A hybrid temporal and spatial speckle-suppression method for laser displays

Qing-Long Deng,[1] Bor-Shyh Lin,[2] Pei-Jung Wu,[2] Kuan-Yao Chiu,[3] Ping-Lin Fan,[4] and Chien-Yue Chen[3,*]

[1] *Institute of Photonic Systems, National Chiao Tung University, Tainan 71150, Taiwan*
[2] *Institute of Imaging and Biomedical Photonics, National Chiao Tung University, Tainan 71150, Taiwan*
[3] *Graduate School of Electronic and Optoelectronic Engineering, National Yunlin University of Science & Technology, Yunlin 64002, Taiwan*
[4] *Department of Digital Technology Design, National Taipei University of Education, Taipei 10671, Taiwan*
[*] *chencyue@yuntech.edu.tw*

Abstract: We propose a system that reduces laser display speckles by vibrating the light pipe. A small displacement of the light pipe appears to allow the total reflection of the laser, thereby resulting in a homogenized speckle field that changes with time. In this case, the speckle interference generated by the pattern projected by the laser through the light pipe destroys the spatial homogenization of the laser beams when the light pipe is vibrated. Moreover, when the light pipe begins the sequential vibration, the phases and paths of the beams are changed after the beams traverse the light pipe. Consequently, temporal speckle wavefront superposition can homogenize the luminous intensity distribution of the speckle pattern. This process reduces the speckle contrast to less than 4% while maintaining a luminous intensity of greater than 70%.

OCIS codes: (030.6140) Speckle; (110.6150) Speckle imaging; (080.3685) Lightpipes; (240.3695) Linear and nonlinear light scattering from surfaces.

References and links

1. H. Furue, A. Terashima, M. Shirao, Y. Koizumi, and M. Ono, "Control of laser speckle noise using liquid crystals," Jpn. J. Appl. Phys. **50**(9), 09NE14 (2011).
2. J. M. Artigas, A. Felipe, and M. J. Buades, "Contrast sensitivity of the visual system in speckle imagery," J. Opt. Soc. Am. A **11**(9), 2345–2349 (1994).
3. L. Wang, T. Tschudi, T. Halldórsson, and P. R. Pétursson, "Speckle reduction in laser projection systems by diffractive optical elements," Appl. Opt. **37**(10), 1770–1775 (1998).
4. L. Wang, T. Tschudi, T. Halldorsson, and P. Petursson, "Method and device for eliminating image speckles in scanning laser image projection," U.S. Patent 6367935, 2002.
5. S. Lowenthal and H. Aresenault, "Speckle removal by a slowly moving diffuser associated with a motionless diffuser," J. Opt. Soc. Am. **61**(7), 847–851 (1971).
6. 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**(11), 1290–1294 (1976).
7. K. Kasazumi, Y. Kitaoka, K. Mizuuchi, and K. Yamamoto, "A practical laser projector with new illumination optics for reduction of speckle noise," Jpn. J. Appl. Phys. **43**(8B), 5904–5906 (2004).
8. S. Roelandt, Y. Meuret, G. Craggs, G. Verschaffelt, P. Janssens, and H. Thienpont, "Standardized speckle measurement method matched to human speckle perception in laser projection systems," Opt. Express **20**(8), 8770–8783 (2012).
9. M. Sun and Z. Lu, "Speckle suppression with a rotating light pipe," Opt. Eng. **49**(2), 024202 (2010).
10. H. Funamizu and J. Uozumi, "Generation of fractal speckles by means of a spatial light modulator," Opt. Express **15**(12), 7415–7422 (2007).
11. C. Joenathan and B. M. Khorana, "Contrast of the vibration fringes in time-averaged electronic speckle-pattern interferometry: effect of speckle averaging," Appl. Opt. **31**(11), 1863–1870 (1992).
12. M. Francon, *Laser Speckle and Applications in Optics* (Academic, 1979).
13. F. Riechert, G. Bastian, and U. Lemmer, "Laser speckle reduction via colloidal-dispersion-filled projection screens," Appl. Opt. **48**(19), 3742–3749 (2009).
14. A. J. Weierholt, E. G. Rawson, and J. W. Goodman, "Frequency-correlation properties of optical waveguide intensity patterns," J. Opt. Soc. Am. A **1**(2), 201–205 (1984).

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15. C. Rydberg, J. Bengtsson, and T. Sandstrom, "Dynamic laser speckle as a detrimental phenomenon in optical projection lithography," J. Microlithogr. Microfabr. Microsyst. **5**(3), 033004 (2006).
16. F. Riechert, "Speckle reduction in projection systems," Ph.D. thesis (Karlsruhe Institute of Technology, 2009).
17. P. C. Ashok, U. Nair, V. Kas, V. N. N. Namboothiri, and V. P. N. Nampoori, "Speckle metrology based study on the effect of chattering on machined surfaces," Proc. SPIE **6671**, 6671V (2007).
18. Y. Kuratomi, K. Sekiya, H. Sato, T. Kawakami, and T. Uchida, "Analysis of speckle-reduction performance in a laser rear-projection display using a small moving diffuser," J. Soc. Inf. Disp. **18**(12), 1119–1126 (2010).
19. J. W. Goodman, *Speckle Phenomena in Optics: Theory and Applications* (Roberts and Company, 2007).
20. B. Redding, G. Allen, E. R. Dufresne, and H. Cao, "Low-loss high-speed speckle reduction using a colloidal dispersion," Appl. Opt. **52**(6), 1168–1172 (2013).

1. Introduction

Lasers are currently being developed as backlight sources to improve optical quality in projection systems. Compared with traditional light sources, lasers have greater power, higher brightness, lower energy consumption, better color rendering, and greater directivity. Nevertheless, the high coherence of lasers hinders their use as backlights. Speckles are the strong interference patterns that are induced by the high coherence of a laser and the topography of an object surface. When coherent light illuminates a rough surface, the original coherent light is destroyed, and scattered light is reflected by the object. This light is received by the detector, and it appears as constructive interference and destructive interference, which further affects the speckle pattern and forms a random brightness-darkness distribution [1]. When the projected image is interfered with by speckles, the detector perceives strong brightness-darkness speckle flares, which could result in serious visual dizziness and even visual fatigue [2].

Phase modulation has been used to suppress speckles [1]. L. Wang *et al.* [3] reduced speckle contrast to 3.80% by using rotating diffraction optical elements (DOE) to superpose laser beamlets, thereby generating different speckle patterns. However, the scattering and absorption of the diffraction optical elements would result in additional luminous intensity loss [3,4]. Other research found that speckle noise could be reduced to less than 1/3 of the original by moving the diffusion sheet or screen to suppress the speckles. Nonetheless, using a diffusion sheet would result in a greater-than-50% loss of luminous intensity, and moving the screen is rather complex [5–8]. When the laser goes through a rotated light pipe, the speckle pattern rotates to decrease the speckle contrast to 3.45%, but the speckle interference in the middle of the image does not effectively decrease the central speckle contrast because of the rotation [9]. Spatial light modulator (SLM) phase modulation could reduce the speckle contrast. Although it avoids mechanical rotation or movement, current technology restricts the speckles suppression effect because the pixel size of the SLM is in the micrometer range [10]. Here, we propose a hybrid despeckle mechanism that combines the destruction of laser spatial coherence and temporal speckle wavefront superposition. We also propose vibrating the light pipe to verify that speckles are suppressed.

The speckles are suppressed by vibrating the light pipe in the experiment. The vibrating element is fixed to the outside of the light pipe such that the speckle pattern is time-homogenized [11]. Thus, when the laser travels through the light pipe, the total reflection on the pipe wall and the tiny displacement successfully reduce the speckle contrast. Moreover, the luminous intensity remains greater than 70% of the original after the laser goes through the light pipe. Compared with diffusers or the DOE, vibrating the light pipe is better because it suppress speckle interference and reduces the luminous intensity loss. Furthermore, the structure volume is not increased when this approach is used in a laser system or laser projection system.

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2. Principle of despeckling

2.1. Suppression of spatial coherence

The destruction of laser spatial coherence effectively destroys the wavefront of the transient horizontal wave of a laser wave, thereby causing the phase relationship between two points to be destroyed or to experience interference that further reduces the coherence. Two factors involved in destroying spatial coherence are considered in this study. First, according to the Huygens-Fresnel principle, when a laser goes through an objective lens, the objective lens destroys the laser wavefront and causes the beamlets, which originally go in the same direction, to homogenously transport over a range of directions, which is specified by the scattering angle. Furthermore, the spatial coherence of the laser is directly proportional to the square of the scattering angle [12]. Thus, the smaller the scattering angle, the greater the directivity of the laser, and vice versa.

Second, regarding the total reflection effect in a static light pipe, when the scattered laser enters the light pipe, the beamlets appear as internal reflections with various angles on the inner wall of the light pipe. Some beamlets do not present total reflections on the inner wall of the light pipe but rather directly penetrate the wall with a paraxial, as shown in Fig. 1.

When $\theta<\theta_1$, the beamlets without total reflection directly illuminate the screen and form the first-layer speckle pattern. When $\theta_1<\theta<\theta_2$, the beamlets proceed to display a total reflection on the inner wall of the light pipe once. This image occurs on the middle layer on the screen. Taking the optic axis as the central line, the light pipe is divided into the upper and lower layers. When the middle layer takes part in the internal total reflection, one-time total reflection in the upper layer (i.e., the range of θ_{up}) and one-time total reflection in the lower layer (i.e., the range of θ_{down}) cause mutual speckle pattern superposition, as shown in Fig. 2. The ray trace in the upper layer θ_{up} requires a one-time total reflection with the pipe wall such that the ray at the end of the upper pipe wall exhibits the total reflection effect. The autocorrelation function of the speckle field in the superposition range integrates the ray-trace superposition in the upper layer and the lower layer, and because it is a non-linear superposition, the speckle contrast in the middle of the speckle pattern is less than at the edges. When $\theta_2<\theta<\theta_3$, the beamlets produce more than twice the total reflection effect within the light pipe. This effect causes a regularly repeated and greater speckle pattern superposition effect on the outer layer, as shown in Fig. 1.

In summary, when the divergent angle approaches the maximum permitted incidence angle, θ_{max}, the number of speckle pattern superpositions is maximized. The generated speckle field is shown in Fig. 3, which illustrates greater superposition in the middle of the speckle than at the edges. Equation (1) defines the restriction of the divergent angle θ when the laser precedes the total reflection in the pipe.

$$90^\circ - \sin^{-1}\left[\frac{1}{n}\sin(\frac{\theta}{2})\right] > \theta_c \tag{1}$$

In this equation, θ is the divergence angle, θ_c is the critical angle on the pipe wall, and n is the refractive index of the light pipe material.

Furthermore, the time difference $\Delta T = \Delta L/C$ (path difference/speed of light) between the speckle patterns in each layer is far less than the reaction time of the human eye (20 ms). Human eyes can hardly perceive the rapid changes of speckle patterns in the light pipe [13,14].

#200420 - $15.00 USD Received 29 Oct 2013; revised 3 Dec 2013; accepted 3 Dec 2013; published 9 Dec 2013

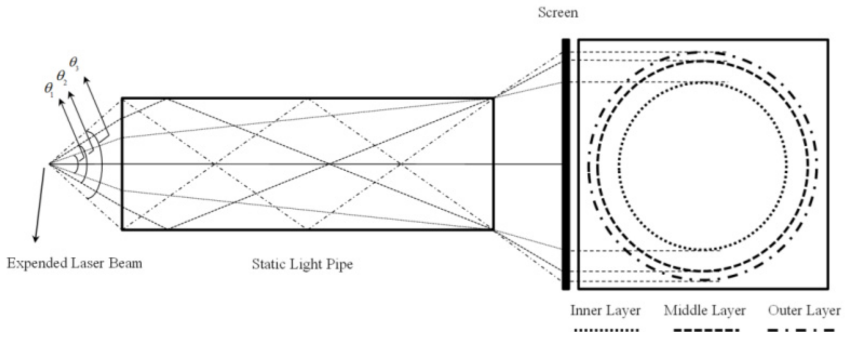

Fig. 1. Speckle field caused by diffusion and total reflection in the light pipe.

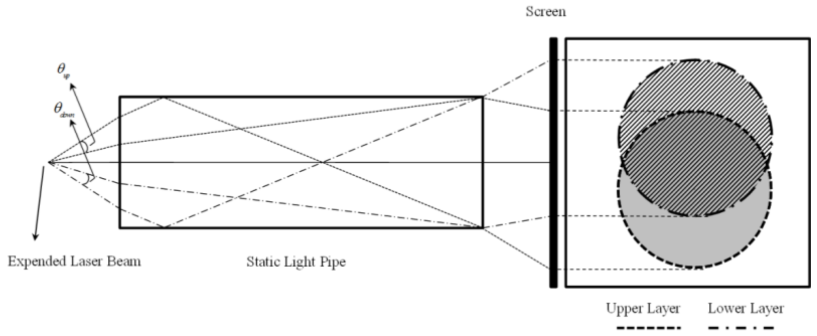

Fig. 2. Speckle field superposition caused by one-time total reflection.

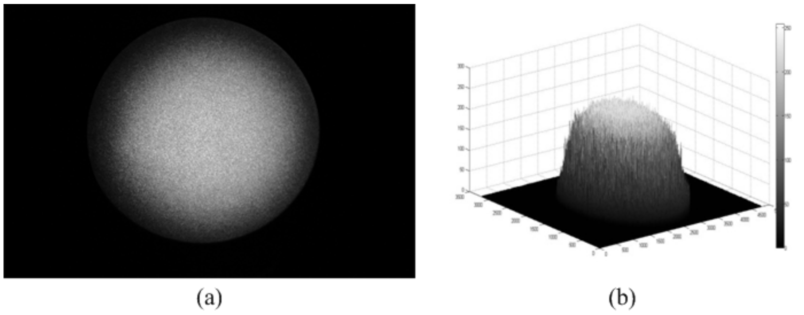

Fig. 3. (a) Speckle field. (b) Luminous intensity distribution.

2.2. Suppression of temporal coherence

To suppress temporal speckling, we propose inducing time-homogenization by vibrating the light pipe. In Fig. 4, the light pipe is vibrated, and the displacement of the pipe wall changes the angle of the incident light. When a fixed light source scatters the incident light at various angles, the laser wavefront appears as mutual interference with the vibration of the inner wall. The original waveforms appear as self-superpositions with sequential vibration, and they have the luminous intensity of the speckle pattern that is homogenized. This process is called time-sequential angular decorrelation and phasefront decorrelation. The vibration amplitude and the vibration frequency are the keys: the faster the vibration frequency of the light pipe, the shorter the time of the one-time vibration. In the integration time of the human eye, the waveforms would be better homogenized with time-sequential superposition. Figure 5 shows the displacement of waveforms caused by spatial coherence before the displacement. When the light pipe is vibrated, the waveforms move back and forth,, and the speckles on the

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speckle pattern are suppressed when the displacement speed is greater than the reaction time of human eyes.

The exposure time of charge-coupled device (CCD) determines the self-superposition level of the waveforms, which is defined in the same time-sequence self-interference in the speckle field [15]. Moreover, the decorrelation appears in the same space, and it is thus called time-sequential spatial decorrelation [16].

In the speckle suppression of temporal coherence, the ratio of the standard deviation of the luminous intensity to the mean of luminous intensity is referred to as the speckle contrast, as shown in Eq. (2). The standard deviation of luminous intensity is defined as the autocorrelation intensity of the speckle field with temporal variation after time-homogenization. This function is named the probability density function of the luminous intensity and is given in Eq. (3).

$$C = \frac{\sigma_s}{\langle I \rangle} \tag{2}$$

Here, σ_s is the standard deviation of luminous intensity, and $\langle I \rangle$ is the mean of the luminous intensity.

$$\sigma_s^2(T) = \frac{1}{T}\int_0^T C_\tau(\tau)\,d\tau \tag{3}$$

In this equation, C_τ is the speckle intensity with temporal variation.

Combining Eqs. (2) and (3) gives Eq. (4), which describes the relationship between speckle contrast and exposure time. The CCD exposure time is set to 20 ms to correspond to the integration time of the human eye (~20 ms).

$$C = \left\{ \frac{\tau_c}{2T}\left[1 - \exp\left(\frac{-2T}{\tau_c}\right)\right]\right\}^{1/2} \qquad \tau_c = \int_{-\infty}^{\infty} \left|\mu_A(\tau)\right|^2 d\tau \tag{4}$$

T is the exposure time, τ_c is the coherence time of the speckle intensity, and $\mu_A(\tau)$ is the wave motion of the speckle luminous intensity.

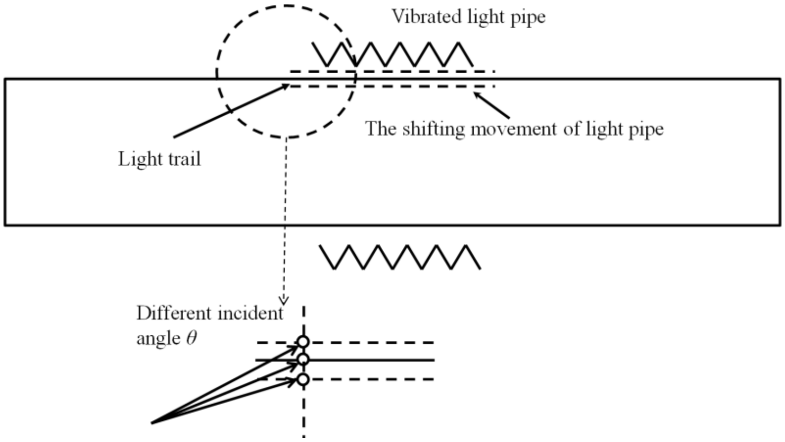

Fig. 4. The shift-vibrated effect of a vibrated light pipe.

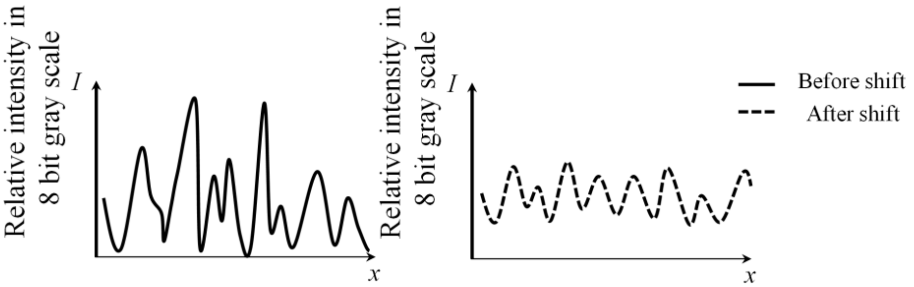

Fig. 5. The shift effect of the waveform.

3. Experiments and results

The experimental diagram for the light pipe vibration is shown in Fig. 6. The green semiconductor laser is used as the light source. The wavelength is set to 532 nm, the power is 16 mW, and the beam diameter is 1.0 mm. The light pipe is a soft stainless steel pipe covered with compound glass. To effectively couple the ray and the light pipe, the acceptance angle of the light pipe is given with its numerical aperture (N.A.).

$$\text{N.A.}=n\sin\theta_{\max} \tag{5}$$

θ_{max} is the maximum permitted incident angle, and n is the refractive index of the medium of incident light. Rays with incidence angles that exceed the incidence angle θ_{max} cannot enter the optical fiber. A light pipe with a high numerical aperture would conduct in the light pipe with close-to-axis and large-range acceptance angles. Simply put, the ray must enter the light pipe with an incidence angle smaller than the acceptance angle to be conducted in the light pipe. Compound glass is used as the material of the light pipe because it allows a larger acceptance angle and restricts the total reflection beams internally. The maximal acceptance angle of the light pipe is therefore 60°.

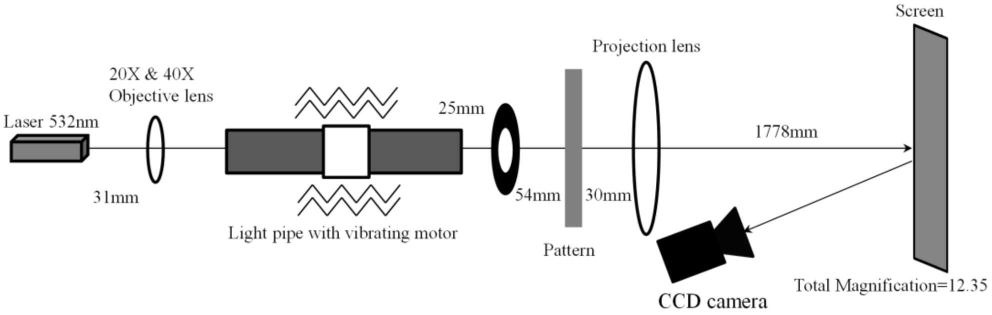

Fig. 6. Schematic diagram of speckle suppression by a vibrating light pipe.

To suppress the interference of speckles, we tested the effects of using light pipes with different lengths, using coupling lenses with distinct numerical apertures, and offsetting different vibration frequencies for the motor. The experimental parameters of the coupling lens are presented in Table 1. To efficiently couple beams with the light pipe, we placed the objective lens 12.5 mm and 7.7 mm away from the light pipe such that beams could completely enter the light pipe and provide total internal reflection. Both the incident diameter and the emergent diameter of the light pipe were 6 mm. The lengths were 20 cm, 40 cm, and 100 cm. The numerical aperture was 0.37, and the vibration frequency was in the range 0-180 Hz.

Table 1. Experimental Parameters of the Objective Lens

Objective lens/ N.A.	20X/0.40	40X/0.65
Distance between light pipe and objective lens	12.5 mm	7.7 mm
Clear aperture diameter	7 mm	5 mm

Given a light pipe length L, a fixed critical angle θ_{max}, and a light pipe diameter R, the number of total internal reflections N can be calculated as follows:

$$N = \left(\frac{L}{R \times \tan \theta_{\max}} \right) - 1 \qquad (6)$$

When the speckle pattern superposition reflects 1 to m times, the number of speckle pattern superpositions with spatial coherence is greater and the speckle contrast is lower.

$$C = (M)^{-1/2} \qquad (7)$$

C is the speckle contrast, and $M = T/\tau_c$

A vibrating element was added to the middle of the light pipe. Its vibration frequency was increased from 0 Hz to 180 Hz, and the vibration amplitude was set to approximately 0.26 mm to reduce the speckle contrast. The increasing vibration frequency caused a corresponding reduction in the speckle contrast. The logo of National Yunlin University of Science and Technology was used as the signal pattern; this pattern was projected onto the screen.

The intensity loss after total reflection of the laser in the light pipe was measured with a power meter, as illustrated in Table 2. The luminous intensity loss was primarily caused by reflection of some of the incident light by the incident surface as the laser entered the light pipe. Some luminous intensity was also absorbed by the medium along the length of the pipe.

Table 2. Loss of Light Intensity of the Light Pipe

Light pipe	20 cm		40 cm		100 cm	
Loss of light intensity	Loss	Save	Loss	Save	Loss	Save
	29.49%	70.51%	33.72%	66.28%	43.14%	56.86%

Figure 6 shows the experimental data recorded by a CCD camera with a fixed focal length of 55 mm, an aperture opening of f/2.8, and an exposure time of 20 ms. The distance from the screen was 900 mm. The CCD resolution was 347 × 347 pixels, and each pixel had dimensions 4.7 μm × 4.7 μm. The CCD parameters were selected to prevent the speckle brightness from being oversaturated or undersaturated [17]. The reaction time of human eyes, 20 ms, was used as the exposure time. The intensity changes of the speckle field would superpose to the human eyes, so image changes would also be superposed [18]. The speckle contrast of the speckle pattern was acquired after processing the images acquired by the CCD (using the Open Source Computer Vision Library, *OpenCV*).

Figure 7 shows the speckle pattern observed in this experiment, and Figs. 7(a) and 7(b) are the speckle patterns with and without vibration in the 100 cm light pipe with a 20X objective lens. As shown in Fig. 7(a), the suppressed speckle was reduced such that the speckle contrast was 22.03%. This reduction was achieved by creating diffusion with the 20X objective lens, thereby allowing total reflection in the light pipe and homogenizing the integration time in the CCD camera. In Fig. 7(b), the vibration has reduced the speckle contrast to 3.96%. Figures 7(c) and 7(d) show the speckle patterns with and without vibration at 40X magnification. Whereas previously, a diffusion angle of 23.57° and a 20X objective lens were used, here the diffusion angle is 40.54°, and a 40X objective was used to provide more total reflection effects when the laser conducts in the light pipe. The speckle contrasts in Figs. 7(c) and 7(d) are 21.71% and 3.46%, respectively. The experimental data are organized in Table 3, which are the measured speckle contrasts matched to the reaction time of the human eye, which is approximately 20 ms [19]. According to the table, the contrast that the 40X objective lens

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reveals is approximately 1-2% less that of the 20X objective lens. With the 100-cm light pipe, the speckle contrast of both the 20X and 40X objective lenses would be less than 4%, which the human eye could detect if the vibration frequency of the light pipe were 180 Hz [20].

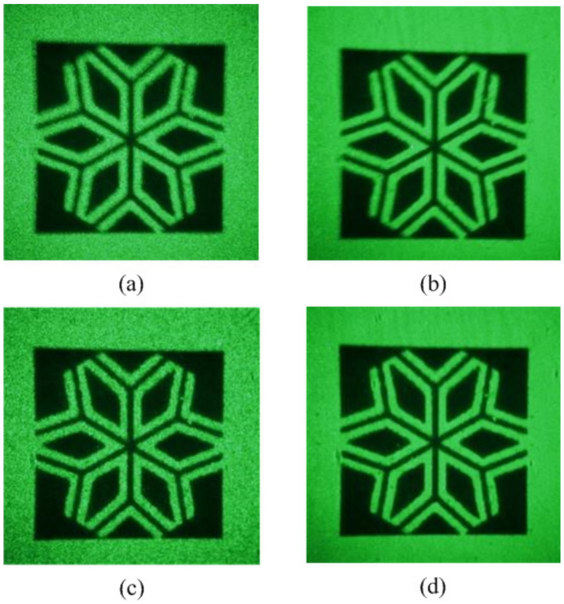
(a) (b)
(c) (d)

Fig. 7. Speckle patterns from the DPSS AMGA-010 laser: (a) 20X without vibration, (b) 20X with maximum vibrated frequency 180 Hz, (c) 40X without vibration, (d) 40X with maximum vibrated frequency 180 Hz.

Table 3. Experimental Results

Light pipe	Objective lens	Vibrated frequency(Hz)	Speckle contrast (%)
20 cm	20X	0 Hz	43.43%
	20X	180 Hz	7.54%
	40X	0 Hz	42.91%
	40X	180 Hz	6.94%
40 cm	20X	0 Hz	31.60%
	20X	180 Hz	6.34%
	40X	0 Hz	29.68%
	40X	180 Hz	5.39%
100 cm	20X	0 Hz	22.03%
	20X	180 Hz	3.96%
	40X	0 Hz	21.71%
	40X	180 Hz	3.46%

4. Discussion

In our experiment, and according to the Huygens-Fresnel principle, the beamlets that originally appeared in the same direction were homogenously conducted through the light pipe in a range of angles given by the diffusion angle. This effect occurs when the laser goes through the objective lens and destroys the wavefront of the laser. Beamlets that enter from different angles precede internal reflection by reflecting at various angles on the inner wall of the light pipe, and they directly emerge with the paraxial when the incident light is conducted into the light pipe. In this case, the speckle field of the light pattern output on the screen exhibits non-linear superposition, which destroys the original laser spatial coherence.

The displacement of the pipe wall caused by vibration changes the angle of the incident light such that the wavefront of the laser experiences interference again. With sequential vibration, the original waveforms cause self-superposition and homogenize the luminous intensity distribution of the speckle pattern. This process is called time-homogenization. In contrast with technologies that pass a laser through a general diffusion sheet to reduce speckling, our approach combines the destructive spatial coherence of a laser with temporal speckle wavefront superposition. Based on our results, we propose a virtual diffuser-like method that successfully reduces speckle noise.

Increasing the CCD exposure time reduces the speckle contrast. Thus, we selected an integration time of approximately 20 ms, which is approximately the speed that the human eye can observe. In Fig. 8, the speckle contrast rapidly decreases when the vibration frequency is 50 Hz, but it slows down when the frequency exceeds 50 Hz, primarily because the probability density distribution of the speckle intensity is an exponential function with a negative exponent. The speckle contrast in the probability density function of luminous intensity approaches saturation when high-frequency vibration is used. As shown in Table 2, a longer light pipe provides better spatial coherence suppression for the laser in the light pipe, but the luminous intensity loss is greater.

Figure 9 shows the speckle pattern with and without vibration using the 40X objective lens with a 100 cm light pipe. The image size is 100 pixel × 100 pixel, and each pixel is 4.7 μm × 4.7 μm. As shown in the figures, the speckle contrast (21.71%) in Fig. 9(a) is greater than it is in Fig. 9(b) (3.46%), thereby demonstrating that vibrating the light pipe effectively suppresses speckle interference and reduces speckle contrast to less than 4%, which human eyes can observe.

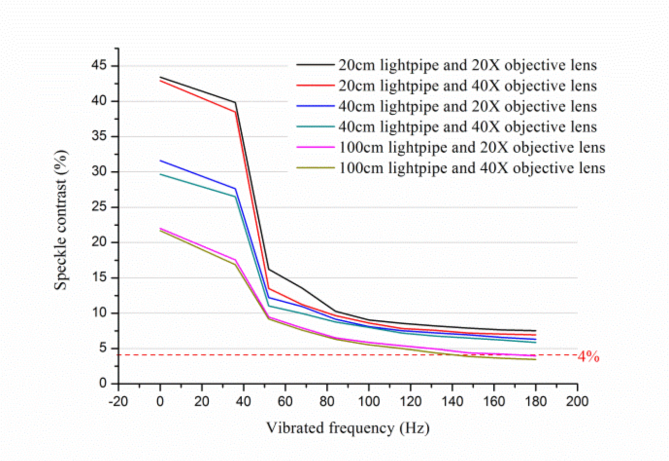

Fig. 8. Speckle contrast and vibration frequency data.

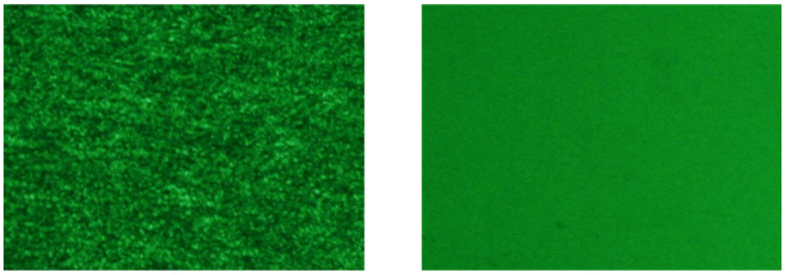
(a)
(b)

Fig. 9. (a) Vibrating light pipe with frequency 0 Hz. (b) Vibrating light pipe with frequency 180 Hz.

5. Conclusions

This study proposes an approach to reduce speckles and maintain laser luminous intensity. In our experiment, the total reflection effect in the light pipe was able to reduce the luminous intensity loss when the laser was conducted through a light pipe. The total reflection effect destroys spatial coherence, much like when a laser goes through a diffusion sheet. We use the term “virtual diffuser-like” in this study. By using time-homogenization when vibrating the light pipe, we keep the displacement of the pipe wall very small, much like it would be in the case of destructive time-coherence generated by diffusion sheet displacement. This reduces the speckle contrast below 4%, but the luminous intensity is kept above 70% of the initial value. Adding a vibrating device to the light pipe in the laser display could reduce the speckling and enhance the image quality. Unlike traditional systems for suppressing speckles with a diffusion sheet, vibrating the light pipe could provide the benefit of enhancing the luminous intensity of the laser.

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