Speckle reduction in line scan laser display system by static diffuser with 2D binary code

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A set of two-dimensional (2D) binary codes are created by the calculation of the speckle contrast in line scan laser display system. According to the 2D binary code, phase plates are fabricated by etched glass or photoresist with different thicknesses corresponding to the code. It is introduced on the intermediate image plane to reduce speckle in laser based line scan display system. The experimental results show that the phase plate with the 2D binary code of order 5 can successfully reduce speckle contrast to 17.5%.

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Laser can be thought as an ideal light source because of its property of extensive color coverage, high efficiency, electrical-optical reduced size, and long lifetime, which is unachievable with conventional sources. Since laser has been invented, people intend to use laser as light source in display system. With several breakthroughs during the last forty years, laser display techniques are now integrated to a wide range of applications, such as mobile handheld devices, large screen front projectors, and rear projection displays. However, when the coherent light scattered from a rough surface, such as a screen, speckle is detected by a square-law detector with a finite aperture, such as human eyes[1]. The image with speckle on the screen appears to be quantized into areas with sizes equal to the detector-resolution spot. The detected spot intensity varies randomly from darkest to brightest, as shown in Fig. 1.

In coherent imaging systems, the presence of speckle tends to mask the image information, therefore the reduction of speckle is highly desirable. Goodman[1] showed that for a static speckle pattern, under ideal conditions (i.e., perfectly monochromatic and polarized waves and absence of noise) the standard deviation is equal to the mean intensity, and the speckle contrast becomes unity, which is the maximum value for the contrast. Laser speckle usually is quantified by the speckle contrast C:

$$C = \frac{\sigma}{\langle I \rangle} = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle}. \qquad (1)$$

Many methods have been developed for speckle reduction. These methods can be classified into three categories: 1) controlling of spatial coherence; 2) controlling temporal coherence by using multiple independent lasers with different wavelengths or a laser with broadband continuous-wave (CW)[2]; 3) spatial averaging, such as providing vibration of the display screen[3], creating N independent speckle patterns by rotating random phase plate (RPP)[3] or by moving diffusers with Hadamard matrix pattern[4,5], or employing static diffractive optical elements (DOE). Trisnadi has created a DOE (wavefront modulator) with grating profile for spatial phase

variation, and introduced it on the image plane to produce multiple speckle patterns that are averaged as the line image is scanned. This method can reduce speckle contrast from 44% down to 20%[6]. Samsung utilized DOE with the Barker code phase profile[7,8] for producing speckle reduction. Barker code is a set of +1 and –1 number with maximum length of 13. Yurlov *et al.*[7,8] utilized Barker code to develop a DOE on which +1 and –1 corresponding to different thickness cells. When a laser beam propagates it, the "–1" cell superimposes the extra π phase change on the incident laser beam compared with the "+1" cell. The width of line focus is divided by the 13 cells if the Barker code of order 13 is used to form the DOE. This method can be used to reduce speckle in line scan projection display system because of the Barker code only coherent itself. The maximum speckle reduction of speckle contrast factor of 13% theoretical value and 17% experimental value was achieved. Other Barker-like codes, such as MPS codes of lengths of 28, 51, and 69, have also been used for speckle reduction in line-scan laser projector because they have a delta-like autocorrelation[9]. However, the size of DOE is big problem for high speckle reduction by high order code. For example, the size of one pixel will be 207 μm when MPS code of order 69 is used and each cell size is 3 μm[6−8]. For the situation of 1 080 linear array pixels on one line image, the DOE with MPS code of order 69 will be 223 mm. So, those one-dimensional (1D) binary codes are not the best to form phase plate for speckle reduction.
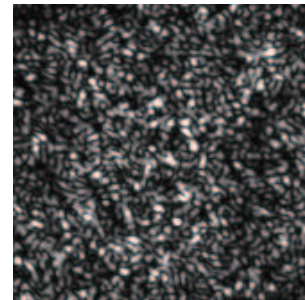

Fig. 1. Speckle pattern.

Assuming a matrix B, which has N columns and N rows binary value $B_{ij} = +1$ or -1, where $j, i = 1, 2, \cdots, N$, a phase plate is developed by etched glass or photoresist with different thicknesses corresponding to $+1$ and -1 according to the matrix B. When a laser beam propagates it, the "-1" cell superimposes an extra π phase change on the incident laser beam compareing with the "$+1$" cell. This phase plate is statically placed in a display system as shown in Fig. 2.

A laser beam is focused on the phase plate formed from binary matrix B. A projection lens projects one column pixels from the phase plate to a screen via a scanning mirror. A two-dimensional (2D) image is presented on the screen by the vibration of scanning mirror. A camera is used to detect the speckle pattern behind the screen. Assuming the camera resolution spot on screen includes N^2 projection lens resolution spot, there are N^2 speckle field elements A_{ij} on screen within one camera resolution spot, where $j, i = 1, 2, \cdots, N$. The random speckle field element A_{ij} is projected to the charge-coupled-device (CCD) sensor from the screen by the camera lens. The phase plate assigns each random field element A_{ij} a phase ϕ (0 or π) according to the matrix of "$B_{i,j} = e^{j\phi}$". By scanning of mirror, the laser beam with the phase pattern of matrix B crosses the camera resolution spot. The scanning process is shown in Fig. 3.

N^2 projection lens resolution spots with the phase B_{ij} scan through camera resolution spot, in this situation $N = 2$. Because cameras are intensity detector with finite spatial and temporal bandwidth, we can calculate the speckle contrast reduction by total intensity integrated $\langle I \rangle$ and second moment of intensity $\langle I^2 \rangle$
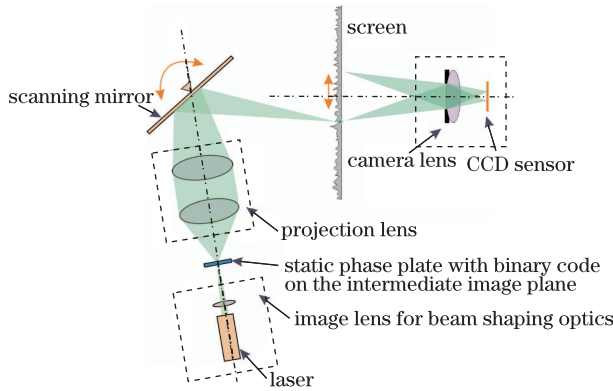

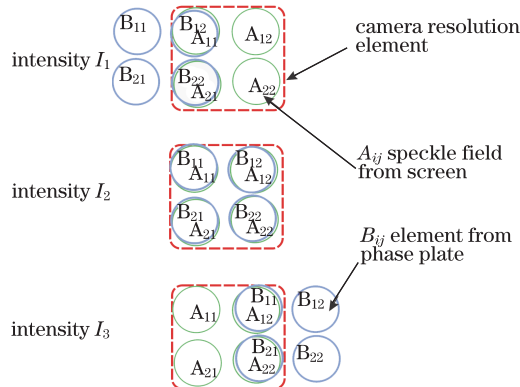Fig. 2. Optical diagram of a scanning display system.

Fig. 3. Laser spot scanning through a camera resolution spot.

integrated over time. From Fig. 3, we can see there is $2N - 1$ light intensity I_m, where $m = 1, 2, \cdots, 2N - 1$. The single camera resolution element integrates $2N - 1$ different intensity patterns during the camera resolution time. One such pattern is the squared magnitude of a sum of N^2 different fields produced by the N projection lens resolution spots lying within one cameral resolution spot.

Following Goodman[1], when $m \leqslant N$, the intensity I_m can be calculated as

$$I_m = \left| \sum_{i=1}^{N} \sum_{j=1}^{m} A_{ij} B_{i,j+N+1-m} \right|^2 = \sum_{i=1}^{N} \sum_{j=1}^{m} \sum_{k=1}^{N} \sum_{p=1}^{m}$$
$$\cdot A_{ij} A_{kp}^* B_{i,j+N-m+1} B_{k,p+N-m+1}. \tag{2}$$

When $N < m \leqslant 2N - 1$, the intensity of I_m is

$$I_m = \left| \sum_{i=1}^{N} \sum_{j=m-N+1}^{N} A_{i,j} B_{i,j-m+N} \right|^2 = \sum_{i=1}^{N} \sum_{j=m-N+1}^{N} \sum_{k=1}^{N}$$
$$\cdot \sum_{p=m-N+1}^{N} A_{ij} A_{kp}^* B_{i,j-m+N} B_{k,p-m+N}^*. \tag{3}$$

Thus the intensity at one point on the CCD sensor is

$$I = \sum_{m=1}^{2N-1} I_m. \tag{4}$$

Substitute of Eqs. (2) and (3) into Eq. (4), the intensity at one camera resolution spot can be gotten as

$$I = \sum_{m=1}^{N} I_m + \sum_{m=N+1}^{2N-1} I_m = \sum_{m=1}^{N} \sum_{i=1}^{N} \sum_{j=1}^{m} \sum_{k=1}^{N} \sum_{p=1}^{m}$$
$$\cdot A_{ij} A_{kp}^* B_{i,j+N-m+1} B_{k,p+N-m+1}^*$$
$$+ \sum_{m=N+1}^{2N-1} \sum_{i=1}^{N} \sum_{j=m-N+1}^{N} \sum_{k=1}^{N} \sum_{p=m-N+1}^{N} A_{ij} A_{kp}^*$$
$$\cdot B_{i,j-m+N} B_{k,p-m+N}^*. \tag{5}$$

The mean intensity of the observed intensity represent by $\langle I \rangle$ under condition of matrix B can be gotten as

$$\langle I | N : B \rangle = \sum_{m=1}^{N} \sum_{i=1}^{N} \sum_{j=1}^{m} \sum_{k=1}^{N} \sum_{p=1}^{m} A_{ij} A_{kp}^*$$
$$\cdot \overline{B_{i,j+N-m+1} B_{k,p+N-m+1}^*}$$
$$+ \sum_{m=N+1}^{2N-1} \sum_{i=1}^{N} \sum_{j=m-N+1}^{N} \sum_{k=1}^{N} \sum_{p=m-N+1}^{N}$$
$$\cdot A_{ij} A_{kp}^* \overline{B_{i,j-m+N} B_{k,p-m+N}^*}. \tag{6}$$

The standard deviation of the observed intensity represented by $\langle I^2 \rangle$ under condition of matrix B can be gotten

as

$$\langle I^2|N:B\rangle = \sum_{m=1}^{N}\sum_{i=1}^{N}\sum_{j=1}^{m}\sum_{k=1}^{N}\sum_{p=1}^{m}\sum_{q=1}^{N}\sum_{l=1}^{m}\sum_{h=1}^{N}\sum_{t=1}^{m}A_{ij}A_{kp}^*A_{ql}$$

$$\cdot A_{ht}^* \overline{B_{i,j+N-m+1}B_{k,p+N-m+1}^*B_{p,l+N-m+1}B_{h,t+N-m+1}^*}$$

$$+\sum_{m=N+1}^{2N-1}\sum_{i=1}^{N}\sum_{j=m-N+1}^{N}\sum_{k=1}^{N}\sum_{p=m-N+1}^{N}$$

$$\cdot\sum_{q=1}^{N}\sum_{l=m-N+1}^{N}\sum_{h=1}^{N}\sum_{t=m-N+1}^{N}A_{ij}A_{kp}^*A_{ql}A_{ht}^*$$

$$\cdot\overline{B_{i,j-m+N}B_{k,p-m+N}^*B_{p,l+N-m+N}B_{h,t-m+N}^*}. \tag{7}$$

Let's use the same property $\overline{|A_j|^2}=\overline{|A|^2}$ and $\overline{|A_j|^4}=2\left(\overline{|A_j|^2}\right)^2=2\left(\overline{|A|^2}\right)^2$ following Goodman[1], and $B_{i,j}$ =+1 or –1 because of $B_{i,j}=e^{j\phi}$, the mean intensity and standard deviation value can be gotten as

$$\langle I|N:B\rangle = F(N)\overline{|A|^2}, \tag{8}$$

and

$$\langle I^2|N:B\rangle = G(N)\left(\overline{|A|^2}\right)^2, \tag{9}$$

where $F(N)$ and $G(N)$ are the function of variation of N according to the Eqs. (6) and (7). According to Eq. (1), the contrast reduction ratio is

$$C(N:B) = \frac{\sigma}{\langle I\rangle} = \frac{\sqrt{G(N)-F^2(N)}}{F(N)}. \tag{10}$$

Enumerating all matrices B with fixed parameter N; calculating the speckle contrast reduction by computer; selecting the matrix B which conducts the minimum speckle contrast reduction as candidate. The matrices B and N from 2 to 5 with minimum speckle contrast reduction are listed as

$$N=2 \quad Cr=0.70 \quad \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix},$$

$$N=3 \quad Cr=0.62 \quad \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & -1 & -1 \end{bmatrix},$$

$$N=4 \quad Cr=0.52 \quad \begin{bmatrix} 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & -1 & -1 & -1 \end{bmatrix},$$

$$N=5 \quad Cr=0.47 \quad \begin{bmatrix} 1 & -1 & 1 & -1 & -1 \\ 1 & 1 & -1 & -1 & 1 \\ -1 & 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & -1 & 1 \end{bmatrix}.$$

To check the algorithm we proposed, the stationary phase plates with Trisnadi profile, Barker code, and the 2D binary code were fabricated by patterning three pieces of glass wafer with photoresist. On the plate, the cell size of phase pattern was 3 $\mu\times$3 μm. The height satisfied the equation $h\times(n_0-1)=\lambda/2$, where λ was the wavelength of laser, n_0 was the photoresist's diffractive index ($n_0=1.645$ for 632-nm wavelength). In this case, we set the height h as 1 540 nm for getting π phase switching. One pixel's phase pattern of one pixel is shown as Fig. 4.

The stationary phase plate was placed on the image plane as shown in the Fig. 2. The 632-nm wavelength laser beam was reshaped by a convex lens and then hit on the stationary phase plates. The projection lens projected the image from the phase plate on a screen. A charge-coupled device (CCD) camera (Sony ICX098BL) received the speckle pattern. The projection lens F/# was set as 1.94 and the magnification was set as 2.47×, it means that projection lens resolution was 3 μm, the pixels sizes were 133 μm(18×2.47×3 (μm)), 96 μm(13×2.47×3 (μm)) and 37 μm (5×2.47×3 (μm)) compared with Trisnadi's phase profile, Baker code, and 2D binary code. So, the CCD camera apertures were reduced to F/90, F/64, and F/22, respectively, the distance between the camera and the screen was 570 mm. Thus experiment matched the theoretical speckle reduction value with the conception we derived for red wavelength. The measurement results were given in Fig. 5.

According to the measurements as shown in Fig. 5, the speckle contrasts are 33.8% when there are no any DOE, and it decreased down to 19.8%, 16.2%, and 17.5%, respectively, by using the stationary phase plates which have the phase pattern of Trisnadi's profile, Barker code, and 2D binary code. So, the speckle contrast reduction by 2D binary code is 51.7% which is very close to the theoretical value of 47%. This measurement result presents
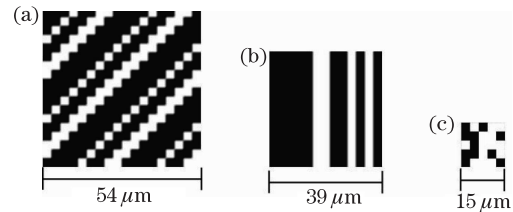

Fig. 4. (a) For Trisnadi's phase profile; (b) barker code phase pattern; (c) 2D binary code phase pattern.
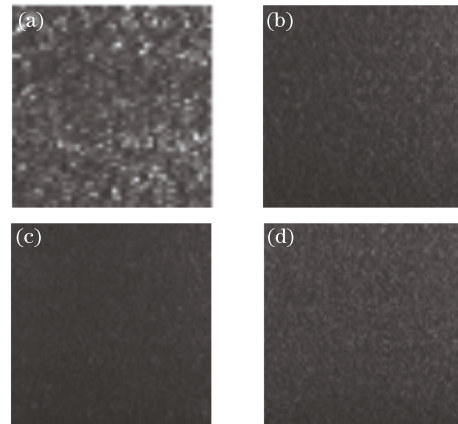

Fig. 5. Measurement result. (a) Speckle contrast (a) without any phase plate (33.8%) and (b) with phase pattern with Trisnadi's profile (19.8%), (c) Barker code of order 13 (16.2%), and (d) 2D binary code (17.5%).

that 2D binary code can be used to reduce speckle in line scan display system.

In the scheme proposed in this letter, the scheme of 2D binary code achieved better speckle contrast than of Trisnadi's profile. The scheme with Barker code of order 13 gets the best speckle contrast 16.2% which is very close to 17.5% of 2D binary code. However, the longest order of Barker code is 13. The 2D binary code proposed can be longer than 13. Using binary code with higher orders, higher speckle reduction is possible to achieve.

In conclusion, we suggest that a 2D binary code is used to form a stationary phase plate to reduce laser speckle in line scan display system. The phase plate is fabricated by etched glass or photoresist with different thicknesses according to the 2D binary code. By calculation and experiment, the binary code of order 5 proposed can be used to reduce speckle and which can achieve the speckle contrast close to the phase plate formed from barker code of order 13.

References

1. J. W. Goodman, *Speckle Phenomena in Optics*: *Theory and Applications* (Roberts and Company Publishers, Greenwood Village, Colorado, 2007).
2. N. George and A. Jain, Appl. Opt. **12,** 1202 (1973).
3. S. C. Shin, S. S. Yoo, S. Y. Lee, C. Y. Park, S. Y. Park, J. W. Kwon, and S. G. Lee, J. Displays **27,** 91 (2006).
4. J. I. Trisnadi, Opt. Lett. **29,** 11 (2004).
5. J. I. Trisnadi, Proc. SPIE **4657,** 131 (2002)
6. J. I. Trisnadi, "Method and apparatus for reducing laser speckle" Patent US US6323984b1.
7. V. Yurlov, A. Lapchuk, S. Yun, J. Song, I. H. Yeo, and S. An Yang, Appl. Opt. **48,** 80 (2009).
8. V. Yurlov, A. Lapchuk, Y. Sangkyeong, S. Jonghyeong, and Y. Haengseok, Appl. Opt. **47,** 179 (2008).
9. M. N. Akram, V. Kartashov, and Z. Tong, Opt. Lett. **35,** 444 (2010).