Optics and Lasers in Engineering 90 (2017) 173–178

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

A ferroelectric liquid crystal spatial light modulator encoded with orthogonal arrays and its optimized design for laser speckle reduction

Zhaomin Tong[a,b,*], Xuyuan Chen[a,b,c]

[a] State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan, Shanxi 030006, People's Republic of China

[b] Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, People's Republic of China

[c] Faculty of Technology and Maritime Sciences, Department of Micro, and Nanosystem Technology, University College of Southeast Norway, Borre N-3184, Norway

ARTICLE INFO

Keywords:
Laser projectors
Speckle reduction
Binary phase diffuser
Two-level orthogonal array
Spatial light modulator
Passive matrix addressing

ABSTRACT

In laser projectors, speckle reduction can be achieved by projecting a changing binary phase diffuser onto the screen. Here, we sequentially encoded a commercialized ferroelectric liquid crystal spatial light modulator (FLC-SLM) with the rows of a two-level orthogonal array of order sixty-four, thus obtaining a changing binary phase diffuser. With the help of this binary phase diffuser, the subjective speckle contrast ratio on the screen is reduced from C_b=0.71 to C_a=0.1. Based on the experimental results, a simplified transparent FLC-SLM design is first proposed. This newly designed FLC-SLM has two phase modulation depths and can be driven with the passive matrix addressing scheme. Therefore, the control electronics of the proposed FLC-SLM can be significantly simplified compared to the currently used one.

1. Introduction

Lasers, as the illumination light sources present in projection displays, have distinguished competitiveness in terms of the color gamut and étendue, among other characteristics [1]. However, speckle exists because of the high spatial and temporal coherence of lasers; thus, speckle reduction techniques must be introduced to improve the image quality [1–11]. The speckle is captured under free-space propagation or under imaging geometry using a detector, known as objective speckle and subjective speckle, respectively [1]. Subjective speckle reduction can be achieved by changing a random phase diffuser (RPD) positioned at an intermediate image plane created between the micro-display chip, such as a digital micromirror device (DMD) or a liquid crystal on silicon (LCoS) device, and the projection screen during the detector integration time [1]. Using this method, the subjective speckle contrast ratio, defined as the ratio between the standard deviation σ and the mean value $\bar{I}$ of the light intensity, can be reduced from C_b=1 to

$$C_a = \sqrt{\frac{M + K \pm 1}{2KM}}, \tag{1}$$

when the RPD over fills (plus sign) or just fills (minus sign) the projection lens, where C_a, M and K represent the subjective speckle contrast ratio after introducing the RPD, the number of independent RPD realization steps during the detector integration time, and the number of projection lens resolution elements lying within one detector resolution spot, respectively. The factor of two is attributed to the independent orthogonal polarizations of the projection screen, and we have assumed that the individual subjective speckle pattern has the same mean intensity $\bar{I}$ [1].

Based on Eq. (1), the minimum subjective speckle contrast ratio, $C_{a\_min}=1/K^{1/2}$, can be obtained when the value of M approaches infinity, indicating that the RPD must travel an extremely long distance. To solve this challenge, in our previous publications, a subjective speckle reduction method involving a temporally changing binary phase diffuser (BPD) generated from a $N_1 \times N_2$ two-level orthogonal array (2L-OA) was reported [12–14]. After carefully assigning the micro-display chip pixel to the predetermined BPD cells (here, we assumed that the detector's resolution spot size was equal to the micro-display chip pixel size), for example, one micro-display chip pixel covering $u \times v = K = N_2$ BPD cells, the temporally changing binary phase masks (BPMs) were projected onto the screen to encode the random speckle fields there. Because of the orthogonal properties of the 2L-OA columns and the generated BPMs, the perceived subjective speckle patterns were independent; thus, the integrated speckle image had a low speckle contrast ratio. Based on our calculations, the BPMs

* Corresponding author at: State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan, Shanxi 030006, People's Republic of China.

E-mail address: zhaomin.tong@sxu.edu.cn (Z. Tong).

http://dx.doi.org/10.1016/j.optlaseng.2016.10.014
Received 12 July 2016; Received in revised form 11 October 2016; Accepted 12 October 2016
Available online 20 October 2016

could reduce the subjective speckle contrast ratio from C_b=1 to C_a=1/$(2N_2)^{1/2}$ with only M=N_1 steps of BPD vibration during the detector exposure time (50 ms for the human eye); this result represents a substantial improvement over an RPD that requires M to be nearly equal to an infinite number of steps of vibration to achieve the same goal [12–14].

The simplest method to fabricate a BPD is by etching fused silica with zero and one quarter wavelength depths. However, this approach requires an individual actuator, such as a voice coil, to drive the diffuser, making the subjective speckle reduction facility noisy and bulky [13,15]. Another BPD fabrication approach is to use an electrostatic binary micromirror array with passive matrix addressing control electronics [12,14]. The binary micromirror array can change the phase masks with applied electronic signals, making it more compact compared to the first approach. However, constrained by the four-beam piston layout of the binary micromirror array and the micromachining ability, the BPD's fill factor is very low (~52%). Part of the laser lights is unmodulated, thus making its speckle reduction efficiency much lower than the expected value [14].

A phase-only liquid crystal spatial light modulator (SLM) is yet another approach to fabricating the BPD; this approach has the potential to improve the BPD's fill factor. The application of an SLM in speckle reduction is not new. For example, people have used a phase-only liquid crystal SLM for speckle reduction by programming it as diffraction gratings [16], by generating independent individual kinoforms [17], and by dividing a laser as the incoherent light sources [18]. In this paper, we have used 2L-OAs to encode a ferroelectric liquid crystal spatial light modulator (FLC-SLM) working under phase-only modulation mode. The subjective speckle contrast ratio is reduced from C_b=0.71 before to C_a=0.1 after driving the FLC-SLM during the charge-coupled device (CCD) camera exposure time. Based on our experimental results, the validity of using a phase-only SLM as the 2L-OA type BPD for efficient subjective speckle reduction is first confirmed. Finally, an optimized FLC-SLM design with a passive matrix addressing scheme is proposed following the Kronecker algebra in 2L-OA construction, and its application in a three-chip LCoS-based laser projector is suggested. Compared to other speckle reduction methods using phase-only SLMs [16–18], our proposed FLC-SLM design significantly simplifies the SLM control electronics, and hence, the expense of laser projectors would be reduced after the introduction the speckle reduction components.

2. Theory and experiment

The columns of the 2L-OAs are orthogonal; thus, the BPMs generated by the rows of the 2L-OAs are orthogonal, and the 2L-OAs can be introduced to produce BPDs [12]. The elements of the 2L-OAs and the phase modulation depths of the BPMs cells fulfill the following relationships: −1=exp(jπ) and 1=exp(j0) [12]. As an example, a Hadamard matrix (HM) of order N =64, HM(64), *i.e.*, a square 2L-OA with $N1$=N_2=N=64, is used to program the FLC-SLM, where the rows of HM(64) correspond to the 8×8 BPMs. Fig. 1 shows the procedure of generating the thirty-second 8×8 BPM(32) from the thirty-second row of HM(64).

The 512×512 pixel reflective FLC-SLM (model A512-0635 from Meadowlark Optics, Inc.) operating as an array of programmable half-wave plates is introduced to generate the BPMs. The FLC-SLM has a fast response time (≤450 μs) and a high switching frequency (maximum 1015 Hz) that could produce more BPMs during the limited detector exposure time, *i.e.*, reduce the subjective speckle more efficiently. It is thus a more suitable candidate than the nematic liquid crystal SLM whose response time is on the order of several-to-tens of milliseconds [20–23]. As the pixel voltage changes, so does the orientation of the optic axis of the FLC-SLM, rotating the polarization state of the incident light beam. When the maximum negative field is present (pixel value of “0” at +2 V), the optic axis of the FLC-SLM will be fully counterclockwise at approximately −22.5 degrees from the vertical. When the maximum positive field is present (pixel value of “255” also at −2 V), the optic axis rotates fully clockwise to approximately +22.5 degrees from the vertical [19,20].

The 512×512 pixel FLC-SLM 8-bit grayscale pattern files are obtained in Matlab according to the row elements of HM(64), where only two pixel values are chosen with “0” and “255” corresponding to the “1” and “−1” elements of HM(64), respectively. For each pattern file, the 8×8 sub-pattern file is in accordance with the HM(64) row, which is repeated sixty-four times both horizontally and vertically to match the 512×512 no. of FLC-SLM pixels. Fig. 2 shows the thirty-second 512×512 pattern file generated using Matlab. The optical setup to reduce subjective speckle by programming the FLC-SLM is shown in Fig. 3.

As shown in Fig. 3, a 5 mW JDSU HeNe laser (model 1125 P from Edmund Optics) with a wavelength of λ=632.8 nm is used as the illumination source, followed by a 20× beam expander to expand the laser beam to ~16 mm in diameter and the first linear glass polarizer, P_1 (95% efficiency). A non-polarizing cube beam splitter reflects the incident laser beam onto the FLC-SLM front surface along its normal direction, and then a projection lens and the second polarizer, P_2 (same as the first one), are introduced. The polarization orientations PO_1 and PO_2 of polarizers P_1 and P_2, respectively, and the slow axes SA_0 and SA_{255} of the FLC-SLM at pixel values of “0” and “255”, respectively, are set to satisfy the following relationship: PO_1 bisects SA_0 and SA_{255} with the same absolute angles of 22.5 degrees, and PO_1 and PO_2 are orthogonal. Under such circumstances, the polarization orientation of the laser beam reflected by the FLC-SLM under “0” pixels is rotated counterclockwise by −45° (or clockwise by +45°), which, under a “255” pixel value, corresponds to a clockwise value of +45° (or a counterclockwise value of −45°). With the help of the second polarizer, P_2, the reflected laser beams under the FLC-SLM pixel values of “0” and “255” are found to be equal in amplitude but opposite in direction (“π” radian phase shift), *i.e.*, binary phase modulation. A diffuser (sandblasted glass from Edmund Optics) is positioned after the second polarizer, P_2, functioning as the projection screen, and a CCD camera (model PL-B700 from Edmund Optics) with a mounted image lens is used to capture the subjective speckle images. The focal length, f_p, and diameter, D_p, of the projection lens are 30 mm and 12.7 mm, respectively, and the image lens has a focal length of f_i=50 mm and an F-number of $F\#_i$=16. The distance between the FLC-SLM and the projection lens is Z_s=250 mm, the distance between the projection lens and the diffuser is Z_p=34.1 mm, and the distance between the diffuser and the image lens is Z_i=68.2 mm.

3. Results and discussions

Under the optical configuration shown in Fig. 3, the lateral resolution of the projection lens on the FLC-SLM is equal to $R_{ps}\approx 1.22\lambda Z_s/D_p$=15.2 μm, which is close to the 15 μm pixel pitch of the FLC-SLM; thus, the projection lens can correctly distinguish each BPM cell. There are $K\approx(Z_iF\#_iD_p/f_iZ_p)^2\approx 64$ projection lens resolution elements lying within one image lens resolution spot, which is equal to the column number of the 2L-OA (or HM), N_2=N=64. The maximum switching frequency of the SLM is 1015 Hz; *i.e,* the minimum delay time of the SLM is 1 ms. We set the working delay time (the time to maintain one BPM) as 2 ms because, at this value, more reliable phase encoding results are expected. The CCD camera exposure time is equal to 130 ms. During the CCD camera exposure time, all of the N_1=N=64 8-bit grayscale pattern files with only two pixel values at “0” and “255” are uploaded to the FLC-SLM sequentially to generate the BPMs. Because the speckle contrast ratio is influenced by background light and the vibration of the optical table induces an additional speckle reduction mechanism, the experiments are conducted in a dark room to avoid the interference of background light, and the optical table is stabilized to eliminate any unwanted vibrations. Fig. 4 shows the