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The very compact and efficient speckle suppression device for laser picoprojector

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Abstract. The original, simple and efficient speckle suppression method has been proposed for laser picoprojector. The method uses simple 1D DOE structure on flexible film roll up in loop for speckle suppression. The structure of 1D DOE is based on binary pseudorandom sequences. It almost does not require energy and volume and can decrease speckle noise bellow human eye sensitivity. The compact and simple construction of picoprojector using this simple method has been presented. The experimental data confirm high efficiency of the proposed method. However, the obtained results of speckle suppression efficiency are not optimal and can be significantly improved by increasing DOE quality and optimization of DOE structure.

Keywords: laser projector, speckle, speckle suppression, diffractive optical element.

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1. Introduction

The lasers are one of the most efficient light sources that produce high quality beam with definite polarization [1]. This allows to build small and energy efficient devices and laser projector with high quality picture [2]. However, creation of an image by laser beam is strongly modulated by speckle noise [3]. The speckle noise is main restriction for designing laser picoprojector with a high quality picture. The value of speckle noise is determined through speckle contrast that is defined as

$$C = \frac{I}{I_m}, \quad (1)$$

where I and I_m are standard deviation and mean intensity in the image plane, correspondingly, in assembling averaging (or averaging on homogeneously illuminated screen). The most simple picoprojector scheme is a pointer or by another words 0D scanner [4]. In this type of laser picoprojector, color thin laser beam having diameter of one image pixels scanned over all the screen to create 2D picture. The picture is obtained by modulation of the laser intensity in accord with a necessary image on the screen. This picoprojector has an excellent energy efficiency, since all the emitted light power is used to create the image. However, this optical scheme has a problem with speckle suppression because of small aperture and small time of one pixel exposure, and therefore there it is not possible to suppress the speckle below human eye sensitivity. Another optical scheme is 1D scanner. In this case, the laser beam is reshaped in narrow strips that illuminate a linear array (1D array) of optical modulator [5-6]. The line picture is created at one time. The mirror in Fourier plane of objective vibrates along one axis to create image. This optical scheme requires complicated beam shaper and also has a problem with speckle reduction. It is related with a small exposure time of one pixel and with the fact that one plane of solid angle of objective aperture is usually used for optical modulation of laser intensity. Therefore, it is not the best solution to design pico-projector with small speckle noise [7]. More preferable scheme for speckle reduction and realization of a high quality picture in small portable laser projector is to use the full picture 2D picoprojector where the optical modulator produces the whole picture at the same time and projects it onto the screen.

2. The speckle suppression mechanism

The speckle suppression efficiency is defined through the speckle suppression coefficient k as

$$k = \frac{C_0}{C}, \tag{2}$$

where C_0 and C are speckle contrast before and after application of speckle suppression method. The hardware speckle suppression mechanism can be based on decreasing time, polarization or special coherence of the illumination beam [3]. Depolarization of laser beam can mainly result in two depolarization laser beams that can cause at most 30% decrease of speckle contrast. The decrease of speckle contrast beyond human eye sensitivity by only the decrease of time coherence with using wideband lasers requires application of a laser having band width approximately more than 100 nm. There are not lasers with such large waveband range, and laser with the waveband range wider than 4 nm have small optical efficiency. Therefore, the method based on decreasing polarization and time coherence can be used only as an additional method for projector with speckle suppression below human eye sensitivity. The decrease of spatial coherence or using angular diversity allows decreasing the speckle contrast below human eye sensitivity. The use of moving diffuser or DOE inside the optical system conjugated in plane with the screen is the most simple way to decrease special coherence of laser beam [8], which does not put any requirement on laser properties. In the case of using one color picture at every moment of time (to use all modulator area for one color), which after that are combined in eye in time sequence, to produce a color picture means that all the beam light creates the image and, therefore, has the best energy efficiency. Human eye has the time resolution approximately 0.04 s, and consequently the projector needs to provide at least 25 color pictures to produce high quality movie without side effects. It means that there is only no more than 13 ms to decrease speckle for one color picture. One smallest possible decorrelation length Δ of DOE cannot be smaller than the optical resolution of objective lens $\Delta > \lambda/\text{NA}$, where λ is the light wavelength, and NA – numerical aperture of objective. For a red laser and NA = 0.5, $\Delta > 0.63\ \mu\text{m}/0.5 \approx 1.3\ \mu\text{m}$. To provide full speckle suppression, we need at least 400 uncorrelated speckle field to get speckle noise bellow human eye sensitivity. Hence, we need the $400 \cdot 1.3\ \mu\text{m} = 520\ \mu\text{m} = 0.52$ mm DOE shift to get a picture pleasant for eye. This corresponds to DOE speed of $v = 0.52 \cdot 75 \approx 40$ mm/s. Most of methods using active DOE for speckle suppression propose to use [9] a vibration as the method for DOE movement. However, it is not difficult to see from DOE speed and amplitude estimated above that amplitude and frequency of DOE vibrations required for total suppression of speckle noise is too large to be realized in small laser projector. The rotating spiral DOE was proposed for speckle suppression [10]. However, this solution is not good for picoprojector, because of a large size of rotated DOE (since only small part of DOE is illuminated by the laser beam). Below, we propose special DOE and special DOE movement mechanism that is good from the viewpoint of the device size, DOE speed and low energy consumption. The 1D DOE structure is based on binary pseudorandom sequences on flexible transparent film [11-13]. It has several parts that are similar to that reports in [12]. The DOE structure is composed of several different 1D DOE structures that are the same except the inclination angle of DOE structure to the film long side with the angle changed within the interval between 45–arctan(1/N)/2 and 45+arctan(1/N)/2 with a small step between to neighbor structure [14]. The example of such DOE is shown in Fig. 1, which consists from three DOE structures with difference in inclination angle of 0.6°. The strips are rolled up in loop and to opposite sides of DOE are glued together, so that DOE strips transform to a loop.

The optical system of projector is shown in Fig. 2. The light from three lasers is collimated separately and combined in one beam by dichroic beams combiners. After that, the laser beam is homogenized at surface of DOE with increasing the beam diameter. Since DOE is situated close to the last lens of beam homogenizer, this optical scheme is robust against interference fringes. The DOE loop is put over of two spindles (see Fig. 2), and after that it passes through optical modulator (LQ optical modulator). One not active spindle is not fixed and can move along the slit. It is connected to spring that pull the DOE on flexible film. The DOE structure is situated at outer surface of DOE, and a film should have two thin projection on the top and bottom parts of inner surface to avoid structure damage. The objective lens projects the obtained image on the screen. Due to different inclination angle of different DOE parts any two of them has the same angle to obtain 2D scanned angle effect. The number of DOE structure parts should be larger than two. The 1D structure on the face part and 1D DOE structure on the back part create 2D DOE periodic structure having

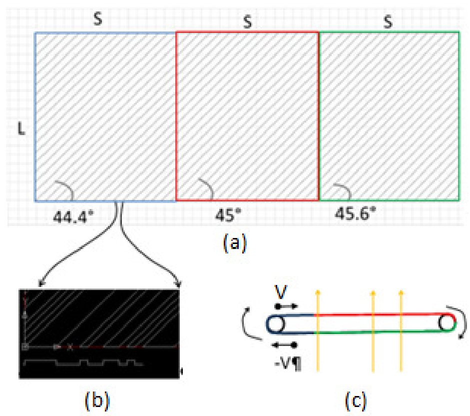


Fig. 1. DOE structure on thin film (a), DOE structure profile (b) and the scheme of DOE movement (c).

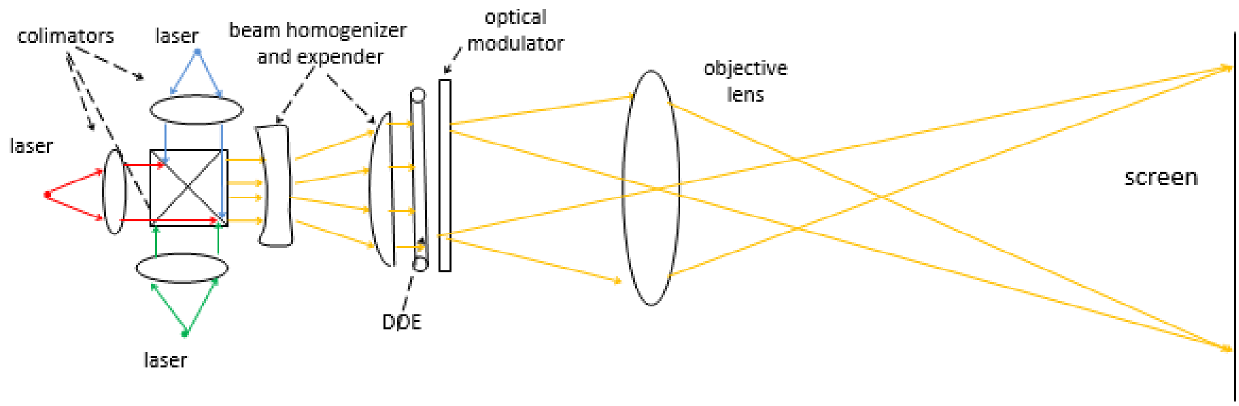
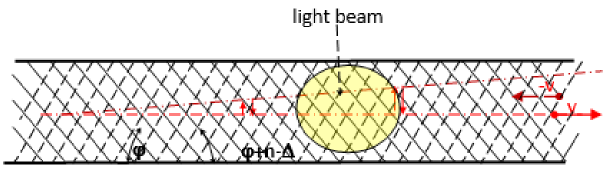
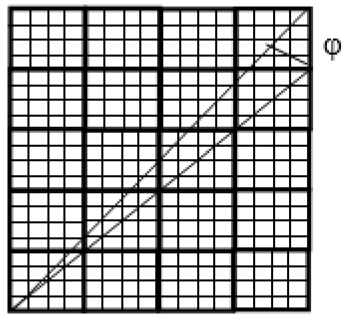


Fig. 2. Principal optical scheme of a laser picoprojector.



(a)



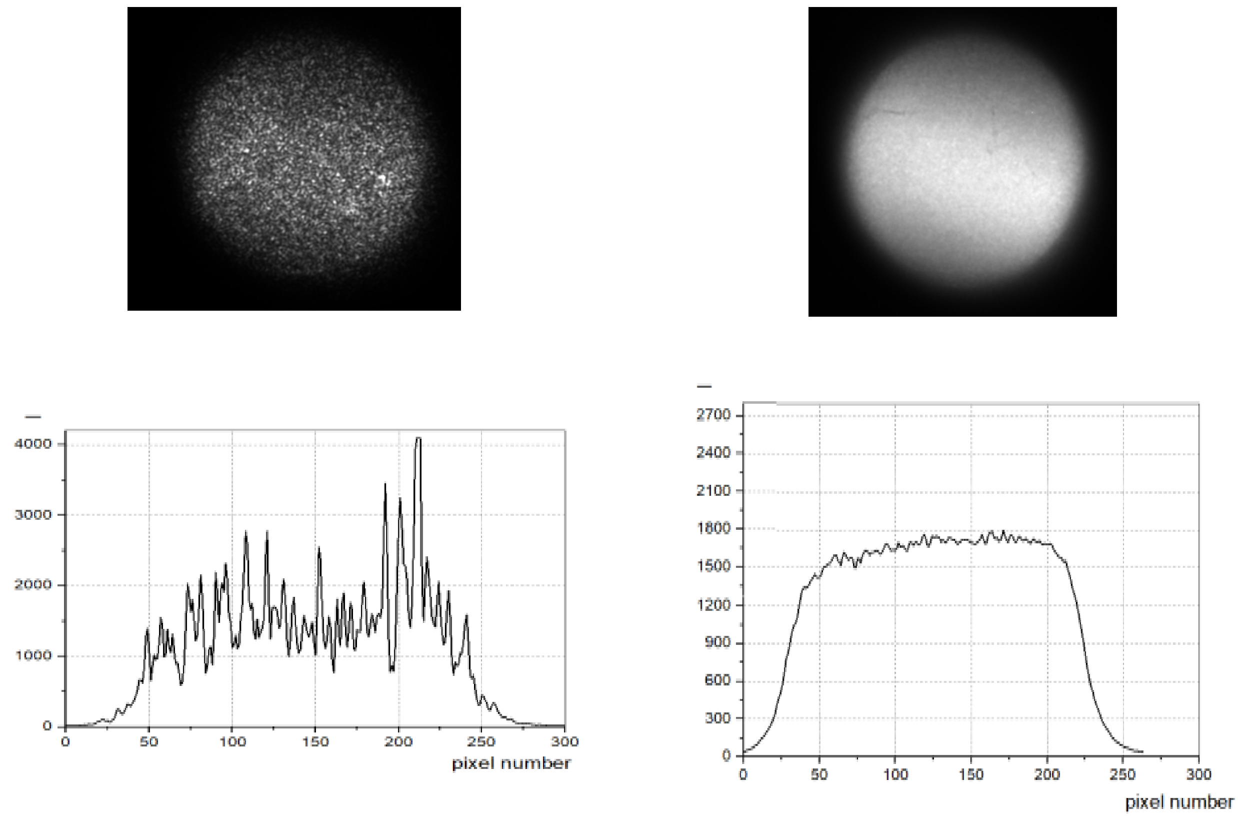
(b)

Fig. 3. a) Principal scheme of forward and backward parts of DOE structure movement (thin solid lines show the boundaries between the periods of forwards part of DOE and dashed lines for boundaries between backward part of DOE) and (b) scheme of the composite 2D DOE structure movement due to two part 1D DOE shifts for the case of DOE code length $N = 4$ (small squares denote smallest elements of the DOE, and large square denotes a one 2D period of composite DOE structure) and maximal angle between the two DOE with large speckle suppression effect.

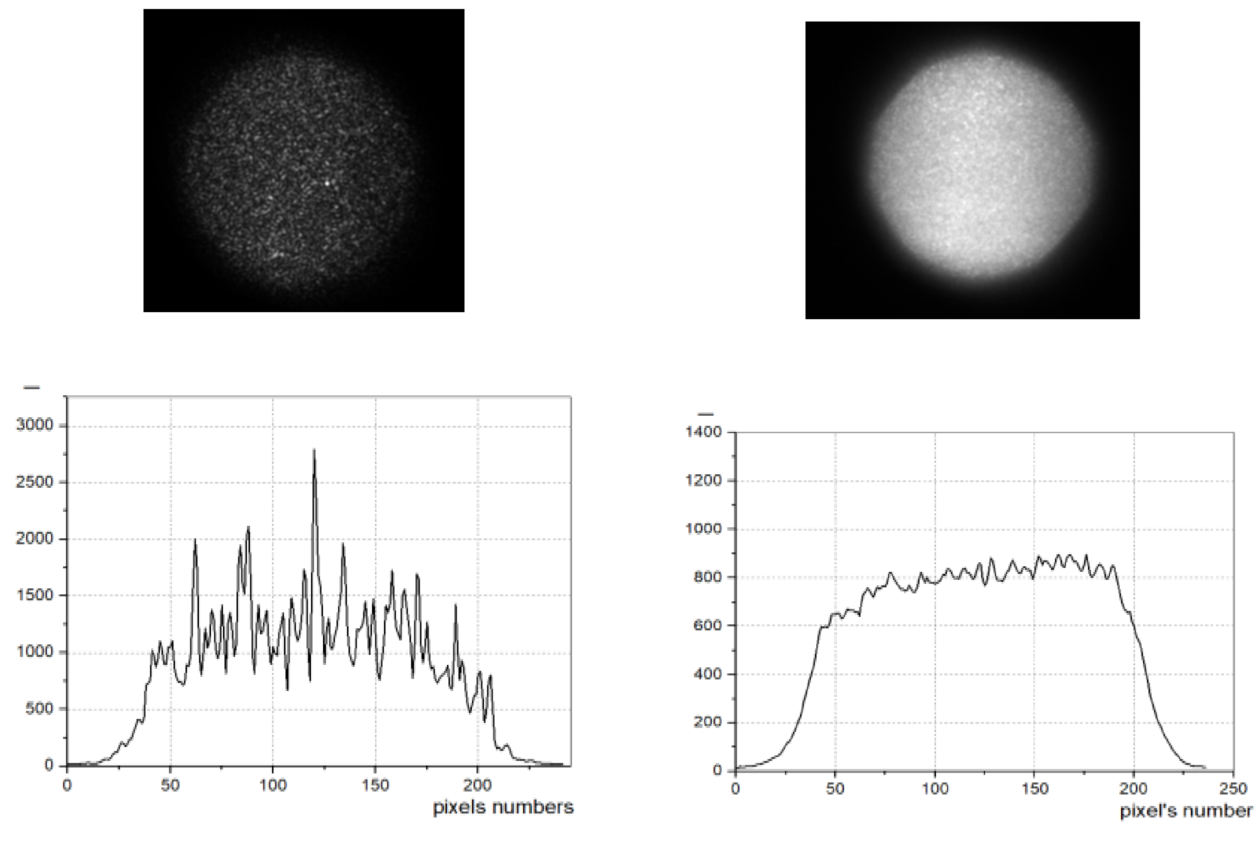
the close to square periodic pattern. In this case, the opposite side of DOE structure illuminated by laser beam should have different inclination angles, which results in 2D beam scanning over 2D period of grating, and therefore all the 2D aperture of objective lens is used for speckle suppression (Fig. 3). This movement is similar in speckle suppression effect to 2D DOE movement with inclination angle a little bit smaller or larger than to 45°. It was previously shown that this inclination angle range has close to optimal speckle suppression efficiency [2]. In Fig 3, one dash-point line shows the direction of DOE structure shift, and another dash-point line shows the direction of periodic 2D DOE pattern shift due to the two 1D DOE movement as a result of difference in inclination angles of two parts of the DOEs. From this picture, it is clear that small difference in inclination angles of different DOE parts results that every point of beam make scanning over all part of square DOE period (2D scanning) that allows to use all the 2D aperture of objective for speckle suppression and the obtained optimal speckle suppression effect. The color pictures are separated in time and all surface of optical modulator is used for laser beam and combined in eye during operation. Since laser has definite polarization, and all surface of modulator is used by laser beam, we get the most possible energy efficiency for 2D laser projector. It follows from Fig. 2 that speckle suppression devices can be placed very closely to the optical modulator, and therefore speckle suppression do not need additional space except for engine to rotate the DOE. Additionally, since rotation without load consumes very small energy even for fast rotation, the engine size and energy consumption can be small. Hence, in principle, we obtained the most small end energy efficient laser projectors.

Table. The speckle suppression efficiency for blue, green and red lasers for two different DOE speeds.

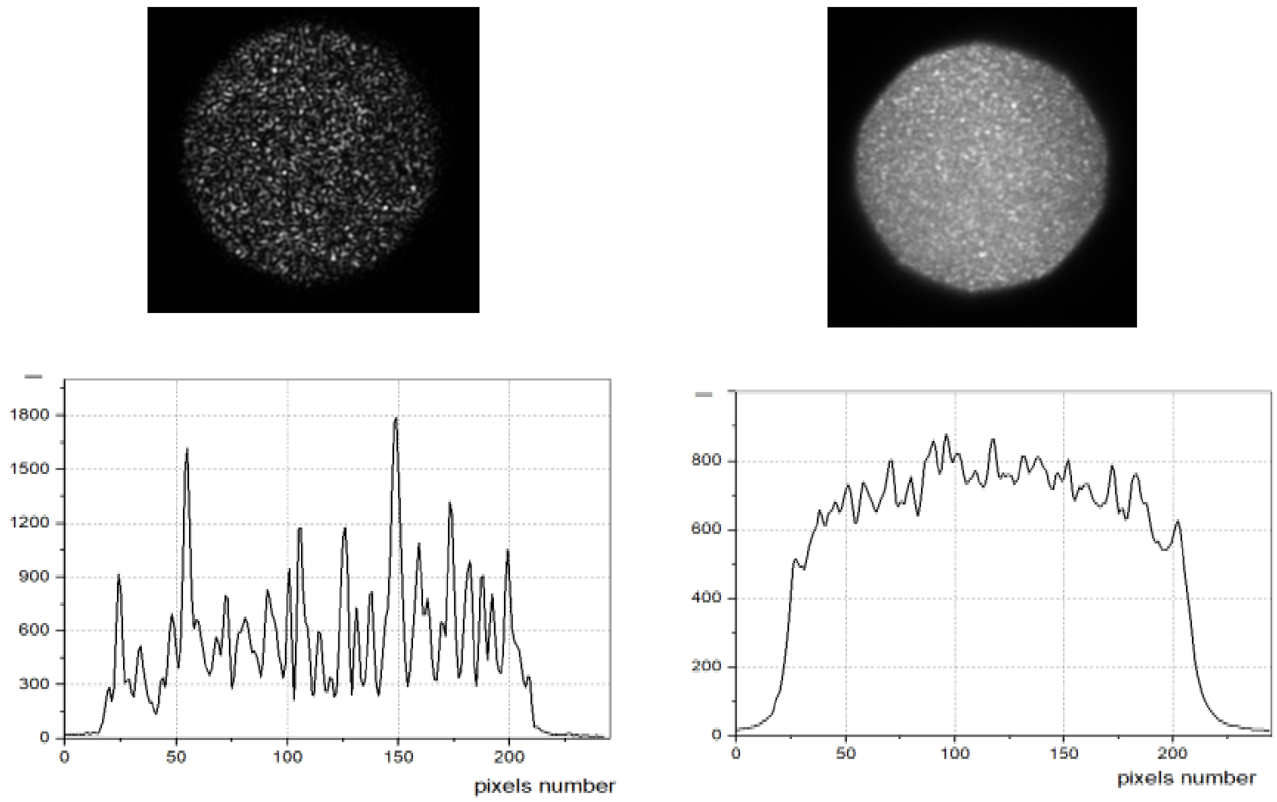
	Blue			Green			Red		
	C_0	C	k	C_0	C	k	C_0	C	k
V_1	32.5	2.24	14.7	39.1	3.9	10	62.5	9.1	6.8
V_2	33.6	2.25	14.7	39.1	3.73	10.5	61	8.9	6.9



(a)



(b)



(c)

Fig. 4. Intensity distribution (top) and cross-section of intensity distribution (bottom) before (left) and after (right) speckle suppression for blue (a) green (b) and red (c) laser beam.

In the angle area close to 45° the maximum angle between two DOE that results in two 2D scanning is $\sin(\varphi) \approx \dfrac{T_0 \sqrt{2}/2}{N T_0 \sqrt{2}} = \dfrac{1}{2N}$.

Since in this range for the case of using three parts DOE structure, the angle between neighbor part should be at least twice smaller, hence not be larger than $1/4N$. To get the small picoprojector one should use the laser diodes with a relatively large divergence angle > 12°…24°. The code length of $N = 15$ is sufficient to get speckle suppression below human eye sensitivity. The elementary size of DOE smallest element T should be as small as possible to use objective with small focal length. Let's assume that the smallest element size is $T = 0.8$ µm. Since at least one DOE period is needed inside one pixel area to get efficient speckle suppression, the pixel size at least of 12 µm should be used in optical modulator. Therefore, the optical modulator size should be at least of $1280 \cdot 12 \cdot 800 \cdot 12 = 1.5 \cdot 1$ cm^2. Our estimation has shown that total size of optical part of laser picoprojector using the high numerical aperture lens can be as small as 10…30 cm^3 (depends on numerical aperture of lens used in beam homogenizer and focal length of objective lens). Since we assumed that all light that falls on optical modulator is used for image creation, the optical scheme would have optical efficiency close to maximum possible for 2D projectors.

3. The experimental setup for measuring speckle suppression efficiency

For experimental verification of this new method for speckle suppression, we made DOE with transverse size of 7.5×75 mm having three parts of diffraction patterns (all three patterns are almost the same except inclination angle and are similar to those shown in Fig. 1. The DOE patterns were produced as being based on binary pseudorandom M-sequences of the length $N = 31$ with period 124 µm and pitch size 4 µm). It was planned to use photolithographic method to produce photoresist DOE structure on flexible film. The DOE structure of the height $h = 360$ nm, which gives the homogeneous speckle reduction in the total vision range for DOE structure formed by photoresist [13]. However, it was found that it is technologically difficult to produce photoresist structure on the surface of flexible film. Therefore, it was decided to use hot stamping technology for DOE production. Firstly, the DOE structure was formed in silica by using photolithography. After that, the nickel stamp was produced in electrolytic bath. The PET film was planned to be used because of its mechanical, thermal and optical (value of refractive index is not far from the photoresist one) properties. However, our technology is not good enough to produce DOE on PET, since it requires large heating temperature of the surface, therefore, we used PVH film. However, since the refractive indexes of PET and PVH film are rather different (1.65 and 1.52, respectively) the obtained DOE has not optimal structure height for red laser. The glue was used to make loop from rectangular shape DOE structure.

The red (640 nm), green (520 nm) and blue (450 nm) lasers were used in our experiments. The objective lens of the diameter D =50 mm and focal length 75 mm was used in experiments. The distance from objective to screen and from screen to camera was 1650 and 1130 mm, correspondingly. The camera objective has the focal length 25 mm, and one photodiode has a transverse size of 5.5. The diameter of input diaphragm of camera was 1mm. The integration time of intensity inherent to the camera photodiode array was 0.230 s. The diameter of cylinder used to rotate DOE was 4.5 mm.

4. Experimental results and discussion

In the experiments, we switch on only one by one blue, green and red laser only at one instance to measure a speckle suppression effect separately for blue, red and green lasers. The speckle suppression efficiency was measured for two different DOE linear speeds v_1 = 8.2 cm/s and v_2 = 11.6 cm/s for all three lasers. The DOE shift is 1.9 and 2.7 cm during integration time of photodiode (speckle averaging time). It is not difficult to see that it is enough for speckle averaging by using the given method and DOE structure ($S = 2\sqrt{2}\cdot N\,T_0$= 1.1 cm). If using the DOE structure (evaluated above for the pico-projector) with T = 0.8 µm based on the code length N = 15, the ten times slower speed is needed $V \sim 1$ cm/s for optimal speckle suppression effect, however it should be approximately the same in a small laser projector, since the human eye integration time is 0.040 s and lasers of different colors are used different time interval to create color picture. The table shows the obtained experimental results of speckle contrast and speckle suppression efficiency.

Fig. 4 shows the intensity distribution in the images of the laser beams on screen before and after speckle suppression for the blue, green and red lasers. The large speckle suppression coefficients of 14.7, 10, 6.8 and small speckle contrast of 2.5, 3.9 and 9% are obtained for blue, green and red lasers, correspondingly. The smaller speckle suppression effect obtained for red laser is due to not optimal DOE structure height, which can be easily corrected by increasing the DOE structure height. It should be noted that the method provides practically the same sensitivity to the DOE speed.

It should be noted that, in spite of large speckle suppression effect, it is approximately twice smaller than theory predicts and has larger dispersion from the similar method but with a different method of DOE movement. There are three factors that can cause discrepancy between theory and experimental results: DOE structure quality, not accurate DOE shift, DOE vibration, not constant angle between front and back DOE parts. Fig. 5 shows dependence of speckle suppression coefficient on DOE shift length during intensity integration time obtained from experiment data and evaluated using the theory. It is not difficult to see that for small shift we have good match theoretical prediction and experimental

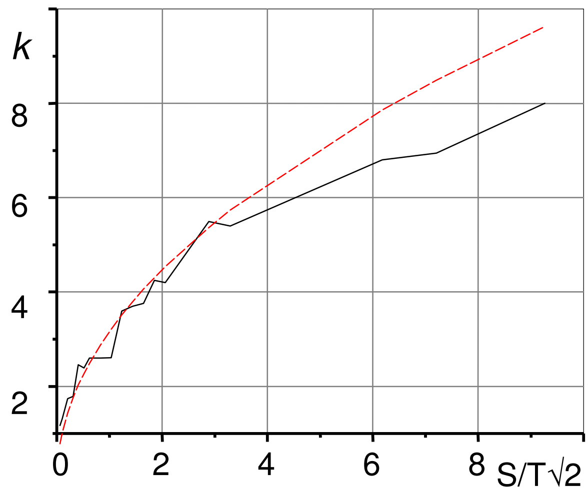


Fig. 5. The dependence of speckle suppression coefficient k on the DOE shift length (in length of diagonal of DOE smallest element) during time integration of the camera: solid line – experimental data; dashed line – theoretical evaluation.

results (the experimental data have normal deviation 0.5 for k). However, for the larger distance the discrepancy between the theory and experiments increases. This fact does not definite dependence on speed of DOE shift but depends on DOE sample. Since different DOE speed cause different amplitudes of vibration, we assumed that the main reason of discrepancy between theoretical and experimental data is quality of DOE structure. This assumption has another validation in laser spot distortion on screen in some places. However, we need more experiments to define the cause of discrepancy between theoretical and experimental data. To make a new experiment, we need to improve our technology of DOE production and change the medium of DOE, since PVH is too soft to be stable during long period of time.

5. Conclusion

The obtained experimental results have confirmed that the new method has large speckle suppression effect due to using 1D binary DOE structure based on pseudo-random binary sequences and having three different parts that are different by a little different inclination angle. DOE on a flexible film can be easily produced using the hot stamping method. The simple method for DOE movement results in fast DOE shift and do not require much energy. The proposed speckle suppression device is compact and simple and, therefore, is good for portable image projector. The speckle contrast below human eye sensitivity has been obtained for blue and green lasers. The theoretical prediction and experimental results with different method of DOE movement predicts that the improvement of DOE quality, the DOE structure optimazation and improvement in accuracy of DOE movement should allow the significantly improved efficiency of speckle suppression of the method (approximately twice) and decrease well below the speckle contrast 4% for all three lasers.

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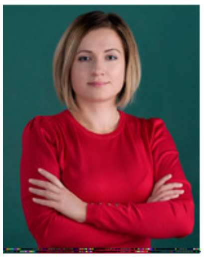

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