and spectrum (b) of ALPD®2.0 light sources.

To solve the red deficiency problem of the ALPD®2.0 architecture, ALPD®3.0 architecture adds red laser lights into the optical path to provide extra red with desired wavelengths. The associated products were developed in 2015 for high-end digital cinema projectors. In the ALPD®3.0 design, a designed combining mirror whose central zone is transmissive for blue and red laser lights while the rest area reflects all the yellow light is used to combine laser and phosphorous lights. Benefiting from the tiny Etendue of lasers, the small central zone minimizes the wasted percentage of collected phosphorous light, which is both cost-effective and energy-efficient. In this this, the red content of the source spectrum is significantly improved. Therefore, the energy loss caused by the notch filter for three primary colors and the energy loss resulting from the white balancing are significantly reduced. 74.2% of the total brightness of the light source can be utilized after white balancing. Therefore, the ALPD®3.0 laser phosphor light source can be used in the digital cinema projectors achieving a high luminous flux output over 30,000 lumens (0.98” 3DMD, F/2.5 projection lens).

Products based on ALPD®4.0 technology were developed in 2018. It utilizes a new light source architecture combining RGB lasers and phosphors, as shown in Fig. 3(a). The RGB lasers and phosphorous beams are combined efficiently at an intermediate image plane using a combining mirror with a specially designed coating, which transmits the tightly focused laser light and reflects the relatively larger phosphorous beam. Fig. 3(b) shows the normalized spectra of our ALPD®4.0 light source with three peaks of RGB lasers and the broad-band yellow phosphor spectrum. The novel RGB laser and phosphor architecture of the ALPD®4.0 enables much wider color gamut, and the DCI-P3 color gamut can be achieved without using a notch filter. As shown in Fig. 3(c), the elimination of the notch filter largely reduces the spectrum loss compared to the xenon lamp and previous architectures. Therefore, the overall efficiency of ALPD®4.0 light source after white balancing can be improved to around 86.9%.

It is worth mentioning that ALPD®4.0 architecture is essentially different from the direct laser technology. It solves the problem of phosphor’s limited color gamut, limited efficiency, and red deficiency. It still has cost advantage compared with direct lasers and also solves the speckle problem of direct lasers.

3 The Performance Characterization of the Projection System

We used a 1.2-inch diagonal size, 2048x1080 resolution 3DMD digital cinema projector (F/2.5 projection lens) as the platform to test different light source’s performance. Light sources based on different generations of ALPD® technology were built and integrated into this projector. We characterized the projector’s system performances in the aspects of energy efficiency, color gamut and speckle noise.

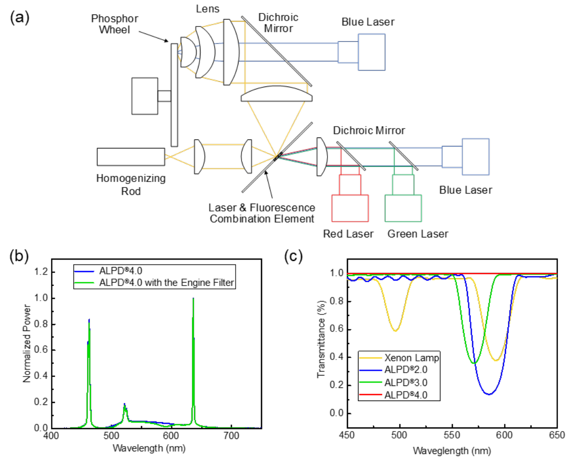

Fig. 3 Architecture (a) and normalized spectrum (b) of ALPD®4.0 light source. (c) Transmittance of the north filters for different light sources.

3.1 Energy Efficiency

Table 1 shows the energy efficiency comparison of the same three-DMD projection system with different light sources based on the DCI-P3 color space. A typical xenon lamp based high-brightness digital cinema projector has the light source efficiency of 5.1 lm/W. The ALPD®2.0 system shows improved efficiency of 8.5 lm/W benefitting from the high efficiency of blue lasers, high yellow phosphor conversion efficiency, and better beam qualities. The ALPD®3.0 light source has improved red content and more saturated red color and therefore the overall efficiency is improved up to 10.5 lm/W. The ALPD®4.0 light source uses 638 nm, 525 nm and 465 nm direct lasers plus 455 nm lasers to excite the yellow phosphor. It does not require a notch filter to achieve DCI primary color coordinates, and the efficiency can achieve 12.4 lm/W with the luminous flux output of 43,500 lumens.

Table 1. Efficiency Comparison of the Same Projection System with Different Light Sources

Light Source	*Xenon Lamp*	*ALPD®2.0*	*ALPD® 3.0*	*ALPD® 4.0*
Projection Flux Output (lm)	33000	23000	33500	43500
Source Power (W)	6500	2700	3200	3500
Efficiency to Achieve DCI Primaries	75.6%	73.4%	79.8%	88.3%
Efficiency of White Balancing	95.4%	79.5%	93.0%	98.4%
Overall Spectrum Usage Efficiency	72.1%	58.4%	74.2%	86.9%
Light Source Efficiency (lm/W)	5.1	8.5	10.5	12.4

3.2 Color Gamut

The ALPD®4.0 light source has a wide and continuous yellow phosphor spectrum plus three discrete (red, green and blue) laser spectra. The luminance of the yellow phosphor light can be adjusted by changing the driving current of the excitation blue lasers. Therefore, the source spectrum and color gamut can be adjusted by modulating the four independent groups of diode lasers (red, green, display blue and phosphor-excitation blue). Fig. 4(a) shows the RGB primary color coordinates of direct lasers and phosphor light in CIE1976 chromaticity diagram. Fig. 4(b) show the color coordinate variation of the projected red color with different r_{Ph} values, which represents for the ratio of red phosphorous luminance over total red luminance. With r_{Ph} varying from 0 to 1, the red color coordinate shifts from pure laser light to pure phosphorous light. The situation is similar for green light, as shown in Fig. 4(c). Therefore, by tuning the red and green r_{Ph} values, a varying color gamut can be achieved.

Besides the current modulation of lasers, adding notch filters can also adjust the spectrum and color gamut. With proper designs, a balance between color gamut area and system efficiency can be maintained. Fig. 4(a) shows an ultra-large color gamut that our latest light source can achieve, which covers 98.5% of the Rec. 2020 standard in the CIE1976 chromaticity diagram.

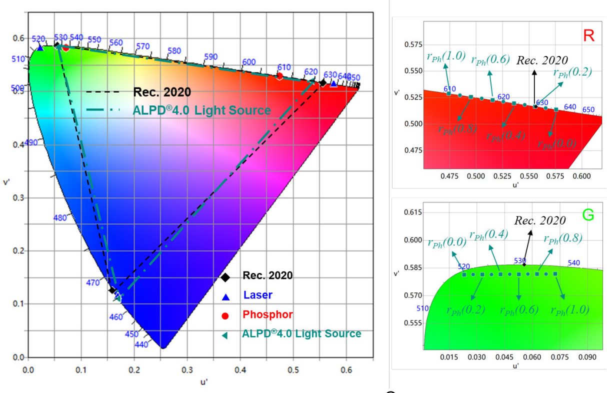

Fig. 4 (a) Color gamut of ALPD®4.0 light source. Different coordinates of (b) red and (c) green color gamut with various r_{ph} values.

3.3 Speckle Noise

As mentioned in the section of 1.3, the speckle noise remains one of the main challenges for direct lasers to be widely adopted in projection applications. Digital cinemas usually use silver screens or white screens. Silvers screens usually have higher gains, preserve polarization states and support passive glass 3D movies, but commonly show much stronger speckle noise. Therefore, the laser phosphor light source becomes a practical solution for high-brightness digital cinema projectors. The speckle noise of the projection system with ALPD®4.0 light source was evaluate by a commercial equipment (OXIDE SM01VS09-S).

Fig. 5(a) shows the speckle contrast values of white images projected on a white screen with a gain value of 1.1 and a silver screen with a gain value of 2.4. With the increase of r_{ph}(Y), namely the ratio between phosphor light luminance over total luminance, the speckle contrast ratio decreases almost linearly. Two images taken by the OXIDE's CCD camera on the white screen are also presented in Fig. 5(a), which shows that the image with r_{ph}(Y) of 96.4% exhibits much reduced speckle noise than that with r_{ph}(Y) of 0%. A subjective scoring test was performed by a group of 10 observers to evaluate the image quality in terms of the speckle noise on a 0 to 10 scale, with 10 corresponding to the best quality. The subjective scoring results are consistent to the experiment results, which means a higher phosphorous light ratio provides better image quality.

The characterizations were also performed for red (R) and green (G) projected images separately, and the results are similar. That is the speckle contrast ratio is reduced almost linearly with increasing of r_{ph}. For a digital cinema projector with ALPD®4.0 light source, r_{ph} has a value close to 70%, and the projected white image has speckle contrast of 1.5% on the white screen and 6.8% on the silver screen, which are acceptable for ordinary viewers.

The subjective scoring test was also performed to evaluate the projected video quality in terms of the speckle noise. Fig. 5(b) shows desirable consistency to previous results. In short, the speckle contrast of our latest RGB laser phosphor light source is significantly reduced compared to the direct laser light source. The speckle noise is acceptable for video playing on a 2.4-gain silver screen (without vibrating), which further reduces the cost for digital cinema customers.

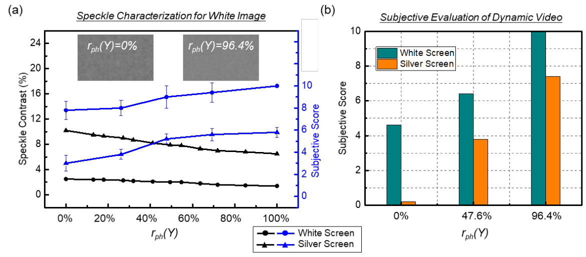

Fig. 5 (a) Speckle contrast ratio and subjective score for red image with various r_{ph}. (b) Subjective scores of projection videos.

4 Conclusion

In this paper, we first review the development of the light source technologies for projection displays, including lamps, LEDs, direct lasers and laser phosphors. Thereafter, we present the evolution of our laser phosphor light source technology. Over the years, four generations of technology have been developed, the key performance of which including the energy efficiency, light output flux and color gamut have been continuously improved. We also present the latest RGB laser phosphor light source architecture. We show that it achieves the energy efficiency up to 12.4 lm/W with 43500 lumen output and the DCI P3 color gamut, and has acceptable speckle noise. We also show that this architecture can enable a color gamut that covers 98.5% of Rec. 2020 standard. The proposed RGB laser phosphor technology solves the cost and speckle problem of direct laser technology, and solves the color, efficiency and luminance scalability problem of phosphors. To our knowledge, it is an optimal light source solution for high performance projection displays.

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