Vertical-aligned liquid crystal devices for ocular wavefront correction and simulation

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Abstract. The potential of vertical-aligned spatial light modulators for use in adaptive-optics visual simulators is demonstrated. We performed visual acuity and contrast sensitivity tests in different subjects, with their eye's optics corrected by the custom adaptive-optics system and with induced aberrations similar to those in severe keratoconus. We tested the system in a see-through configuration, achieving a total corrected field of view of ∼13 deg. The applicability of these modulation devices for a wearable visual adaptive optics system is discussed. [DOI: 10.1117/1.OE.61.12.121806]

Keywords: adaptive optics; spatial light modulators; high-order aberrations; vision.

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1 Introduction

Spatial light modulators (SLMs) have been a part in ophthalmic instrumentation since they became widely available, especially for the applications of adaptive optics in ophthalmology and vision sciences.[1–5] These devices can essentially modify the amplitude and/or phase of an incident wavefront, although for vision applications, phase-only modulation is the most widely used feature due to its higher efficiency and versatility in comparison with amplitude modulation.[6]

Most SLMs are composed of liquid crystal (LC) molecules placed between two linear polarizers. They consist of an array of pixels, in which each pixel is a cell filled with LC molecules with individual control of the electric field through a voltage applied between two electrodes. In liquid crystal on silicon (LCoS) devices, one of the electrodes is transparent and the other serves as a mirror, operating as reflective displays. Alignment layers are attached to the cell structure to control the director axis of the molecules along the propagation axis. Thus LC molecules in the nematic phase can be parallel aligned (PA-LCoS), vertically aligned (VA-LCoS), or twisted (T-LCoS). The use of T-LCoS as phase modulators is possible,[7] although it is not common due to the requirements of the complete polarimetric characterization of the LC display and the use of quarter-wave plates. PA-LCoS has been the preferred option for phase-only applications due to its phase-modulation efficiency, temporal phase stability, and large depth of phase modulation (DPM).[8,9] VA-LCoS is typically used as a high-contrast amplitude modulator[10] due to its much higher contrast ratio. These devices do not hold a large DPM, barely surpassing π radians, which initially made them not suitable for phase modulation. This is due to the dielectric anisotropy achieved with this technology, which describes the response of the LC molecules to the applied electric field, being positive in PA-LCoS and negative in VA-LCoS.[11] Their phase-only modulation capabilities are dependent on the coincidence of the orientation of both the polarizer and the analyzer with the director axis of the molecules when the electric field is applied. These magnitudes are known as the maximal DPM and are different for negative and positive dielectric anisotropies, being typically lower for VA-LCoS. In a recent study, we examined the modulation properties of VA-LCoS; it was shown that using two VA-LCoS arranged in series or in a double pass through one of these (thus allowing phase summation) produced phase modulation outcomes similar to those of PA-LCoS, but with a significantly lower cost (at least an order of magnitude less) and improved compactness.[12]

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In this context, we demonstrate here the potential of this phase-modulation approach consisting of two VA-LCoS devices for the simulation and correction of high-order aberrations (HOAs) in the human eye. We perform visual acuity (VA) and contrast sensitivity (CS) tests in a group of subjects, with their eye's aberrations either corrected or induced with amounts similar to that in severe keratoconus [root-mean-square (RMS) error $= 1\ \mu$m for 5-mm-diameter pupil]. We also test the aberration correction capabilities of the system using physical masks with up to 0.5 μm-RMS (in a 5-mm pupil). The aberration correction was performed statically not using a closed-loop adaptive optics correction. Finally, the applicability of this modulation approach for ocular wavefront correction and simulation is discussed.

2 Methods

2.1 *Full-Depth Phase Modulation*

Due to the limited DPM of the VA-LCoS technology, we need to perform a phase summation by the use of either two modulators or a double pass through the same modulator. In the modulation unit based on VA-LCoS devices with limited DPM, the wrapped phase is first represented using the whole DPM of VA-LCoS 1 (defined as $2\pi - \Delta$ rad) and completed with Δ rad by VA-LCoS 2 (so adding 2π in total). This is achieved due to the coherent summation of the optical fields at conjugated planes, where the phase summation is performed. The transversal alignment of the displayed phase maps on VA-LCoS 1 and 2 needs to be finely adjusted to assure perfect overlap. Figure 1 shows an example of this situation compared with the case of PA-LCoS.

2.2 *Experimental Configuration*

Figure 2 shows the experimental setup used with the phase-only modulation unit consisting of two VA-LCoS devices (LCD, SYE2271-AS-IMM-00, Syndiant Inc., USA) arranged in series. The optical components of this unit include two VA-LCoS modulators (SLM1 and SLM2) with their optical axis at 45 deg from the horizontal in operating conditions (polarization angle in which phase-only modulation is achieved); a linear polarizer P oriented at 45 deg from the horizontal, coincident with the director axis of the SLMs, to achieve phase-only modulation; and two lenses (L3 and L4) and a mirror (M2) forming a unit-magnification telescope, which optically conjugates SLM1 and SLM2 to rigorously implement the phase summation. The optical stimulus is displayed using a 9.7 inch display (TFT LCD, LP097QX1, Adafruit, USA) with resolution (1536×2048) placed at 2.7 m from the aperture of the system. The aperture has a diameter of 5 mm and is conjugated to the surface of the first SLM via a 4-f system with lenses L1, L2 and mirror M1. The modulated pupil undergoes the last 4-f system consisting of lenses L5, M3 and L6, finally conjugating this pupil plane on the eye's pupil plane. A beam splitter (BS) in front of the eye opens an extra path for the pupil camera, monitoring the centering of the eye in the system.

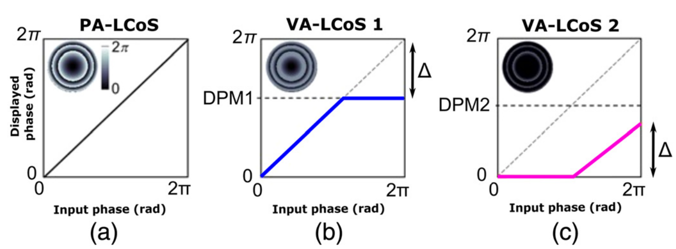


Fig. 1 Representation of the input wrapped phase for the different LCoS devices. (a) The linearized phase function of PA-LCoS. (b) Phase function of the first VA-LCoS, where the phase used reaches its maximal DPM1. (c) Phase function of the second VA-LCoS, where only the remaining phase from the previous modulator is programmed. An example of a coded two-dimensional spherical phase map is within each plot.

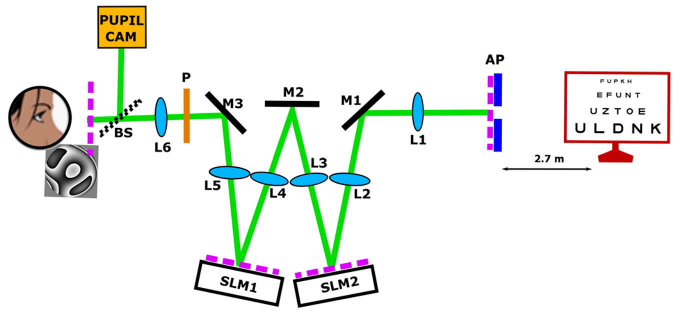
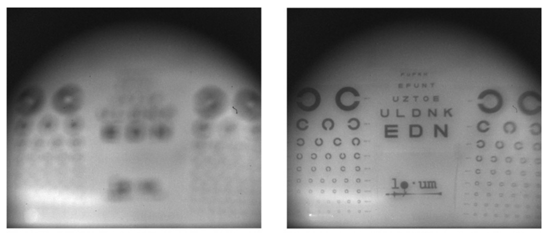


Fig. 2 Optical setup for the phase-modulation testing with two VA-LCoS devices arranged in series to evaluate the VA and CS in different subjects. AP, system aperture; L1–L6, lenses conjugating the different planes; SLM1 and SLM2, VA-LCoS used in the system; M1–M3, mirrors redirecting the optical path; P, polarizer with an axis that is coincident with the director axis of the SLMs for phase-only modulation; and BS, beam splitter, giving the Pupil Camera access to the pupil positioning information. The conjugated planes are depicted by the pink dashed lines.



(a) (b)

Fig. 3 FOV through the system when (a) a 3D trial lens is placed at the AP and (b) the physical lens is corrected by the adaptive optics system.

We measured a total of nine subjects, 22 to 49 years old, three of them with a small quantity of HOAs, being 0.19 ± 0.02 μm RMS for a pupil of 5 mm. The aberrations of each subject were first measured with a commercial adaptive optics visual simulator (VAO, Voptica S.L., Murcia, Spain). The measurements were taken under mesopic conditions, allowing for the natural full 5-mm pupil dilation in every subject. Subjects were fixed to the system using a biter for improved stability. A pupil tracking camera was used for correct positioning of the patient, both axial and coaxially. Rigorous positioning was very important because the aberrations measurement was taken in a separate system. The experiment was performed in accordance with the tenets of the declaration of Helsinki. All subjects signed informed consent after they had been informed of the nature of the study and possible consequences.

The system was designed to be in a see-through configuration, so we could evaluate the maximal field of view (FOV). We took two different images, placing an auxiliary camera (UI-324xCP-NIR, IDS Imaging Development Systems GmbH, Germany) with an objective (Nikkor AF 50 mm/1.8, Nikon, Japan) at the eye's pupil plane and a physical lens of three diopters of defocus at the aperture plane (AP). Figure 3 shows the uncorrected and corrected images, covering a total size of 63-cm wide, at 2.7 m of distance, resulting in a total covered FOV of ~13 deg.

2.3 *Visual Tests*

Two different tests were carried out, VA and CS. The VA test consisted in 40 trials of high-contrast tumbling E's using the minimum expected entropy staircase procedure of Psychtoolbox in MATLAB (Mathworks, USA).[13,14] CS was tested using a set of tilted sine-wave gratings with the contrast evaluated using the QUEST procedure of Psychtoolbox and taking 40 trials in each test.

For subjects with a low amount of HOAs, we added a simulated phase profile similar to keratoconus on top of the subject's aberrations, from the third to fifth Zernike orders. The keratoconus phase map used was obtained from clinical measurements in real patients, holding a high-order RMS ≈ 1 μm. The maps were rescaled from 1 to 0.6 and 0.3 μm to have different levels of aberrations. In the case of subjects with elevated HOA, we performed the test with their own HOA corrected and HOA uncorrected and then induced the 0.6- and 1-μm keratoconus profiles. Every subject performed three repetitions of each test for each aberration condition.

3 Results

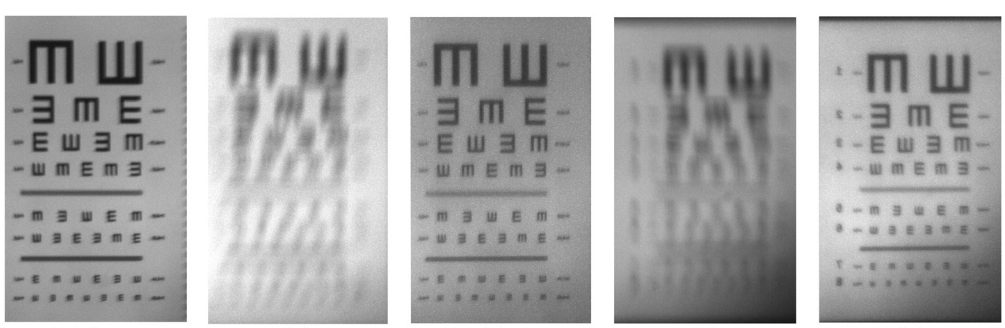
To show the correction capabilities of the system, we used physical masks with large amounts of HOA using peripheral areas of power progressive ophthalmic lenses.[15] In this case, we placed a camera (UI-324xCP-NIR, IDS Imaging Development Systems GmbH, Germany) with an objective (Nikkor AF 50 mm/1.8, Nikon, Japan) in the place where the eye should be and the masks at a conjugate pupil plane, where the AP is in Fig. 2. Figure 4 shows examples in which two different masks were used, with combinations of aberrations accounting for a total high-order RMS = 0.27 μm [(b) and (c)] and 0.5 μm [(d) and (e)] for a 5-mm pupil diameter. Figure 4(a) shows the image of the screen through the system when no correction is displayed by the system; (b) and (d) show the distorted image, and (c) and (e) show the corrected ones, respectively. The FOV of the images in Fig. 4 correspond to ∼3.2 deg of the total field. The decimal VA of the four last lines corresponds to 1, 1.17, 1.64, and 2, respectively. The small distortion that we observe in the last lines is only due to the optical path aberrations attributed to 0.15 D of astigmatism, which was not corrected for in this demonstration.

Figure 5 shows the results of VA and CS. (a) and (b) correspond to the subjects with low HOA, and (c) and (d) show the results of the three subjects with larger amounts of aberrations. As expected, VA decreases as the induced high-order amount of aberrations increases. Figure 5(b) shows the measured CS for different values of induced HOAs with a similar trend as VA. (c) and (d) show the VA and CS for different values of induced HOA-RMS, this time for the subjects with larger amounts of ocular HOA. The values for 0 and 0.2 correspond to the HOA corrected and uncorrected by the system.

4 Discussion and Conclusions

We have demonstrated the potential of using VA-LCoS modulation for ophthalmic applications. We developed an instrument with a see-through configuration that is able to correct and induce ocular aberrations while performing visual testing in a working FOV of 13 deg. We showed how this approach for phase modulation works appropriately both in a model eye and in real subjects.

In the experimental setup, two VA-LCoS modulators are used to implement the phase summation; however, the use of one modulator and a double pass through its two halves is also feasible if compactness is required.



(a) (b) (c) (d) (e)

Fig. 4 (a) Real image of the stimulus display seen through the system with no correction. (b) Image of the display after passing through an HOA mask in the pupil plane with a high-order RMS = 0.27 μm. (c) Image of the display after correcting for the HOA mask of (b). (d) Image after passing through an HOA mask with a high-order RMS = 0.5 μm. (e) Image of the screen after the correction of the HOA mask (d) by the adaptive optics system.

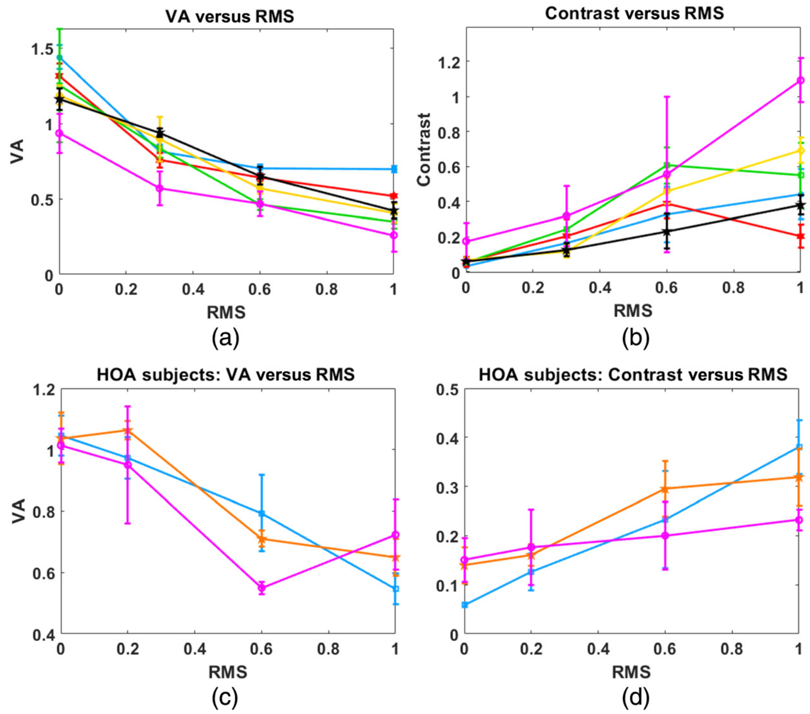


Fig. 5 (a) VA of six different healthy subjects with three different amounts of induced HOA. (b) CS for the same set of subjects than (a) for different amounts of HOA. (c) VA for three subjects with small amounts of HOA versus an increasing amount of HOA. (d) CS for the same three subjects with HOA for different amounts of aberrations. Each color represents a different subject.

The DPM of these VA-LCoS devices is dependent on the display's temperature; thermoelectric modules were used to maximize the DPM at values slightly larger than π. The phase modulation properties of these devices present temporal fluctuations (or flickering) at high frequencies,[12] although these are negligible for visual applications.

Because of their considerably lower production cost, the end market cost of VA-LCoS is on average one order of magnitude cheaper than PA-LCoS, which places VA-LCoS devices for adaptive optics as a potential cost-effective solution to incorporate into ophthalmic applications requiring moderate costs. In addition, their improved compactness makes them suitable for possible wearable devices based on wavefront shaping and adaptive optics.

In conclusion, we have demonstrated how two VA-LCoS devices, with limited DPM can be used as a single operation unit, correcting and inducing optical aberrations, both in a model eye and in real subjects. These results pave the way for the use of economic and compact VA-LCoS modulators in affordable ophthalmic instruments, carrying all of the advantages of adaptive optics in a see-through wearable design.

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