Flat-Panel Coherent Backlight for Holographic Displays with Improved Diffraction Efficiency

Wei Hu, Chao Ping Chen, Yan Li, Zhenghong He, Xiao Li, Pengcheng Zhou, Jiangang Lu, and Yikai Su*

National Engineering Lab for TFT-LCD Materials and Technologies, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, China

Abstract

Coherent backlight is an important component in holographic 3D displays. In this paper, a novel coherent backlight featuring a compact design is presented. The feasibility of this structure is experimentally verified by reconstructing 3D images with a spatial light modulator. The diffraction efficiency of the system is ~4.3%.

Author Keywords

holographic display, coherent design, volume grating, liquid crystal.

1. Objective and Background

Holography is considered as an ultimate three-dimensional (3D) display technique because it can exactly reconstruct the wavefront and thus render a 3D scene perfectly [1-3]. Holography is based on the light interference, which requires high coherence and thus lasers are used as light sources. The laser beams are expanded to a proper size using lenses which need too much room in current holographic display systems [4]. These optical components are usually too bulky to be applied in consumer electronics, especially for flat-panel display devices. In order to address this issue, a coherent backlight with a compact form factor is necessary for realizing flat-panel holographic displays.

Although some efforts have been made on compact expanders for lasers using optical folding method or edge-illuminated holograms [5-9], they can only expand beam in one dimension. In another compact beam expander introduced by Revital et al. [10], the output are multiple light spots which cannot be used as an entire plane wave. In our previous work, Xiong et al. [11] proposed a coherent backlight system using a scattered wave to read a reflection hologram. Nevertheless, its diffraction efficiency (DE) is as low as 0.3%, which is a critical problem to resolve towards practical applications.

In this paper, a novel coherent backlight design is proposed that improves the DE to 4.3% which is more than 10 times higher than the previous result [11]. In our design, the first grating elongates beam spot in one dimension and the second grating expands the elongated beam in the orthogonal dimension to form a circular expanded beam with an area of ~0.7 cm^2. To verify the feasibility, 3D images are reconstructed using this coherent light.

2. Compact backlight design and Experiments

(a) Compact backlight design

We use two linear gratings to expand a laser beam in two dimensions to achieve both compact structure and higher DE.

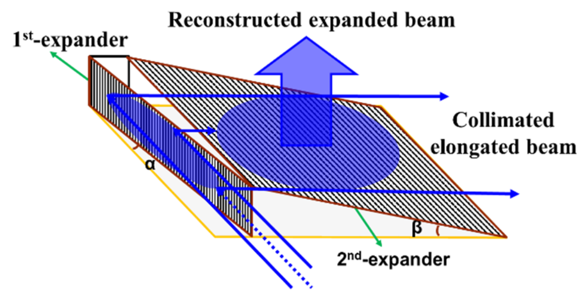

Figure 1. Schematic drawing of the proposed coherent backlight structure.

The schematic drawing of the proposed compact backlight design is shown in Fig. 1. A 1st-expander is used to convert a laser beam to a collimated elongated beam, which is further expanded in the orthogonal direction by a 2nd-expander. Therefore, two dimensional (2D) beam expansion is realized, and the expanded beam is coherent and uniform, which can be used as the backlight for holographic displays. Both expanders are holographic gratings recorded with polymer dispersed liquid crystal (PDLC) [12] cells. The slant angles of two expanders α, β should be set to proper values to achieve a compact form. The propagation direction of undiffracted wave is perpendicular to the diffracted direction which reduces disturbance. All other higher diffraction orders are negligible as both two expanders are transmission volume holograms [13].

It should be noticed that the 1st-expander and the 2nd-expander cannot be simply replaced with two mirrors. Otherwise, the shape of the laser spot keeps unchanged before and after reflection, which means that the laser beam cannot be expanded. Moreover, the grating can diffract wave to a desired direction, while reflected wave of the mirror propagates in a determined direction that cannot be adjusted.

(b) Experimental results

A proof-of-concept experiment is carried out to prove the feasibility of the new backlight system. Furthermore, the expanded wave is projected onto a SLM (PLUTO, Holoeye) to display a holographic 3D image.

The material used in experiment is PDLC which comprises 50 wt%: 35.4 wt%: 13 wt%: 1 wt%: 0.6 wt% of liquid crystal (5CB, HCCH): TMPTA monomer (Aldrich): N-vinylpyrrollidone (Aldrich): N-phenylglycine (Aldrich): Rose Bengal (Aldrich). The uniform PDLC mixture is injected into an empty cell, whose thickness is controlled by a 30-μm Mylar spacer.

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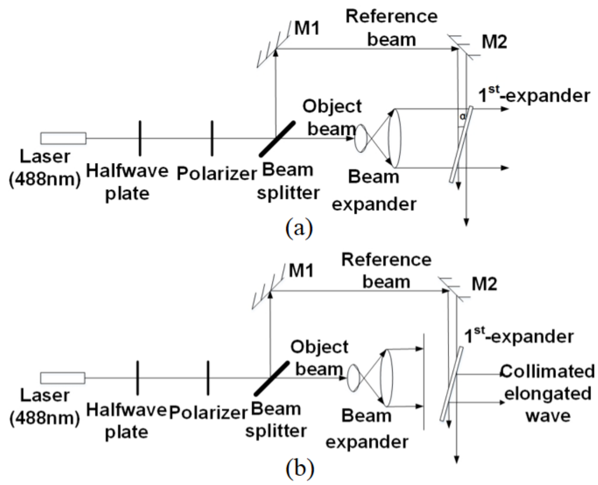

Figure 2. Experimental setup for the 1st-expander (a) recording and (b) reconstruction. M1, M2 are mirrors.

Figures. 2(a) and 2(b) illustrate the experimental setups for the 1st-expander recording and reconstruction, respectively. In Fig. 2(a), light derived from a 488 nm laser is set to s-polarization by a half wave plate and a polarizer to ensure interference efficiency as the recording angle is ~90°. The reference beam is emitted from the laser with a diameter ~0.1 cm and the area of the spot is ~0.0079 cm^2. The slant angle of the 1st-expander α is ~6° which enables that the reference beam to illuminate an elongated elliptic area (~0.075 cm^2) on the 1st-expander. In addition, the object beam is expanded to 1 cm in diameter by a conventional beam expander in Fig. 2(a). The intensities of both recording waves are 2 mW/cm^2 on the 1st-expander, and exposure time is 1 min. In Fig. 2(b), the object plane wave is blocked by a black board and the reference beam reconstructs a collimated elongated beam which further interferes with another plane wave in the 2nd-expander recording process.

As shown in Fig. 3(a), the collimated elongated beam with an area of ~0.075 cm^2 is reconstructed by the reading beam. Figure. 3(b) is the normalized intensity distribution of Fig. 3(a). The power of the elongated beam is measured to be 0.033 mW when the power of the reading beam is 0.158 mW. The DE of the 1st-expander is 21% defined as the ratio of the power of the reconstructed collimated elongated wave to that of the reading beam.

We use the collimated elongated wave generated by the 1st-expander as the reference beam, and a circularly expanded beam from a conventional beam expander as an object beam, to record the 2nd-expander as shown in Fig. 4(a). Because the interbeam angle is ~90°, both waves are set to s-polarization to maximize the interference efficiency. The slant angle of the 2nd-expander β is ~6°, and the collimated elongated wave illuminates a circular area (~0.7 cm^2) on the 2nd-expander. The object plane wave is expanded to 1 cm. The intensities of both recording waves are 1 mW/cm^2, and exposure time is 2 mins.

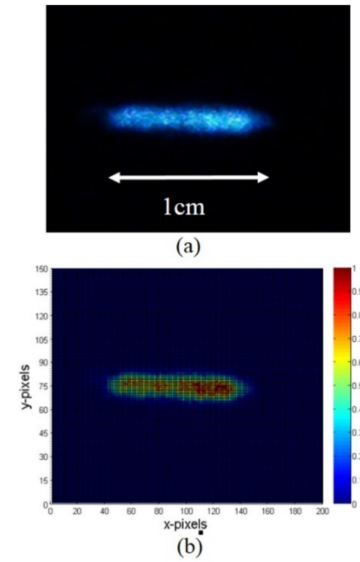

Figure 3. (a) Image of diffracted waves of the 1st-expander, (b) normalized intensity distribution of the pattern.

Figure. 5(a) shows the reconstructed expanded beam with a power of 0.0068 mW when the power of the reading beam is 0.158 mW. Figure. 5(b) is the normalized intensity distribution of Fig. 5(a). The total DE, defined as the ratio of the power of exiting the 2nd-expander to the incident power on the 1st-expander. The measured DE is 4.3%, which is more than 10 times higher than the result in [11]. However, the expanded plane wave is round or elliptical in shape while the shape of SLM is rectangular which implies part of the output wave cannot be used. Therefore the total DE could decrease to 2.75%, about 64% ($2/\pi$) of the maximum value.

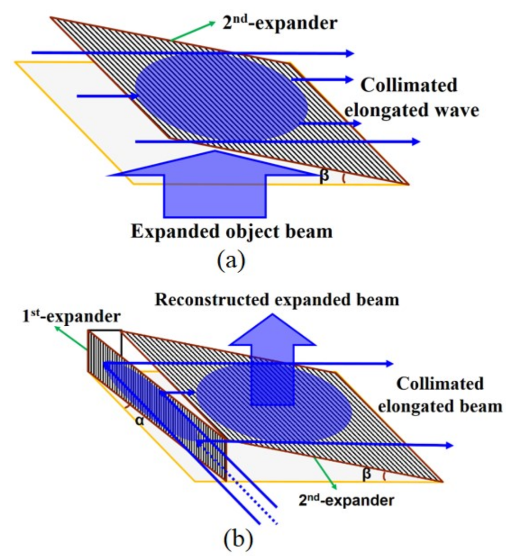

Figure 4. Schematic drawings of the 2nd-expander during (a) recording and (b) reconstruction.

Then this reconstructed expanded beam is projected onto the SLM loaded with a computer generated hologram (CGH) to obtain holographic 3D display. The CGH based on Kinoform algorithm [14] is also used in the previous work [11]. The 3D image consists of a letter 'A' located at 2 m away from the SLM, and a letter 'B' located at 1m away from the SLM.

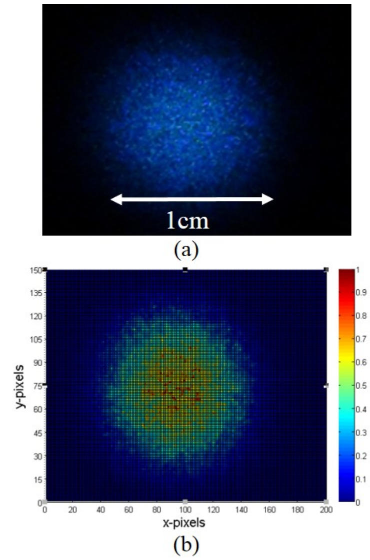

Figure 5. (a) Image of diffracted waves of the 2nd-expander, (b) normalized intensity distribution of the pattern.

As shown in Fig. 6, we use conventional beam expander and the proposed compact beam expander to generate expanded collimated beams which are incident on the SLM and form holographic 3D images, respectively. In Figs. 6(a) and 6(b), one can see that when the camera focuses on one letter, that letter is clear in focus, while the other letter becomes blurred because out of focus. As seen in Figs. 6(c) and 6(d), there is a little distortion in the 3D images formed by the reconstructed expanded beam.

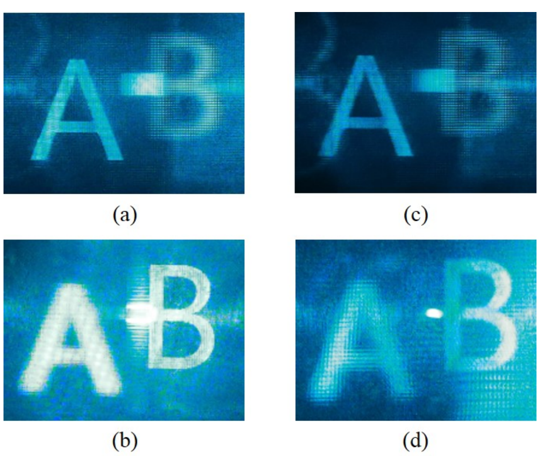

Figure 6. Holographic 3D images constructed with a SLM using a conventional beam expander and focuses on (a) 'A', (b) 'B'; using the proposed compact beam expander and focuses on (c) 'A', (d) 'B'.

3. Discussion

We have demonstrated a novel backlight design with a higher DE compared with a previous design. The laser beam spot with an area of ~0.0079 cm^2 is expanded to a beam with a size of ~0.7 cm^2 in the proof-of-concept experiment, which is almost increased by two orders. However, for the device fabrication, several important issues merit special care. Firstly, the slant angles of the 1st-expander and the 2nd-expander α, β should be made smaller to preserve a compact form in a large-size backlight system. In this case, a simple analysis is demonstrated to ensure the feasibility of the proposed design. As shown in Fig. 7, DE is $\eta = sin^2(\pi n_1 d/\lambda cos\theta)$ according to Kogelnik's coupled-wave theory [13], where n_1 is the amplitude of refraction index modulation, d is the thickness of grating, λ is the incident wavelength in the sample, θ is the incident angle. For a larger scale backlight design, angle θ is closer to 90°, then cosθ is closer to 0, meaning that a larger phase shift can be achieved. It is seen that the DE obtained in experiment could also be realized for a larger size backlight system.

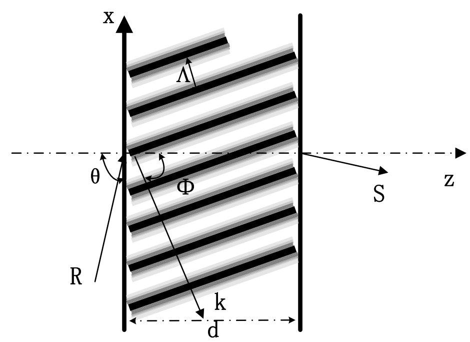

Figure 7. Geometry of a thick hologram grating.

Secondly, each expander in our system is a transmission volume hologram. It is known that the DE of a volume hologram can reach ~90%. However, the DE of each expander in the experiment is ~21%, which can be attributed to the following reasons. According to the work reported by Qi et al. [15], the grating cannot be formed perfectly when the grating pitch is small, on the order of 100 nm. In the experiment, the grating pitch of each expander is ~420 nm implying that the formation of the grating could be affected. In addition, part of the energy of the reading beam could be absorbed by the residual photoinitiator (Rose Bengal) in the reconstruction process.

Thirdly, to avoid the Bragg mismatch for achieving a high DE during the process of reading, the reading beam, the 1st-expander, and the 2nd-expander should be firmly fixed relative to each other.

4. Impact

The basic idea of our backlight system is to use the 1st-expander to realize one-dimensional expansion at first, and then use the 2nd-expander to achieve two-dimensional beam expansion. A laser beam spot with a size of ~0.0079 cm^2 is expanded to a beam with a size of ~0.7 cm^2 in the experiment. The total DE of the 2D expander is 4.3%. Finally, holographic 3D images are formed with a SLM using the reconstructed expanded beam.

5. Acknowledgements

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6. References

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