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NEW TYPE OF DLP OPTICAL ENGINE EQUIPPED WITH THE COLOR LED AND THE COMPOUND PARABOLIC CONCENTRATOR

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Abstract. *The technique of DLP optical projection is a sort of major techniques of optical projection. The traditional optical engine uses a UHP lamp, a light pipe and a color recapture as the major components of an optical engine. This study provides an optical engine that is suitable for the new type of DLP system: replacing the UHP lamp with LEDs to reduce the energy consumption; replacing the light pipe with the CPC to reduce the size of the optical engine, and replacing the color recapture with color LEDs for allowing DLP color output to be fully controlled by a circuit. The result that we acquired through the simulation on the optical engine simulated by the optical simulation software, TracePro, has shown that the optical engine's performance of the new type of DLP system tallied with the performance of the traditional DLP optical engine. This result has proved that the new-type optical engine designed in this study could replace the traditional one. In addition, its volume is smaller; it saves more energy, and it could achieve the color management with higher efficiency.*

Keywords: Digital light procession, Optical engine, LED, Compound parabolic concentrator, Color recapture

1. **Introduction.** Most of the applications of projection and display at present adopt LCD and DLP techniques. The DLP is the technique of digital projection using the DMD (Digital Micromirror Device), and every DMD would have only two statuses: "on" and "off". The advantage of the technique of digital projection is that this technique could keep generating images vividly and repeatedly without being affected by the environmental factors. Every DMD equipped with DLP™ core technique could switch itself on and off at the speed of 5,000 times per second. This switching speed of the DMD greatly surpasses that of the LCD. Most important of all, only one projection panel and one color recapture are required for the DLP™ technique to adjust and alter the beams of the three primary colors – red, green and blue – at the same time. By contrast, due to the slower speed of the LCD technique, the adoption of a framework comprising three projective panels is required and thus it makes a very complicated structure. The single-panel framework only needs a simple and slight optical system to develop a projector and a monitor whose total volume and weight are smaller and slighter than those of the three-panel system. Another advantage of the DLP™ technique is its simple and slight optical system: the mechanical structure of the optical device is simpler than the three-panel structure no matter it is installed in a projector or a big-screen TV, and this could bring

a higher contrast to itself. The higher contrast could provide a screen image with more abundant details, render the black color to look blacker, and make the screen image look more vivid, clear and sharp. According to the framework of the design, the single-panel system would never lose its focus; nevertheless, the LCD system equipped with three panels might lose its focus when it is being affected by the environmental factors, making the image look a bit of blurred. However, the image provided by the single-panel system could remain clear and sharp for good [1-4]. Beniamin has calculated the influence cast by the light tunnel's length and by the sectional area upon the uniformity of the outputting rays [5]. Due to the rapid development of LEDs in recent years, the trend of replacing UHP lamps with LED illuminants is gradually emerging. In both of C. Peng and C. Hung's studies, LEDs were adopted as the illuminants of the DLP projection [16,17].

2. **The Traditional DLP Optical Engine.** The traditional DLP optical engine adopts a UHP (Ultra high performance) lamp as its light source. The rays emitting from the UHP lamp would go through the light-tunnel system, and the light-tunnel system would thus unify the energy of the rays, turn the shape of the outputting rays into a square, and control the emissive angle. And then, the rays travel through the color recapture and are tinted with the colors required. After going through the DMD's pattern selection, the rays finally project the image outward through the projection lens. The UHP (Ultra high performance) lamp is the most adopted light source in the DLP (Digital light procession) system. Because of the UHP lamp's excellent efficiency, it is the most ideal light source for a projection system. However, a UHP lamp also has many shortcomings: its lifespan is about 5,000 hours, and the lifespan of the projection system is thus limited as well. Also, its over-high driving voltage, its oversized volume and its use of high-pressure vaporized mercury all become its obstacles to achieve the microminiaturization and the portability of a projection system. The traditional DLP optical engine uses the color recapture to create colors. The color recapture is often designed to be equipped with the three colors – red, green and blue, and it is rotated by a small motor. The color distribution of the color recapture would have different ways of arrangement due to different designs. Of the beams emitted from a UHP light source, there are higher wavebands as 440nm, 550nm and 580nm. After the rays are given one single color through the color recapture, a major part of the energy could not be fully utilized for it is absorbed in the selection process of the color recapture. Thus, the energy output is reduced with the energy absorption [6-9].

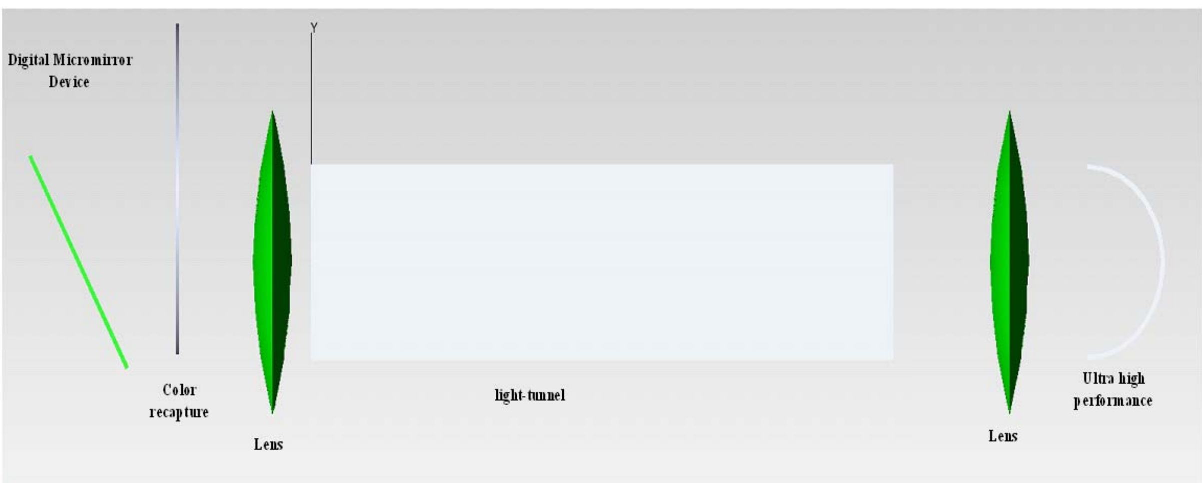

FIGURE 1. The traditional DLP optical engine

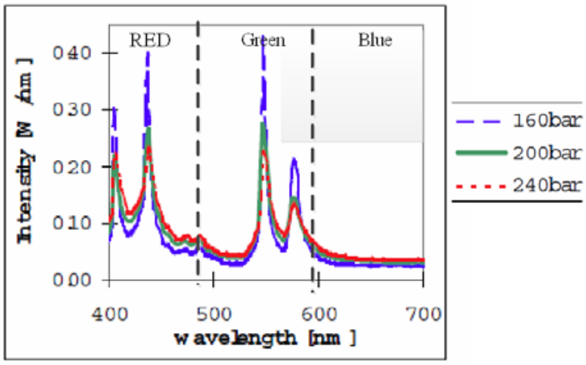

FIGURE 2. The spectra of UHP rays

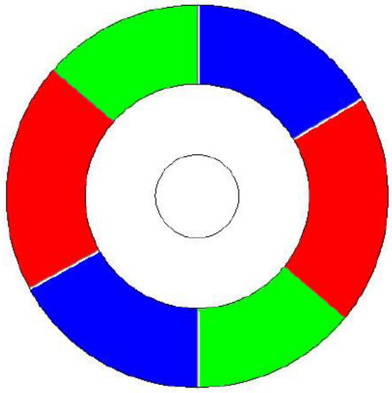

FIGURE 3. The structure of color recapture

The UHP light source works under the extremely high vapor pressure of the vaporized mercury. It is the sort of light source with a short electric arc, and the length of its luminous electric arc is 1mm. The optical particularity of the UHP light source is very similar to point light source. This is the reason why the DLP system favors the UHP lamp and adopts it as the light source for the optical engine of the DLP system. In order to heat up the mercury to the vapor state and to enable the luminous electric arc to happen, the UHP lamp will produce a lot of thermal energy, and the efficiency is thus reduced.

The traditional DLP optical engine adopts the light tunnel to unify the rays emitting from the light source in the optical engine and to output the rays from a lower angle. The energy emitting from the UHP lamp is reflected into the light-tunnel system through the reflectors, and through the multiple reflections within the light-tunnel system, the uniform emergent light is acquired. In order to output the rays evenly, multiple reflections of the rays are required. The more frequent the reflections are, the longer the light-tunnel system needs to be. Therefore, in a traditional DLP optical engine, the required length of the light-tunnel system is the longest length [10,11].

3. **The Adjustment of DLP Colors.** This study replaces the UHP light source with RGB LEDs as the illuminant of DLP system. In order to produce suitable colors, it simply requires the mixture of the three basic colors – red (700nm), green (516.1nm) and blue (435.8nm) – to be able to obtain almost all colors. In the fields of light mixing and illumination, these three colors are frequently used. Thus these three colors are termed the primary colors. Through adjusting the ratio of the primary colors, we could produce

the illuminant with the proper color temperature, hues and brightness conforming to the requirements of the DLP technique.

3.1. **The transformation of the chromaticity coordinates.** When color LEDs are adopted as the illuminant of a DLP projector, in order to modulate the suitable color for the illuminant, the following discussion concerning color simulation is required: in order to present different colors precisely, the chromaticity diagram is adopted to represent colors. X and Z simply represent the chromaticity of colors, and Y represents the values of brightness. X, Y and Z are termed tristimulus values. The transformation between the three tristimulus values (X, Y and Z) and primary colors (R, G and B) could be represented by the equation as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 2.7689 & 1.7517 & 1.1302 \\ 1 & 4.5907 & 0.0601 \\ 0 & 0.0565 & 5.5943 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \tag{1}$$

However, the obtainment of the three tristimulus values through the three primary colors (R, G and B) relies on the linear relation between the primary colors and tristimulus values.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.7689 & 1.7517 & 1.1302 \\ 1 & 4.5907 & 0.0601 \\ 0 & 0.0565 & 5.5943 \end{pmatrix}^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 0.041844 & -0.15866 & -0.08283 \\ -0.09117 & 0.25242 & 0.01570 \\ 0.00092 & -0.00255 & 0.17858 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{3}$$

3.2. **Color modulation.** Although the color we need could be modulated with the primary colors (R, G and B), the linear superposition does not exist between the coordinates of the color we need and the given colors (e.g., R, G and B) in the CIE1931 standard chromaticity diagram. However, the linear superposition exists between the tristimulus values of the color we need and the given colors. Thus the three tristimulus values of the color we need have to be obtained first to acquire the relation between the color we need and the given colors.

If the color we need could be modulated with two of the given colors, then the tristimulus values of the color we need are represented as follows:

$$X = X_1 + X_2, \quad Y = Y_1 + Y_2, \quad Z = Z_1 + Z_2 \tag{4}$$

where X_1, X_2, Y_1, Y_2, Z_1, Z_2 are the tristimulus values of the given colors.

The equation above could be applied to the addition of various colors, in other words, knowing simply the tristimulus values of every color could make us acquire the tristimulus values of the mixed color. When we come to know CIE1931 chromaticity coordinates (x and y) of one color and the tristimulus value of its brightness Y, we could acquire the tristimulus values of that color with the equations as follows [12,13]:

$$X = \frac{x}{y}Y, \quad Y = Y \tag{5}$$

$$Z = \frac{z}{y}Y = \frac{1-x-y}{y}Y \tag{6}$$

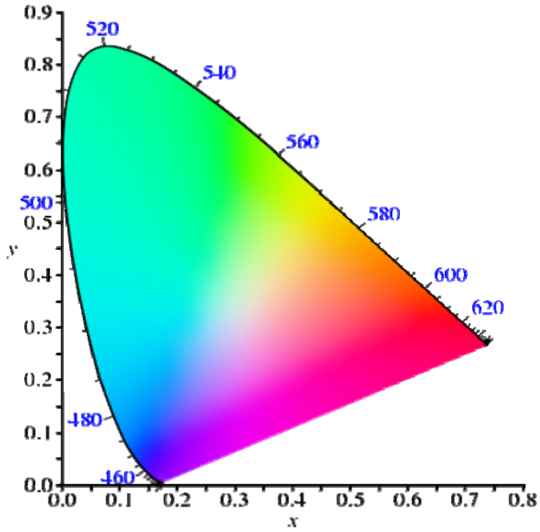

FIGURE 4. CIE1931

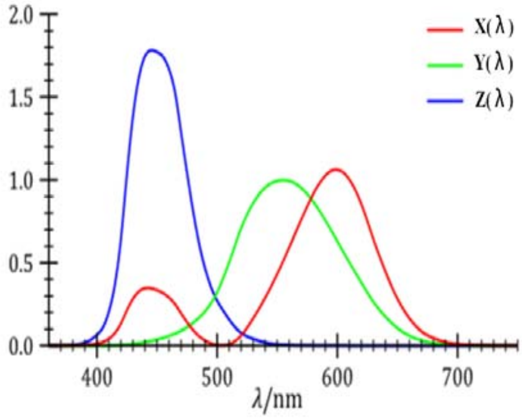

FIGURE 5. Three tristimulus values with wavelength

4. **The Design of the Optical Engine Using LEDs and the CPC.** This research designed a sort of optical engine using LEDs and the CPC. A light-emitting diode (LED) is the component that uses the PM structure of a semiconductor or similar structures to transform the electric energy into the luminous energy through the recombination of electrons and electron holes. LEDs have the advantages of high efficiency, long lifespan, being mercury-free, abundance of colors and it is easy to control. In recent years, LEDs with high efficiency are being continuously developed, creating a trend for LEDs to replace UHP lamps as the light source in the projection system [14,16,17].

4.1. **Compound parabolic concentrator, CPC.** The principle of a compound parabolic concentrator (CPC) is: to use the relation between the parabola and the focus as a basis; as long as the incident rays reach the paraboloid, the rays will be reflected into the focus. In Figure 4, the incident rays within the angle of will all be collected by the compound parabolic concentrator and emerge from the area $\overline{pp'}$. The curved surface equation of a CPC is as follows:

$$(r\cos\theta_i + z\sin\theta_i)^2 + 2a'(1+\sin\theta_i)^2 r - 2a'\cos\theta_i(2+\sin\theta_i)z - a'(1+\sin\theta_i)(3+\sin\theta_i) = 0 \quad (7)$$

where, the r is the section radius of the section area of the rotationally symmetric aspheric surface;

$$r^2 = x^2 + y^2 \tag{8}$$

the a is the incident pupil; the a' is the displacement of the parabolic focus; the relationship between a and a' is:

$$a = \frac{a'}{\sin\theta_i} \tag{9}$$

the condenser's total length is:

$$L = \frac{(a + a')\cos\theta_i}{\sin\theta_i} \tag{10}$$

According to the optical inverse theorem, we turn the condenser with the function of condensing the light into a lampshade with the function of outputting the light [15]. C. Peng et al. have designed an illuminant for the projection system by sticking the red, the blue and the green LEDs respectively on CPC modules. Only one single LED is used for each color; thus the energy output is smaller. In addition, the adoption of CPC modules will render the whole optical structure overweight. This study adopted the hollow CPC as the modulator of the optical engine. Compared with a solid module, the hollow CPC has a larger incident area and the lighter weight. Furthermore, the entire interior surfaces of the hollow cavity are reflection surfaces. Compared with a solid module, the adoption of the hollow CPC could disregard the energy absorption induced by the interior material of the solid module. In terms of the equal area of outputting rays, the optical engine adopting light-tunnel components requires more than twice the length of the optical engine adopting CPC components [16].

4.2. **The design of the LED light source.** In order to reduce energy wastage of the beam, this study designed a sort of colorful LED light source to replace the color-giving function of the color recapture. And in order to increase the overall energy output of the optical engine, we have designed five illuminant plates of 10mm wide and 10mm deep. Each illuminant plate is filled with the red, the green and the blue LEDs as it is illustrated in Figure 7. This design could increase the energy output of the DLP optical engine. Compared with the traditional color recapture, the advantages of a LED as its

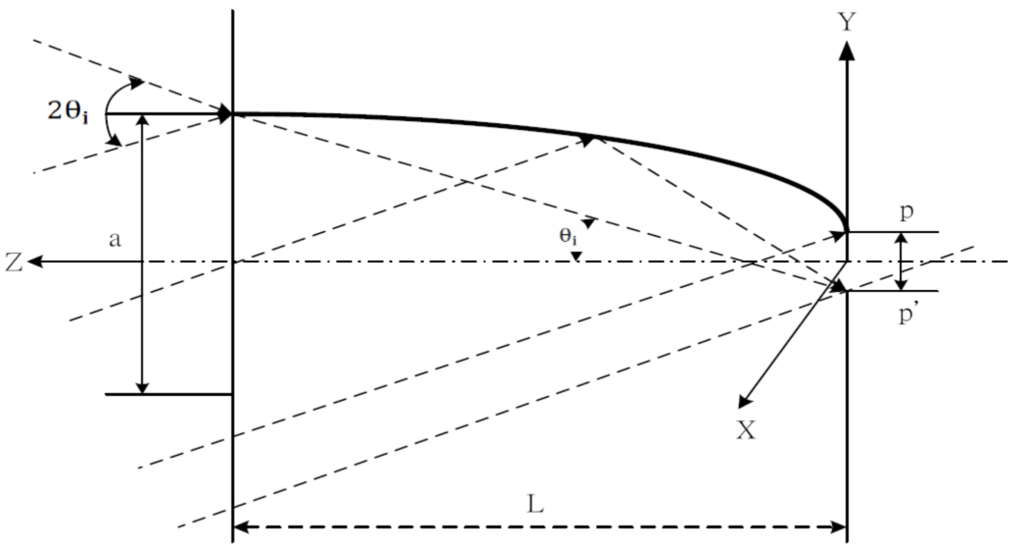

FIGURE 6. The diagram of the CPC design

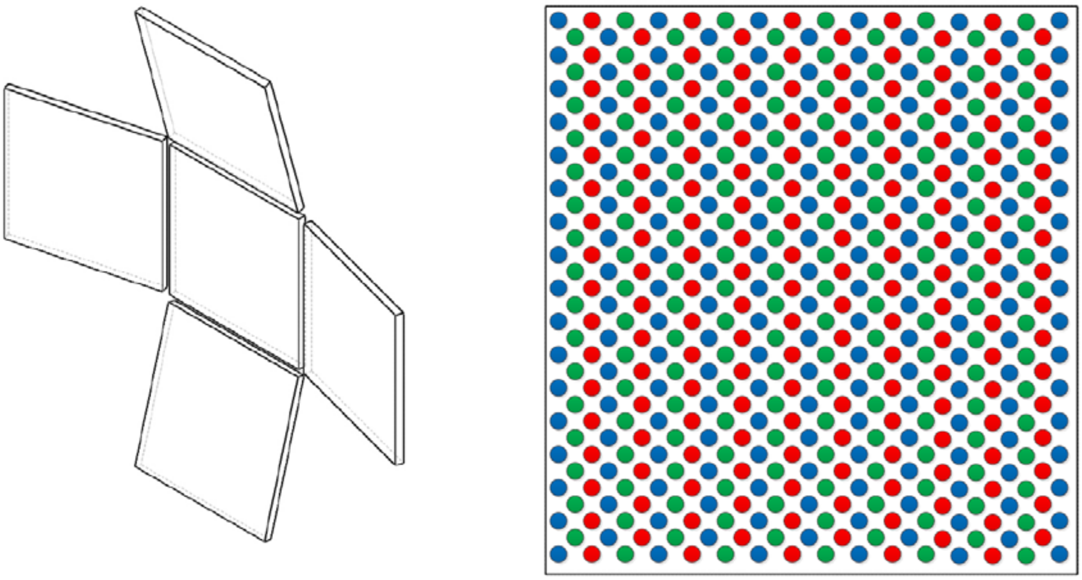

FIGURE 7. The color LED light source

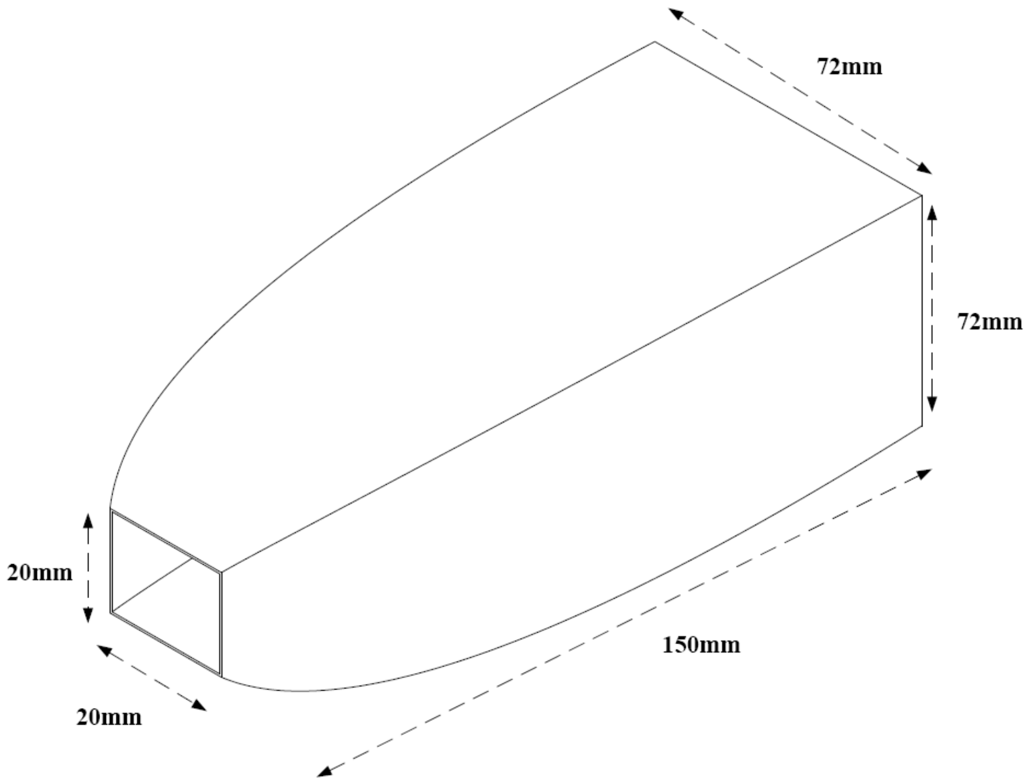

FIGURE 8. The shape and size of a CPC

ability to be controlled by a circuit and its ability to twinkle, along with the advantage of a DMD's high switching frequency, all of the above contribute to the enhancement of the coloring function of a DLP optical engine. For the maximum optical path in an optical engine is less than 500mm and the speed of light is 3×10^8m/s, the condition of the rays' mutual permeation happening when the rays are switching among different colors could be therefore ignored. In order to enhance the utility rate of the rays, we place a lens at one end of the CPC to converge the rays. Compared with the traditional DLP optical

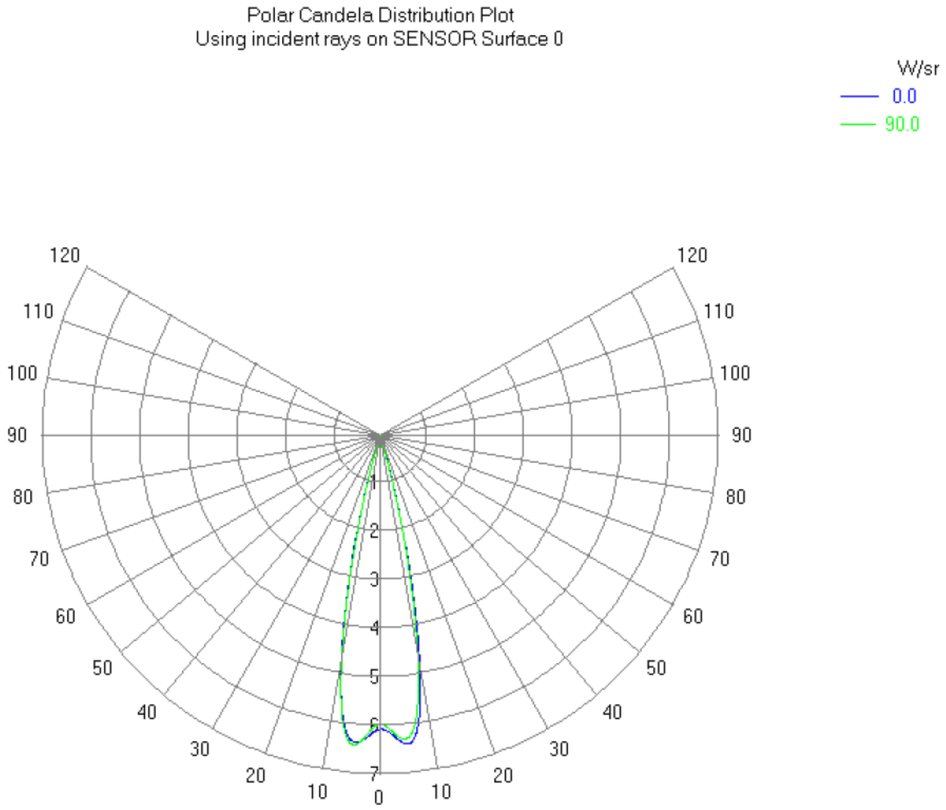

FIGURE 9. The polar candela distribution plot on CPC output

engine equipped with a color recapture, the adopting of color LEDs as the light source could avoid the energy wastage happening when the color recapture is selecting colors. Meanwhile, the mechanism for determining the outputting colors is shifted as well, from the original mechanism of a motor driving the color recapture to determine the color output, to the new mechanism that determines the color output by circuit control. When we need to output certain colors, we only have to activate and control the related panels with a circuit, and then we could control the output colors. Therefore, the efficiency of the adoption of LEDs is way higher than that of the DLP in the aspects of color management and color application. Compared with the traditional UHP lamp, this study adopted LEDs as the illuminant, which could largely reduce the energy wastage. The principles of chromatics were also applied in this study; thus the red, the green and the blue LEDs were adopted as the illuminant for reducing the energy wastage caused in the process of color selection. In addition, the color recapture which needs to be driven by a motor could also be removed to reduce the required components in the entire DLP projection system.

In this study, we used the CAD software Solidworks to build a model of the LED light source and the CPC condenser. We used TracePro to set up the LEDs' luminous curve, color, strength, and the trait of the CPC condenser's surface reflection. We used the rays with three different wavelengths to initiate the simulation. Five million streams of light were set to simulate the light emitting from the real LEDs. And we examined whether the LED array and the CPC could meet the expected goals of our design. At the output terminal, with the help of TracePro's optical tracing of the rays, we discovered that the outputting light could be controlled within an angle of 12 degrees, being able to meet the requirements of our design.

5. **Conclusion.** The design of the optical engine in the DLP optical projection system in this study is to replace the traditional UHP lamp, the light pipe and the color recapture with the color LEDs and the CPC. This study is to design a type of hollow CPC with large caliber and a type of optical engine with the LEDs in three colors as its illuminant, and to apply both designs in the DLP system. Compared with the traditional DLP technique, the optical engine designed in this study has the advantages as small volume, high energy utility rate and high energy output. This study is also to design an optical engine meeting the requirements of DLP technique and to use the simulation software for establishing a model and simulating its performance and efficiency. Through the simulation, we acquired the result that accorded with the function of the DLP optical engine, and according to this result, the performance of the design in this study accorded with that of the traditional DLP optical engine. In the aspects of saving energy, reducing the volume and controlling the colors, the optical engine designed in this study is superior to the traditional one.

REFERENCES

[1] J. B. Sampsell, An overview of Texas instruments' digital micromirror device (DMD) and its application to projection displays, *Society for Information Display International Symposium Digest of Technical Papers*, vol.24, pp.1012, 1993.
[2] M. A. Mignardi, Digital micromirror array for projection TV, *Taxes Instruments White-Paper*, 1995.
[3] L. A. Yoder, An introduction to the digital light processing (DLP) technology, *Taxes Instruments White-Paper*, 1998.
[4] L. A. Yoder, The fundamentals of using the digital micromirror device (DMD) for projection display, *International Conference on Integrated Micro/Nanotechnology for Space Applications*, Houston, 1995.
[5] A. J. Beniamin, Beam-shape transforming devices in high-efficiency projection systems, *Proc. of SPIE*, vol.3139, no.141, 1997.
[6] S. Magarill, Optical system for projection display, *US Patent 5552922*, 1996.
[7] F. Poradish and D. S. Dewald, Stable enhanced contrast optical system for high ressolution displays, *US Patent 6249387*, 2001.
[8] H. Chu, A. Gonzalez, T. Oudal, R. Aldridge, D. Dudasko and P. Barker, DMD superstructure characterizations, *Texas Instruments Technical Journal*, vol.15, no.3, 1998.
[9] M. Douglass, Lifetime estimates and unique failure mechanisms of the digital micromirror device (DMD), *Proc. of International Reliability Physics Symposium*, pp.9-16, 1998.
[10] D. B. Doherty and R. C Meyer, Color phase control for projection display using spatial light modulator, *US Patent 5657099*, 1997.
[11] S. D. Dewald, Illumination system for scrolling color recycling, *US Patent 6591022*, 2003.
[12] B. Fortner and T. E. Meyer, *Number by Colors*, Springer, 1996.
[13] R. W. G. Hunt, *Measuring Colour*, Fountain Press, 1998.
[14] S. Magarill, Apparatus for uniformly illuminating a light valve, *US Patent 5625738*, 1997.
[15] W. T. Welford and R. Winston, *The Optics of Nonimaging Concentrators*, New York, 1978.
[16] C. Peng, X. Li, P. Zhang, L. Xiong and X. Liu, RGB high brightness LED modules for projection display application, *J. Disp. Technol.*, vol.7, no.8, pp.448-453, 2011.
[17] C. Hung, J. Sun, Y. Tzeng, J. MacDonald, W. C. Lai, S. Li, Y. Fang, H. Sun and Y. Chen, A study of extended optimization of U-type rod for LED projectors, *Optik*, vol.122, no.5, pp.385-390, 2011.