Study on the Phase Modulation Characteristics of Liquid Crystal Spatial Light Modulator

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Abstract. A special Twyman-Green interferometer is designed to measure the phase modulation characteristics of liquid crystal spatial light modulator (LC-SLM), namely, the relationship between phase shift and gray value (applied voltage). By measuring a reflective LC-SLM produced by BNS (Boulder Nonlinear Systems), it is indicated that the LC-SLM has linear phase response within a gray value range between 60 and 200, and the RMS deviation between the average phase and the spatially resolved phase measurements increases with the gray value but is always less than $\lambda/10$.

1. Introduction

With the advantages of small weight and size, low power consumption, high transmission rates, programmable and non-mechanical device, liquid crystal spatial light modulator (LC-SLM) has been used in many fields of optical information processing [1]. Now, because of the potential application in the fields of laser scanning, phase reset and wave front correction, more attention is paying to studying on the pure phase modulation characteristics of LC-SLM. So, the purpose of this paper is to design an experimental setup to measure the phase modulation characteristics, namely the relationship between phase shift and voltage command of LC-SLM.

The ways used to measure the phase shift are always based on interferometry, such as Mach-Zehnder interferometer, Twyman-Green interferometer and so on [2]. Generally speaking, these ways are restrained by the environment and result in the lower precision. Recent years, with the digital wave front phase-shifting interferometer is commercial available, researchers have been using it to investigate the phase modulation characteristics of LC-SLM and gained perfect results [3]. However, the high price of the interferometer also restrained the application of this method. In this paper, we will adopt a new way, it is based on the Twyman-Green interferometer and utilizes the birefringent characteristics of liquid crystal [4, 5], more detail will be introduced in the following part.

2. Principle of experiment

2.1. Phase modulation characteristics of LC-SLM

Liquid crystal spatial light modulators use nematic liquid crystal cells as phase shifters, whose optical axis parallel to the average direction of quiescent molecular orientation. With no applied voltage, the liquid crystal molecules align with an average orientation parallel to the substrate, according to the liquid crystal alignment layer at the substrate interface. By supplying a relatively low voltage, on the order of 1-10 V, the liquid crystal molecules are reoriented and the effective refractive index of the
liquid crystal is changed. The phase shift is proportional to the thickness of the liquid crystal layer, described as follow:

\[ \delta = \frac{2\pi}{\lambda} \cdot \Delta n \cdot l \]  

(1)

where \( \Delta n = n_c - n_o \) is the birefringence of the material, \( l \) is the thickness of the liquid crystal layer, \( \lambda \) is the free space wavelength. If \( l \) is constant, the phase shift \( \delta \) is proportional to \( \Delta n \) which changes with the applied voltage.

2.2. The principle of phase shift measurement

For Twyman-Green interferometer, the interference intensity is given by equation (2)

\[ I(x, y) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta(x, y) \]  

(2)

where \( I_1 \) and \( I_2 \) correspond to the intensity of reference and measuring beam, respectively. Since the SLM only modulates the horizontal polarized phase component which can be seen as the signal arm, the vertically component is used as the reference arm. Then, we need only to substitute \( I_1 \) and \( I_2 \) with \( I_o \) and \( I_e \) severally, and the applied voltage \( u \) is treated as a variable, thus the interference intensity is

\[ I(x, y, u) = I_e(u) + I_o(u) + 2\sqrt{I_e(u)I_o(u)} \cos \delta(x, y, u) \]  

(3)

when the position parameter \((x, y)\) is constant, the equation (3) is rewritten as

\[ I(u) = I_e(u) + I_o(u) + 2\sqrt{I_e(u)I_o(u)} \cos \delta(u) \]  

(4)

from this equation, the phase shift can be calculated

\[ \delta(u) = \arccos\left(\frac{I(u) - I_e(u) - I_o(u)}{2\sqrt{I_e(u)I_o(u)}}\right) \]  

(5)

3. Experiment

3.1. Experimental setup

A simple experimental method for obtaining the phase shift vs. voltage characteristics of a reflective LC-SLM is shown in figure 1. A laser beam (632.8nm) passes through a polarizer \( P_1 \) oriented at 45° relative to the optical axis of the SLM, which is attested paralleling to the oy or oz direction of the coordinates oxyz as seen in figure 1. Thus, the component of the light that is aligned with the optical axis experiences variable, additional phase retardation relative to the vertical component which has constant delay, however, their amplitudes are equal, that means \( I_o(u) = I_e(u) \). To analyze the phase shift, the beam being reflected by the SLM passes through the second polarizer, the analyzer \( P_2 \). The analyzer is normally arranged either in the same direction as the polarizer (+45°), or in the opposite direction (-45°). Then the beam strikes a photodiode PD which is located on the image plane of a 70mm focal length lens L. For the polarizer/analyzer, +45°/-45° (parallel) or +45°/-45° (perpendicular) described above, the interference intensity will vary as

\[ I_{//} = I_0(u) \cos^2 \frac{\delta(u)}{2} \text{ or } I_{\perp} = I_0(u) \sin^2 \frac{\delta(u)}{2} \]  

(6)

where \( I_0(u) = I_{\text{max}} \) is always the maximum intensity received by the PD, so the phase shift can be obtained:

\[ \delta_{//}(u) = 2 \arccos \sqrt{\frac{I(u)}{I_{\text{max}}}} \text{ or } \delta_{\perp}(u) = 2 \arcsin \sqrt{\frac{I(u)}{I_{\text{max}}}} \]  

(7)

Now, there is also a problem that the trigonometric functions are no 1-to-1 mappings. To obtain \( \delta \), we need to unfold the result from the inverse of the trigonometric functions. Let \( \tilde{\delta} \) be the folded phase response gained by equation (7). From theory, \( \delta(u) \) is a monotonous function, this makes it possible to unfold it by cumulatively summing the absolute value of the differences between successive measurement [5]:
The spatial uniformity of the device phase response can be evaluated by computing the RMS difference, $\xi(u)$, between the average phase, $\overline{\delta}(u) = \frac{1}{N} \sum_{i=1}^{N} \delta_i(u)$ (N is the total number of measured points), and the spatially resolved phase measurements. Equation (9) is for computing the RMS flatness of the phase front [4].

$$\xi(u) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [\delta_i(u) - \overline{\delta}(u)]^2}$$

3.2. Experimental results

To obtain a series of points, the PD is mounted on an AOB translation stage as seen in figure 1. The analyzer parallels to the polarizer and we choose the Look-Up Table SLM290 to compensate the non-linear phase response of the SLM. The experimental results of 12×12 measured points across the aperture of the SLM are shown in figure 2 and 3. Figure 2 shows the measured average intensity as well as the folded- and unfolded phase response, Figure 3 shows the phase response and the RMS deviation as a function of applied voltage.
Figure 2. Measured phase response. (a) Spatially averaged normalized intensity
(b) folded phase response, (c) unfolded phase response

Figure 3. (a) Phase shift spatially resolved across the SLM, (b) phase shift averaged along the pixels, from bottom to top, the command is 0, 56, 112, 168, 248, and 12×12 measurements were made across the electrodes, (c) the RMS deviation over the entire SLM
4. Conclusion
This paper has presented an experimental technique that can be used to investigate the phase modulation characteristics of liquid crystal spatial light modulators. When this technique is applied to a reflective 256×256 pixels LC-SLM produced by BNS, it reveals that the device has linear phase response in the gray value range of 60 to 200, and the phase response is relatively uniform across the whole effective aperture of the SLM, with an RMS deviation from the mean of less than 0.45 rad, it also means that the RMS deviation is less than $\lambda/10$. In the system, the horizontal and vertical polarization components of the light in the liquid crystal layer correspond to the reference and signal arms of a conventional Twyman-Green interferometer. Since both arms of the interferometer travel along identical paths, the setup is insensitive to vibrations and airflow and has better precision.

References
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