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Phasor averaging for wavefront correction with liquid crystal spatial light modulators

Fernando Vargas-Martín [1], Pablo Artal [2]

Laboratorio de Óptica, Departamento de Física, Universidad de Murcia, Campus de Espinardo (Edificio C), 30071 Murcia, Spain

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Abstract

We describe strategies for zonal wavefront correction and generation using liquid crystal spatial light modulators (LC-SLM) with 2π radians phase dynamic range and limited spatial resolution. Computer simulations using realistic wavefront aberrations and the specification of a commercially available LC-SLM device are shown. In spite of the general modest improvement in the correction of large aberrations, the best performance after compensation is attained with a phasor averaging strategy for driving the LC-SLM. Experimental results for wavefront generation are shown as well. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Wavefront correction (or generation) techniques are mainly used in astronomy [1]. However there are also possibilities of application in other areas, notably in medical imaging, and in particular in retinal imaging [2–5]. Deformable mirrors are the most widely used devices for wavefront correction. As an alternative, high optical quality liquid crystal spatial light modulator (LC-SLM) devices have also been proposed [6,7]. In comparison with deformable mirrors, LC-SLM devices have a limited dynamic range, a relatively slow temporal response and they currently need the use of polarized light (that can be overcome by using two LC-SLM [8]). On the other hand, the advantages of LC-SLM are possible lower cost, low complexity, high flexibility and transmissive nature. In this paper, we propose a more efficient method to drive the elements of the LC-SLM obtaining more accurate wavefront correction than those attained by standard procedures. We also present experimental results of wavefront generation when the LC-SLM is driven using different strategies. The method we propose is also useful for other wavefront corrector devices, especially for those that do not fit well low modes of aberration (e.g., piston only correctors), and other application areas such as diffractive optical element design.

2. Theory

We consider conditions of monochromatic illumination, far-field Fraunhoffer diffraction and isoplanatic linear systems. With these assumptions, the point spread function (PSF) of a given system in the image plane with coordinates (x,y) is a function of the generalized pupil function (GPF) with coordinates (u,v) through the expression [9]:

$$p(x,y) = |\Im(\boldsymbol{P}(u,v))|^2 = |\Im(P(u,v)\exp(iW(u,v)))|^2, \quad (1)$$

where $\Im$ means Fourier transformation, $P(u,v)$ is the modulus of the GPF, called pupil function, and $W(u,v)$ the wave aberration (WA). Several orthogonal bases (e.g. Zernike polynomial base for circular pupils [1]) have been proposed to describe the WA, creating a linear functional vector space context. Once the WA of the system is

[1] E-mail: vargas@fcu.um.es
[2] E-mail: pablo@fcu.um.es

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known, optical compensation is usually performed by introducing in the pupil plane a predetermined dephase at each location.

The LC-SLM device we use has 69 corrector elements (facets) distributed in a two-dimensional hexagonal array (HEX69 SLM, Meadowlark Optics, Longmont, CO, USA).

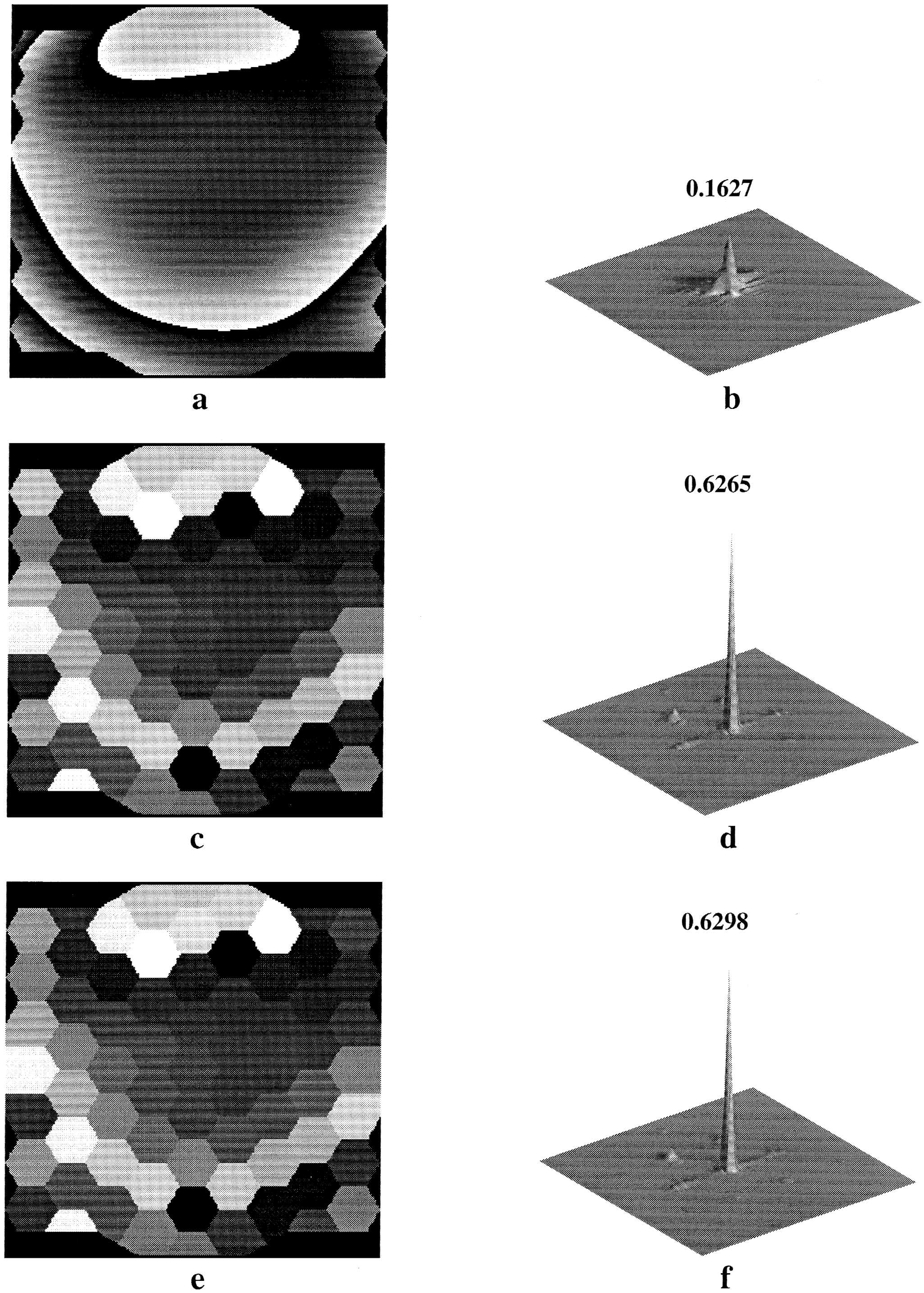

Fig. 1. Results of correction with the different strategies for a mildly aberrated wavefront. Initial aberration (a) and associate PSF (b). The value maps w_n (c) and f_n (e), and PSFs after each compensation ((d) and (f)). The associate numbers are the Strehl Ratio in each case.

The performance of the LC-SLM devices for wavefront generation and compensation is limited by the number of elements, their size and the phase dynamic range. If we generate or compensate an aberrated wavefront that is not well adapted to piston correction (larger phase steps within a single facet), the performance of the device is quite

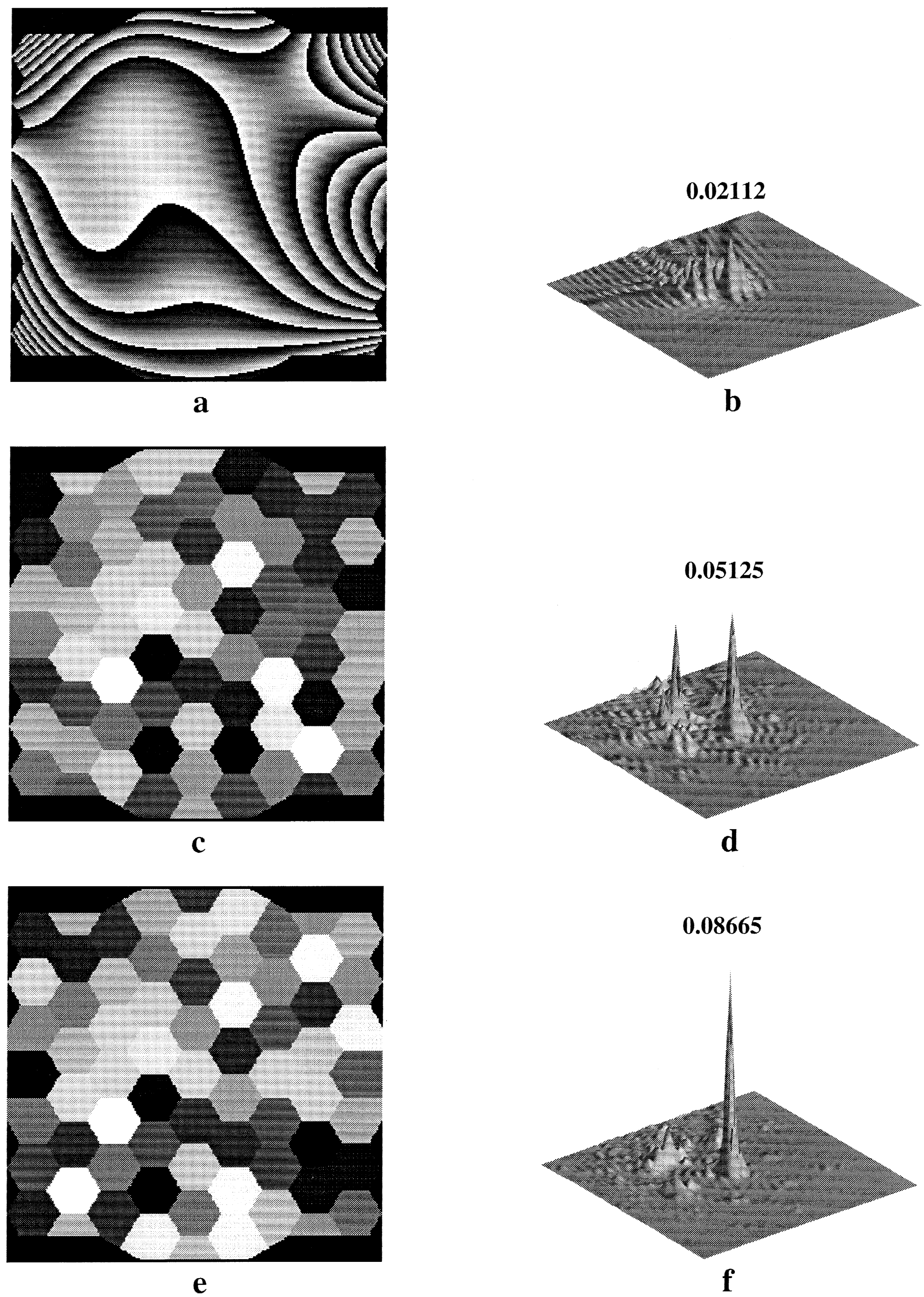

Fig. 2. Results of correction with the different strategies for a severely aberrated wavefront. Initial aberration (a) and associate PSF (b). The value maps w_n (c) and f_n (e), and PSFs after each compensation ((d) and (f)). The associate numbers are the Strehl Ratio in each case.

dependent on the way the phase in each facet is determined. The most used method for this phase determination is to calculate the mean value of the WA in the area of the considered facet ($w_n = -\langle W \rangle_n$). Compensation using this estimation yields the lower root mean square error (RMSE) in the phase. However, the phase RMSE does not predict well the optical image quality of moderate or severe aberrated systems. We propose an alternative method to determine the value of the phase at each facet based in a phasor scheme. We compute the phase of the average generalized pupil ($f_n = -\text{phase}(\langle \boldsymbol{P}(u,v) \rangle_n)$. This dephase provides the lowest value for a different error function given by

$$\epsilon = \langle |P(u,v)\exp(i(W(u,v) + f_n(u,v))) - 1|^2 \rangle, \qquad (2)$$

where the angular brackets represent in this case the average over the whole pupil plane. In fact, this is the square of the RMSE in the GPF, using as reference a diffraction limited system with binary pupil (1 if $P(u,v) > 0$, else 0). As stated by the Parseval theorem [9], this error in the pupil is proportional to the square of the RMSE of the far field amplitude (with a diffraction-limited system as reference). This phasor averaging scheme is better adapted to characterize the image quality of the system, and in addition phase unwrapping techniques are not required, since only the principal argument of the WA is used in the calculations.

3. Computer simulations of wavefront correction

We have evaluated the performance of our LC-SLM driven with these two strategies in computer simulations using two different WAs. As we have a final interest in using this device to correct the aberrations of the human eye, we selected for the simulations two ocular WAs [10,11]. However, it must be pointed out that the results of the simulations are still valid for any moderately aberrated system. One of the selected WAs can be considered as slightly aberrated, and the other presents more severe aberrations. In these simulations, we considered the circular pupils inscribed in 256×256 pixels in a window of 512×512 pixels, and we derived the PSFs by using the Fast Fourier transform algorithm. The effects of the connections in the spatial modulator are not considered. Fig. 1 shows the results of the compensation of the slightly aberrated wavefront. The original wave aberration (256×256 pixels) and the computed PSF (central 100×100 pixels) are shown in the top of the figure. The phase maps in the LC-SLM w_n and f_n, and the computed PSFs after the two compensation processes are also presented. The value above each PSF represents its Strehl ratio. After compensation using both phase maps, w_n and f_n, the corrected PSFs have a Strehl ratio of 0.63. This is a considerable improvement in the overall image quality without noticeable differences between the two compensation methods.

Fig. 2 shows the results for the severe aberrated wavefront (Strehl ratio of 0.02). In this case both compensations are poor, but that based on the phasor scheme f_n provides the best reconstruction, nearly two times better than the conventional procedure. With severely aberrated wavefronts, the phasor averaging is the most appropriate strategy to compensate the aberrations.

The performances using either the mean phase or the mean phasor are different because the far field complex electric field is related with the WA through an exponential integration, instead of the linear dependence with the GPF [9]. For smooth WAs, the exponential becomes approximately a linear dependence, but in the case of abrupt WAs this approximation is no longer correct.

For systems with an amount of aberrations between the two examples shown in Figs. 1 and 2, the use of the LC-SLM for wavefront correction improves the image quality but without reaching diffraction limited performance, due to the small current number of correcting elements. In addition, there are significant benefits if the LC-SLM device is driven using the proposed phasor averaging scheme.

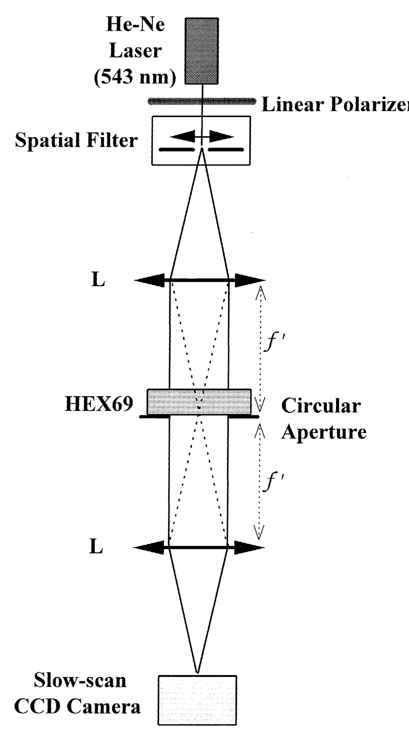

Fig. 3. Experimental system for imaging the PSF associated to the generated WAs. The two lenses L have focal length $f' = 0.5$ m.

4. Experimental results of wavefront generation

We have also recorded far-field PSFs using a scientific grade CCD camera for different phase maps generated in the LC-SLM. Fig. 3 shows a schematic diagram of the experimental setup used. We placed the LC-SLM in an optical correlator configuration with two lenses L (both with 0.5 m focal length). Collimated linear polarized monochromatic light was obtained using a He-Ne laser (543 nm), a linear polarizer, a spatial filter and the first lens L. The modulator was placed in the Fourier plane of the first lens. A circular pupil with 15 mm diameter was placed close to the LC-SLM. The second lens L placed at 0.5 m distance from the modulator worked as objective of

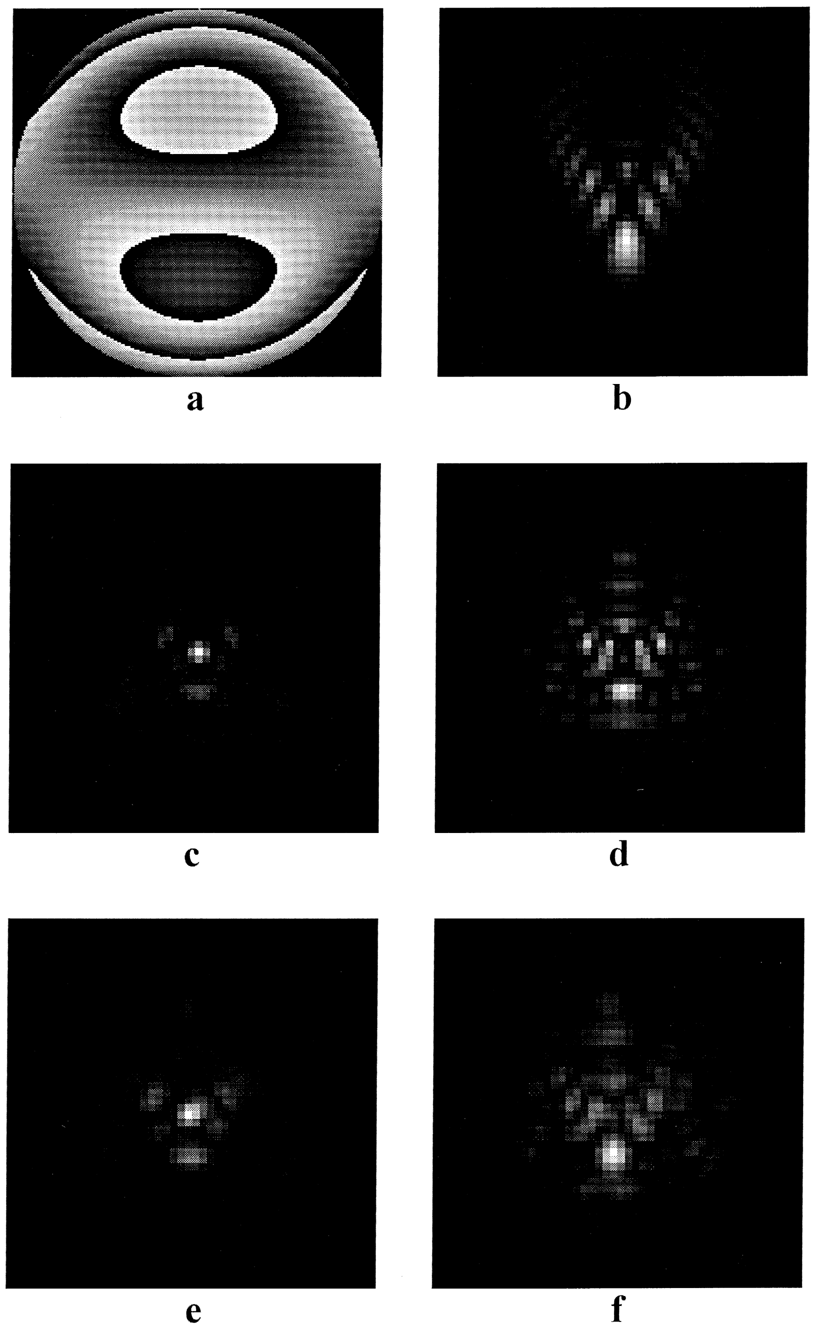

Fig. 4. Results for wavefront generation: the wavefront test (a); its related PSF (b); computer simulated PSFs by using estimations w_n (c) and f_n (d); measured PSFs for w_n (e) and for f_n (f).

the CCD camera (Spectrasource MCD100). The CCD pixel size is 27 μm × 27 μm and the dynamic range for each pixel is 16 bits.

To evaluate the behaviour for wavefront generation by using the two strategies w_n or f_n, we compared the recorded PSFs with those computed from the same residual WAs (with the same criteria as in Section 3). The results are presented in Fig. 4. The wavefront corresponds to the 7th Zernike circle polynomial term (coma) with 0.07 Strehl ratio [12], using a circular pupil.

It is important to notice that the PSF obtained using the phasor averaging (estimation f_n) has a coma-like shape similar to that expected for the WA test, while estimation w_n seems not to be able to reproduce the correct spread pattern. Therefore, the strategy based on the phasor averaging also has a better behavior for WA generation. Although improvement of the phasor averaging depends on the aberration to be generated, Eq. (2) ensures the lowest deviation between PSFs. It is also interesting to point out the poor performance of the phase averaging scheme in this smooth aberration case due to a significant RMSE in the phase.

5. Conclusions and summary

We have studied the performance of LC-SLMs for wavefront correction of aberrated systems. We used in the computer simulations, two realistic wavefront aberrations and the characteristics of a commercially available LC-SLM. Although some benefits, in terms of Strehl ratio, are obtained after compensation, the system remains far from a diffraction limited system. We proposed an alternative strategy for zonal wavefront correction or generation with current LC-SLM devices. This strategy is based on phasor averaging and we have compared it with the more common procedure to estimate the phase map from the mean value of WA over the single facet area. With slightly aberrated systems, the behavior of the phasor technique is similar to the mean phase method. On the contrary, in the case of severely aberrated wavefronts, the estimation using the mean phasor leads to noticeable improvement in the Strehl ratio. In addition this method does not require unwrapping techniques. Therefore, this procedure to drive the LC-SLM is especially appropriate when large aberrations must be corrected. In particular, it can be of significant benefit for correction of aberrations of the human eye with a LC-SLM [4,5].

Acknowledgements

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References

[1] R.K. Tyson, Principles of Adaptive Optics, Academic Press, New York, 1991.
[2] A.W. Dreher, J.F. Bille, R. Weinreb, Appl. Optics 28 (1989) 804.
[3] J. Liang, D.R. Williams, D.T. Miller, J. Opt. Soc. Am. A 14 (1997) 2884.
[4] P. Artal, F. Vargas, I. Iglesias, Wavefront correction in the human eye with liquid crystal, OSA Annual Meeting 1996.
[5] F. Vargas-Martín, P.M. Prieto, P. Artal, Correction of the aberrations in the human eye with a liquid crystal modulator: limits to the performance, submitted to J. Opt. Soc. Am. A.
[6] G.D. Love, J.S. Fender, S.R. Restaino, Opt. Photon. News 6 (1995) 16.
[7] G.D. Love, Appl. Optics 36 (1997) 1517.
[8] G.D. Love, S.R. Restaino, R.C. Carreras, G.C. Loos, R.V. Morrison, T. Baur, G. Kopp, OSA Technical Digest Series 13 (1996) 288.
[9] J.W. Goodman, Introduction to Fourier Optics, 2nd ed., McGraw-Hill, New York, 1996.
[10] J. Liang, B. Grimm, S. Goelz, J. Bille, J. Opt. Soc. Am. A 11 (1994) 1949.
[11] I. Iglesias, P. Artal, OSA Technical Digest Series 1 (1997) 24.
[12] R.J. Noll, J. Opt. Soc. Am. 66 (1976) 207.