applied optics

High-performance laser projection display illumination system based on a diffractive optical element

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Lasers have been regarded as the potential illumination source for next generation projectors. With the additional feature of coherency, diffractive optical elements (DOEs) become available in the illumination light path. DOEs in laser projection display systems add strong beam-shaping ability, good uniform performance and small size, which makes it is possible to realize efficient and uniform illumination on a spatial light modulator (SLM). Moreover, it is helpful for the simplification and compactness of illumination optics. This paper proposed what we believe is a novel RGB laser projection display illumination system based on a DOE, which used the DOE and optical path compensation system (OPCS) as the beam-shaping and relay system (BSRS), instead of a light pipe and relay lens group in the conventional laser projection display illumination system. We designed the DOE and established the simulation model of the illumination system. The simulation results show that the new illumination system is simple and compact, the illumination uniformity is more than 90%, the illumination efficiency of RGB illumination in BSRS is more than 75%, and the numerical aperture (NA) of the illumination beam is about 0.01.

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1. INTRODUCTION

With the increase in luminous efficiency and reliability, lasers are attracting widespread attention for imaging applications, such as in laser projectors, due to their large color gamut, high brightness, and long life [1,2]. Moreover, for most conventional light valve projection displays illuminated by UHP or xenon lamps, the light collection efficiency on the spatial light modulator (SLM) is constrained by the large source etendue [3]. Because laser light sources provide a potential solution, lasers have been regarded as the potential illumination light source for next generation projectors [2,4].

The design of illumination systems is one of the key technologies in laser projection displays. It determines the illumination efficiency and uniformity of the system. The intensity distribution of laser beam usually is circular Gaussian, which cannot achieve fully uniform illumination on the SLMs in laser projection display systems [5]. To improve the illumination efficiency in laser projection display systems, the laser beam generally needs to pass through a beam-shaping and homogenization unit to transform the circular Gaussian beam into a flat-top rectangular pattern. Then it must go through a relay illumination unit to realize fully uniform illumination on the SLMs. Diffractive optical elements (DOEs) for laser beam shaping and homogenization are widely used [6,7]. Compared to light pipes [8] or lens arrays [9], which were used in conventional laser projection display illumination systems, DOEs can meet the illumination uniformity and size requirements better and increase the illumination efficiency with a stronger ability to control intensity distribution. Simultaneously, the illumination path based on DOEs is simple and the devices can be miniaturized, which is helpful for the compactness of the illumination system.

This paper proposes what we believe is a novel RGB laser projection display illumination system based on a DOE, which used a DOE and optical path compensation system (OPCS) as the beam-shaping and relay system (BSRS), instead of the light pipe and relay lens group used in a conventional laser projection display illumination system. The DOE for illumination was designed, and the simulation model of the illumination system was established. Compared to a conventional laser projection display illumination system, the new illumination system has higher illumination efficiency and better compactness. Moreover, the numerical aperture (NA) of the illumination beam in the new system is very small, and the influence of the illumination beam aperture angle to color separation devices can be neglected. It also helps enhance the color uniformity, and reduce the design difficulty and the size of the projection lens.

2. MODEL OF ILLUMINATION OPTICS BASED ON A DOE

A. DOE for Illumination

Figure 1 presents the DOE illumination model. The phase distribution function $\phi_{\mathrm{DOE}}(x, y)$ provided by the DOE needs to turn the circular Gaussian beam $U_i(x, y)$ into a rectangular top-hat distribution $U_o(\xi, \eta)$ on the target plane at the specified distance L, to fully achieve uniform illumination on the SLMs. According to the scalar diffraction theory, $U_o(\xi, \eta)$ is the Fresnel diffraction pattern of $U_i(x, y)$. Equation (1) expresses the mathematical representation of the relationship as

$$U_o(\xi,\eta) = \frac{1}{\lambda L}\iint U_i(x,y)\exp[i\phi_{\mathrm{DOE}}(x,y)] \cdot \exp\left[i\frac{\pi}{\lambda L}(x^2+y^2)\right] \cdot \exp\left[-i\frac{2\pi}{\lambda L}(x\xi+y\eta)\right]\mathrm{d}x\mathrm{d}y. \quad (1)$$

The NA of the illumination beam can be expressed by Eq. (2),

$$\mathrm{NA} \approx \tan\theta = \frac{D-d}{2L}, \quad (2)$$

where D is the diameter of the DOE and d is the size of the SLM.

During our research, we found an important nature of DOEs. According to Eq. (1), a DOE is designed based on a laser of wavelength λ_1 to form a rectangular uniform pattern at a distance L_1. If this DOE is illuminated by a laser beam of wavelength λ_2, then it will get a same rectangular uniform pattern at a distance L_2. L_2 can be expressed by Eq. (3),

$$L_2 = \frac{\lambda_1}{\lambda_2}L_1. \quad (3)$$

Using this property, we designed what we believe is a novel RGB laser projection display illumination system based on a DOE.

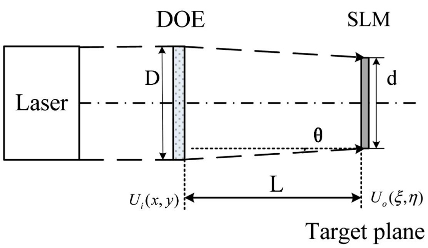

Fig. 1. Illumination model of the DOE.

B. RGB Laser Projection Illumination System Based on a DOE

Figure 2 presents the apparatus used in the proposed RGB laser projection display system based on a DOE. The collimated RGB laser beams combine together through an X lens, and then the combined laser beams perpendicularly illuminate a DOE. By the modulation of the DOE, the RGB laser beams are transformed into rectangular uniform spots at different distances, respectively. The RGB rectangular uniform spots illuminate the corresponding SLMs with same size as the SLMs. According to Eq. (3), the spot formation distance of red light is the shortest, while the spot formation distance of blue light is the longest. As the distances between the DOE and the three SLMs are the same to make the RGB rectangular spots accurately illuminate the corresponding SLM, an OPCS is required to compensate for the optical path difference between the RGB spots. As shown in Fig. 2, the OPCS is composed of two longpass dichroic mirrors, LP1 and LP2; two shortpass dichroic mirrors, SP1 and SP2; and two mirrors, R1 and R2. The longpass dichroic mirrors, LP1 and LP2, transmit a red laser beam while reflecting a green laser beam and a blue laser beam. The shortpass dichroic mirrors, SP1 and SP2, transmit a blue laser beam while reflecting a green laser beam. Because the OPCS compensates for the optical path difference between the RGB spots, the RGB illumination spots forming by the DOE can be located exactly at the respective SLMs, thereby realizing uniform illumination on the SLMs.

The main difference between the laser projection display illumination system based on a DOE and a conventional laser projection display illumination system is that the DOE and OPCS are used instead of the light pipe and a relay lens group, as shown in Fig. 2. The part in the dashed box is the BSRS. In Section 3, we will build a simulation model of the laser projection display illumination system based on a DOE to verify the effect of the BSRS changing on the performance of the laser projection display illumination system.

3. RESULTS AND DISCUSSION

As an example, we designed a laser projection display illumination system based on a DOE. The size of the digital

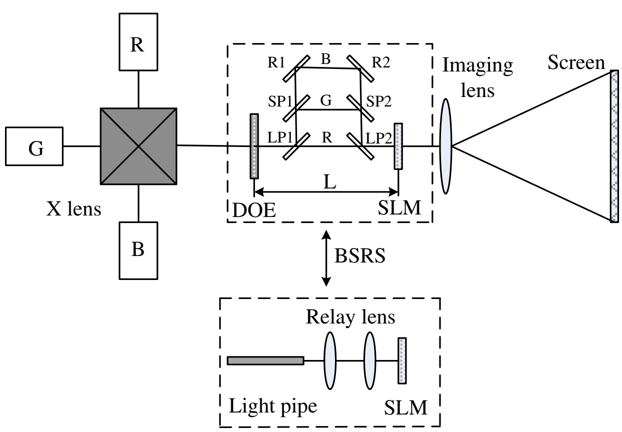

Fig. 2. Apparatus used in the proposed RGB laser projection display system based on a DOE.

mirror device (DMD) in the system is 14.39 mm × 8.09 mm. According to the RGB laser wavelength selection method described in various literature [10,11], and combined with the existing laser products on the market, RGB lasers of 635 nm, 527 nm, and 447 nm were chosen as the illumination source.

We used the concept of the iterative Fourier transform algorithm [12–14] to design the DOE for illumination. The DOE was designed for a 635 nm wavelength, 17 mm diameter, 8.5 μm pixels size, propagation distance of 360 mm, and for a target plane pattern of 14.39 mm × 8.09 mm, which is equal to the size of the DMD. Figure 3(a) presents the phase distribution of the DOE. Generally, the DOE can be fabricated with the masks' etching process, which uses staircase surface relief instead of continuous surface relief. Here, we use the etching process on four masks to obtain a 16-staircase surface structure. Figure 3(b) shows the local phase structure of Fig. 3(a) along the X direction, and the 16 staircase structure is obvious. The four masks provide a phase shift of π, $\pi/2$, $\pi/4$, and $\pi/8$, respectively, and their pixel size is 8.5 μm. The etching depth of the masks can be calculated by Eq. (4),

$$h_i = \frac{\lambda}{2^i(n-1)} \qquad i = 1, 2, 3, 4, \tag{4}$$

where λ is the wavelength, n is the refraction index of the fabrication material, and i is the number of the mask. Figure 4 shows the intensity distribution of the RGB with different propagation distances. Figures 4(a)–4(c) show the intensity distribution of the RGB with a propagation distance 360 mm. Figure 4(a) indicates the R light forms a uniform rectangular spot at the diffractive plane, the diffractive efficiency is 85.73%, the rms error of the illumination pattern is 7.56%, and the uniformity is 91.68%. The G light and B light with a propagation distance 360 mm form bad spots, as shown in Figures 4(b) and 4(c). According to Eq. (3), if the DOE is illuminated by lasers of 527 nm and 447 nm, then we will get the same rectangular spot as Fig. 4(a) at distances of 433.78 mm and 511.41 mm, respectively. Figures 4(d)–4(f) show the intensity distribution of the RGB with a propagation distance 433.78 mm. Figures 4(g)–4(i) show the intensity distribution of the RGB with a propagation distance 511.41 mm. Figure 4(e) indicates the G light with a propagation distance 433.78 mm forms a uniform rectangular spot that is the same as Fig. 4(a), and the same as the spot formed by the B light with a propagation distance 511.41 mm, as shown in Fig. 4(i).

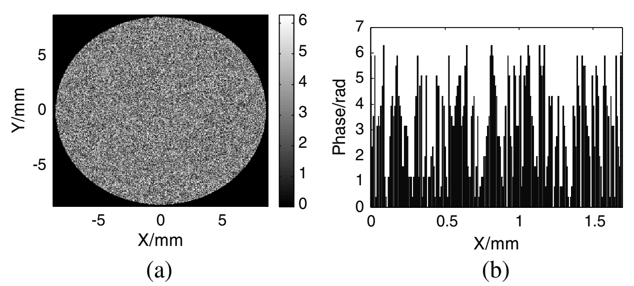

Fig. 3. (a) Phase distribution of DOE. (b) Local phase structure of (a) along the X direction.

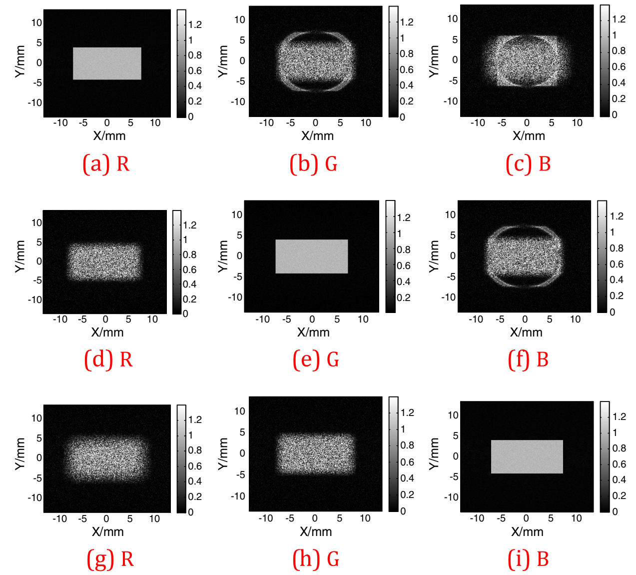

Fig. 4. Rectangular intensity distribution of RGB light with a propagation distance of (a)–(c) 360 mm, (d)–(f) 433.78 mm, and (g)–(i) 511.41 mm.

Figures 4(a), 4(e), and 4(i) prove the idea proposed in Section 2.A.

Based on the DOE designed previously, a simulation model of a 3DMD laser projection display illumination system was designed and established, as shown in Fig. 5. In this model, the longpass dichroic mirrors used in the OPCS are model DMLP550 (Thorlabs Inc., Newton, N.J.) and have a cutoff frequency of 550 nm. The laser with a wavelength higher than 550 nm will be transmitted and the transmittance is 98%. Lower than 550 nm will be reflected and the reflectance is 97%. The shortpass dichroic mirrors used in the OPCS are model FF01-SP468 (Semrock, Inc. Rochester, N.Y.) and have a cutoff frequency of 468 nm. The laser with a wavelength lower than 468 nm will be transmitted and the transmittance is 98%. Higher than 468 nm will be reflected and the reflectance is 99%. The reflectance of mirrors in the OPCS is 99%. The Philips lens system is model DT310 (Keting Optical Technology Inc., Hangzhou, China).

The optical path length of the incident illumination beam traveling in the DT310 is 170 mm. Next, we compared the performance of the BSRS based on a DOE with the BSRS based on a light pipe to evaluate illumination efficiency, illumination uniformity, and compactness to illustrate the advantages of an illumination system based on a DOE.

First, we focus on the illumination efficiency. The energy efficiency of the BSRS based on a light pipe is determined by the efficiency of the light pipe, the relay lens system, and the illumination field. Generally, in the BSRS based on a light pipe, the energy efficiency of the light pipe is 88%, and the energy efficiency of the relay lens system is 92% [15]. In the BSRS based on a light pipe, we must consider the energy loss caused by the edge of the illumination field at the same time. Because of the distortion aberration of the relay lens system, when the uniform rectangular spot in the output plane of the light pipe passes through the relay lens system, the edge of the spot will deteriorate and the illumination quality will be decreased. It is general practice to set a certain amount of light margin to ensure good illumination uniformity. Since the edge area of the illumination spot is discarded, the energy efficiency of the system is reduced. Assuming the spot margin is 0.5 mm, then the size of illumination spot is 14.89 mm × 8.59 mm, and the energy efficiency of the illumination field is approximate 91%. Therefore, the energy efficiency of the BSRS based on a light pipe is 88% × 92% × 91% = 73.67%. The energy efficiency of the BSRS based on a DOE is only determined by the efficiency of the DOE and the OPCS. Because there is no distortion aberration in the OPCS, when the illumination field passes through the OPCS, the edge of the illumination field remains unchanged and the illumination quality also remains unchanged. In other words, the energy efficiency of the illumination field is 100% and cannot be considered. In the BSRS based on a DOE, the diffractive efficiency of the DOE is 85.73%. Since the RGB light in the OPCS goes through different devices, respectively, the respective energy efficiency in the OPCS is not the same. The energy efficiency of the R light in the OPCS is $0.98^2 = 96.04\%$, the energy efficiency of the G light in the OPCS is $0.97^2 \times 0.99^2 = 92.21\%$, and the energy efficiency of the B light in the OPCS is $0.97^2 \times 0.98^2 \times 0.99^2 = 88.57\%$. Then the respective total energy efficiency of the RGB light in the BSRS based on a DOE is 82.34%, 79.05%, and 75.93%. Compared to the energy efficiency of the BSRS based on a light pipe, the energy efficiency of the BSRS based on a DOE is higher, the energy efficiency of the B light increases 3.1%, the energy efficiency of the G light increases 7.3%, and the energy efficiency of the R light increases nearly 11.8%.

Then, we were concerned about the illumination uniformity. Usually the illumination uniformity of the three DMDs in the BSRS based on a light pipe is approximately 96% [15]. In the BSRS based on a DOE, the illumination uniformity is determined by the DOE. We get the illuminance distribution on the three DMDs by ray tracing. Figures 6(a)–6(c) show the illuminance distribution pattern on the RGB DMD, respectively. According to the 13 points ANSI standard, the respective illuminance uniformity of the RGB DMDs is 92.84%, 93.17%, and 93.78%. Compared to the BSRS based on a light pipe, the illuminance uniformity of the BSRS based on a DOE is slightly lower, but the uniformity performance is also good, and is more than 90%. Moreover, the illumination uniformity of the BSRS based on a DOE can be further increased by improving the DOE design algorithm.

Next, we pay attention to the compactness of the BSRS. In the BSRS based on a light pipe, since the illumination uniformity is determined by the length of the light pipe, the length of the light pipe is usually more than 100 mm to get good illumination uniformity. In addition, the relay lens system usually consists of 3–4 lenses, the diameters of the lens are tens of

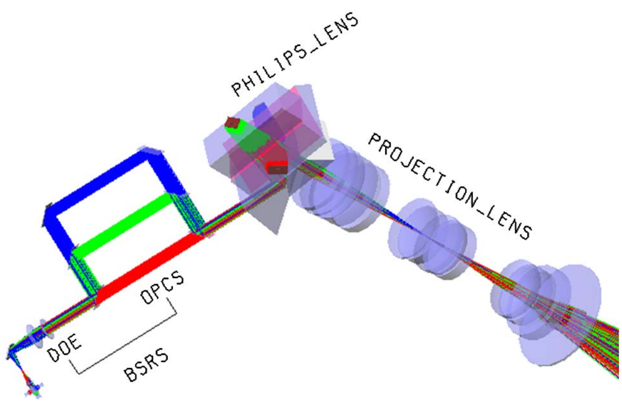

Fig. 5. Simulation model of the laser projection display system based on a DOE.

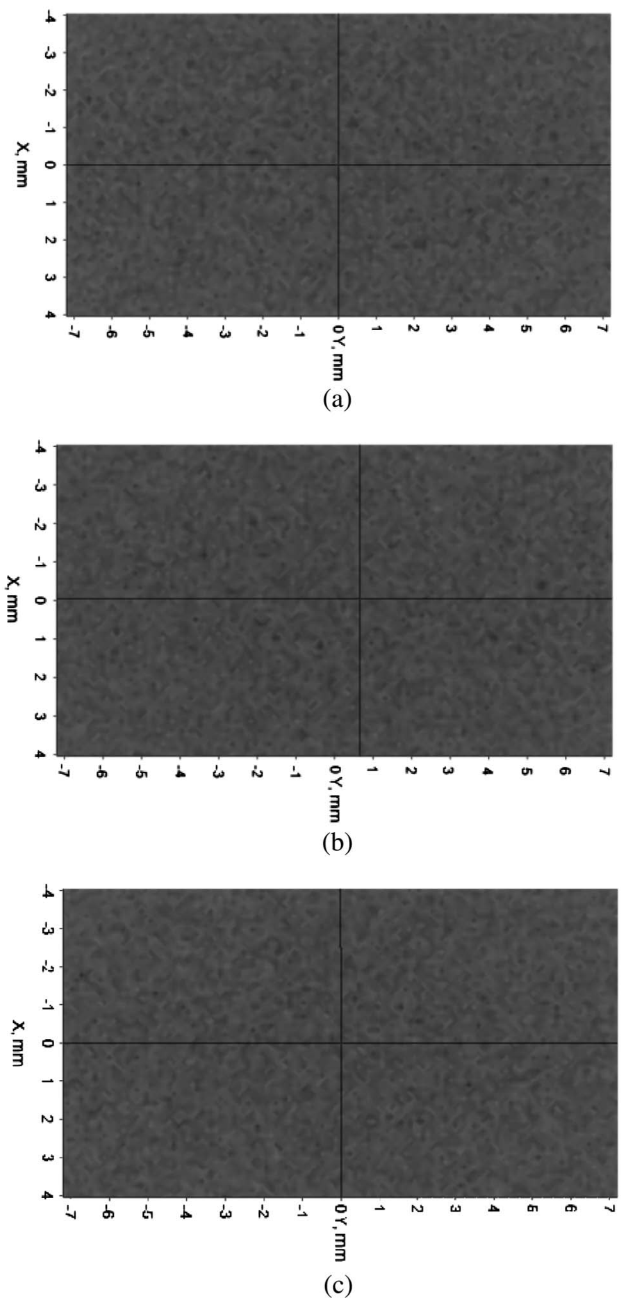

Fig. 6. Illuminance distribution pattern on the RGB DMDs in the BSRS based on a DOE: (a) R DMD; (b) G DMD; and (c) B DMD.

millimeters, and the total length of the relay lens system will be hundreds of millimeters. It can be known that the BSRS based on a light pipe has a big size and long length, which is harmful to the compactness of the illumination system. In the BSRS based on a DOE, the diameter of the DOE is 17 mm, and the thickness of the DOE is only 2 mm. Although the working distance of the DOE is long, the optical path is folded by the OPCS, and the Philips prism system includes a part of the distance, which makes the structure of the BSRS based on a DOE is very compact. As shown in Fig. 5, the DOE working distance for the R light is 360 mm, while the optical path length of the incident illumination beam traveling in the Philips prism system is 170 mm, then the distance between the DOE and the Philips prism system incident surface is 190 mm, which is only slightly longer than the length of the light pipe. So the BSRS based on a DOE has a much more compact structure.

In addition, there is a bid difference in the NAs of the illumination beams in the two BSRSs. The NA of illumination beam in the BSRS based on a light pipe is about 0.2. On the other hand, in the BSRS based on a DOE, according to Eq. (2), the NA of the illumination beam of RGB can be calculated as 0.012, 0.01, and 0.009, respectively, which is much smaller than the NA of the illumination beam in the BSRS based on a light pipe. The characteristic of the dichroic coating is related to the incident angle. As the illumination system inevitably has a certain aperture angle, the incident angle of the color separation devices has a certain angle range, so the beam incident angle at different locations of the color separation devices is different, which causes a change in the transmittance and cutoff wavelengths at different positions of the dichroic devices. It will decrease the color uniformity and energy efficiency of the illumination system. The bigger the NA of the illumination system, the larger the negative impact. Therefore, the effect of the illumination aperture angle on the color separation device can be neglected in the illumination system based on a DOE because of its much smaller NA. It is advantageous to improve the color uniformity and energy efficiency of the illumination system. What's more, the projection display system is an etendue-limited system, and the device that limits the etendue is the SLM. According to the non-imaging optical theory, if the etendue of the illumination beam is greater than the etendue of the SLM, then a portion of the illumination beam will not be used by the system, resulting in a reduction in energy efficiency. The low NA of the illumination system corresponds to a low etendue of the illumination beam, which is beneficial to the improvement of system energy efficiency. Moreover, a low illumination NA is helpful to reduce the design difficulty and size of the projection lens.

Finally, we focus on the difference between the two systems in dealing with the laser speckle. In the laser projection display system based on a light pipe, to reduce the laser speckle, the usual method is to add a device in the light path and vibrate it [16–18]. While in the laser projection display system based on a DOE, DOE itself can play an important role in speckle suppression. By fine designing the DOE, a low speckle image can be obtained, which is illustrated in Ref. [14]. Compare to the system based on a light pipe, the system based on a DOE does not require additional devices for speckle reducing, and does not require a complex mechanical vibration device, which is helpful to improve the compactness, energy efficiency, and stability of the system.

4. CONCLUSION

This paper proposed what we believe is a novel laser projection display illumination system based on a DOE, which used the DOE and OPCS as the BSRS, instead of a light pipe and relay lens group used in a conventional laser projection display illumination system. In the new laser projection display illumination system, the DOE transforms the RGB laser beam into a uniform rectangular spot with the same size at different distances, respectively. The optical path difference between the DOE and the RGB SLMs is compensated by the OPCS, so that the RGB light spot generated by the DOE can accurately illuminate on the respective SLM. It is worth mentioning that the DOE also can play an important role in speckle suppression. Compared to a conventional laser projection display illumination system based on a light pipe, the new laser projection display illumination system has higher illumination energy efficiency, a more compact structure and a much smaller illumination beam NA. The simulation result shows that the illumination efficiency of the RGB light in the new laser projection display illumination system is increased by 3.1%, 7.3%, and 11.8%, respectively. Although the new illumination system has slightly worse illumination uniformity, but the effect is good, and is more than 90%. The illumination uniformity can be further increased by improving the DOE design algorithm. The proposed scheme provides the potential to integrate all the components, including lasers and optics, on a micro bench to become a micro opto-electro-mechanical device for miniature projectors.

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REFERENCES

1. K. V. Chellappan, E. Erden, and H. Urey, "Laser-based display: a review," Appl. Opt. **49**, F79–F98 (2010).
2. Y. Zhang, H. Dong, and R. Wang, "Demonstration of a home projector based on RGB semiconductor lasers," Appl. Opt. **51**, 3584–3589 (2012).
3. N. Madamopoulos and F. Papageorgiou, "Laser based projection system for displays, signage and illumination," J. Display Technol. **10**, 832–839 (2014).
4. G. Hollemann, B. Braun, P. Heist, J. Symanowski, U. Krause, J. Kraenert, and C. Deter, "High-power laser projection displays," Proc. SPIE **4294**, 36–46 (2001).
5. Y. S. Chang, C. H. Lin, K. H. Hsu, W. F. Hsu, L. J. Hsiao, and H. Y. Lin, "Laser speckle reduction by phase range limited computer generated hologram in laser projection display system," Appl. Opt. **53**, G157–G162 (2014).
6. P. H. Yao, C. H. Chen, and C. H. Chen, "Low speckle laser illuminated projection system with a vibrating diffractive beam shaper," Opt. Express **20**, 16552–16566 (2012).
7. Y. S. Chang, W. F. Hsu, K. H. Hsu, and H. Y. Lin, "Full-frame projection displays using a liquid-crystal-on-silicon spatial light modulator for beam shaping and speckle suppression," Appl. Opt. **53**, G214–G221 (2014).

8. G. Zheng, B. Wang, T. Fang, H. Cheng, Y. Qi, Y. W. Wang, B. X. Yan, Y. Bi, Y. Wang, S. W. Chu, T. J. Wu, J. K. Xu, H. T. Min, S. P. Yan, C. W. Ye, and Z. D. Jia, "Laser digital cinema projector," J. Display Technol. **4**, 314–318 (2008).
9. P. C. Chen, C. C. Chen, P. H. Yao, and C. H. Chen, "Double side lenslet array for illumination optics of laser projector," Proc. SPIE **7232**, 72320X (2009).
10. E. Buckley, "Laser wavelength choices for pico-projector applications," J. Display Technol. **7**, 402–406 (2011).
11. L. Wallhead, R. Ocana, and P. Quinza, "Designing a laser scanning picoprojector. Part 1: characteristics of the optical displaying system and color-management-related issues," Appl. Opt. **51**, 4803–4809 (2012).
12. R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," Optik **35**, 237–246 (1972).
13. J. R. Fienup, "Iterative method applied to image reconstruction and to computer-generated holograms," Opt. Eng. **19**, 297–305 (1980).
14. W. D. Qu, H. R. Gu, Q. F. Tan, and G. F. Jin, "Precise design of two-dimensional diffractive optical elements for beam shaping," Appl. Opt. **54**, 6521–6524 (2015).
15. H. Dong, Y. F. Zhang, H. Li, J. Y. Duan, A. C. Shi, Q. Fang, and Y. L. Liu, "High-performance illumination system design with new light source of LD array for laser projection display," Proc. SPIE **8335**, 83350F (2012).
16. E. G. Rawson, A. B. Nafarrate, R. E. Norton, and J. W. Goodman, "Speckle-free rear-projection screen using two close screens in slow relative motion," J. Opt. Soc. Am. **66**, 1290–1294 (1976).
17. L. Wang, T. Tschudi, T. Halldorsson, and P. R. Pétursson, "Speckle reduction in laser projection systems by diffractive optical elements," Appl. Opt. **37**, 1770–1775 (1998).
18. A. Lapchuk, A. Kryuchyn, V. Petrov, V. Yurlov, and V. Klymenko, "Full speckle suppression in laser projectors using two Barker code-type optical diffractive elements," J. Opt. Soc. Am. A **30**, 22–31 (2013).