A Low Speckle Laser Pico-Projector with Dynamic Light Scattering Liquid Crystal Devices

Yong-Han Chen[1], Guan-Chih Chen[2], Jui-Wen Pan[2*], Shie-Chang Jeng[3]**

[1]Institute of Lighting and Energy Photonics, National Yang Ming Chiao Tung University, Taiwan,
[2]Institute of Photonic System, National Yang Ming Chiao Tung University, Taiwan,
[3]Institute of Imaging and Biomedical Photonics, National Yang Ming Chiao Tung University, Taiwan.
*Corresponding author: juiwenpan@gmail.com
**Corresponding author: scjeng@nycu.edu.tw

Keywords: speckle, dynamic light scattering, liquid crystal, laser projector

ABSTRACT

Dynamic light scattering liquid crystal (DLS-LC) device with a low driving field is used to reduce the speckle in the laser pico-projector. The DLS-LC device produces the time-varying scattering patterns, which can eliminate the degrees of temporal and spatial coherences of the laser and achieve a very effective reduction in the speckle contrast.

1.Introdution

In a laser pico-projector, due to the high coherence of the laser [1], a speckle phenomenon will appear in the image [2]. This speckle phenomenon will seriously damage the image quality of the projection. Therefore, reducing speckle is a very important issue in laser projection displays. So far, the speckle phenomenon has been extensively studied, and many techniques have been developed to reduce it. The conventional methods for speckle reduction are by averaging of N statistically independent and uncorrelated speckle patterns in a certain integration time, and the speckle contrast can be ideally reduced by a factor of $1/\sqrt{N}$ [3]. Many technologies, such as wavelength diversity [4], angle diversity [5], and polarization diversity [6], have been demonstrated to generate independent patterns. To achieve a very effective reduction in the speckle phenomenon, most techniques usually combine several schemes, such as time-varying angle diversity. Although the above mentioned methods can achieve a speckle contrast as low as C = ~0.04, the required additional bulky and complicated mechanical parts making them unsuitable for the compact and vibration-free applications, such as pico-projectors. To overcome these problems, a compact and simple dynamic light scattering liquid crystal (DLS-LC) device is proposed in this work.

2. EXPERIMENT

We mixed 98 wt % of negative LCs ($\Delta\varepsilon$ = -5.4, Δn = 0.212) with 2wt % photoinitators for the DLS-LC device. Spin coating was used to apply the commercial photo-cross-linking polyimide (PI) materials to indium-tin-oxide (ITO) substrates to form the homeotropic alignment layers followed by linear polarization UV light irradiation. The LC device was assembled from two pieces of ITO-PI glass substrate with a 12 μm gap controlled by mylar films. The LC mixture was then loaded into the LC device by capillary filling. Finally, the LC device was illuminated by an ultraviolet light source to initiate the photoinitators. A polarizing optical microscopy (POM) was applied to examine the various optical textures of the DLS-LC device driven at different electric field amplitudes and frequencies.

The schematic diagram of DLS-LC device is shown in Fig. 1 [7]. For the DLS-LC device without voltage, most of the incident light passes through the LC device without scattering because the LCs are aligned perpendicular to the substrates as shown in Fig. 1(a)(c). For the DLS-LC device with a voltage larger than a threshold value, the LCs with negative dielectric anisotropy will begin to align perpendicular to the electric field. If the applied voltage is large enough and the driving frequency is proper selected, the motion of ions caused by the electrohydrodynamic instabilities (EHDI) effect brings about turbulence, which randomly influences the LC molecules [8]. Then, the incident light is strongly scattered by the randomly distributed small-domain LCs as shown in Fig. 1(b)(d). A DLS-LC device can provide excellent controllable scattering properties by using this operation.

A schematic of a simple digital light processing (DLP)-based laser projector is shown in Fig. 2 [9], wherein the digital micromirror device (DMD) usually used in a laser projector has been replaced by a static rectangular pattern for this study. The applied laser light source was 532 nm. The DLS-LC device placed in front of the light pipe produced DLS for scattering the incident laser light. The laser light would enter the light pipe, generating homogenized light at the end of the light pipe. A relay lens system converted the incident angle to an exit angle of 12 ° to match the tilt angle of the mirror on the DMD [10]. A rectangular pattern was projected on the screen in order to study the influence of the DLS-LC device on the speckle reduction. Both the projection lens and the camera are at a distance of 50 cm from the screen. To correspond to the human visual system, the f-number of the camera lens is determined to be ~14 in this work [11]. The integration time of 50 ms is applied for detection due to the temporal integration time of the human eye [11].

3. Experimental result

The voltage and frequency dependent optical textures observed by a POM are shown in Fig. 3. The DLS LC device appears dark before applying voltages due to the vertical alignment of LC molecules (not shown here). The LC molecules are becoming aligned perpendicular to the electric field and showing a typical texture of nematic LC as the driving voltage increases, such as the LC device with 10 V/20 Hz driving. When the applied voltage and frequency increase in certain regions, the ions start to move. The momentum of the moving ions can be transferred to the LC molecules, and the electro-hydrodynamic instability is triggered and LC molecules begin to move, which will produce turbulence in the device, such as the LC device with 20 V/200 Hz driving. As the applied voltage and frequency increase, the turbulence becomes stronger, and produce more small turbulence domains which produces stronger light scattering, such as the LC device with 40 V/2k Hz driving. When the driving frequency is getting higher than 2 kHz, the turbulence is reduced and the scattering is getting weak, and the POM image shows the texture of nematic LC again, such as the LC device with 30 V/4k Hz driving.

The DLS properties under different driving conditions are further characterized by transmittance measurements as shown in Fig.4. In the case of 10 V, the LCs only show the nematic phase without turbulence the LC device exhibits a high transmittance for all frequency ranges. It indicates the applied voltage is too small to generate the EHD effect. By increasing the applied voltage to 50V, the transmittance of LC device decreases with a wider frequency ranges for generating EHD effect. The operating frequency range is changed from 200 to 1k Hz to 40 to 2k Hz as the voltage increases from 30 V to 50 V. The DLS effect can be controlled by both amplitude and frequency of the applied voltage as shown in Fig. 4. According to Fig.3 and Fig.4, the optical texture of the device driven by the proper voltage and frequency, such as 50 V/200 Hz, corresponding to the minimum T% exhibits a well DLS state.

The images of speckle pattern with the use of a DLS-LC device subjected to different voltages and frequencies are presented in Fig.5 and Fig.6, respectively. As shown in Fig. 5, when the driving frequency is fixed at 400 Hz, the LC device is operated from the nematic state (10 V) to DLS state (50 V) and the speckle contrast is greatly reduced from C = 0.41 to C = 0.16 with increasing voltage. As shown in Fig. 6, when the driving voltage is fixed at 50 V, the LC device is operated from the nematic state (0 Hz and 40 Hz) to DLS state (400 Hz) and back to the nematic state (4k Hz), the speckle contrast is greatly reduced from C = 0.42 to C = 0.16 as DLS state occurred.

The dependences of speckle contrast on driving voltages and frequencies are summarized in Fig. 7. When the applied voltage is below 20V, the LC device show the nematic texture, the spectral contrast is ~0.41 and there is no speckle contrast reduction for any frequency. As the applied voltage increase and the frequency is proper selected, the EHD induced scattering help to increase speckle reduction and the speckle contrast can be reduced by as much as 60%. From the above discussion, it is known that the minimum speckle contrast occurs when the LC device reaches the most turbulence condition, where both temporal and spatial variation are produced for the laser light simultaneously, which can achieve the effects of angular diversity and vibration. At this amplitude and frequency (50 V/400 Hz), the speckle contrast is reduced from C = 0.42 to a speckle contrast of C = 0.16.

4. CONCLUSION

We have demonstrated a DLS-LC device designed with a simple mixture of materials for application in a pico-laser projector system for the reduction of speckle. The DLS-LC device can be driven with a low electric field amplitude and high frequency, to continuously generate a series of independent speckle patterns within a finite integration time, allowing us to achieve both temporal and spatial variation simultaneously, which can greatly reduce the speckle contrast by as much as 62%.

The authors would like to thank the National Science and Technology Council of Taiwan for their financial support of this research under contract number MOST 110-2112-M-A49-030, MOST 110-2622-E-A49-003 and MOST 111-2112-M-A49-036.

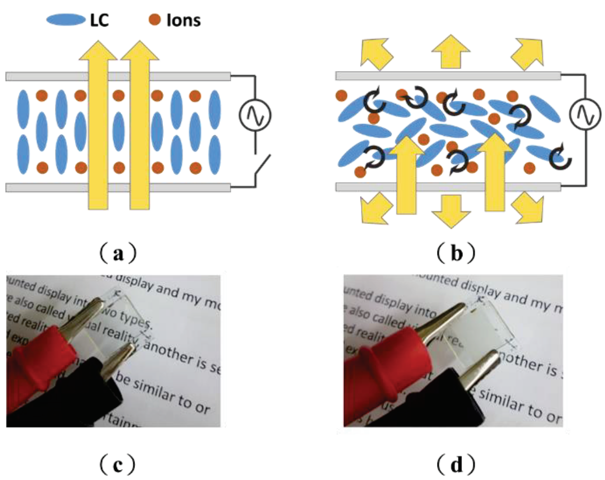

Fig. 1. The operation of the DLS-LC device: (a) without and (b) with the electric field and corresponding pictures of the DLS-LC device: (c) without and (d) with the electric field.

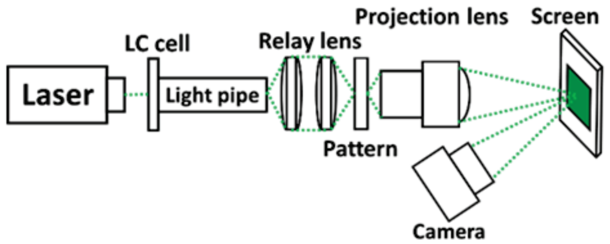

Fig. 2. Schematic of a simple laser projector for speckle reduction measurement.

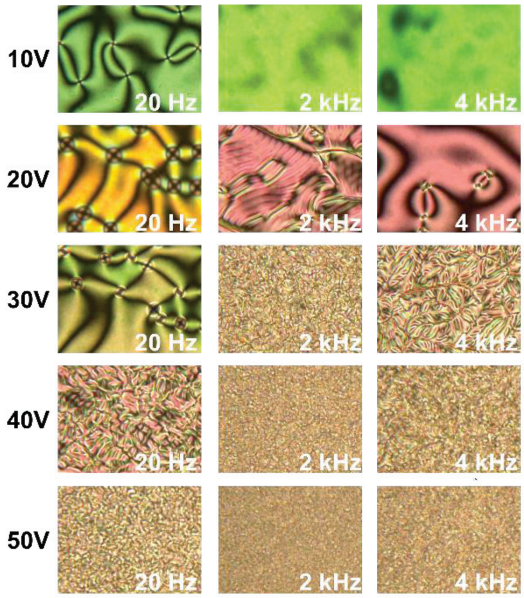

Fig. 3. POM images of DLS-LC devices operated at different electric field amplitudes and frequencies.

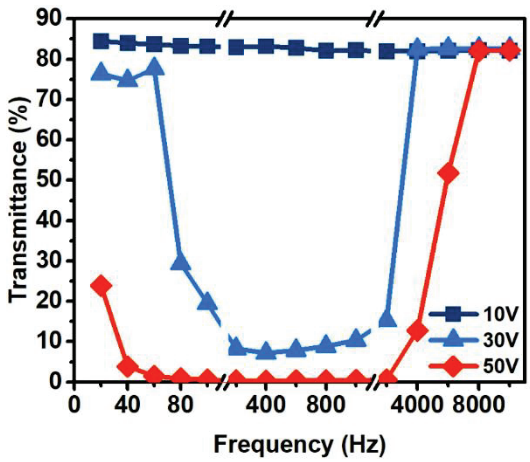

Fig. 4. Transmittance of the DLS-LC device operated at different electric field amplitudes and frequencies.

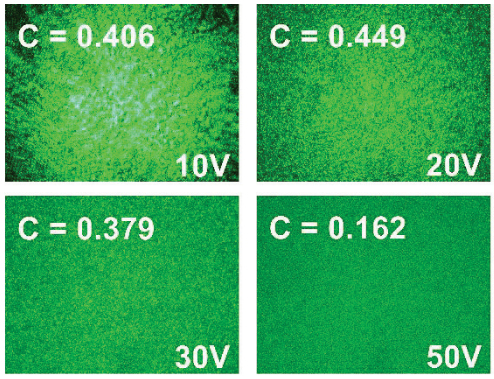

Fig. 5. Characteristics of speckle reduction for a DLS-LC device subjected to different electric field amplitude at a frequency of 400 Hz. (images are normalized by the average intensity)

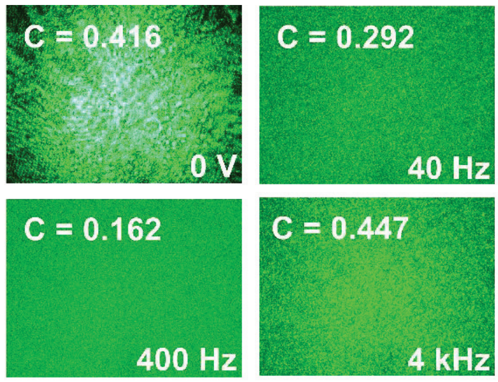

Fig. 6. Characteristics of speckle reduction for a DLS-LC device subjected to different frequencies at the electric field amplitude of 50 V. (images are normalized by the average intensity)

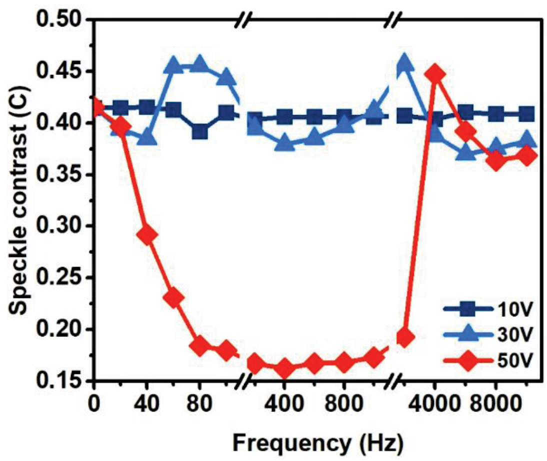

Fig. 7. Speckle contrast as a function of driving frequency for different electric field amplitudes.

REFERENCES

[1] O. Svelto, and D. C. Hanna, "Principles of lasers," Springer, 1998.

[2] J.W. Goodman, "Speckle phenomena in optics: theory and applications," Roberts and Company Publishers, 2007.

[3] J. Trisnadi, "Speckle contrast reduction in laser projection displays," Proc. SPIE 4657, 131–137 (2002).

[4] T. T. Tran, Ø. Svensen, X. Chen, and M. N. Akram, "Speckle reduction in laser projection displays through angle and wavelength diversity,“ Appl. Opt. 55(6), 1267–1274 (2016).

[5] D. S. Mehta, D. N. Naik, R. K. Singh, and M. Takeda, "Laser speckle reduction by multimode optical fiber bundle with combined temporal, spatial, and angular diversity,“ Appl. Opt. 51(12), 1894–1904 (2012).

[6] E. Götzinger, M. Pircher, B. Baumann, T. Schmoll, H. Sattmann, R. A. Leitgeb, and C. K. Hitzenberger, "Speckle noise reduction in high speed polarization sensitive spectral domain optical coherence tomography," Opt. Express 19(15), 14568–14585 (2011).

[7] G. H. Heilmeier, L. A. Zanoni, and L. A. Barton, "Dynamic scattering: A new electrooptic effect in certain classes of nematic liquid crystals," Proc. IEEE. 56(7), 1162-1171 (1968).

[8] L. M. Blinov, "Electrohydrodynamic effects in liquid crystals," Sci. Prog. 70, 263 (1986).

[9] L. J. Hornbeck, "Digital light processing for high-brightness high-resolution applications," Proc. SPIE. 3013, 27-40 (1997).

[10] M. S. Brennesholtz, and E. H. Stupp, "Projection displays," John Wiley & Sons, 2008.

[11] S. Roelandt, Y. Meuret, G. Craggs, G. Verschaffelt, P. Janssens, and H. Thienpont, "Standardized speckle measurement method matched to human speckle perception in laser projection systems," Opt. Express 20(8), 8770-8783 (2012).