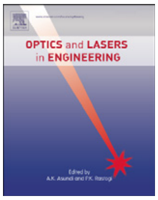
Optics and Lasers in Engineering 49 (2011) 743–748

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Recursive wavefront aberration correction method for LCoS spatial light modulators

J. García-Márquez*, J.E.A. Landgrave, N. Alcalá-Ochoa, C. Pérez-Santos

Centro de Investigaciones en Óptica A.C., Loma del Bosque 115, CP 37150, León, Mexico

ARTICLE INFO

Available online 5 March 2011

Keywords:
Spatial light modulators
Aberration compensation
Phase measurement
Pupil engineering

ABSTRACT

We present two accurate and relatively simple interferometric methods for the correction of wavefront aberrations of about 3 wavelengths (3λ) in spatial light modulators (SLMs) of the liquid crystal on silicon (LCoS) type. The first is based on a recursive use of a wavefront fitting algorithm in a Wyko$^{\mathrm{TM}}$ interferometer, in which Zernike polynomials are employed as the basis functions. We show here that the successive use of only three measurements is required to obtain a peak-to-valley (PV) error as low as $\lambda/10$, with an uncertainty of $\lambda/30$, in the compensated wavefront. The second method makes use of the actual optical path difference (OPD) computed by the interferometer at each pixel of the image of the interferogram of the LCoS modulator (LCoS-M). From numerical interpolation of these OPD values we were able to assign the required OPD compensation at each pixel of the LCoS-M. With this method, PV errors of the compensated wavefront as low as $\lambda/16$, with an uncertainty of $\lambda/30$, were obtained for the entire LCoS-M, or of $\lambda/33$ for the disk that we used as the domain of the Zernike polynomials in the first method.

1. Introduction

Spatial light modulators (SLM) have been used in a broad variety of applications, such as corneal topography [1], saturated-patterned excitation microscopy [2,3], apodization [4], focus tracking [5], astronomic instrumentation [6], and high-resolution wavefront sensing and correction [7]. In most of these applications, the wavefront aberration introduced by the SLM has to be taken into consideration. Given that SLMs with aberrations larger than 2λ are common [8], and that this would have a marked effect on the image quality of the optical system in which they work, the need for compensating their aberrations is amply justified.

To achieve this, some authors have first measured interferometrically the out coming wavefront of an SLM, and then compensated its aberrations by inducing a phase with the opposite sign in the modulator [6,9]. They have shown that an SLM with an aberration comparable to its maximum modulation depth, typically around 1λ, can be reduced to roughly $\lambda/10$ in small matrix arrays.

It has also been shown that peak-to-valley (PV) aberrations as large as 19λ in a Liquid Crystal on Silicon Modulator (LCoS-M) can be reduced to nearly $\lambda/10$, by wrapping the compensating phase, modulo 2π, in the modulator [10]. This was achieved after careful measurements of the birefringence induced by successive gray level screens on the LCoS-M, and interferometric tests of the aberrated wavefront emerging from the inactive modulator.

Finally, a third, non-interferometric method [11] can be used to compensate the aberration, not just of the modulator, but of the entire optical system of which this forms a part. By generating an optical vortex with the SLM (Fig. 1), a light intensity distribution in the form of a doughnut is projected on a CCD. Due to the aberrations of the optical elements in the system, including those of the LCoS-M, this doughnut will appear distorted in the image that we obtain from the digital camera. By means of the Gerchberg–Saxton algorithm [12], the doughnut distortion is iteratively removed through successive phase modifications in the SLM, achieving thus the desired correction of aberrations in the whole system.

An SLM that is corrected from aberrations, or programmed to correct those of a complete optical system, can in principle contribute to form diffraction limited images. This, of course, would be essential in applications like those mentioned at the beginning of this section. In this paper we show how to correct an aberrated SLM up to $\lambda/16$ PV error, yielding nearly perfect tilt fringes in an interferometric test, or equivalently, a Strehl ratio which is fairly close to 1, in the point spread function (PSF) computed with the corrected wavefront. In our results in this article $\lambda = 633$ nm.

2. Aberration correction of the LCoS-M by means of a phase-modulated grating

The SLM that we used for this work was a liquid crystal on silicon (LCoS) bi-dimensional array of 1024×768 pixels,

---

* Corresponding author.
E-mail address: jgarciam@cio.mx (J. García-Márquez).

0143-8166/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlaseng.2011.01.024

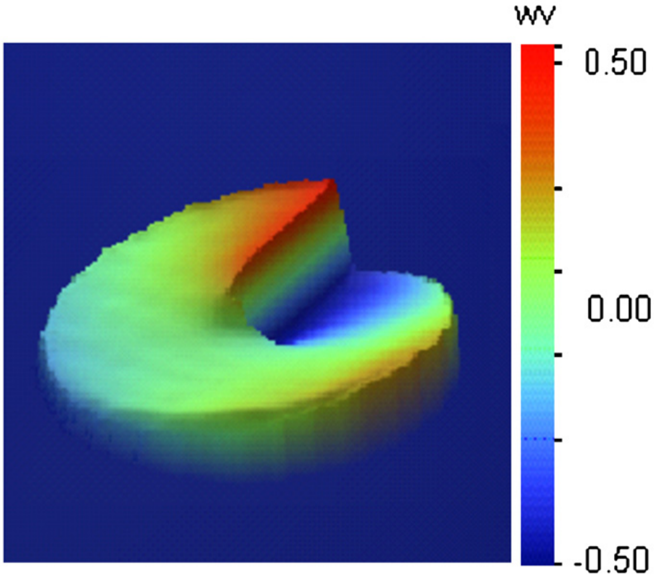


Fig. 1. 3-D OPD graph of an optical vortex of topological charge 1 obtained with an aberration-free LCoS-M in a Wyko^{TM} interferometer.

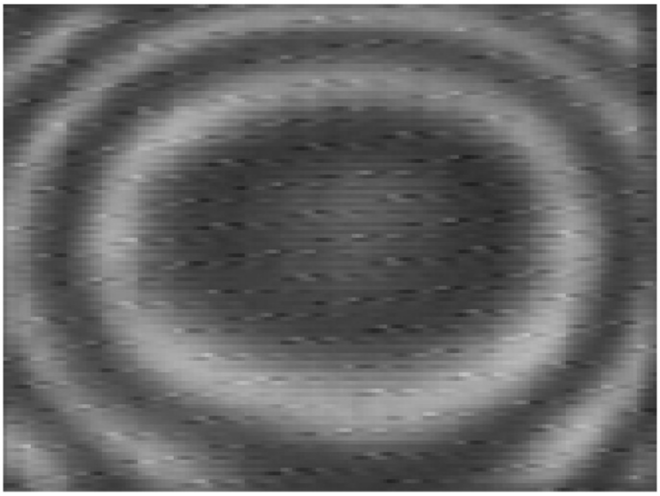


Fig. 2. Interferogram of an inactive LCoS-M obtained with a Wyko^{TM} interferometer.

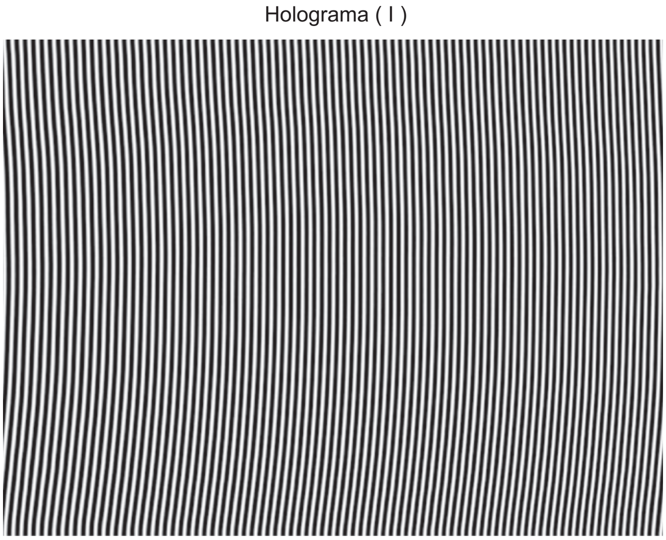


Fig. 3. Phase-modulated grating used to compensate aberrations in an LCoS-M. It has an average period of 12 pixels and ~85 line-pairs (lp). Its contrast can be readily varied to control the intensity of the diffracted beams.

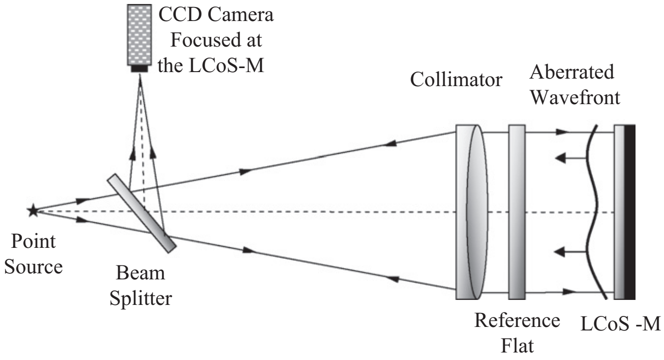


Fig. 4. Testing configuration to measure the aberration introduced after reflection at an LCoS-M. The LCoS is slightly tilted, in such a way that the beam diffracted in the first order is aligned to be inspected by the interferometer. The tilt adjustment would be clearly dependent on the frequency of the phase grating that we generate in the LCoS.

commercialized by Holoeye^{TM} as model LC-R 2500. The optical quality of this display was first tested in a Twyman–Green configuration and it was established that a relatively strong astigmatism was present (Fig. 2). But correction of a mixture of aberrations exceeding 2λ is not an easy task in a device, which can only attain a maximum phase excursion of 2π. Although this direct approach has been used for aberration compensation [6,9,10], as we mention above, the experimentalist should be aware of its limitations. Perhaps the most important of them is the need to use the whole phase displacement range, or phase stroke, of the device to attain the compensation of its aberration. This would prevent him, for example, from reducing the depth of modulation that is required in order to lessen the flickering in the LCoS, as suggested in Ref. [13].

An alternative approach to correct the aberrations of the LCoS-M is the use of a phase-modulated grating, where the phase distortion due to the aberrations of the modulator is encoded in the phase of the grating (Fig. 3). This grating may be thought of as a hologram, in which the conjugate of the aberrated wave is recorded, using a plane wave as the reference beam. This method requires, of course, an accurate measurement of the aberrated wavefront of the LCoS-M. A Fizeau digital interferometer (Wyko^{TM}) was used for this purpose, allowing us to represent the aberration in terms of Zernike polynomials, or as a matrix with the values of the optical path differences (OPDs) sensed by the digital camera of the interferometer (Fig. 4). The advantage of the first description is that we only need a few dozens of numbers, typically 36 polynomial coefficients, to have a good account of the wavefront aberration over a circular domain in the LCoS-M surface. In the second case we need thousands, but they offer a thorough description of the aberration through the entire surface of the LCoS-M. It is to be expected that the matrix representation of the aberration would lead to a better aberration compensation of the LCoS-M. We shall next present a simple theory to discuss some details common to both methods.

2.1. *Theory*

Let

$$r_0 = a\exp[i\varphi_0(x,y)] \tag{1}$$