Speckle reduction and maintaining contrast in a LASER pico-projector using a vibrating symmetric diffuser

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Abstract: We proposed a design for a LASER pico-projector with a low speckle contrast value and high contrast ratio that maintains system efficiency. The method for speckle contrast reduction utilizes two diffusers and a Voice Coil Motor (VCM) oscillator. The two different diffusers for a high contrast ratio and high system efficiency can be divided into two categories. In Category 1, the speckle contrast value can be decreased to 2.80% by using a circular symmetric diffuser. At the same time, the full-on/full-off (FO:FO) contrast ratio can be maintained within 1200:1-1300:1, but the system efficiency decreases 1.50%. In Category 2, the speckle contrast value can be reduced to 6.50% by using an elliptically scattering diffuser. At the same time, the FO:FO contrast ratio can be maintained within 1300:1-1400:1, and the system efficiency decreases by only 1.00%.

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1. Introduction

With the development of semiconductor manufacturing, solid-state light sources for display [1] have to be mass-produced. Solid-state light sources have some advantages, such as they are energy saving, and have no mercury content, in compliance with the RoHS rules. Solid-state light sources can be divided into two types: light emission diodes (LED), and light amplification by stimulated emission of radiation (LASER). Nowadays, the LED is a commonly used light source in the pico-projector. However, for the pico-projectior, the etendue of the LED is still too large to reduce the size of the illumination system. The LED is thus unsuitable as a light source for this purpose. The other solid state light source, the LASER, is suitable for the pico-projector. Because the LASER is highly collimating, the etendue is much smaller than that of LED and can thus be used in an illumination system that requires such a compact size. So the LASER is a good choice for the light source of a pico-projector.

The speckle phenomenon is an inevitable problem when a LASER is used as the source in a pico-projector. This is the interference pattern caused by the scattering of light from the screen or the rough surface. Elimination of the speckle phenomenon, which reduces image quality, is an important issue in the LASER pico-projector design. This phenomenon can be reduced by destroying the degree of temporal coherence or spatial coherence. There are some well-known methods for this such as using a LASER array [2], moving screen [3], scanning micromirrors [4], rotating diffuser [5], vibrating diffractive optical elements [6], vibrating volume phase holographic beam shaper [7,8], rotating light pipe [9], stimulated-Raman-scattering (SRS) in the optical fiber [10], or vibrating multimode optical fiber bundle [11]. The above methods can reduce the speckle contrast value to an invisible level, but the size or system weight are still too large for pico-projector applications. Consequently, they cannot be adapted for use in the LASER pico-projector.

In this study, we use diffusers, a circular symmetric diffuser and an elliptically scattering diffuser [12], to reduce the value of the speckle contrast [13]. Diffusers are placed on both sides of a light pipe for speckle reduction, homogenization, and maintaining of the contrast ratio. The first diffuser is a fixed circular symmetric diffuser, and the second diffuser is either a circular symmetric diffuser or an elliptically scattering diffuser. It is found that two circular symmetric diffusers can efficiently reduce the speckle contrast value to 2.82%. At the same time, the FO:FO contrast ratio can be maintained at 1182.36:1.

2. Speckle definition and measurement setup

2.1 Speckle contrast value

In the LASER pico-projector, the speckle contrast value is used to quantify the speckle phenomenon. The speckle contrast value is defined as follows:

$$C = \frac{\sqrt{<I^2> - <I>^2}}{<I>} \times 100\% \tag{1}$$

The denominator is the mean intensity, and the numerator is the standard deviation [14]. The speckle contrast value lies between 0% and 100%. If the image was not influenced by the speckle phenomenon, the speckle contrast value would be 0%. When the speckle contrast value is lower than 5% [15,16], the speckle phenomenon cannot be observed by the human eye therefore the speckle contrast value of the LASER pico-projector must be lower than 5%.

2.2 Measurement setup

The experiment setup is shown in Fig. 1. The LASER pico-projector and objective lens are placed at a distance of 500mm from the screen [15]. A green LASER is used in the experiment setup, because the human eye is more sensitive to green light. The wavelength of the green LASER is 532nm. The resolution of the CCD camera [17] is 1280 × 1024, and the pixel size of the CCD camera is 5.2µm × 5.2µm. The integration time of the CCD camera is 20ms [18,19]. The F/# of the camera lens [20] is 1.3.
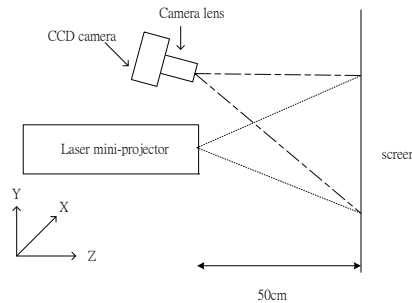

Fig. 1. Sketch of the experiment setup.

3. Homogeneous method and VCM feature for speckle reduction

The illumination system in the digital light processing (DLP) pico-projector must produce a homogeneous light field before the light passes through the imaging system. Two different methods have been used in the illumination system for the purpose, one is the lens array, and the other is the light pipe.

   Considering the compact size, the lens array is not a suitable element for a pico-projector. The LASER source would need a light expander to increase the etendue for working with a lens array. This application would add to the cost and require additional elements in the illumination system [21–23]. Therefore, we choose a light pipe.

   For this type of illumination system, the light should diverge before entering the light pipe because if the light source is collimated, like with the LASER, it cannot bounce about within the light pipe. Therefore, the first diffuser is located at the entrance of the light pipe to allow the collimated light to diverge. The LASER light can thus bounce about in the light pipe for homogenous distribution. However, at the same time, the diffuser can produce various speckle patterns. The speckle contrast value can be reduced through the superpositioning of the various speckle patterns by a relay lens system. Using the same method, the second diffuser is placed at the end of the light pipe. The first diffuser is also vibrated by a Voice

Coil Motor (VCM) oscillator whose function is to reduce the speckle phenomenon by destroying the degree of temporal coherence [13]. If the second diffuser is vibrated by a VCM oscillator, the edge of the illuminance appearing on the Digital Micromirror Device (DMD) is not sharp.

A relay lens, total internal reflection (TIR) prism and the projection lens from an LED projector [21] are used in the LASER pico-projector. The size of the DMD for the LASER pico-projector is 0.3 inches (7.62mm) [24]. The lateral magnification of the relay lens of the LED projector is 2.4. The size of the light pipe can be calculated based on the means of the lateral magnification and the DMD's size. The size of the light pipe is 2.7mm × 2mm and is 12 mm in length, as determined by balancing the JBMA uniformity and light pipe efficiency [25]. Therefore, the light pipe volume is 64.8 mm^3. The optical layout of the LASER pico-projector is shown in Fig. 2.
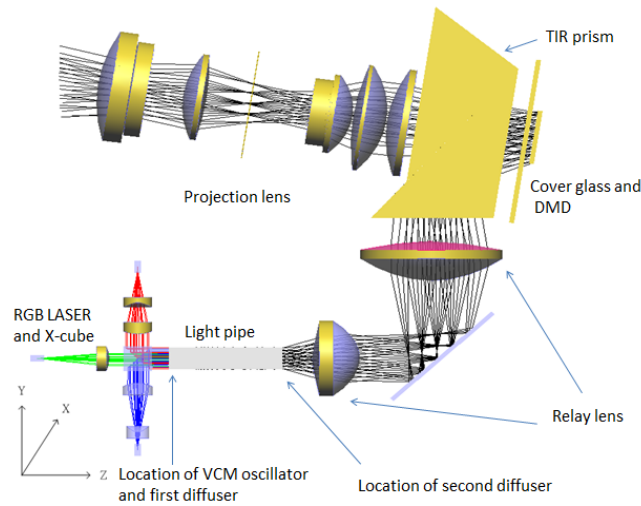

Fig. 2. Layout of the LASER pico-projector.

In the experiment setup, a VCM oscillator is used to vibrate the first diffuser. The vibrating amplitude of the VCM oscillator is shown in Fig. 3. When the oscillator's frequency decreases, the vibrating amplitude of the oscillator increases. The vibrating amplitude is approximately 0.5mm, when the frequency is lower than 180Hz.
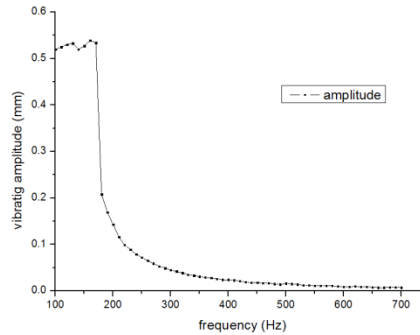

Fig. 3. Dependence of the vibrating amplitude of the VCM oscillator on the oscillator's frequency.

4. Reduction of speckle contrast by vibrating different diffusers

Methods for speckle contrast reduction with different diffuser types can be divided into two categories: Category 1 using two circular symmetric diffusers; Category 2 where the first diffuser is a circular symmetric diffuser and the second diffuser is an elliptically scattering diffuser. The divergent angles of the circular symmetric diffusers are 5 degrees (5X5), 10 degrees (10X10), and 30 degrees (30X30), while the divergent angles of the elliptically scattering diffusers are 30 degrees and 5 degrees (30X5), 50 degrees and 10 degrees (50X10), and 80 degrees and 20 degrees (80X20). The divergent angle is defined by the Full Width at Half Maximum (FWHM) angle of intensity distribution for the X and Y directions, respectively. For instance, 5X5 means this is a circular symmetric diffuser, and the FWHM angle of the diffuser is 5°, while 30X5 means that this is an elliptically scattering diffuser, and the FWHM angle of the diffuser is 30° and 5°, respectively.

4.1 Category 1: both diffusers with angle symmetrical distribution

When the second diffuser is a circular symmetric diffuser, the vibrating mode can be divided into two kinds of modes. An example of a light pipe system with the first diffuser being 30X30 and the second diffuser being 30X30 is shown in Fig. 4. In Fig. 4(a), "30X30V, 30X30", indicates that the vertical vibrating direction of the first diffuser corresponds to short side of the light pipe. "30X30H, 30X30" indicates that the horizontal vibrating direction of the first diffuser corresponds to the long side of the light pipe, as shown in Fig. 4(b).
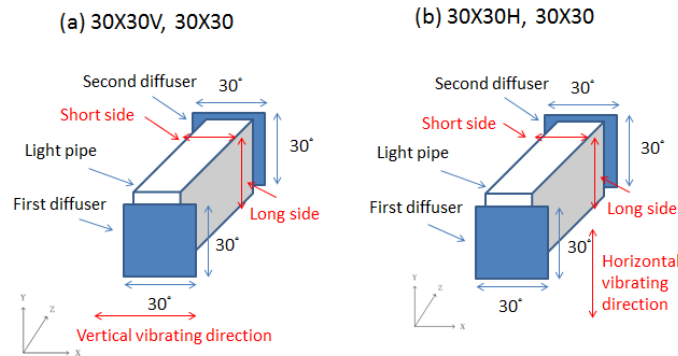

Fig. 4. When the second diffuser is a circular symmetric diffuser, the vibrating mode can be divided into two modes: (a) 30X30V, 30X30; (b) 30X30H, 30X30.

The speckle contrast value is determined by the frequency of the VCM oscillator, the FWHM angle of second diffuser, and two vibration mode, as shown in Fig. 5. When the first diffuser is 10X10, the speckle contrast value can be reduced from 19.62% to 7.01% with a different vibrating mode and second diffuser, as shown in Fig. 5(a). The lowest speckle contrast is "10X10V, 30X30" at a VCM oscillator frequency of 100Hz. The speckle contrast value is not lower than 5%. If the first diffuser is 30X30, the speckle contrast value can be reduced from 16.73% to 2.80% with a different vibrating mode and second diffuser, as shown in Fig. 5(b). The lowest speckle contrast value is obtained with "30X30V, 30X30" and is 2.80% at a 100Hz VCM oscillator frequency.

The relationship between the vibrating frequency and displacement is shown in Fig. 3. It can be seen that the vibrating frequency increases as the displacement of the diffuser decreases. This behavior is inherent to a VCM. Owing to this feature, the speckle contrast value is inversely proportional to the displacement of the diffuser [23]. Thus, the vibrating frequency is linear dependence on the speckle contrast value in the region 100 Hz-700 Hz. Moreover, when the vibrating frequency of the VCM is 0 Hz, the displacement is 0 mm. The speckle contrast value is the largest number for a different frequency under the same diffuser

condition. Moreover, the displacement of the diffuser is the largest value under a frequency of 100Hz. Under this condition, the speckle contrast value has the lowest value when the VCM oscillator frequency is 100Hz, because this is when the amplitude of the vibration is the largest

Moreover, under the VCM frequency, the speckle contrast of the second diffuser with a large divergent angle will be lower than that of the second diffuser with a small divergent angle. The main reason is that with a large divergent angle, more speckle patterns can be created [11]. The superposition of the speckle patterns by the relay lens system can efficiently reduce the speckle contrast value. Moreover, the speckle contrast value is less in the vertical vibrating direction than in the horizontal vibrating direction, as shown in Fig. 5. The main reason is that it takes more for the light to bounce in the light pipe in the vertical direction than in the horizontal direction. The light pipe in the vertical vibrating direction has a short edge, so the number of reflections increases. Number of reflections is proportional to the number of reflected laser light images [26]. The more LASER light image reflection occurs, the greater the formation of speckle patterns. The number of reflections for a 12mm long light pipe with the first diffuser are shown in Table 1.
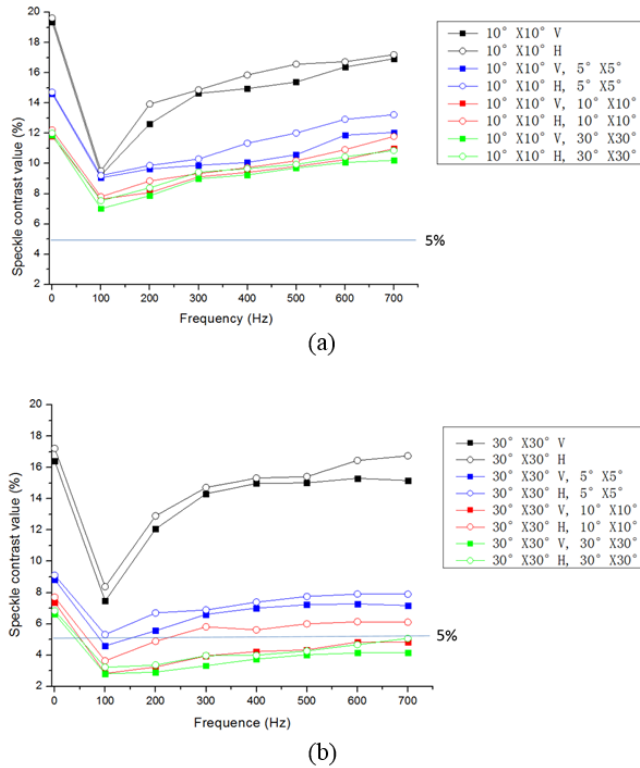

(a)

(b)

Fig. 5. The dependence of the speckle contrast value on the VCM oscillator frequency for different diffusers: (a) the first diffuser is 10X10 with a series of second diffusers; (b) first diffuser is 30X30 with a series of second diffusers.

Table 1. Number of Reflections with the First 10X10 Diffuser and the First 30X30 Diffuser with a 12mm Long Light Pipe

First diffuser type	10X10	30X30
Number of reflections for long side	0-1	0-3
Number of reflections for short side	0-1	0-4

4.2 Category 2: circular distribution diffuser and elliptical distribution diffuser

Owing to traditional LED projector structure, the distribution of the light angle at the entrance of the light pipe is circular. The first diffuser chosen at the entrance of the light pipe is the circular symmetric diffuser. The second diffuser at the other side of the light pipe is an elliptically scattering diffuser for high contrast value [27].

The orientation of the elliptically scattering second diffuser and the direction of the vibration of the first diffuser can be driven in four modes, as shown in Fig. 6. The first 30X30 diffuser and the second 80X20 diffuser are used as an example. In Fig. 6(a), "30X30V, 80X20", indicates that the vibrating direction of the first diffuser is parallel to the short side of the light pipe and the large divergent angle of the second diffuser corresponds to the long side of the light pipe. In Fig. 6(b), "30X30V, 20X80" indicates that the short side of the light pipe is parallel to the vibrating direction of the first diffuser and the long side of the light pipe corresponds to the small divergent angle of the second diffuser. In Fig. 6(c), "30X30H, 80X20" means that the vibrating direction of the first diffuser is parallel to the long side of the light pipe and the small divergent angle of the second diffuser corresponds to the short side of the light pipe. Moreover, "30X30H, 20X80" indicates that the long side of the light pipe is parallel to the vibrating direction of the first diffuser and the small divergent angle of the second diffuser corresponds to the long side of the light pipe, as shown in Fig. 6(d).
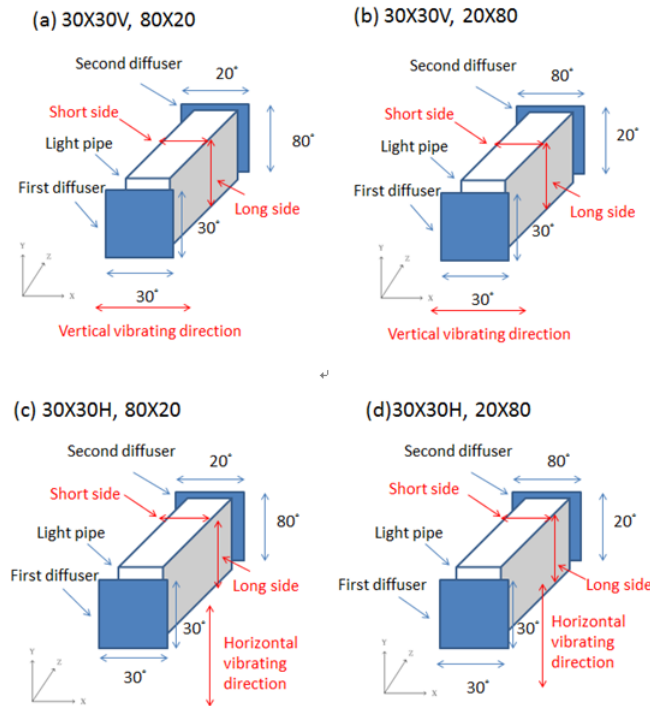

Fig. 6. When the second diffuser is an elliptically scattering diffuser, the vibrating mode can be divided into four types: (a)30X30V, 80X20; (b)30X30V, 20X80; (c)30X30H, 80X20; (d)30X30H, 20X80.

The speckle contrast value is relative to the frequency of the VCM oscillator, the FWHM angle of second diffuser, and two vibrating mode, as shown in Fig. 7. With a different second diffuser, the speckle contrast value is reduced from 14.84% to 7.89%, 13.48% to 7.51% and 13.02% to 6.49%, respectively. The speckle contrast value does not become lower than 5%,

but we can see that with a large divergent angle, the second diffuser is capable of reducing the speckle contrast to almost 5%.

From Fig. 7, it can be seen that the value of the speckle contrast is linear dependence on the frequency of the VCM oscillator in the region 100 Hz-700 Hz. This tendency is the same for Category 2 as for Category 1. Moreover, the speckle contrast value is higher for Category 2 than for Category 1. For a detailed explanation, a discussion of the angular space is needed. In the angular space, the cone angle of the light pipe system and that of the relay lens system are mentioned, as shown in Fig. 8. The cone angle of the light pipe system is induced by the elliptically scattering diffuser. The cone angle of the relay lens system is made by the relay lens of the LASER pico-projector. The two cone angles above are coupled together for energy transformation. As can be seen in Fig. 8, the cone angle space of the two systems can be divided into three regions. In region I, the cone angle of the light pipe system overlaps the cone angle of the relay lens system. The energy at the overlapped region can transform well without energy loss. Region I is defined as the effective cone angle region. In region II, the cone angle of the light pipe system is larger than the cone angle of the relay lens system. The energy of the light pipe system at region II is not collected by the relay lens system. Moreover, a large cone angle takes more number of reflections in the light pipe system and creates more speckle patterns. Therefore, the energy of the light pipe system at region II effectively reduces the speckle contrast value [11,13]. Finally, the energy with more speckle patterns at region II cannot be collected by the relay lens system. This is called an ineffective speckle reduction region. In region III, the cone angle of the light pipe system is smaller than the cone angle of the relay lens system. Thus, the energy of the cone angle of the light pipe system does not pass through region III. Moreover, speckle reduction ability is low under the small cone angle of the light pipe system. Region III is called an ineffective energy region.

In other words, the speckle contrast value of Category 1 is lower than Category 2. In Category 1 the best condition is obtained with "30X30V, 30X30" at a VCM oscillation frequency of 100Hz. The test image results with and without speckle reduction are shown in Fig. 9. There are large differences in image quality shown under different speckle reduction levels.
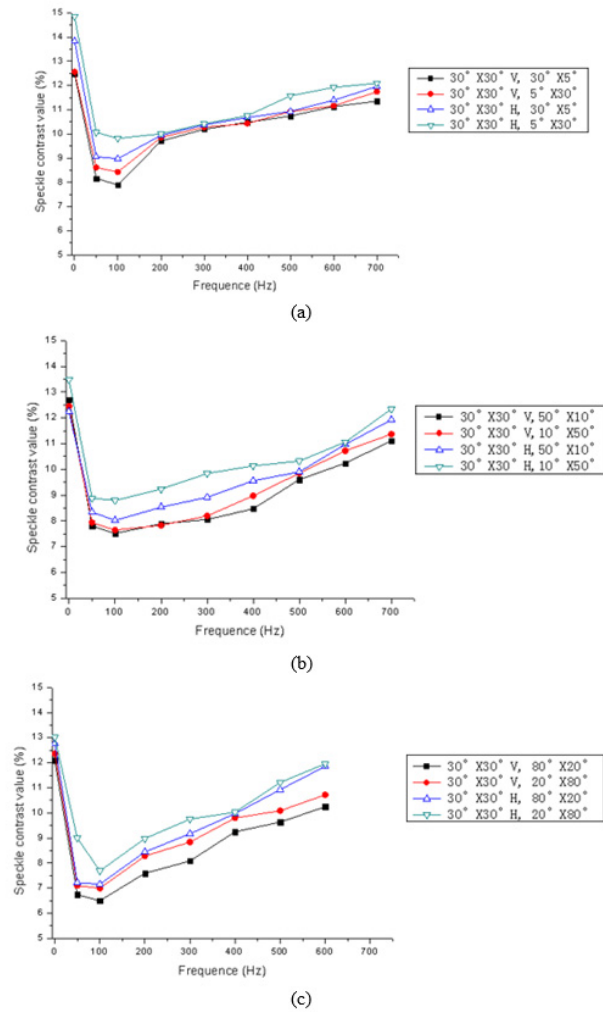
Fig. 7. The dependence of the speckle contrast on the VCM oscillation frequency for different second diffusers: (a) second diffuser is 30X5 with different vibrating modes; (b) second diffuser is 50X10 with different vibrating modes; (c) second diffuser is 80X20 with different vibrating modes.
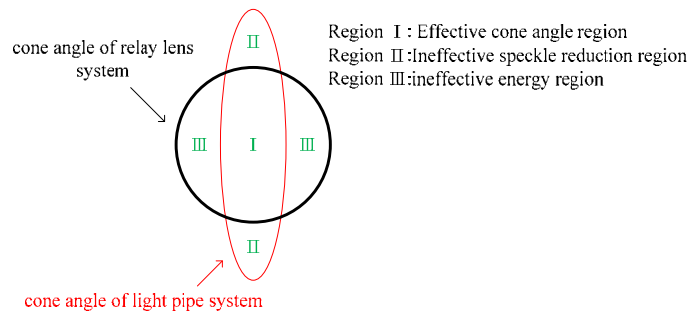

Fig. 8. The relationship between the cone angle of the light pipe system and the cone angle of the relay lens system in angular space.
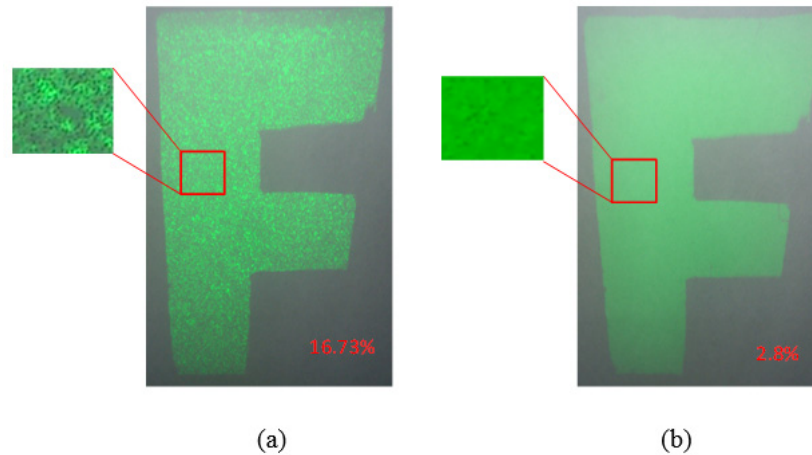
Fig. 9. Test image results: (a) only first 30X30 diffuser without vibrating VCM oscillation; (b) "30X30V, 30X30"with a VCM oscillator frequency of 100Hz.

5. The FO:FO contrast ratio for a laser projector with two diffuser conditions

In a DLP projector system, the contrast ratio is an important issue for image quality. The contrast ratio is related to the light cone angle distribution. An elliptical cone angle distribution can enhance the contrast ratio and maintain the system efficiency [27]. Moreover, a diamond type of DMD [24] is more suitable for a compact LASER pico-projector when the incident angle is in the horizontal direction. In order to understand the relationship between contrast ratio enhancement, optical efficiency, and diffuser's BSDF, the elliptical scattering diffuser and circular symmetric diffuser were used in the LASER pico-projecor.

The projector contrast ratio is familiar defined as the full-on/full-off (FO:FO) contrast ratio [1]. The FO:FO contrast ratio is defined as in Eq. (2):

$$\text{FO : FO contrast ratio} = \frac{L(on\ state)}{L(off\ state)} \tag{2}$$

where L(on state) means that the luminance produced at the center of the screen when the DMD is at on state; L(off state) means that the luminance produced at the center of the screen when the DMD is at on state; The system efficiency is defined as the total flux on the screen divided into the total flux on the second diffuser.

In the simulation, the asymmetric stop is placed at the projector lens stop. The relationship between the projection lens stop, light cone angle of the illumination system and asymmetric stop position is shown in Fig. 10(a). Here, Z = 0 means that the asymmetric stop is located at the rim of the projection lens stop. When Z increases, the asymmetric stop approaches the center of the projection lens stop. As Z increases, the flat-state cone angle can be blocked for low optical efficiency. However the FO:FO contrast ratio was enhanced when less flat-state light was passed into the projector lens. The optical software, Light Tools, was used to carry out the simulation to determine the FO:FO contrast ratio and system efficiency. Moreover, the effect of the diffuser was described by a Bidirectional Scattering Distribution Function (BSDF). The diffuser's BSDF is measured by the Imaging Sphere for Scatter and Appearance (IS-SA) of Radiant Zemax [29].
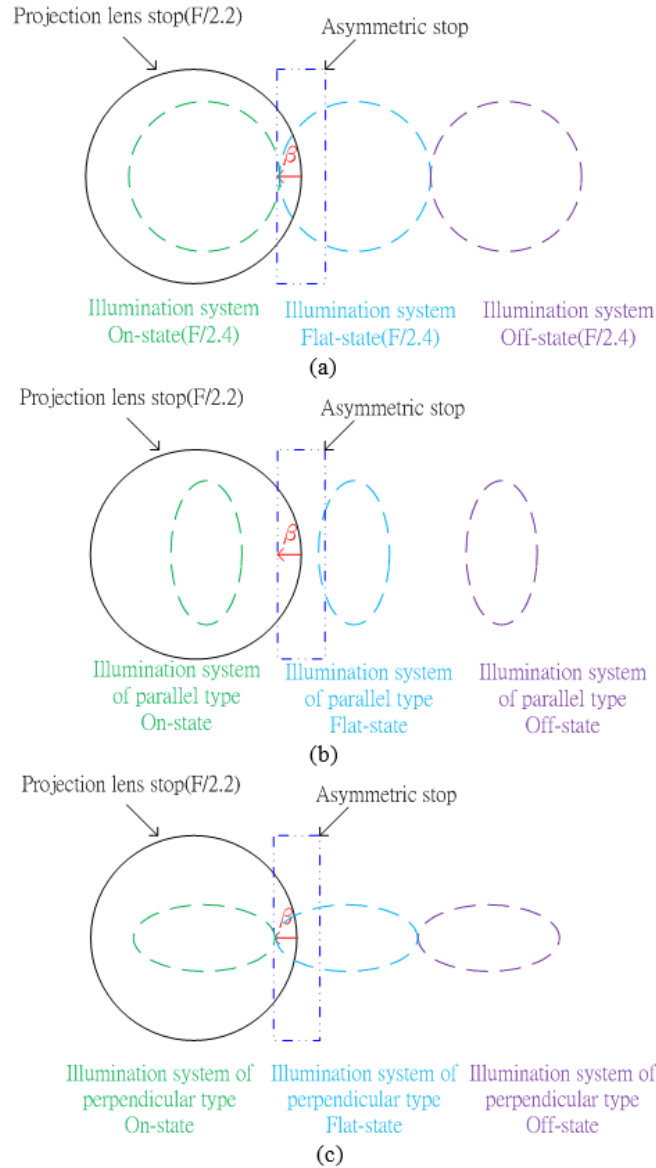
Fig. 10. The relationship between the projection lens stop, cone angle of illumination system and the asymmetric stop for: (a) circular cone angle distribution; (b) parallel type cone angle distribution (30X30, 5X30); (c) perpendicular cone angle distribution (30X30, 30X5).

The relationship between the system efficiency and FO:FO contrast ratio with different asymmetric stop positions under different second diffusers is shown in Fig. 11. These can be divided into two Categories as discussed in section 4.

In Category 1, both the first diffuser and second diffuser are circular and symmetric. The FO:FO contrast ratio and system efficiency results for Category 1 are shown in Fig. 11(a). When the asymmetric stop Z increases to 1 mm, the FO:FO contrast ratio can be kept stable. The FO:FO contrast ratio can reach 1200:1-1300:1 with different second diffuser conditions. At the same time, the system efficiency decreases about 1.50% with asymmetric stop positions ranging from 0 mm to 1.4 mm.

In Category 2, the first diffuser is circular and symmetric and the second diffuser is elliptical and symmetric. The FO:FO contrast ratio and system efficiency results for Category 2 are shown in Fig. 11(b). Conditions can be divided into two types, perpendicular and parallel. Under the perpendicular condition, the long axis of the elliptically scattering diffuser "30X30, 30X5" is perpendicular to the tilt axis of the DMD. Under the other condition, the long axis of the elliptically scattering diffuser "30X30, 5X30" is parallel to the tilt axis of the DMD. The FO:FO contrast ratio and the system efficiency of the parallel type are higher than for the perpendicular type. The FO:FO contrast ratio of the parallel type can reach 1300:1-1400:1 with different second diffuser conditions, when the asymmetric stop Z increases to 1 mm. At the same time, the system efficiency decreases 1.00% with asymmetric stop positions ranging from 0 mm to 1.4 mm. Moreover, under another condition, the FO:FO contrast ratio can only reach 1000:1-1150:1, and the system efficiency decreases 2.50% with the same asymmetric stop position range.

The two types of cone angle distribution are shown in Fig. 10(b) and Fig. 10(c). For the parallel type, the projection lens stop has difficulty collecting the flat-state light. Therefore, the FO:FO contrast ratio can be inherently enhanced. Moreover, the on-state light is not blocked by the asymmetric stop. For this reason, the system efficiency of the parallel type is higher. For the other type, the perpendicular type, the flat-state light can easily leak into the projection lens stop. The FO:FO contrast ratio is therefore lower. Furthermore, the asymmetric stop can block the on-state light easily. Therefore, the system efficiency becomes lower. Accordingly, The FO:FO contrast ratio and the system efficiency of the parallel type are higher than those of the perpendicular type.

In other words, the tendencies of Category 1 and Category 2 FO:FO contrast ratios and system efficiencies are the same. As the divergent angle of the second diffuser increases, the FO:FO contrast ratio and the system efficiency decrease. As the divergent angle of the second diffuser increases, the cone angle distributions of the on-state light and flat-state light become wider. Therefore, the projection lens stop collects more flat-state light. The FO:FO contrast ratio also decreases more. At the same time for contrast enhancement, we try to remove more flat state light using large movement of the asymmetric stop. In the meantime, more of the on-state light is blocked by the asymmetric stop, so the system efficiency decreases.
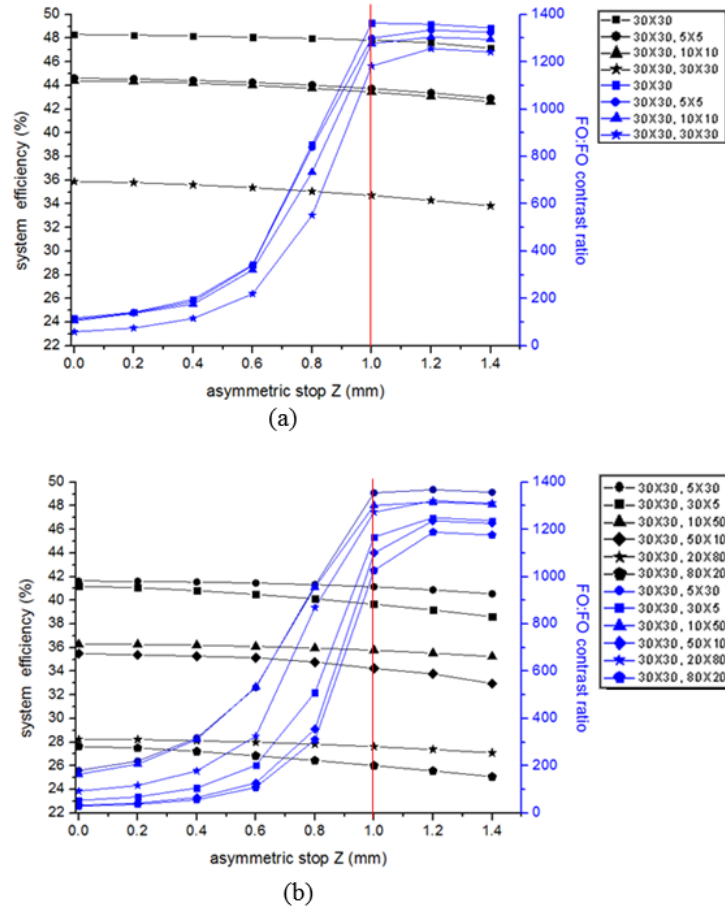
Fig. 11. The relationship between system efficiency and the FO:FO contrast ratio for different asymmetric stop positions and different second diffusers: (a) circular symmetric second diffuser; (b) elliptically scattering second diffuser.

From Fig. 5, Fig. 7 and Fig. 11, when the system adds the circular symmetric second diffuser, there is an obviously lower speckle contrast value and FO:FO contrast value than adding the elliptically scattering second diffuser. The resulting data for system efficiency, the lowest speckle contrast value, and the highest FO:FO contrast ratio with different diffuser conditions are shown in Table 2. The data can be divided into three states. In State 1, both diffusers are circular symmetric. The system efficiency, the lowest speckle contrast value and the highest FO:FO contrast value decrease with an increasing in the divergent angle of the second diffuser. Because the cone angle of the light pipe system is larger than the cone angle of the relay lens system, the system efficiency decreases with angle mismatch for system energy loss. At the same time, massive speckle patterns can be produced as a consequence of the larger divergent angle of the second diffuser and more number of reflections. Thus effective reduces the speckle contrast to its lowest value. On the other hand, the flat-state light is collected by the projection lens stop with the large divergent angle of the second diffuser. Therefore, there is a decrease in the highest FO:FO contrast ratio. In State 2, the first diffuser is circular symmetric and the second diffuser is elliptically scattering. The tendencies are the same as for State 1 for the same reasons. In the vertical direction, the two divergent angles of the second diffuser are the same. In the horizontal direction, the divergent angles of the second diffuser are different. In the horizontal direction, the cone angle of the light pipe

system is smaller than the cone angle of the relay lens system. Therefore, the system efficiency of the small divergent angle is higher than the system efficiency of the large divergent angle. On the other hand, the smaller divergent angle has low ability of speckle reduction. Therefore, the lowest speckle contrast value under "30X30V, 5X30" is higher than the lowest speckle contrast value under "30X30V, 30X30". Moreover, it is difficult for the flat-state light to leak into the projection lens with the small divergent angle in the horizontal direction. The highest FO:FO contrast ratio of "30X30V, 5X30" is higher than the highest FO:FO contrast ratio of "30X30V, 30X30".

Table 2. The Relationship Between the Relay System Efficiency, the Lowest Speckle Contrast Value, and the Highest FO:FO Contrast Ratio for Different Diffuser Types

Diffuser type	System efficiency (%)	Lowest speckle contrast value (%)	Highest FO:FO contrast ratio
30X30V	47.83	7.46	1363.88
30X30V, 5X5	43.73	4.60	1300.27
30X30V, 10X10	43.44	2.83	1277.25
30X30V, 30X30	34.70	2.81	1182.36
30X30V, 5X30	41.14	8.42	1354.74
30X30V, 10X50	35.78	7.64	1301.49
30X30V, 20X80	27.61	6.99	1272.71

6. Conclusion

In this study, we design a LASER pico-projector that has the advantages of lower speckle contrast value and higher FO:FO contrast ratio while still maintaining system efficiency. The first diffuser, the second diffuser and the light pipe are designed to work together to reduce the speckle phenomenon. By vibrating the first diffuser, the speckle contrast value can be decreased efficiently by destroying the degree of temporal coherence. For the vertical vibration mode, there are lower speckle contrast value. The main reason is that the light increases reflect time in the light pipe in the vertical vibrating direction than in the horizontal vibrating direction. The light pipe in the vertical vibrating direction has a short edge, so the number of reflection increases. Under the first diffuser vertical vibration frequency at 100 Hz, the speckle contract value of "30X30, 5X5", "30X30, 10X10" and "30X30, 30X30" diffuser is 4.60%, 2.83% and 2.81%, respectively. For the speckle phenomenon to be invisible to the human eye, the speckle contrast value must be lower than 5%. The three conditions are suitable for a LASER pico-projector. Moreover, the FO:FO contrast ratio can be enhanced by moving the asymmetric stop, while still maintaining system efficiency. Under this condition, the FO:FO contrast ratio and the system efficiency for the LASER pico-projector can be made as high as possible. Therefore, the "30X30V, 5X5" diffuser is more suitable for a LASER pico-projector. The use of this diffuser for the LASER gives a speckle contrast value of 4.60%, an FO:FO contrast ratio of 1300.27:1, and a system efficiency of 43.73%.

Acknowledgments