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Application of LCoS to dynamical focusing in an optical system

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Abstract. Imaging of samples by different microscopy techniques has produced a relevant impact in the development of new diagnosis techniques in biology, medicine and material science. In many biological applications, where the sample changes or moves during the observation, a moving spot to track an identified sample is required. We introduce here an optical system that can perform this tracking without mechanical components. The system is based on the use of a high resolution liquid crystal on silicon (LCoS) device working as a mostly phase wave front modulator. The additional advantage of this system is performing the motion of the spot at video rate. In general, these devices produce coupled phase and amplitude modulation responses as a function of the applied voltage. This coupling effect deteriorates the response of those ideal optical elements designed as phase only or amplitude only functions. By means of an elliptical polarization light we can reduce the amplitude modulation and improve the phase modulation. We have experimentally found a configuration where the amplitude is almost constant while the phase reaches a high modulation. For this configuration we show how the spot can be moved through focus plane by means of linear phases, or displaced out of this plane by using a quadratic phase.

Keywords: Beam shaping, Beam profile, Beam intensity, Image forming and processing, Filters
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1. INTRODUCTION

In the last years, a great variety of applications using nematic liquid crystal displays, LCDs, as spatial light modulators have been explored. According to this, commercial displays have been used as a way to represent a transmission, complex in general, which modifies the wavefront of the incident field. Thus, many applications have been found from pulse compression for optics communications to simulation of quantum phenomena. For example, it has been shown how this modulators can be reconfigured dynamically to be applied in atomic optics [1]. Moreover, using spatial light modulators based on liquid crystal displays have been proposed in order to generate diffractive optics that can be used in laser trapping [2]. In other field, optical information processing, these elements have been widely used in coherent systems as media to represent holographic filters, as well as in incoherent ones by introducing chromatic corrections in compact configurations [3–8].

An application of special interest in biology, medicine as well as in material science is the one related to microscopy. It has been already shown a tracking mechanism for microscopy based on liquid crystal panels [9] and even more recently it has been demonstrated how biology objects with low contrast may be distinguished by using a spiral phase on a spatial light modulator [10, 11]. According to this, it is worth mentioning that the most recent progresses about the comprehension of dynamical biological systems make use of fluorescence microscopy. Particle tracking may be achieved by the focalization of a laser beam onto a fluorescence sample. The obtained signal may be analized to get both position and displacement of the particle to refocus in real time on the sample path. A well known tracking method is the triangulation one, obtained by generating three dots in the vertex of a triangle to localize the sample on a plane. This method consists on the alternation of those three vertex and on taking the light that comes from the fluorescence. The nearer the sample is with respect to one of the vertex the more fluorescence. The extension of this method to three dimensions is obtained by the addition of a fourth dot outside the triangle plane. So this three dimensional method requires the control of the four vertex of a tetrahedron.

In this work we explore the posibility of using a liquid crystal nematic display as a spatial light modulator with microscopy applications. We worked with reflective displays (LCoS, *liquid crystal on silicon*). One of the main differences with transmissive liquid crystal nematic displays lies on the LCoS larger filling factor, allowing smaller pixels and therefore more resolution. Secondly, it is known that LCoS displays reach greater phase shifts (even greater that 2π for certain polarizations) than transmissive LCDs. However, configurations where phase and amplitude are uncoupled have not been achieved yet .

We present in sections 2 and 3 a study of the posible configurations of a LCoS in order to modulate the phase mainly and we show a configuration with elliptical polarization that allows a complete phase shift with a 25% intensity variation. In the following sections, 4 and 5, we show that it is possible to generate the tetrahedral geometry that may allow us to localize a sample in space.

2. EXPERIMENTAL ARRANGEMENT

In this section we analize, from the point of view of Fourier optics, how phase shifts in the spatial frequency plane may influence the beam displacement. The position of a laser spot in a mycroscopy system may be changed by adding a linear phase in the Fourier plane. The experimental arrangement is shown in Figure 1.

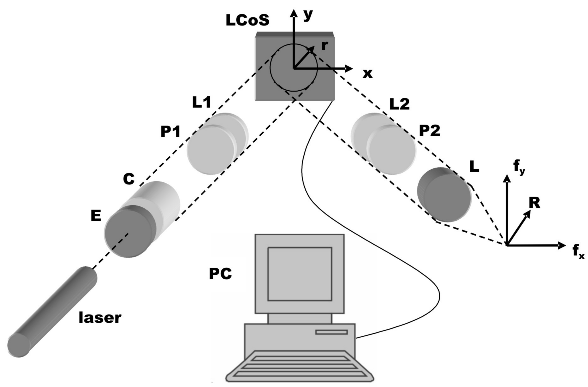

FIGURE 1. Experimental arrangement used to modify the position of the illumination spot.

The idea is to introduce in the beam path an expander (E), a collimator (C), a LCoS (driven through a PC) and a lens (L) to focus the spot. In the figure we show the polar coordinates on the modulator (r) and on the focus plane (R). We considered uniform illumination over the whole modulator. We call x the centered coordinate in the modulator, f_x the associated spatial frequency and L the modulator's width. We assume this coordinate goes from $-0.5L$ in the left extreme of the modulator to $0.5L$ in the right one. Moreover, we assume there is a linear phase on the modulator which values go from ϕ_1 in $-0.5L$ to ϕ_2 in $0.5L$. According to this, the phase may be exppressed as:

$$\phi(x) = (\phi_2 - \phi_1)x/L + \frac{\phi_2 + \phi_1}{2} \tag{1}$$

The amplitude of the electric field in a lens focus, or the field in the Fraunhofer approximation, is proportional to the Fourier tranform of this function in a frequency $f_{x_0} = (\phi_2 - \phi_1)/2\pi L$. Owing to the fact that a beam with radial symmetry falls on the modulator, the Fourier transform has the same symmetry around a new origin horizontally displaced. In this way, the electric field measured from that origin is:

$$U(R) \propto \int_0^{0.5L} r J_0(2\pi r\rho) dr \propto \frac{J_1\left(\frac{\pi LR}{\lambda f}\right)}{\frac{\pi LR}{\lambda f}} \tag{2}$$

where $\rho = \sqrt{(f_x - f_{x_0})^2 + f_y^2} = \frac{R}{\lambda f}$ is the spatial frequency in polar coordinates, λ the laser wavelength, f the lens focal distance where the final spot is observed and J_0 and J_1 are the spherical Bessel functions of the first kind. To get a null phase difference, we look for the first zero of the function expressed in equation (2). This is obtained at $\rho = 1.22/L$. Varying the phase shift along the modulator it is possible to reach a displacement of the laser spot to distances near the centre or to distances beyond the first minimun. Thus, for example, if the difference in phase is π then the movement of the spot corresponds to $0.5/L$. If the difference is 2π, the movement obtained is $1/L$. This is approximately of the order of half of the total width. Clearly, if larger displacements are required, then straight lines with larger slopes will be needed. However, it is possible to obtain these responses with a modulator capable of modulating complete phases from 0 to 2π, representing the phase modulus 2π. In this case, the linear phase is represented as a blazed grating formed by right triangles. In this ideal diffraction grating one would get only one order of diffraction, that is exactly the displaced spot. In case a complete 2π modulation is not obtained, it is possible to generate blazed gratings where the intensity of one of the orders is much higher than the others (that are not null).

3. MOSTLY PHASE MODULATION

We worked with a liquid crystal reflective display *Holoeye LC-R-2500* with a resolution of 768x1024 pixels. Its dimensions are 2 cm x 1.5 cm and it is driven as an additional monitor from a PC through an adaptive card DVI-D.

To get the mostly phase modulation with the LCoS display we first needed to decide how to carry out the measurements and at the same time, which optical components would be the appropriate. We took as a starting point the arrangement used by *Kohler et al.* [12]. In that work, they obtained a 2π phase modulation with a 65% intensity variations. They worked with two polarizers: one before and the other after the display. However, to our purpose of getting mostly phase modulation, the addittion of wave plates improved the performance of the LCoS as a phase modulator.

In our experimental arrangement the He-Ne laser incidence was almost normal to the LCoS display (aproximately 4^o from the normal). The LCoS display was reached after the light passed through a first polarizer $P1$ and a first wave plate $L1$ (90^o phase shift). The distance between the He-Ne and the display was $230cm$ in order to get a better *almost normal incidence*. After the display, another wave plate and polarizer, $L2$ (72^o phase shift) and $P2$ respectively, were added. We measured the intensities of diffraction orders 0 and 1 with a photosensor *Universal Optical Power Meter, Melles Griot*. These diffraction orders were the result of sending to the LCoS a *Ronchi* grating so as to determine the phase and amplitude modulation according to *Zhang et al.* [13]. We tested the LCoS phase and amplitude responses for different rotation angles of the four elements P1, P2, L1, L2. All angles measured follow this convention: in the sense of light propagation, angles increase clockwise being angle 0 the corresponding to the vertical axis of the laboratory.

The best arrangement of polarizers and wave plates gives us the result shown in Figure 2. There, it is possible to see a 2π phase modulation together with a 25% variation in intensity. It should be mentioned that variations in small angles (no more than 5^o) in either $P2$ or $L2$ did not mean significant qualitative variations in the phase response.

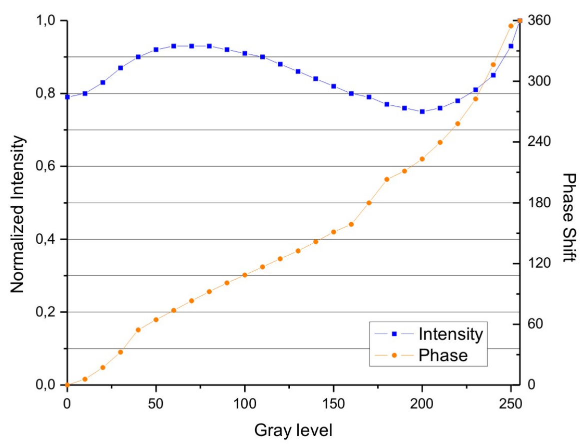

FIGURE 2. Intensity and phase modulation for gray levels in the LCoS display. We use $P1$ at 50^o, $L1$ at 110^o, $L2$ at 2^o and $P2$ at 7^o. It reaches a complete phase modulation with an intensity variation of 25%.

Once we obtained the desired modulation, we made an inverse adjustment of the modulation phase curve. With an appropriate software we transformed the desired phase shift in gray levels to be sent to the LCoS. It is shown in a work by *Engström et al.* [14], that when the phase shift is near π the phase retrieval algorithm that we used [13] does not perform as well as in the other values. To avoid this problem, we forced the value of π to the gray level in which we had the maximun gain in the first order with respect to the zeroth in the diffraction pattern generated with the Ronchi grating.

4. DISPLACEMENT IN THE FOCUS PLANE

The results obtained according to Figure 2 were used to generate the displacement of the laser spot in the focus plane. To capture the spot image we used a microscope lens 40X and a CCD (*charged coupled device*) camera. In order to generate those displacements of the laser spot we built different images, some of them shown in Figure 3. All images proposed, have a centered circle with a 150 pixels of radius inside which the phase is arranged. The rest of the image is a Ronchi π phase grating with an 8 pixels period. This grating makes null completely the zeroth order. In this way, the spot will be generated only by light passing through the linear phase. We selected three directions for the linear phase in order to move the spot to the vertex of an equilateral triangle. We used two different slopes inside the circles: going from 0 to 2π and 3π.

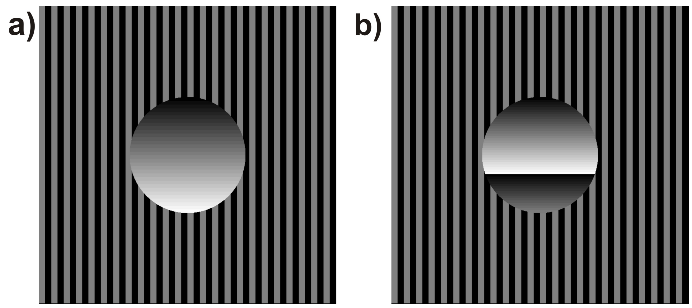

FIGURE 3. Examples of images represented on the modulator to produce the movement of the laser spot on the focus plane. The center corresponds to a linear phase of 150 pixels of radius. In the background there is a Ronchi grating of 8 pixels period with phases 0-π. The scale of the circle and the background are different for a better visualization. We can see one direction that will produce the vertical displacement for: **a)** phase 2π circle, **b)** phase 3π circle.

The displacements achieved by the 2π and the 3π phases are shown in Figure 4. Here we superimpose the images obtained by successively representing the three linear phases that produce the displacements to each vertex of an equilateral triangle. It is clear to see that the displacement with the 3π phase is greater than with the 2π. Nevertheless, from Figure 5, we can see that a complete resolution of the spots is reached using a 2π phase image.

It should be noted that some interference artifact is present due to the normal protection at the input of the CCD.

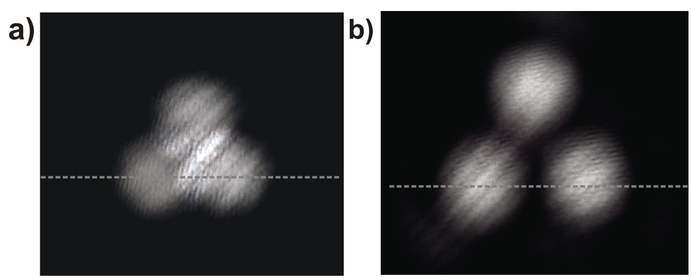

FIGURE 4. Displacement of the laser spot by means of the generation of linear phases in circles, like shown in Figure 3. We superimpose the images obtained by three linear phases. The corresponding phases are: **a)** 2π, **b)** 3π.

5. AXIAL DISPLACEMENT

The last step to get an arbritary 3D displacement consists on making a displacement of the spot out of the focus plane. With this purpose, the image proposed was a lens inside a circle of radius equal to 150 pixels. The lens was implemented by displaying a quadratic phase. We used a phase 2π which image is shown in Figure 6.

Measurements of the intensity were carried every 100μm using a micrometrical translational stage over which the objective lens was mounted. We got the intensity of the spot from the image taken by the CCD. In Figure 6 it is possible to see the results achieved for the movement out of the focus plane (with reference to the no lens image in the focus plane). The crossing between these two axial intensities is under 0.5 for the spot with no lens leading us to conclude that the movement is resolved out of the focus plane.

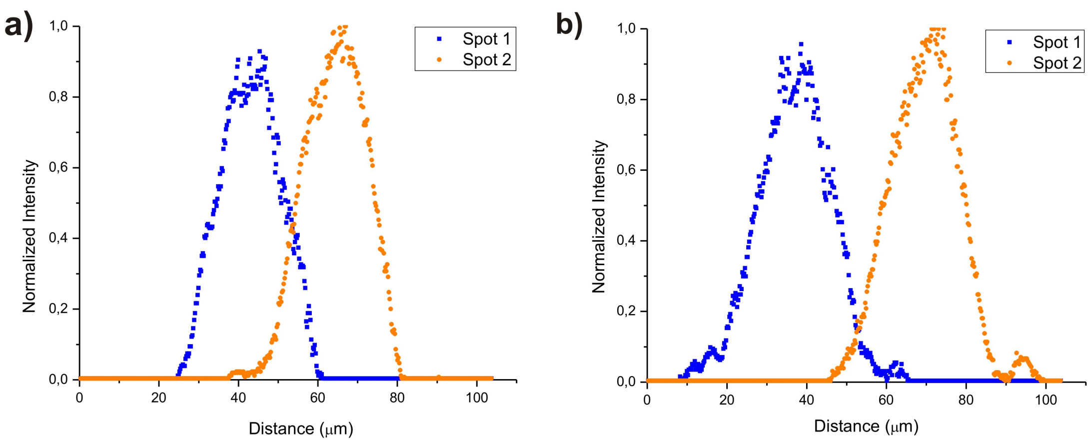

FIGURE 5. Intensity profile for two points of the triangle generated with circles with a linear phase. **a)** 2π, **b)** 3π (see Figure 4).

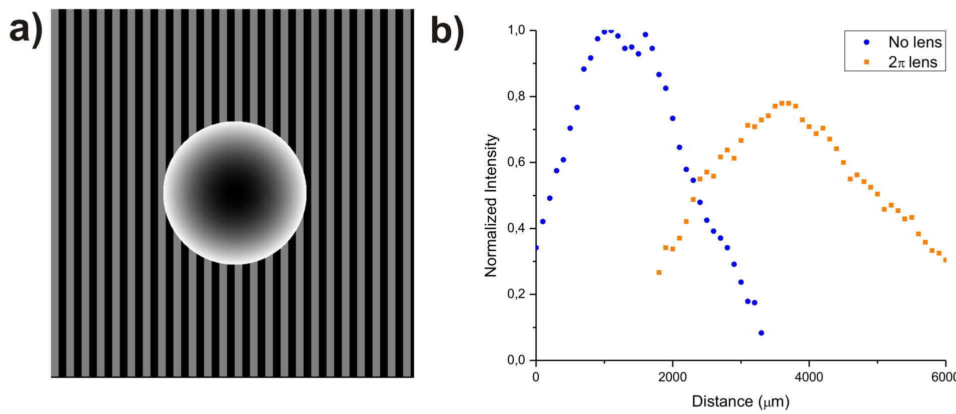

FIGURE 6. **a)** Image represented on the modulator to produce the axial displacement of the laser spot. The center corresponds to a quadratic phase of 150 pixels of radius of 2π. In the background there is a Ronchi grating of 8 pixels wide with phases 0-π. The scale of the circle and the background are different for a better visualization. **b)** Normalized intensities for the axial displacement generated with the circle with a quadratic phase, compared with the intensity of the empty circle in the focus plane.

6. CONCLUSIONS

We propose a possible experimental arrangement for the use of the LCoS display. It consists on an almost normal incidence using large distances between the laser and the measurement device, and the display. With the use of elliptical light we achieved to find empirically a curve that possesses a mostly phase modulation, reaching the maximum desired of 2π. We obtained intensity variations of about 25%.

It was demonstrated that it is possible to generate the displacement of the laser spot using an LCoS display with a mostly phase modulation. It was verified that the movement of the spot in the focus plane can be made by means of the representation of images with linear phases on the LCoS display. It was possible to produce the movement to the vertex of an equilateral triangle. There was no remaining intensity in the zeroth order. In the axial axis, the displacement of the spot was resolved with respect to the circular image in the focus plane using a lens with a quadratic phase of 2π.

These results could be implemented at video rate in fluorescence microscopy for particle tracking.

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