2007

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10.1109/COMMAD.2006.4429891

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Optimization of Liquid-Crystal Spatial Light Modulator for Precise Phase Generation

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Abstract— Spatial light modulators (SLMs) are recently emerging as wavefront generation or reconstruction devices. In this paper, we use a liquid-crystal SLM (LC-SLM) as a wavefront generation device through the modulation of the spatial phase distribution of an incident light beam. We characterize the phase modulation performance of the LC-SLM, and identified a polarization-configuration to minimize its amplitude modulation effects in order to maximize the contrast of reconstructed phase holograms. We also investigated the feasibility of determining the optical surface uniformity of the LC-SLM through computations of the interference fringes, and identified the disadvantages of this method. This new approach may be used to determine the optical surface quality of other optical devices.

Keywords – liquid-crystal spatial light modulator (LC-SLM), wavefront correction, adaptive optics, retinal imaging, optical surface quality, phase distributions.

I. INTRODUCTION

SLMs have been used in a wide range of applications, including in high-energy laser applications for intracavity beam shaping [1] and focal spot control [2], in digital holography for the optical reconstruction of digital holograms [3], in modern optical technology as real-time refractive lenses [4-6] and in astronomy and retinal imaging as wavefront correction devices [7-9]. Recent advances in the fabrication of high-resolution SLMs have extended the use of SLMs into various disciplines, especially in the field of adaptive optics.

Adaptive optics is the branch of science that aims to dynamically correct wavefront aberration with flexible and reconfigurable optics in order to improve the optical system's performance. An adaptive optics system typically employs a real-time wavefront sensor to detect the aberration in the system and a wavefront compensator to correct this measured aberration. In the field of vision science, SLMs are emerging as adaptive wavefront correction devices for the compensation of aberrated ocular wavefront. SLMs have high number of correcting elements and low power consumptions; are compact, highly reliable, and electronically-controlled and software-configured. As a result of their high resolution wavefront generation capabilities and easy controllability, they

are highly attractive in adaptive optical applications, such as retinal imaging.

An SLM typically works as a wavefront modulation device by modulating the polarization, intensity, phase or both the intensity and phase simultaneously of an incident light beam. In an adaptive optical system in retinal imaging, the phase modulation capability of an SLM is employed such that the device dynamically corrects the phase error of the measured ocular wavefront to attain perfect visual acuity. Through the computations of an optimum conjugated wavefront, the reconstructed optical wavefront is then applied onto the SLM as a phase hologram.

Such an ideal modulator would require a phase-only modulation response of at least 2π , has high spatial resolution and has an optically flat surface. In order to achieve the best reconstructed phase wavefront, the properties and phase modulation response of such a device have to be fully known. Due to its manufacturing process, the optical surface of the SLM may be slightly deformed, and this curvature may contribute additional phase turbulence to the reconstructed wavefront [3]. Because the device's properties are not optimal, the characterization becomes even more important so that the performance of the SLM is optimised to offer the best optical reconstructed wavefront.

This paper reports an optimum method for the characterization of a commercially available LC-SLM to investigate its potential use as a wavefront correction device in an adaptive optical system in retinal imaging. We also investigate a new method of determining the optical surface quality of the device through its intensity-phase relationship.

II. CHARACTERIZATION OF A SPATIAL LIGHT MODULATOR

A. Properties and Important Parameters of an SLM

An SLM has an array of liquid-crystal (LC) molecules on a silicon backplane, integrating high density electronics, and reflective [3] or transmissive [10-11] pixel pads. The modulation of an incident light beam is performed through the change of the orientation of the birefringent parallel-aligned, ferroelectric or twisted-nematic LC molecules when different

digital voltages are applied to the control electrodes of the SLM. Due to the different refraction indices of the LC molecules, the incident complex wavefront may undergo a phase shift as well as a change in polarization state. Hence, it is highly important to obtain a good knowledge to isolate the coupled phase and amplitude modulation performance. An optimised reconstructed phase hologram can only be obtained from an LC-SLM by minimizing the coupled effect of amplitude modulation with high phase shift.

B. Experimental Setup and Results

The experimental setup for determining the phase and amplitude modulation performance of an LC-SLM is shown in Fig. 1. The device used in our experiments is a Holoeye LC-R 2500 LC-SLM which consists of 1024×768 independently addressed pixels, with a $19\mu\text{m}$ pixel pitch, giving a total working area of $19.5 \times 14.6\text{mm}^2$. This reflective LC-SLM is polarization dependent, and its optimum contrast ratio is obtained by using linearly polarized light. Its transparent indium-tin oxide (ITO) electrode pad serves to route digital signals to its reflective mirror. The RMS values of the digital signals are then applied onto the LC molecules in a pulse-width modulation mode. The 8-bit digital input is mapped by a look-up-table (LUT) in its driver chip to produce images with 256 gray levels.

An ideal phase modulator would offer a phase-only modulation mode. Therefore, the phase modulation performance of this LC-SLM has to be fully characterized as this would affect the wavefront generation and reconstruction capabilities. Because the LC-SLM is polarization-dependent, it is important to find the polarization settings at which it performs with a phase-mostly modulation mode so that the contrast of the reconstructed phase hologram is at its maximum.

Figure 1. Experimental setup for determining the performance of phase shift and effect of amplitude modulation. LS: laser source, SF: spatial filter, L1, L2, L3: lens, WP: waveplate, AP: aperture, RfM: reflective reference mirror, PC1, PC2: personal computers, NPBS: non-polarizing beam-splitter, RM: reflective mirror, P: polarizer, NDF: neutral-density filter, CCD: charge-coupled device.

The laser source used in our experiments is a He-Ne laser with a wavelength of 632.8nm . We used a $\lambda/2$ waveplate to ensure that the collimated, spatially-filtered light beam illuminating the LC-SLM is a linearly polarized light, whose orientation is parallel to the LC molecules' orientation. Different uniform gray images are continuously applied onto the LC-SLM, and these images are converted into digital

voltages by the LUT in the device's driver. Each pixel of the LC-SLM is then applied with the digital voltage corresponding to the gray level applied. The collimated light beam's intensity is then equally divided by the non-polarizing beam-splitter. One part of the divided incident light beam is bounced back by the reflective reference mirror, and this arm of light beam serves as the reference beam. The other part of the divided incident light beam is reflected off the reflective SLM, and this arm of light beam serves as the test beam. The combination of the reference and test beams resulted in interference, and the interference pattern was imaged onto a charge-coupled device (CCD) camera. The calibration procedure had earlier been carried out by replacing the LC-SLM (labelled Ob2) with another reflective mirror in order to find the optimum positions to place Ob1 and Ob2. The optical paths of reference beam and the test beams have approximately the same length, resulting in interference patterns with good contrast. As shown in Fig. 2, the interference fringes obtained in this configuration were straight, parallel and equidistant.

Figure 2. Interference fringes obtained from the optical path difference between a reference mirror and the LC-SLM.

The $\lambda/2$ waveplate in the incident optical path was rotated until a phase shift of at least 2π was obtained. Once the orientation of the waveplate has been determined for a phase shift of 2π , the reflective reference mirror (labeled Ob1) in the incident optical path is removed, and a polarizer is added into the optical output path. By rotating this polarizer, we can thus determine its corresponding amplitude modulation by measuring the intensity of transmitted light for different gray-level images applied.

Figure 3. Phase shift curve with waveplate setting at 110° (relative) for a maximum phase shift of 2π , and its corresponding amplitude modulation effects.

Fig. 3 illustrates that a phase shift of 2π at an illuminating wavelength of 632.8nm can be achieved at a particular $\lambda/2$ waveplate orientation. The intensity transmission in Fig. 3 has been normalized with respect to its maximum value. Its high intensity contrast ratio (ratio between the maximum normalized intensity and the minimum normalized intensity [12]) shows that it can be efficiently be used as a phase-mostly modulator. As this LC-SLM can be used as an efficient modulator with a modulation of 2π phase depth and constant amplitude modulation effects, it can thus be used as a wavefront generation device in adaptive optics systems for retinal imaging.

III. OPTICAL SURFACE PHASE DISTRIBUTION FROM INTERFERENCE FRINGES

A. Intensity-phase distribution mapping method

Apart from determining the LC-SLM's phase modulation response from the interference fringes, the uniformity of the optical surface of the LC-SLM can also be determined. We describe a new method to evaluate the phase uniformity of the optical surface of the LC-SLM. Using the same experimental setup as illustrated in Fig. 1, through an interferometric measurement, we first obtain interference fringes with *Ob1* and *Ob2* as reference mirrors. Subsequently, we replace *Ob2* by the LC-SLM, and we obtain another set of interference fringes which are shifted with respect to the interference fringes with two reference mirrors. This shift depends on the relative optical path difference between the reference mirror and the LC-SLM. The phase difference of these two sets of fringes enables us to determine the phase uniformity of the LC-SLM's optical surface, as outlined in Fig. 4.

Figure 4. Algorithm for determining the phase uniformity of the LC-SLM through interference fringes measurements.

As the interference fringes are captured by the CCD camera, these images are distinguished only by their relative intensity levels. Knowing that the change from one bright band to an adjacent bright band of the interference fringes corresponds to a 2π phase change, we can then outline its corresponding unwrapped phase distribution. Fig. 5 shows this intensity-phase mapping relationship in a 1D perspective. A peak represents a bright band, and a trough represents a dark band.

For accurate evaluation of the intensity-phase relationship, the intensities of each bright band of the interference fringes have been normalized to their corresponding maximum value,

as shown in Figs. 5(a) and 6(b). Figs. 5(b) and 6(c) show the mapped phase distribution corresponding to the intensity distribution of the interference fringes in 1D and 2D perspective respectively. Because of the irregularity of the intensity distributions, we filtered the images so that each bright band (or dark band) along the horizontal axis has only one maximum (or minimum) peak in order to eliminate the occurrence of false peaks (or troughs). We use a zero-phase filter algorithm to suppress the transient intensity response for accurate calculations of the phase distributions. This can be observed from the red lines of Figs. 5(a) and (b), as well as in Fig. 6(b). Consequently, Figs. 5(b) and 6(c) shows that with 4 fringes, we can accurately map the phase distribution to be around 8π .

Figure 5. 1D perspective: the intensity-phase relationship of the interference fringes (blue:original data plot, red: filtered data plot) (a) normalized intensity distribution of interference fringes, and (b) its corresponding mapped unwrapped phase distribution.

Figure 6. 2D perspective: the intensity-phase relationship of the interference fringes (a) intensity distribution of interference fringes, (b) normalized intensity distribution of interference fringes, and (c) its corresponding mapped unwrapped phase distribution.

B. LC-SLM's mapped phase uniformity

The result of computing the algorithm as illustrated by Fig. 4 is as shown below in Fig. 7. A fraction of the optical surface of the LC-SLM has been computed to vary from -0.4344π to 0.5105π , giving this area of the LC-SLM surface a PV value of 0.9449π . It can be observed from Fig. 7 that there appears to be regions having approximately the same phase distributions, such as the red regions (highest phase distribution) and the blue regions (lowest phase distribution). This observation would not arise if the interferometer fringes were obtained sequentially, with minimal time difference between each interference image. In our experiments, much time had elapsed between the retrieval of one set of interference fringes from the second set. As a result, three problems have been identified with this approach: (1) the time elapsed while changing *Ob2* from a reference mirror to the LC-SLM, and then realigning the system, is too long to accurately determine the phase uniformity of the LC-SLM; (2) the ambient conditions may have changed during this time elapsed, so that the temporal fluctuations can contribute discrepancies to the images captured by the CCD, and (3) the interference fringes have to be in the exact same positions whether *Ob2* is a reference mirror or an LC-SLM, so that the pixel-to-pixel subtraction can be computed. Therefore, this approach may only serve as an alternative method for the determination of the surface uniformity of an optical device.

Figure 7. Phase distribution of LC-SLM's optical surface through measurements of interference fringes.

IV. CONCLUSIONS

In this paper, we have characterized the spatial light modulator to function as a phase-mostly modulator with minimal amplitude modulation effects, thus making the LC-SLM a potential device as a wavefront generation or reconstruction device in an adaptive optics system. We have also outlined a new approach to determine the LC-SLM's optical surface uniformity through the computations of its interference fringes in relative to a high quality reference mirror. Through a series of computations and mappings, we were able to deduce the

optical phase distribution of a portion of the LC-SLM. This approach may also be extended to measure the phase uniformity of other optical devices.

ACKNOWLEDGMENTS

Thanks are extended to Dr. Rong Zheng for her assistance in the programming code.

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