Improvement of the complex modulated characteristic of cascaded liquid crystal spatial light modulators by using a novel amplitude compensated technique

Mei-Li Hsieh,[a] Mao-Ling Chen,[b] and Chau-Jern Cheng[b]
[a]National Taiwan Normal University
Institute of Electro-Optical Science and Technology
Taipei, Taiwan
[b]National Taipei University of Technology
Department of Electro-Optical Engineering
Taipei, Taiwan

Abstract. To achieve the full complex modulated range of the cascaded twisted nematic liquid crystal spatial light modulator (TNLC-SLM), we propose and demonstrate a novel amplitude compensated technique. Optical reconstructions of complex digital holograms with higher image quality are discussed in both analytical and experimental results.
[DOI: 10.1117/1.2750658]

Subject terms: digital hologram; liquid crystal spatial light modulator; amplitude compensation; complex modulation.

Paper 070037LR received Jan. 16, 2007; revised manuscript received Apr. 19, 2007; accepted for publication Apr. 19, 2007; published online Jul. 2, 2007.

1 Introduction

In recent years, digital holography has been investigated widely in many attractive areas, such as 3-D displays, 3-D images recognition, optical coherent tomography, digital holographic microscopy, and so on.[1–4] Digital holograms can be recorded by high quality charge-coupled device (CCD) sensors and the phase-shifting technique,[5] and displayed in a dynamical spatial light modulator (SLM), which can modulate the wavefront of light in real time.[6,7] However, the distribution of digital holograms usually is a complex field after recording procedures. A commercially available twisted nematic liquid crystal spatial light modulator (TNLC-SLM) only can modulate either phase or amplitude distribution of the wavefront individually.[8] Therefore, it is impossible to achieve the full range of complex modulation with a single TNLC-SLM panel.

For displaying complex digital holograms, we need to build a 4F system to combine two commercial TNLC-SLM panels, which are operated in phase-only and amplitude-only modulated modes, respectively. It is called the cascaded TNLC-SLM module. If each single TNLC-SLM cannot achieve the phase-only or amplitude-only modulated mode, the variation of amplitude in phase mode or phase in the amplitude mode will reduce the complex modulated range of the commercial cascaded TNLC-SLM module, and it will degrade the image quality of the hologram reconstruction. Therefore, we have to measure the modulated characteristic of the commercial TNLC-SLM panel in both phase and amplitude modulated modes. The influence of the amplitude or phase variation for the reconstruction is analyzed and discuss. In addition, we propose a compensated method to improve the complex modulated range of the commercial cascaded TNLC-SLM module. Also, the optical reconstruction of complex digital Fresnel holograms is demonstrated, and reconstruction with higher image quality can be obtained using the amplitude compensated method.

2 Modulation Properties of the Cascaded Commercial Twisted Nematic Liquid Crystal Spatial Light Modulator Module

In general, the TNLC cell of a display panel is sandwiched between the polarizer and analyzer, and thus the modulated properties of the TNLC cell can be analyzed using the Jones matrix method.[9] The properties of the transmitted light through the TNLC cell depend on the applied voltage, the twist angle, and the angles of the polarizer and analyzer. For example, when the twist angle of the TNLC cell is $\pi/2$, then intensity transmission T and phase shift δ of the transmitted light are the function of the applied voltage and the angles of the polarizer and analyzer. However, the applied voltage can be controlled by the input gray level from the computer. For the given angles of the polarizer and analyzer, the transmission and phase shift of the transmitted light is a function of the input gray level. This is called the modulated properties of the TNLC cell. In this case, we can select the suitable angles of the polarizer and analyzer to obtain the phase-mostly and amplitude-mostly modes for the commercial TNLC panel.

For measuring the modulated properties of the commercial TNLC panel, we set up a Mach-Zehnder interferometer to measure the phase modulated characteristic of the TNLC panel. The input gray level is from 0 to 255, and a diode-pumped solid state (DPSS) laser with a wavelength of 532 nm is used. In addition, the transmission of the TNLC panel can be measured when one arm of the interferometer has been block. By rotating the angles of the polarizer and analyzer from 0 to 360 deg, we can obtain the intensity transmission and phase shift of the TNLC-SLM as a function of gray level with different angles of the polarizer and analyzer. From those experimental results, we can find that the TNLC panel is operated in the phase-mostly modulated mode when the angles of the polarizer and analyzer are 18 and 66 deg, respectively. The modulated properties are shown in Fig. 1(a). The maximum of the phase shift is 353 deg, but the transmission is not a constant with the different input gray level. The maximum variation of the normalized transmission is 0.8. On the other hand, when the angles of the polarizer and analyzer are 90 and 180 deg, the TNLC panel is operated in the amplitude-mostly mode and the modulated properties are shown in Fig. 1(b). The transmission can be modulated from 0 to 1, and the maximum variation of phase shift is approximately 63 deg with input gray level from 0 to 255. These results in Fig. 1 show that the commercial TNLC panel cannot be operated in either phase-only or amplitude-only modulation. Therefore, for displaying the complex digital hologram, we should

0091-3286/2007/$25.00 © 2007 SPIE

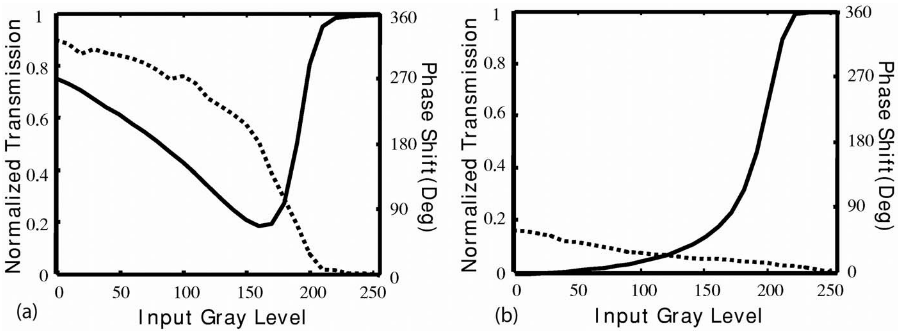

Fig. 1 Transmission properties of the commercial TNLC-SLM as a function of input gray level: (a) phase-mostly modulation mode and (b) amplitude-mostly modulation mode. (The solid line represents the intensity transmission, and the dashed line represents the phase shift.)

align two commercial TNLC panels using a 4F system by one pixel to one pixel, shown in Fig. 2. Even so, we still cannot get the full complex modulated range due to the nonperfect modulated property of the commercial TNLC panel. The cascaded TNLC-SLM module cannot be operated in full complex range, shown in Fig. 3(a). It will degrade the image quality of the reconstruction.

For example, we calculate a complex distribution of the Fresnel hologram using the diffraction theory.[10] Figure 3(b) is the input pattern with 7.7×7.7 mm^2, and the amplitude and phase distribution of the hologram with 13.8×13.8 mm^2 can be calculated by computer. The distance between the input pattern and the hologram is 40 cm. According to the complex modulated properties of the cascaded TNLC-SLM module in Fig. 3(a), the reconstruction of the complex hologram also can be calculated and shown in Fig. 3(c). We can see that it is not as clear as the input pattern. This is because that the modulated range of the cascaded TNLC-SLM module cannot be operated in the full complex range. Therefore, some information of the complex digital hologram cannot be displayed on the cascaded TNLC-SLM module, thus causing the reconstructed image quality of Fig. 3(c) to be diffuse. Figure 3(d) shows the optical experimental reconstruction, and it is consistent with the computer simulated results. Therefore, how to increase the complex modulated range of the cascaded TNLC-SLM module is an important issue for displaying the high quality reconstruction of the complex hologram.

3 Amplitude Compensated Method

The complex modulated property of the cascaded TNLC-SLM module can be described as:

$$\text{output}(g1,g2) = A\exp(i\delta) = A_1(g1)A_2(g2)\exp\{i[\delta_1(g1) + \delta_2(g2)]\}, \tag{1}$$

where A_1 and δ_1 represent the amplitude and phase components of the transmitted light through the TNLC1 panel, respectively. Similarly, A_2 and δ_2 represent the amplitude and phase components of the TNLC2 panel, respectively. In an ideal case, the TNLC1 is operated in the phase-only mode, which means that the value of the phase δ_1 can be adjusted from 0 to 2π, and the amplitude A_1 is a constant by adjusting the input gray level $g1$. Also, TNLC2 is operated in the amplitude-only mode, which means that the value of the amplitude A_2 can be adjusted from 0 to 1 and the phase δ_2 is a constant by adjusting the input gray level $g2$. In this ideal case, Eq. (1) can be rewritten as:

$$\text{output}(g1,g2) = A_1A_2(g2)\exp\{i[\delta_1(g1) + \delta_2]\}. \tag{2}$$

Therefore, the complex modulated range of the cascaded TNLC-SLM module can be controlled by phase δ_1 and amplitude A_2, which depend on the input gray levels $g1$ and $g2$ in the TNLC1 and TNLC2 panels individually. It shows that the full complex modulated range can be achieved when the TNLC panels can be operated in the phase-only and amplitude-only modulated modes. However, the commercial TNLC panel cannot be operated in the phase- and amplitude-only modulated modes. The transmission variation of TNLC in the phase-mostly mode in Fig. 1(a) is large and cannot be assumed as a constant with the input gray level, and the phase variation of TNLC in the amplitude-mostly mode in Fig. 1(b) is smaller and it can be assumed as zero with the different input gray level. Therefore, the phase term of the complex modulation of the cascaded TNLC-SLM module still can be controlled by the phase δ_1 of TNLC1. For the amplitude term of the complex modulation, it will be controlled by the amplitude A_1 and A_2, which are the functions of the input gray level $g1$ and $g2$, respectively. In this case, Eq. (2) can be rewritten as:

$$\text{output}(g1,g2) = A\exp(i\delta) = A_1(g1)A_2(g2)\exp\{i[\delta_1(g1) + \delta_2]\}. \tag{3}$$

According to Eq. (3), we propose an amplitude compensated method to modify amplitude A_2 for achieving the ex-

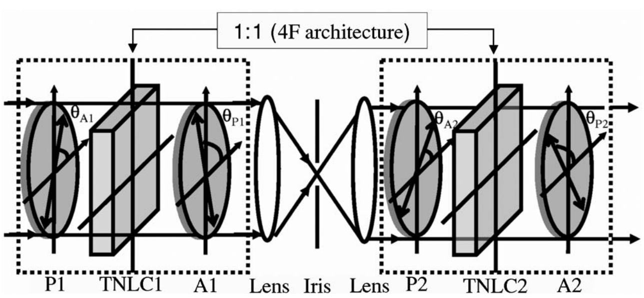

Fig. 2 The schematic diagram of the cascaded TNLC-SLM module.

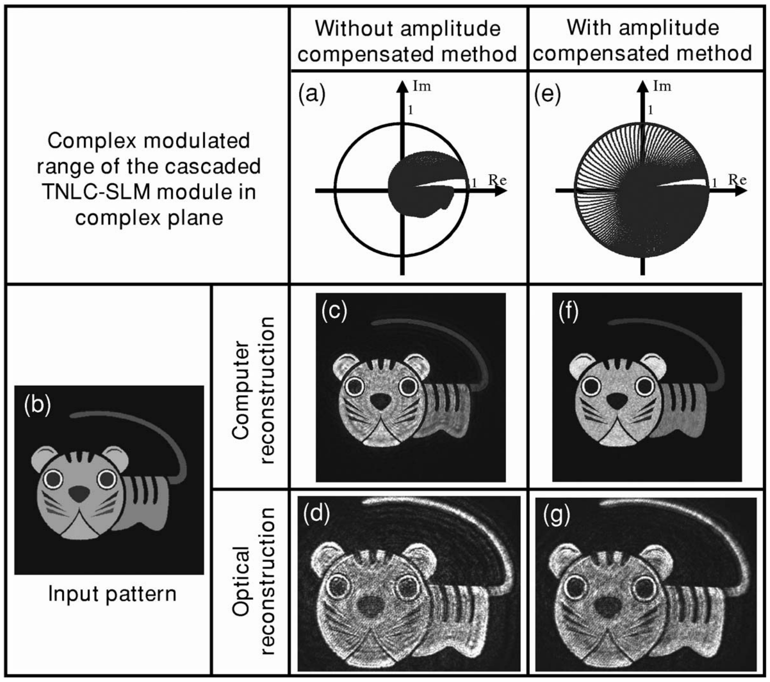

Fig. 3 (a) The modulated properties in the complex plane without amplitude compensated method. (b) Input pattern of the Fresnel hologram. (c) and (d) Computer and optical reconstruction of the complex hologram without amplitude compensated method. (e) The modulated properties in the complex plane with amplitude compensated method. (f) and (g) Computer and optical reconstruction of the complex hologram with amplitude compensated method.

pected amplitude A of the complex hologram. The phase term of the complex modulation is controlled by the input gray level $g1$ of TNLC1. Also, amplitude A_1 of TNLC1 is given by the input gray level $g1$. Thus, the amplitude A_2 of TNLC2 should be modified as amplitude A of the expected complex modulation divided by amplitude A_1 of TNLC1, such as $A_2(g_2)=A/A_1(g_1)$. According to this concept for compensating the amplitude variation of the TNLC2 panel, we can obtain the complex modulated range of the cascaded commercial TNLC-SLM module as Fig. 3(e). It shows that the complex modulated range with the compensated method has larger range than without the compensated method in Fig. 3(a).

In addition, the reconstruction of the digital hologram with the amplitude compensated method is calculated and shown in Fig. 3(f). Note that the reconstruction with the amplitude compensated method is clearer than reconstruction without the amplitude compensated method in Fig. 3(d). However, the modulated range with the amplitude compensated method still cannot reach the whole complex range. It is why some details of the reconstructed image are diffuse, but the image quality is improved compare to Fig. 3(c). Also, the experimental result is shown in Fig. 3(g), which indicates that optical reconstruction with the amplitude compensated method can achieve better image quality than that of the optical reconstruction in Fig. 3(d). The experimental results are consistent with the computer simulated results.

4 Conclusions

In summary, a novel amplitude compensated method is proposed to display the expected complex digital hologram using the cascaded commercial TNLC-SLM module, and perform better image quality of optical reconstruction of the complex digital hologram.

Acknowledgments

This work is supported in part by the National Science Council, Taiwan, under contract numbers NSC95-2215-E-003-001 and NSC95-2221-E-027-093-MY3.

References

1. U. Schnars and W. P. O. Jueptner, *Meas. Sci. Technol.* **13**, 85 (2002).
2. B. Javidi and E. Tajahuerce, *Opt. Lett.* **25**, 610 (2000).
3. P. Yu, L. Peng, M. Mustata, J. J. Turek, M. R. Melloch, and D. D. Nolte, *Opt. Lett.* **29**, 68–70 (2004).
4. P. Marquet et al., *Opt. Lett.* **30**, 468 (2005).
5. I. Yamaguchi and T. Zhang, *Opt. Lett.* **22**, 1268 (1997).
6. O. Matoba, T. J. Naughton, Y. Frauel, N. Bertaux, and B. Javidi, *Appl. Opt.* **41**, 6187 (2002).
7. T. Kreis, P. Aswendt, and R. Höfling, *Opt. Eng.* **40**(6), 926–933 (2001).
8. L. G. Neto, D. Roberge, and Y. Sheng, *Appl. Opt.* **35**, 4567 (1996).
9. P. Yeh and C. Gu, *Optics of Liquid Crystal Display*, John Wiley and Sons, New York (1999).
10. J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, New York (1996).