Optimal full speckle suppression in laser projectors using one 2D Barker code-type optical diffractive elements

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The effective method of a speckle suppression using one moving 2D diffractive optical elements based on the periodic Barker code sequence is developed. It was proved that method has the same optical parameters as method based on two 1D Barker code DOE stretched and moving in orthogonal directions. It is shown that DOE movement in special direction allows to use full numerical aperture of objective lens for speckle averaging by angle diversity. It is found that 2D DOE based on Barker code of length of 13 allows to decrease speckle contrast below human eye sensitivity with optical losses less than 10%.

OCIS codes: 110.6150, 110,1650.

1. Introduction

The lasers projectors and displays allow to obtain high-color saturated images, have high optical efficiency and small size. The high optical efficiency and small size are especially important for mobile devices. The engineering advantages and peculiarities of laser projectors are summarized in [1]. However, speckle noise [2] strongly decreases image quality and has inhibited the widespread application of lasers in image systems [1]. The speckle contrast (C) is used to measure the depth of light intensity modulation caused by speckles. It is defined as the ratio of the standard deviation to the mean of the laser light intensity on screen and is given by the following expression [2]:

$$C = s_I / < I > \qquad (1)$$

where s_I and $< I >$ are standard deviation and the mean value of light intensity on the screen. The speckle suppression methods are based on speckle pattern averaging. Speckle averaging can uses the wavelength, angle or polarization diversity of a laser beam [2]. The angle diversity is one of the most effective method of speckle suppression. It is possible to achieve large speckle suppression by moving or vibrating a random diffuser inside optical systems [3-5]. Full speckle suppression can be obtained by a rapidly vibrating diffuser [5]. However, the use of a random diffuser requires high-frequency and large-amplitude of DOE vibration, and the method has high optical losses.

The original method of speckle suppression was proposed by Trisnadi [6]. Trisnadi proposed the DOE which modulate the phase of the laser beam wavefront by using Hadamard matrix algorithm. It was proved that method has the high level of speckle suppression. However, the method requires very accurate, fast and complex DOE movement, which is very difficult to realize in technical devices. A prior study [7] reports on a modification of the Trisnadi method in which the 2D structure of the DOE is changed to a pair of 1D DOE structures that together realized the Hadamard matrix modulation method.

It is possible to obtain high speckle suppression by laser beam scanning along the screen by a vibrating mirror in the Fourier plane of the objective lens [8-10] in 1D laser scanning projectors and in laser pointer projectors [11]. A simple and effective (with small optical losses) method of speckle suppression is proposed in [10, 12-13]. The Barker code-type DOE is used to generate a wide spatial frequency band and to increase the beam width to a diameter of the input numerical aperture of objective lens independent of the initial width of the laser beam. However the method uses for speckle suppression only an aperture along direction of the beam scanning and significant optical system complication is required for using of an aperture in the orthogonal direction [14].

In [15] is proposed a method of speckle suppression based on two 1D Barker code DOE stretched in otthogonal direction which is situated on different transparent plate. The two DOE structure should moving in orthogonal direction to get a large speckle suppression. It was proved that method can decrease speckle contrast below human eye sensitivity and has small optical losses. However using two close situated the DOE structure moving in orthogonal direction is not good technology solution. Below, we describe the new method which uses only one moving DOE structure and have the same speckle suppression and optical efficiency as method based on two 1D Barker code type DOE.

2. Speckle suppression method based on one moving 2D diffractictive optical element based on Barker code sequence

In our previous publication [15] we propose to use two Barker code type DOE moving in orthogonal directions which allows to suppress speckle noise below human eye sensitivity and has small below 10% optical losses. The optical scheme of the method is shown on Fig. 1. One 1D Barker code-type DOE is a sequence of groves of depth h which provides phase shift of a wavefront of transmited beams in a correspondence to the periodic Barker code sequence. It was proved that method uses all aperture of objective lens for speckle suppression and therefore provides the best speckle suppression. It was shown that one pair of DOEs can be used for laser beam of different color.

However using two moving DOEs situated close to each other is not good technical solution for the technical implementation. Is it possible to get the same effect speckle suppression effect and optical efficiency with one moving DOE?

Fig. 2 shows the transparent plate with two Barker code type DOE on opposite surface of transparent plate stretched in orthogonal directions. This structure is similar to structure proposed in [15] with large difference, the two DOE structure are situated on one transparent plate. The optimal speckle suppression is achieved when DOE with 1D structure developed along x axis is moving along x direction and DOE with 1D structure developed along y axis is moving along y axis with speed ratio equal to Barker code length N. So due to different direction movement of the two DOE structures at first glance it is impossible to obtain optimal speckle suppression effect when the two DOE placed on one plate. However, since upper structure has not dependence on x, any movement along x transform structure to himself and does not give any change of phase distribution of transmitted through the DOE plate. Similar, lower DOE structure has not dependence on y and any movement along y transform structure to himself and therefore does not provide any change to phase change of transmitted through plate wave. Therefore the movement of transparent plate with the two DOE structure with velocity

$$\vec{V} = V_x \hat{e}_x + V_y \hat{e}_y \tag{1}$$

can be represented as upper DOE movement along y axis with velocity V_y and lower DOE movement along x axis with velocity V_x. So from optical point of view it look like the two DOE movement independently in orthogonal direction with different velocity. By choosing the ratio of velocity of two DOE equal to

$$V_x / V_y = N \quad \text{or contrary} \quad V_y / V_x = N \tag{2}$$

where N is Barker code length, and under the condition that movement along slow axis is sufficient to move DOE sturcture on one period during time resolution of human eye [15] we obtained the same phase shift in time as in [15]. Therefore the new method is equivalent to the method developed in [15]. Hence a speckle contrast of a new method the can be calculated by formula derived in [15] for two 1D Barker code-type DOE Method:

$$C = C_x * C_y = \frac{1}{\sqrt{2}} 2\sqrt{\int_{-\infty}^{\infty} \left| \frac{A_0(Du)}{A_0(0)} \right|^2 Q(u)du}\, 2\sqrt{\int_{-\infty}^{\infty} \left| \frac{A(Dv)}{A(0)} \right|^2 Q(v)dv}, \tag{4}$$

where [10] $Q(u) = \int_{-\infty}^{\infty} \sin c^2 [2p(u+x)] \sin c^2 [2px] dx = \frac{1 - \sin c^2 (4pu)}{8p^2 u^2}$,

$$C_x = 2\sqrt{\int_{-\infty}^{\infty} \left| \frac{A_0(Du)}{A_0(0)} \right|^2 Q(u)du}\,, \tag{5a}$$

$$C_y = 2\sqrt{\int_{-\infty}^{\infty} \left| \frac{A(Dv)}{A(0)} \right|^2 Q(v)dv}\,, \tag{5b}$$

$A(x_2 - x_1) = \int_0^{NT} H(u + x_1) H^*(u + x_2) du$ is the autocorrelation function of the periodic Barker code function and $A_0(x_2 - x_1) = \sum_{k=0}^{N-1} H(x + k*T) H^*(x + k*T + x_2 - x_1) = \sum_{n=1}^{N} B_i B_{i+k}$ is the discrete autocorrelation function of the periodic Barker code sequence (autocorrelation function of the discrete Barker code sequence). It was proved [15] that method provides large speckle suppression and has a large optical efficiency (close to 100%). In the case of using objective lens with large optical aperture (NA> l/T) the speckle contrast can be decrease [15] to a level of

$$C = 1/\left(N\sqrt{3}\right) \tag{6}$$

It is easy to see that for N=13 this method would decrease speckle contrast to level of

$$C = 1/\left(N\sqrt{3}\right) \approx 1/(13 \cdot 1.73) = 4.4\% \,, \tag{7}$$

what is below of human eye sensitivity of 5% .

However placing the two DOE structures on different side of transparent plate is often not acceptable. Is it possible to used one 2D DOE structure on one side of the plate instead of the two 1D DOE on different surface of transparent plate? Fig. 4 shows 2D DOE structure placed on one side of transparent plate. The 2D DOE structure copies the groves of upper and bottom groves of the DOE structure shown on Fig. 3 in the case if their transverse positions do not coincide and turn groove to land if their positions coincide. On Fig. 4 the white cells correspond to the grove and yellow to the land. The depth of groves should provide the half wavelength shift of the wavefront of transmitted laser beam. It is not difficult to see that the 2D DOE structure has the transmission coefficient the same as in the case of the two DOE structure on opposite side of the plate analyzed above. The DOE structure in Fig. 4 is similar to a chess desk with different cells length. The length of meshes corresponds to the length of consecutive 1 or -1 in the Barker code sequence. The structure has period equals to T_0=NT in both directions (N = 7 on Fig. 4).

Since the 2D DOE structure is identical to structure with two 1D DOE structure on opposite side of transparent plate for transmitted beam it would provides the same speckle suppression efficiency in the case when speed of DOE movement correspond to Eq. (2). Hence, the optical properties of the 2D DOE structure is the same as optical properties of two 1D DOE structure. Therefore the new method will provide the optimal high speckle suppression and high optical efficiency.

3. Conclusion

The method of speckle suppression based on special 2D DOE structure is developed and it is proved that it is equivalent to the method based on two 1D Barker code-type optical diffractive elements. From of equivalence of two method and from analysis of two 1D Barker code-type optical diffractive elements [15] it is followed that new method allows to suppress speckle below human eye sensitivity and has small optical losses (below 10%).

A square aperture was used in [15] to simulate the eye in the mathematical model to simplify the obtained formulae. The model can be easily generalized to the actual case of a circular aperture for the eye. Additional analysis is required for accurate method optimization to take into account the actual shape of the aperture (circular shape).

4. References

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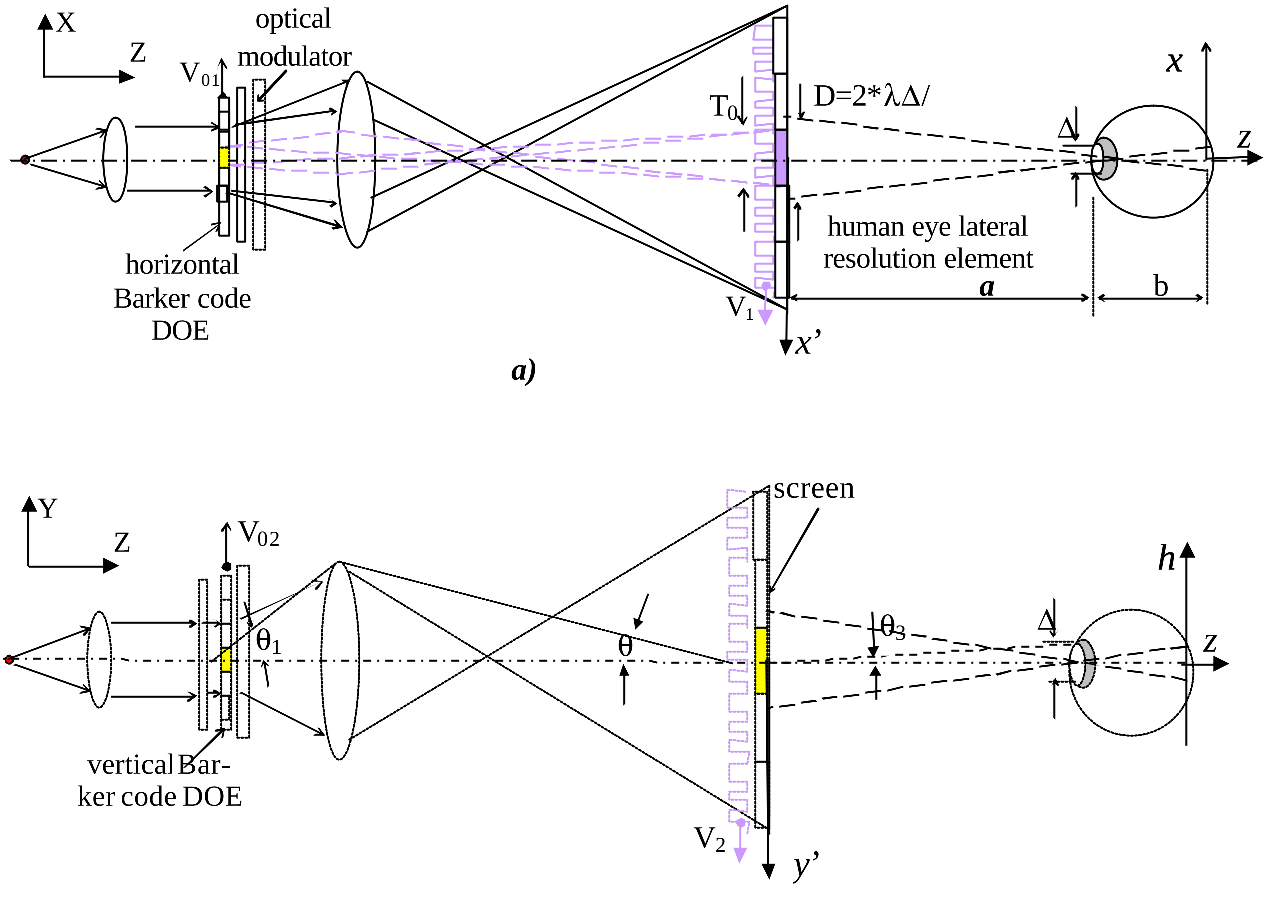
Figure captions

Fig.1. Optical scheme of the laser projector with two 1D Barker code-type DOEs.

Fig. 2. Optical scheme of speckle suppression method with one 2D Barker code-type DOE .

Fig. 3. Transperent plate with two 1D Barker code-type DOEs (three projections).

Fig. 4. 2D DOE structure based on two 1D Barker code-type DOE periodic structure (N=7). The upper and left side of the figure shows one-dimensional Barker code-type DOE on the basis of which the two-dimensional DOE is formed. White color denotes grooves, yellow – land.


X
Z
optical
modulator
V_{01}
T_0
D=2*λΔ/
Δ
x
z
human eye lateral
resolution element
a
b
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DOE
V_1
x’
Y
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V_{02}
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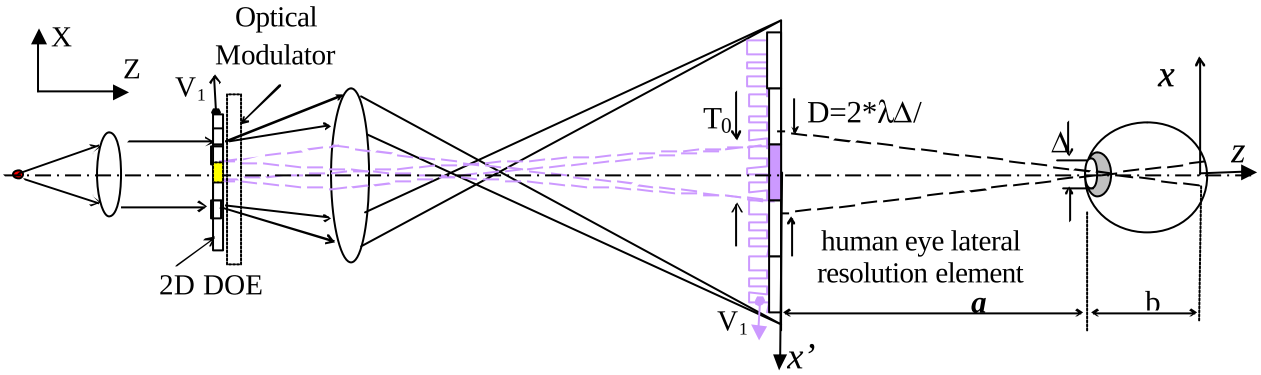
vertical Barker code DOE
V_2
y’

a)

b)

Fig.1.


X
Z
Optical
Modulator
V1
2D DOE
T0
D=2*λΔ/
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z
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resolution element
a
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x'

Fig. 2.

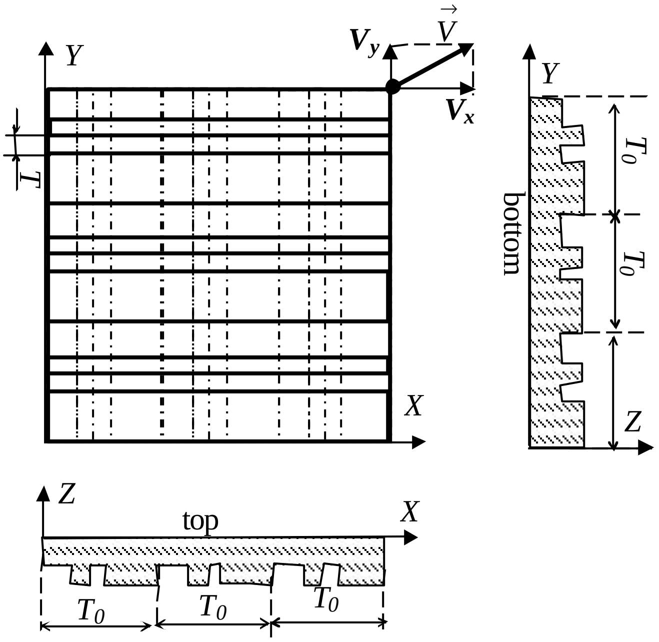

Fig. 3.

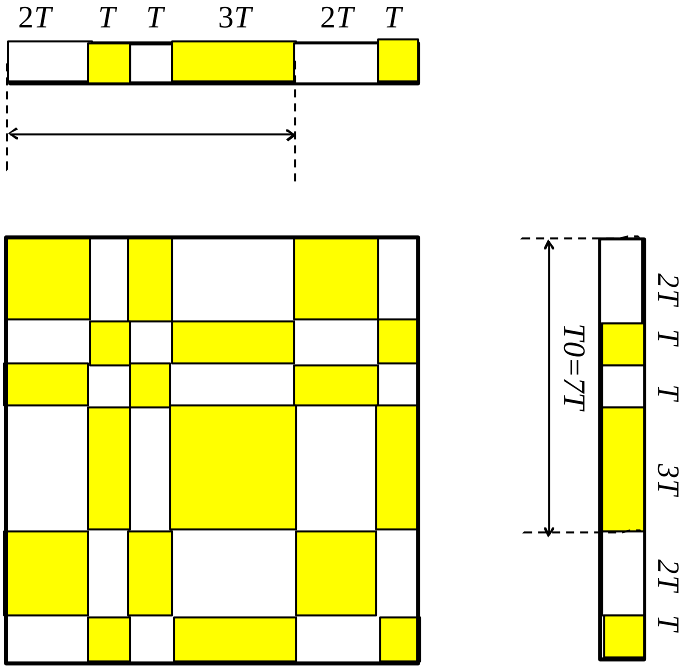

Fig. 4.