Astigmatic phase correction for the magneto-optic spatial light modulator

E. Carcole, Jeffrey A. Davis, and Don M. Cottrell

We report a simple low-cost technique for evaluating the phase distortion in a magneto-optic spatial light modulator. We find that the dominant distortion is caused by astigmatism and is easily compensated by encoding of the complex-conjugate pattern onto the device. Two experimental results are shown. First, the focused spot size from a Fresnel lens is sharpened when the aberrations are corrected. Second, we show that the pattern that generates a first-order Bessel-function nondiffracting beam does not work unless the aberrations are corrected.

Key words: Aberrations, adaptive optics, computer-generated holograms, Fresnel zone plates, spatial light modulators, diffractive optical elements.

Programmable spatial light modulators (SLM's) are of interest for optical pattern recognition and for programmable diffractive optical elements. In these types of applications the performance can be seriously degraded by phase errors introduced by the optical quality of the SLM.[1] This was originally a great concern with low-cost consumer-grade liquid-crystal televisions[2–5] but is also a factor with higher-quality SLM's, such as the magneto-optic spatial light modulator[6] (MOSLM).

One can remove the spatial distortions by using such techniques as passing the light beam through a phase-correcting hologram[2] or by immersing the SLM in a liquid gate.[3,4] Although these techniques do not require prior measurement of the phase distortion, they require additional optical components.

An easier technique is to encode a phase-conjugate mask for the distortion directly into the pattern that is written onto the SLM.[5,6] Although extremely effective, this approach can be expensive because it requires both a high-quality interferometer and automatic fringe-analysis software[6] for measurement of the phase distortion.

In this Note we demonstrate an easier and less expensive technique for evaluating the phase distortion present in any SLM. In particular we examine the MOSLM and find that it displays significant astigmatism. One can analyze this type of aberration without an interferometer by encoding a lens onto the SLM and examining the focused spot. When the phase conjugate of this aberration is written onto the SLM, the phase distortions are removed. Experimental results are reported for patterns written onto the MOSLM.

Previous measurements of the phase distortion of SLM's indicate smoothly varying functions of position.[2–6] Accordingly this phase distortion $\phi(x, y)$ can be approximated in terms of a second-order polynomial expression as

$$\phi(x, y) = a + bx + cy + dx^2 + ey^2 + fxy, \qquad (1)$$

where the letters a, b, c, d, e, and f are the coefficients of the expansion.

The first term is a constant phase factor and can be ignored. The b and c terms are linear phase shifts. Their effect is to shift laterally the reconstruction of any hologram that is encoded onto the SLM, and they do not affect the quality of the hologram. Because the effect of a linear phase shift is equivalent to a small tilt of the SLM, it can be easily compensated during the alignment of the optical system.

The d and e terms are cylindrical-lens functions along the x and y directions, respectively. They can correspond to either positive or negative lenses, depending on the signs of the coefficients. When the two terms are equal, the distortion acts as a spherically symmetric positive or negative lens. In this case we can correct the distortion simply by moving the focal plane.

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When the terms are not equal, the phase distortion corresponds to an anamorphic lens[7] function with different focal lengths in the x and the y directions. The f term in Eq. (1) rotates the principal axes of the anamorphic-lens function. This type of astigmatic distortion results in a smearing of the focal point and, unlike the previous types of distortions, cannot be corrected with simple alignment techniques.

The phase profile for the MOSLM shown in Fig. 2 of Ref. 6 suggests that it will exhibit astigmatism. One can detect astigmatism by focusing the light that passes through the SLM with an additional lens and by examining the focal plane. The astigmatism causes two orthogonal line focus points. The angular orientation of these focused lines gives the relative orientation of the principal axes for the anamorphic lens, and the locations of the planes allow the focal lengths to be determined.

In our case the focusing spherical lens is directly written on the MOSLM. Consequently the resulting focal length of the combination of the spherical and the anamorphic lenses is given by the equation for two lenses in series,

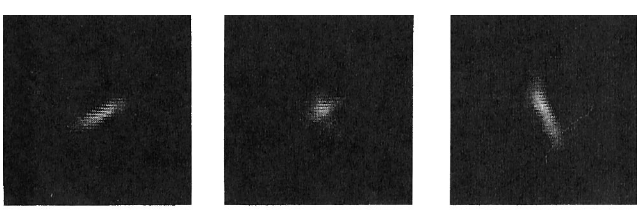
$$\frac{1}{f_X} = \frac{1}{f_1} + \frac{1}{f_{2X}}, \qquad (2a)$$

$$\frac{1}{f_Y} = \frac{1}{f_1} + \frac{1}{f_{2Y}}, \qquad (2b)$$

where f_1 is the focal length of the spherical-lens pattern written on the MOSLM and f_{2X} and f_{2Y} represent the principal focal lengths associated with the anamorphic lens. Because f_1 is encoded onto the MOSLM, its value can be adjusted to increase experimental accuracy, depending on the amount of astigmatism.

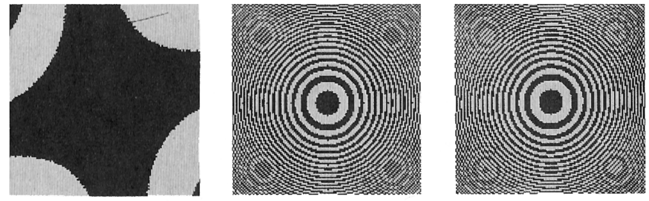
Experimental results illustrate the effects of these aberrations very clearly. In our experiments a MOSLM,[8] manufactured by Semetex Corporation and operating in the binary phase-only mode,[9] was illuminated with collimated light from a He–Ne laser. A lens function having a focal length of 1.138 m was written onto the MOSLM, and the focused output was monitored with a Sony model SS-M350 CCD camera (having a pixel size of 12.3 μm) connected to the Macintosh computer through a ComputerEyes interface system.

Figure 1 shows the focused spot formed by the lens at distances of 110.5, 114, and 117 cm. The horizontal lines in the photos are caused by the camera–digitizing system. We confirmed this by expanding the beam. The separation of the horizontal lines remained constant when the beam diameter increased. The large difference between the positions for the focused lines indicates a strong astigmatism. The best focus (point of least confusion) is formed at 114 cm. However, the shape of the focused spot is very irregular, and the spot size is ~3 times larger than the diffraction limit.



(a) (b) (c)

Fig. 1. Experimental intensity patterns from a 113.8-m focal-length lens encoded onto a MOSLM. Astigmatism is shown by comparison of intensities measured at distances of (a) 110.5 cm, (b) 114 cm, and (c) 117 cm.



(a) (b) (c)

Fig. 2. Binary patterns (a) for a focusing lens with a focal length of 113.8 cm, (b) representing phase compensation for a MOSLM, and (c) showing the product of a Fresnel-lens pattern with a compensating pattern.

The line focus at 110.5 cm indicates a positive cylindrical lens with a focal length of $f_{2X} = 36$ m oriented at an angle of 33° counterclockwise relative to the direction in which the light is traveling. The orthogonal line focus at 117 cm indicates a negative cylindrical lens with a focal length of $f_{2Y} = -44$ m and oriented at an angle of −57°. When the SLM was flipped so that the entrance and exit faces were reversed, the orientations of the focused lines changed, but their positions remained constant. This confirmed that the aberrations were caused by the SLM and not by the rest of the optical system. The peak-to-valley phase distortion corresponding to these focal lengths is ~0.53λ and is in qualitative agreement with the values for a different MOSLM from Ref. 6. Experiments show that this aberration reduces the peak height of the focused spot to ~25% of the original value, representing a significant degradation in optical performance.

The complex conjugate of this anamorphic-lens function was calculated, and a binarized version is shown in Fig. 2(a). This function was multiplied with the phase distribution for a lens having a focal length of 1.138 m, as shown in Fig. 2(b). The resulting pattern is shown in Fig. 2(c) and was written onto the MOSLM.

Figure 3 shows the corrected output pattern mea-

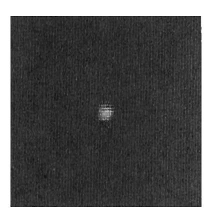


Fig. 3. Experimental intensity pattern measured at the focal point for the phase-compensated 113.8-m focal-length lens encoded onto the MOSLM. The size of the focused spot is much smaller.

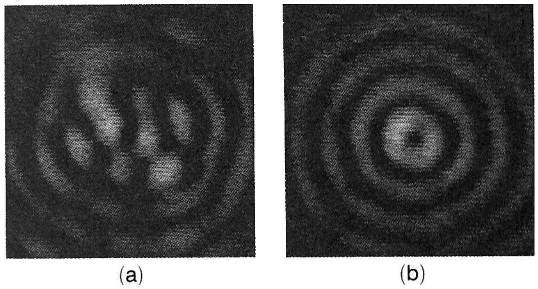


Fig. 4. Output intensity pattern for a first-order Bessel-function beam measured at a distance of 220 cm for a MOSLM (a) with uncorrected astigmatism and (b) with a pattern that compensates for astigmatism.

sured at the focal point, and the aberrations are clearly corrected. Again the horizontal lines are caused by the camera–digitizing system. The diameter of the focused spot for the corrected lens was measured as 168 µm, in excellent agreement with the diffraction-limited spot size[10] of 150 µm.

The consequences of these aberrations are clearly demonstrated in another application. We can generate higher-order nondiffraction Bessel-function beams $J_n(r)$ by encoding a pattern onto the MOSLM, given[11,12] by

$$T_n(r, \theta) = \exp(in\theta)\exp(-i2\pi r/r_0). \qquad (3)$$

Figure 4(a) shows the output from this pattern at a distance of 220 cm from the MOSLM when the pattern of Eq. (3) is used for $n = 1$. In this case the aberration is not corrected, and the output shows significant distortion compared with the expected $J_1(r)$ beam. Figure 4(b) shows the output when the aberration is compensated and clearly displays the expected Bessel beam output.

In conclusion, we have demonstrated a simple and elegant technique for calculating the phase distortion of the MOSLM and have written a phase-compensating pattern that corrects this distortion. We find similar astigmatic behavior in a second MOSLM, and our values agree with those in Ref. 6. Our technique is faster, less expensive, and easier than the use of an interferometer to measure these phase distortions. In addition, it allows qualitative understanding of the types of phase errors that result from these SLM's. Such astigmatic phase distortions are not negligible. The degradation of the intensity and the width of the output focused spot has dramatic implications for optical correlators. In addition, these distortions affect the capability for writing diffractive optical elements onto programmable SLM's.

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