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Beam Shaping and Speckle Reduction in Laser Projection Display Systems Using a Vibrating Diffractive Optical Element

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The laser has been regarded as the potential illumination source for the next generation of projectors. However, currently the major issues in applying the laser as an illumination source for projectors are beam shaping and laser speckle. We present a compact solution for both issues by using a vibrating diffractive optical element (DOE). The DOE is designed and fabricated, and it successfully transforms the circular Gaussian laser beam to a low speckle contrast uniform rectangular pattern. Under a vibration frequency of 150 Hz and amplitude of 200 μm, the speckle contrast value is reduced from 67.67% to 13.78%, and the ANSI uniformity is improved from 24.36% to 85.54%. The experimental results demonstrate the feasibility and potential of the proposed scheme, and the proposed method is a feasible approach to the miniaturization of laser projection display illumination systems.

Keywords : Laser projection display, Diffractive optical element, Beam shaping, Speckle
OCIS codes : (110.6150) Speckle imaging; (050.1970) Diffractive optics; (110.2945) Illumination design; (030.6140) Speckle

I. INTRODUCTION

With the increasing of luminous efficiency and reliability, lasers receive widespread attention in imaging applications, such as laser projectors, due to their large color gamut, high brightness and long life [1]. 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 [2]. Laser light sources provide a potential solution for this issue. Therefore, lasers have been regarded as the potential illumination light source for next generation projectors.

In order to achieve rectangular uniform illumination on the SLM by converting the Gaussian laser beam into a flat-top profile, several methods have been proposed, such as a double-sided micro-lens array [3], a light pipe [4], and a bi-convex aspheric lens [5]. However, DOEs exhibit better compactness. The main algorithms applied to the design of a DOE can be categorized into the iterative Fourier transform algorithm (IFTA) [6, 7] and the global optimization algorithm [8, 9]. However, the surface relief of the designed DOE is continuous, which is difficult to realize with high accuracy. Generally, we use staircase surface relief instead of continuous surface relief, which can be more easily fabricated with high accuracy but will degrade the performance of the DOE, and there may be zero-order diffraction in the illumination pattern of the DOE because of the quantization or fabrication error of the DOE surface relief.

Another major issue is the existence of a speckle pattern which significantly degrades the illumination uniformity and image quality. The speckle phenomenon is an inevitable problem when a laser is used as the source in projection display systems. This is the interference pattern caused by the scattering of light from the screen or the rough surface.

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A number of schemes for speckle reduction, which could mainly be categorized into light source modulation [10-13] and temporal integration, have been developed in recent years [14-18]. Light source modulation includes destroying the spatial coherence by using a special laser [10, 11] and destroying the temporal coherence by using broadband sources [12, 13]. Temporal integration is most widely used; it can effectively reduce the speckle by utilizing a moving screen [14], ultrasonic devices [15], colloidal dispersion [16], rotating diffractive optical elements [17] or moving Baker code type diffractive optical elements [18].

The abovementioned two issues for laser projectors are mostly resolved individually with corresponding dedicated devices, which generally increase the complexity of the system. In this paper, a vibrating DOE is proposed as a compact total solution to resolve both issues. The design, fabrication and characterization of the DOE are described first, followed by the speckle contrast tested with different frequency and amplitude of the vibrating DOE. The proposed method can provide a reference to the design and miniaturization of the laser projection display illumination systems.

II. DOE FOR ILLUMINATION

We design a beam shaping DOE for projection efficiency. The phase distribution function $\phi_{DOE}(x, y)$ provided by the DOE needs to turn the circular Gaussian beam $U_i(x,y)$ into a rectangular top-hat distribution $U_s(\xi,\eta)$ on the target plane at the specified distance L. According to scalar diffraction theory, $U_s(\xi,\eta)$ is the Fresnel diffraction pattern of $U_i(x,y)$. Eq. (1) expresses the mathematical representation of the relationship.

$$U_s(\xi,\eta) = \frac{1}{\lambda L}\iint U_i(x,y)\exp[i\phi_{DOE}(x,y)] \cdot \exp[i\frac{\pi}{\lambda L}(x^2+y^2)] \cdot \exp[-i\frac{2\pi}{\lambda L}(x\xi+y\eta)]dxdy \quad (1)$$

The laser wavelength is 632.8 nm, the diameter of the DOE is 16.5 mm, the pixel size of the DOE is 16.2 μm, the propagation distance L is 220 mm, and the size of the rectangular pattern at the target plane is 4.84×2.72 mm. The beam shaping DOE is then designed using the concept of the iterative Fourier transform algorithm (IFTA), the flow diagram of which is presented in Fig. 1.

The optical field distribution in the DOE plane is originally set as $U_i(x,y)$ with a circular Gaussian distribution and randomized phase distribution. The field $U_i(x,y)$

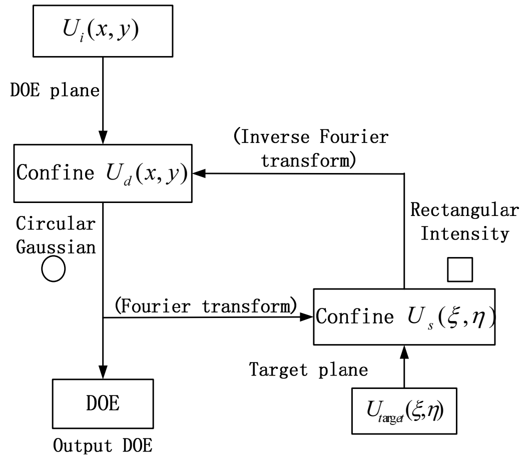


FIG. 1. Flow diagram of IFTA.

is transferred to the target plane by a Fourier transform, resulting in a field distribution $U_s(\xi,\eta)$, then the amplitude of $U_s(\xi,\eta)$ is replaced by the target field $U_{target}(\xi,\eta)$. Following this, $U_s(\xi,\eta)$ is transferred to the DOE plane through an inverse Fourier transform, resulting in a field $U_d(x,y)$, and its amplitude is replaced by $U_i(x,y)$. These operations represent one loop of the IFTA, which are iteratively conducted until convergence. The phase of the final $U_d(x,y)$ is the phase of the DOE. Figure 2 presents the phase distribution of the DOE we designed and the intensity distribution associated with diffraction.

The DOE was fabricated with the three mask etching process, and fused silica was used for the material. The three masks, which provide phase shifts of π, π/2 and π/4, are shown in Fig. 3(a), (b) and (c), respectively. The magnified images of the black-line parts in Fig. 3(a), (b) and (c) are shown in Fig. 3(d), (e) and (f), respectively. The pixel size of the mask is 16.2 μm. The black and white areas in the masks correspond to land and pit, respectively. The etching depth of the masks can be calculated by Eq. (2):

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

Where λ is the wavelength, n is the refractive index of the fabrication material, and i is the number of the mask. According to Eq. (2), we can get the etching depths of the masks shown in Fig. 3(a), (b) and (c) as 692.3 nm, 346.15 nm and 173.08 nm, respectively.

Figure 4 shows the DOE, which was etched on a disk with a diameter of 1 inch and the centric blurred area is the function region. Figure 5(a) shows top-view image of a small portion of the DOE. Figure 5(b) shows part of the cross section of the DOE structure obtained by surface profilometer.

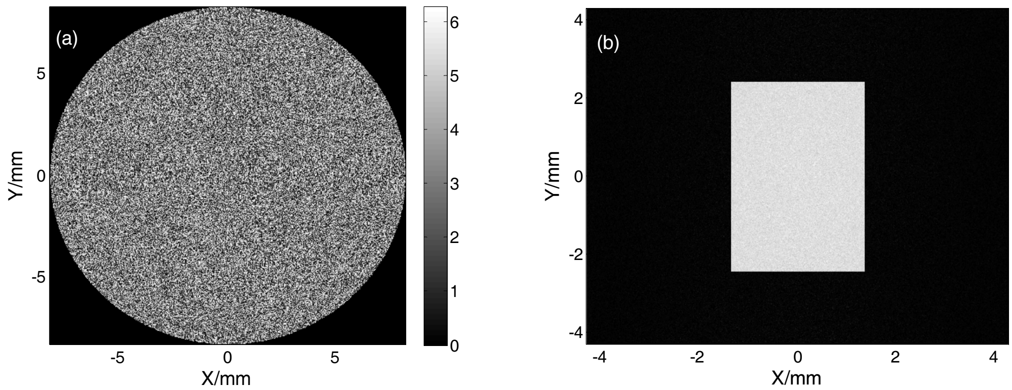


FIG. 2. (a) The phase distribution of DOE, (b) Diffraction rectangular intensity distribution.

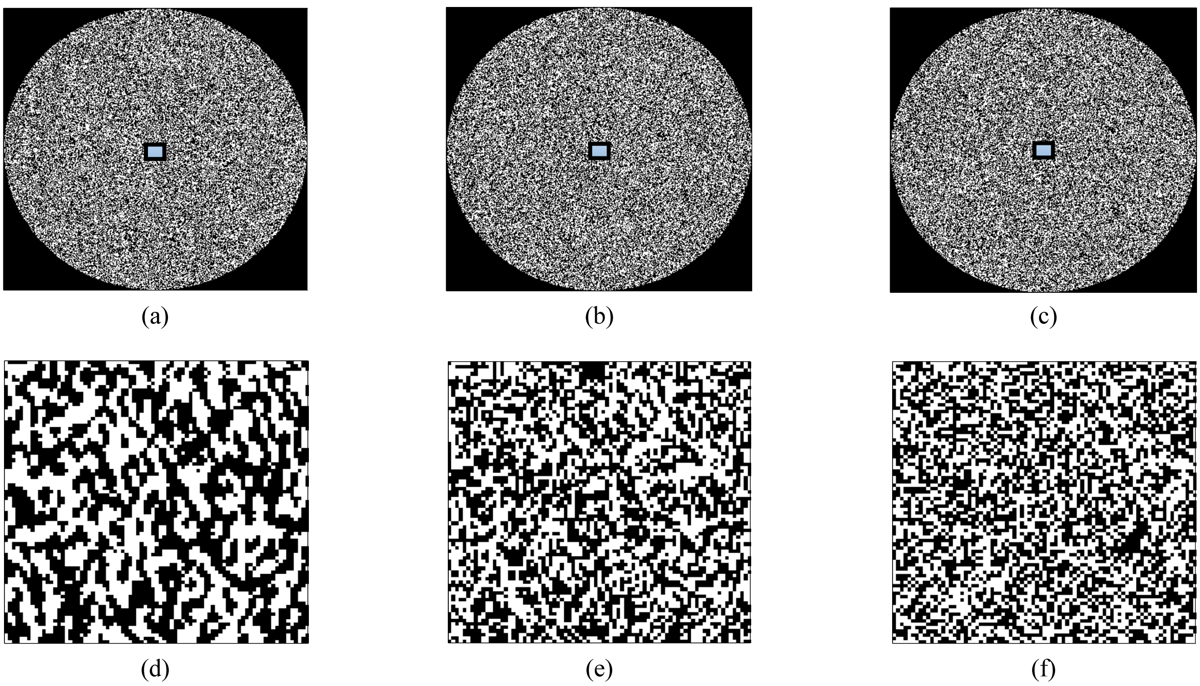


FIG. 3. Masks for the DOE fabrication provides phase shifts of (a) π, (b) π/2, (c) π/4. (d), (e), (f) Magnified images of the black-line part in Fig. 3(a), (b) and (c), respectively.

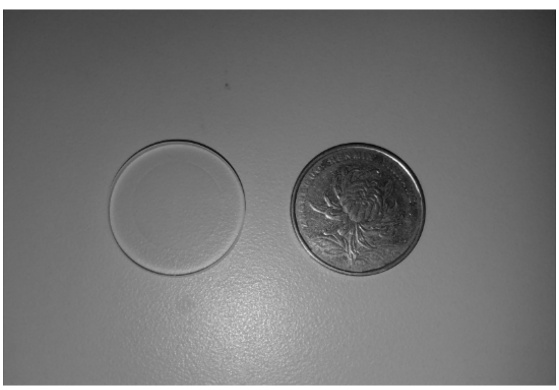
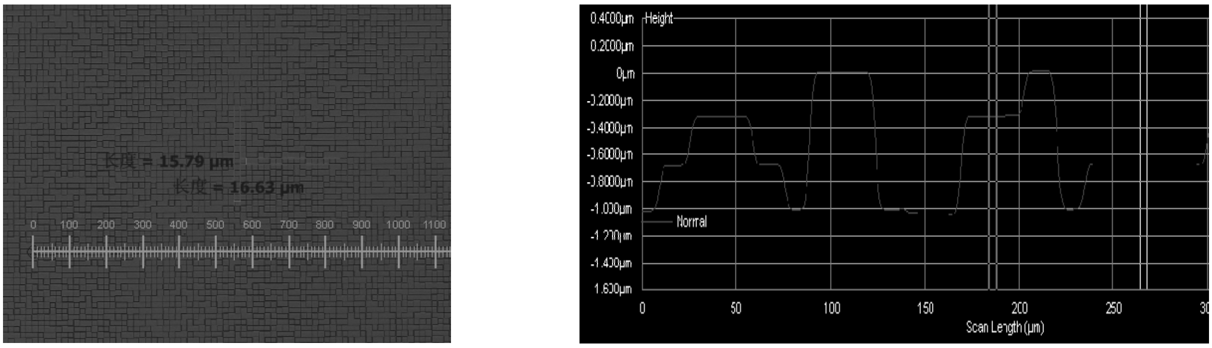


FIG. 4. The beam shaping DOE.



(a) (b)

FIG. 5. (a) Top-view image of a small portion of the DOE, (b) Part of the cross section of the DOE structure.

III. EXPERIMENTAL SETUP

Speckles always appear in images of laser imaging systems and degrade image quality. The proposed scheme to reduce speckle is to vibrate the DOE so as to temporally mix slightly different illumination patterns, and laser speckle should be averaged out on the screen if the illumination pattern changes sufficiently within the effective averaging time period.

The illustration of the experimental setup is shown in Fig. 6. The laser was driven in the continuous wave condition. In order to avoid the saturation of the charge-coupled device (CCD) camera, neutral density filters were used to absorb a part of the light intensity of the laser beam. The transmission beam was spatially filtered by a pinhole and then collimated to a parallel beam by a collimating lens. The parallel beam illuminated the DOE and generated a rectangular speckle pattern on the target plane. The diffraction pattern was recorded by the CCD, which has a resolution of 1024×1024 pixels, with the pixel pitch of 5.5 μm × 5.5 μm.

In order to generate multiple illumination patterns on the target plane to perform the temporal-averaging operation, an oscillator was used for vibrating the DOE. The vibrating amplitude of the oscillator is increased when the input current is raised, and if the oscillator's frequency is increased, the maximal vibrating amplitude of the oscillator will be decreased.

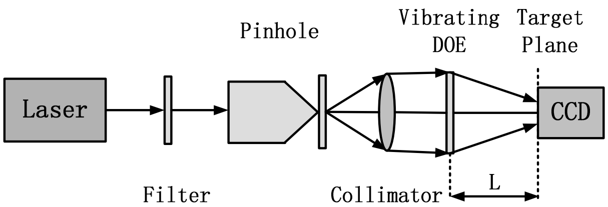


FIG. 6. Experimental setup for speckle reduction using a vibrating diffractive optical element.

IV. RESULTS AND DISCUSSION

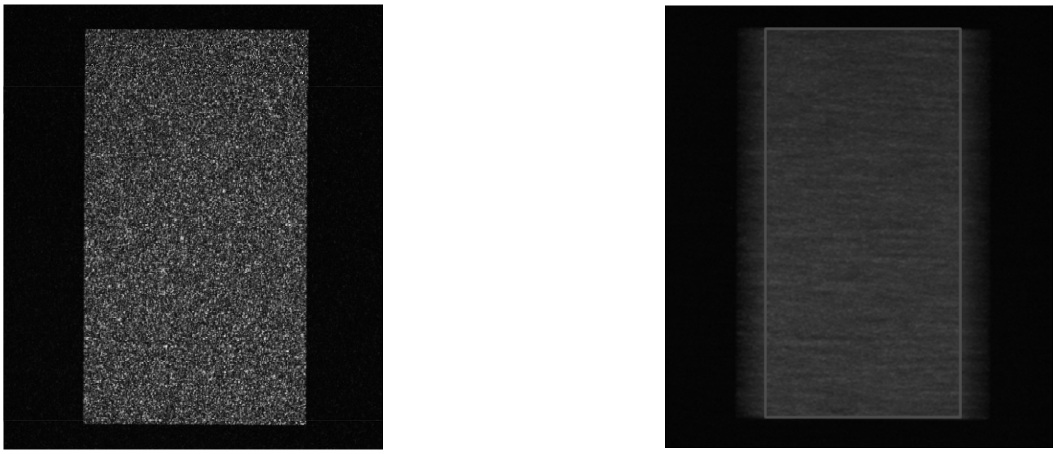
Figure 7(a) shows the illumination pattern on the target plane without a vibrating DOE. The DOE successfully transformed the circular laser beam to a rectangular pattern. Unfortunately, compare to the pattern in Fig. 2(b), the experimental result was not as good as the designed result. The fabrication error is one reason, but the major reason may be that the sampling interval on the output plane is not small enough, only the intensity distribution of the selected sampling points was controlled by the optimization algorithm [19]. The intensity distribution of other points on the output plane is far away from the ideal distribution. Because of the bad performance of the nonselected points in the optimization, the experimental result was not as good as the simulated result and included many speckles.

The speckle contrast (SC) value is used to quantify the speckle phenomenon. The SC value is defined as follows:

$$SC = \frac{\sigma_I}{\bar{I}} \tag{3}$$

The denominator is the mean intensity, and the numerator is the standard deviation [20]. The SC value of the illumination pattern in Fig. 7(a) we measured is 67.67%.

Then we measured the SC value with a vibrating DOE. The SC value is determined by the frequency and amplitude of the oscillator, as shown in Fig. 8. The SC curves show that the SC value decreases if the amplitude increases with a stable frequency, such as the SC value ranges from 67.67% to 17.33% between 0 μm and 200 μm of DOE amplitude with frequency at 50 Hz. The SC curves also reveal that when the DOE amplitude is constant, the higher the frequency, the lower the SC value, for instance, the SC value ranges from 17.33% to 13.78% between 50 Hz and 150 Hz with amplitude at 200 μm. Because of the restriction of the oscillator's intrinsic characteristic, the lowest SC value we got is 13.78%, with a vibrating DOE frequency at 150 Hz and amplitude at 200 μm, as shown in Fig. 7(b).



(a) (b)

FIG. 7. The illumination pattern on the target plane (a) without a vibrating DOE, (b) with a vibrating DOE frequency of 150 Hz and amplitude of 200 μm.

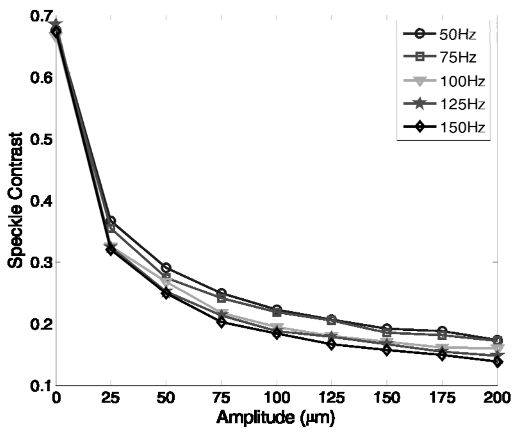


FIG. 8. The dependence of the SC value on the oscillator frequency and amplitude.

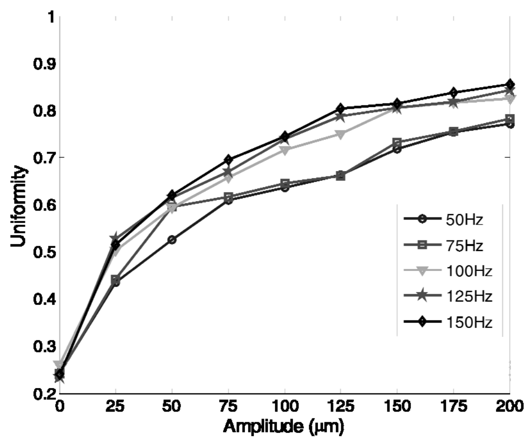


FIG. 10. The dependence of the uniformity on the oscillator frequency and amplitude.

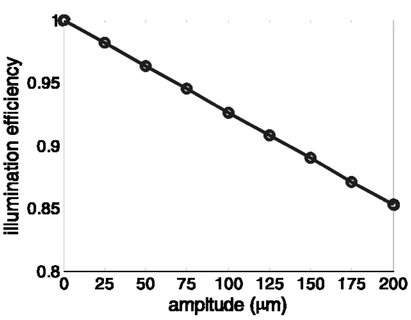


FIG. 9. Illumination efficiency versus vibration amplitude.

The region surrounded by the box in Fig. 7(b) is the effective illumination area. We should note that the larger the amplitude of the DOE is, the smaller the effective illumination region will be, and the lower the illumination efficiency is. We should make a trade-off between the speckle reduction and the illumination efficiency. Figure 9 shows the relationship between the illumination efficiency and the vibration amplitude.

Uniformity is an important parameter to measure the quality of the illumination pattern. It is calculated using a 13 point ANSI standard [21] for projectors. ANSI uniformity of the illumination pattern is affected by the speckle suppression level, as shown in Fig. 10. The lower the SC value is, the higher the ANSI uniformity will be. The ANSI uniformity of the illumination pattern in Fig. 7(b) is 85.54%. From the pattern in Fig. 7(b) we can observe several slight bright striations, which limit the performance of the speckle suppression and decrease the uniformity. They are caused by the existence of the portion of extremely bright spots in Fig. 7(a), which represent the low frequency modulations in the diffraction pattern. These low frequency modulations cause the obvious undulation envelope of the intensity, so that bright or dark spots in the local area are formed.

We have basically achieved the goal to transform the circular Gaussian laser beam to a low speckle contrast uniform rectangular pattern with a vibrating DOE. The further work we need to do is to improve the DOE's real performance. There are two ways we can do that; one is to modify the optimization algorithm to take into account the intensity distribution of the selected sampling points and the nonselected points simultaneously. The other one is to control the low frequency modulation components in the intensity pattern to further improve the uniformity.

V. CONCLUSION

In the present work, we proposed a method of beam shaping and speckle reduction in laser projection display systems by vibrating a DOE. The DOE is designed and fabricated to transform the circular Gaussian laser beam into a rectangular pattern. By vibrating the DOE, the SC value can be decreased efficiently by superimposing different illumination patterns temporally. Under the DOE vibration frequency at 150 Hz and amplitude at 200 μm, the SC is reduced from 67.67% to 13.78%, and the ANSI uniformity is improved from 24.36% to 85.54%. Due to the feature of compact size, the vibration of the DOE can be easily modulated with different frequency and amplitude for accommodating to different application conditions to achieve desired illumination quality and speckle contrast. The proposed method provided a reference to the miniaturization design of the laser projection display systems.

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REFERENCES

1. K. V. Chellappan, E. Erden, and H. Urey, "Laser-based displays: A review," Appl. Opt. **49**, 79-98 (2010).
2. C. M. Chang and H. P. D. Shieh, "Design of illumination and projection optics for projectors with single digital micromirror devices," Appl. Opt. **39**, 3202-3208 (2000).
3. 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-9 (2009).
4. 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).
5. S. Zhang, "A simple bi-convex refractive laser beam shaper," J. Opt. A, Pure Appl. Opt. **9**, 945-950 (2007).
6. R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," Optik . **35**, 237 (1972).
7. J. R. Fienup, "Iterative method applied to image reconstruction and to computer-generated holograms," Opt. Eng. **19**, 193297 (1980).
8. S. Kirkpatrick, C. D. Galatt, and M. P. Vecchi, "Optimization by simulated annealing," Science **220**, 671-680 (1983).
9. L. I. Voicu, W. A. Rabadi, and H. R. Myler, "Object support reconstruction from the support of its autocorrelation using multiresolution genetic algorithms," Opt. Eng. **36**, 2820-2827 (1997).
10. B. Redding, M. A. Choma, and H. Cao, "Speckle-free laser imaging using random laser illumination," Nature Photon. **6**, 355-359 (2012).
11. M. Nixon, B. Redding, A. A. Friesem, H. Cao, and N. Davidson, "Efficient method for controlling the spatial coherence of a laser," Opt. Lett. **38**, 3858-3861 (2013).
12. Z. Cui, A. Wang, Z. Wang, S. Wang, C. Gu, H. Ming, and C. Xu, "Speckle Suppression by Controlling the Coherence in Laser Based Projection Systems," J. Display Technol. **11**, 330-335 (2015).
13. N. E. Yu, J. W. Choi, H. Kang, D.-K. Ko, S.-H. Fu, J.-W. Liou, A. H. Kung, H. J. Choi, B. J. Kim, M. Cha, and L.-H. Peng, "Speckle noise reduction on a laser projection display via a broadband green light source," Opt. Express **22**, 3547-3556 (2014).
14. 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).
15. L. L. Wang, T. Tschudi, M. Boeddinghaus, A. Elbert, T. Halldorsson, and P. Petursson, "Speckle reduction in laser projections with ultrasonic waves," Opt. Eng. **39**, 1659-1664 (2000).
16. B. Redding, G. Allen, E. R. Dufresne, and H. Cao, "Low-loss high-speed speckle reduction using a colloidal dispersion," Appl. Opt. **52**, 1168-1172 (2013).
17. L. Wang, T. Tschudi, T. Halldorsson, and P. R. Petursson, "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).
19. 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. **21,** 6521-6525 (2015).
20. J. W. Goodman, Speckle Phenomena in Optics: Theory and Applications (Roberts & Company, Colorado, USA, 2007).
21. American National Standards Institute, "American National Standard for audiovisual systems-electronic projection fixed resolution projectors," U.S. Standard, IT7.228-1997 (1997).