

# Cylindrical diffractive lenses recorded on PVA/AA photopolymers

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## ABSTRACT

Photopolymers are optical recording materials appealing for many different applications such as holography, data storage, interconnectors, solar concentrations, or wave-guides fabrication. Recently the capacity of photopolymers to record diffractive optical elements (DOE's) has been investigated. Different authors have reported proposes to record DOE like fork gratings, photonics structures, lenses, sinusoidal, blazed or fork gratings. In these experiments there are different experimental set-ups and different photopolymers. In this work due to the improvement in the spatial light modulation technology together with the photopolymer science we propose a recording experimental system of DOE using a Liquid Cristal based on Silicon (LCoS) display as a master to store complex DOE like cylindrical lenses. This technology permits us an accurate control of the phase and the amplitude of the recording beam, with a very small pixel size. The main advantage of this display is that permit us to modify the DOE automatically, we use the software of the LCoS to send the voltage to each pixel. In this work we use a photopolymer composed by acrylamide (AA) as polymerizable monomer and polyvinyl alcohol (PVA). We use a coverplated and index matched photopolymer to avoid the influence of the thickness variation on the transmitted light. In order to reproduce the material behaviour during polymerization, we have designed our model to simulate cylindrical lenses and used Fresnel propagation to simulate the light propagation through the DOE and analyze the focal plane and the properties of the recorded lenses.

**Keywords:** diffractive optical elements, holographic recording materials, photopolymers, spatial light modulators.

## 1. INTRODUCTION

Photopolymers are versatile optical recording materials, classically ~~were~~ used for holographic and data storage applications [1-3], and nowadays many new applications have been explored [4-8]. For each particular application, the different families of photopolymers are chemically optimized. Photopolymer materials enable modulation of the material's permittivity and thickness presenting low values of scattering. Their optical properties can be exploited to record phase diffractive optical elements (DOE), using the relief surface changes and the refractive index modifications [8, 9].

One of the most used materials of this type because of its good properties, is a photopolymer based on an acrylamide (AA) monomer. These materials have an acceptable energetic sensitivity compared with other available materials and the possibility of easily adapting their spectral sensitivity to the type of the recording laser used; only changing the sensitizer dye. They also have a large refractive index modulation, an acceptable resolution and signal/noise ratio [10-14]. This work is focused specifically on polyvinyl alcohol/acrylamide (PVA/AA).

In previous works, the parameters involved on the diffractive phase image formation have been determined [15] in a simple model that predicts the surface variations and refractive index distribution in PVA materials using different kind

of monomers with their different polymerization rates and diffusion velocities [15]. The simplicity of this model resides in the reduction of many parameters involved in the process of grating formation in photopolymers, like the non-local effects, kinetics parameters and dye influence [10-12]. Furthermore, for many diffractive optical elements, such as lenses or axicons, a phase depth of  $2\pi$  is required; this value depends on the refractive index variation and the thickness. In this sense, we have developed different studies to find out the minimum thickness required to obtain this phase depth value for each chemical composition.

Once we are sure that the properties of the photopolymer are enough to record cylindrical diffractive lenses, we design the hybrid digital-optical experimental set up to record the lenses in the photopolymer, presented in Figure 1. The diffractive lenses are projected onto the material using a last generation spatial light modulator based on Liquid a Cristal on Silicon (LCoS) microdisplay working in the amplitude mode. In this setup is both used to register and analyze the diffractive optical lenses. The recording process uses the wavelength 532 nm, and the lenses are calculated to be used with the 633 nm wavelength. The system is designed to measure the performance of the lenses in real-time, while the recording process is taking place. We distinguish two arms: the recording arm, using the wavelength 532 nm provided by a solid-state Verdi laser (Nd:YVO4) with recording intensity of  $0.5 \text{ mW/cm}^2$ , and the analyzing arm, using the wavelength 633 nm, to which the material presents no absorption, provided by a He-Ne laser. In the recording arm we place the LCD sandwiched between two polarizers (P), which are oriented with the appropriate angles ( $45^\circ$  for the first one and  $-45^\circ$  for the last one) to produce amplitude-mostly modulation with a contrast of 20. Then, a 4F system is used to image the intensity transparency displayed on the reflective LCD onto the recording material. In previous works, a transmissive LCD was used [19]. To generate the diffractive lenses, we use an LCoS-Pluto provided by Holoeye with a resolution of  $1920 \times 1080$  (HDTV) pixels and a pixel size of  $8 \times 8 \text{ }\mu\text{m}^2$ , previously characterized [1]. The analyzing arm is designed so that the beam of light incident onto the recording material is collimated. D1, a diaphragm, is used to limit the aperture of the collimated beam. We need to introduce a non-polarizing beam-splitter to make that both beams of light, the recording and the analyzing, follow the same path. After the recording material, we have introduced a red filter so that the light incident onto the final CCD camera is only coming from the analyzing beam. The lens recorded on the photopolymer is responsible for the focusing of the 633 nm wavelength beam. We image the point spread function (PSF) generated by the diffractive lens onto the CCD camera. We can control the magnification of our experimental set-up using a 4-F system by the focal lengths of L3 and L4 [16]. We use a high dynamic range CCD, which is necessary to appreciate details in the PSF. This CCD camera model is pco.1600 from pco.imaging. A high dynamic 14 bits cooled CCD camera system with a resolution of  $1600 \times 1200$  pixels and a pixel size of  $7.4 \times 7.4 \text{ }\mu\text{m}^2$ . The camera is also used on the plane of the recording material to evaluate the intensity pattern actually imaged from the LCoS plane.

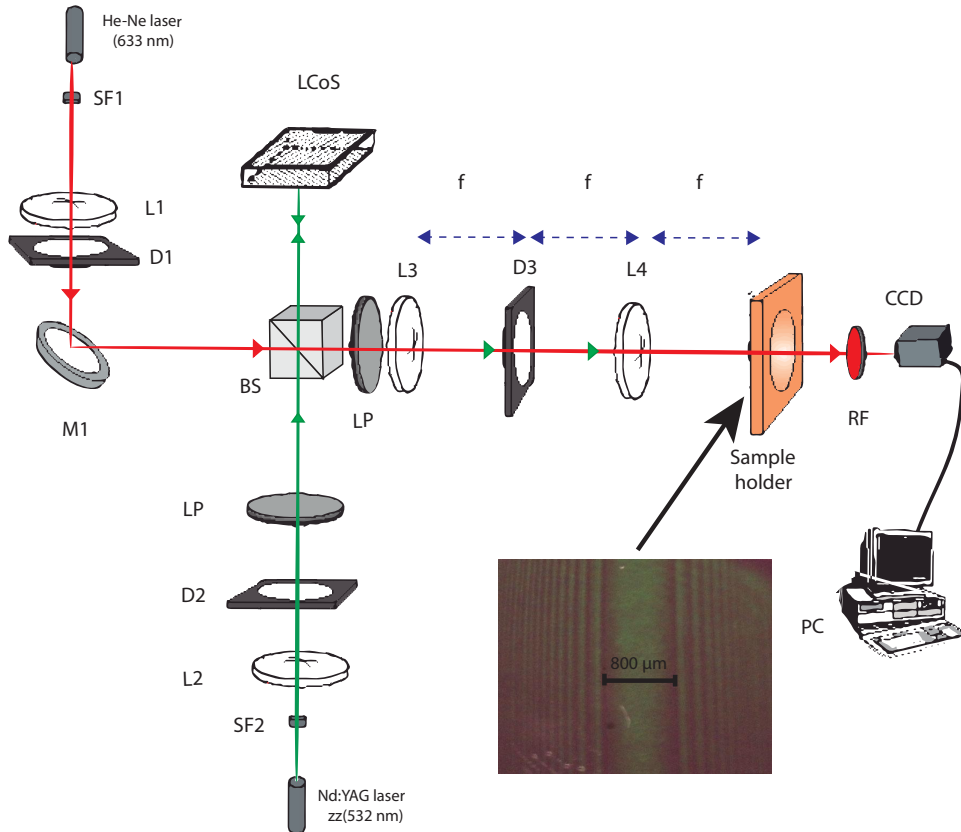


Figure.1 Experimental setup used to register and analyze in real-time the DOEs (diffractive lenses) D, diaphragm, L, lens, BS, Beam splitter, SF, spatial filter, LP, lineal polarizer, RF, red filter.

The recording intensity distribution from the spatial light modulator in the amplitude regime is projected on the material and produces the corresponding phase element. In particular, in the case of the spherical lens with focal  $f$ , we need to generate a convergent spherical wave front, where the phase depends on the quadratic value of the distance between the point and the lens centum, thus we want to obtain at the first attempt can be write as:

$$I(x, y) = \exp\left[j \frac{\pi}{\lambda f} (x^2 + y^2)\right] \quad (1)$$

To obtain this phase distribution we assume a linear response of the recording material concerting an amplitude distribution generated by LCoS into a phase distribution. Therefore Eq. 6 has to be wrapped to  $2\pi$  value and normalized to the maximum of the intensity,  $I_0$ . In this sense for  $f=1\text{m}$  when we imaged an amplitude distribution with a maximum intensity in the middle and there are a series of rings of zeros located at:

$$r_m = \sqrt{m(2\lambda f)} \quad (2)$$

Where  $m$  is a natural number,  $f$  is the focal length and  $\lambda$  is the light wavelength. Moreover, we know that the maximum phase shift achieved for photopolymers at these spatial frequencies range is slightly higher than  $2\pi$ . Therefore, we have to wrap the phase as is depicted in Fig. 2; this desired intensity distribution is generated using a LCD.

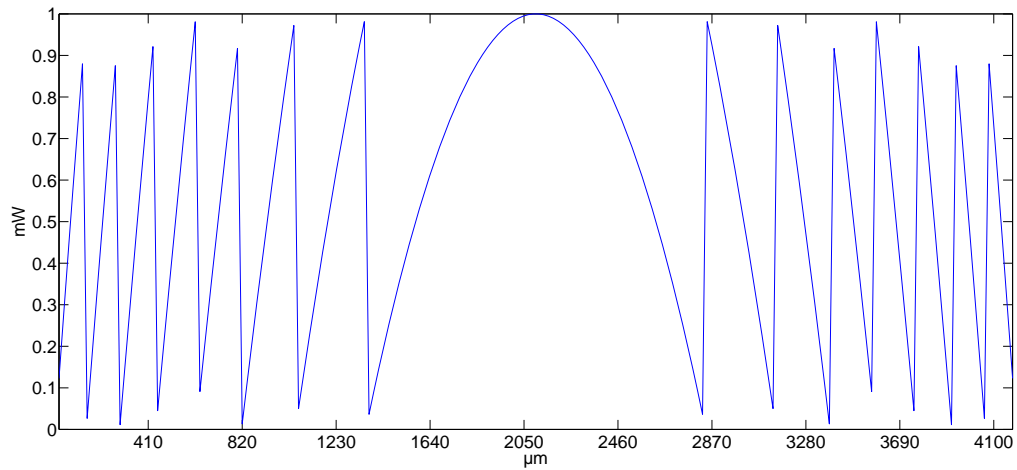
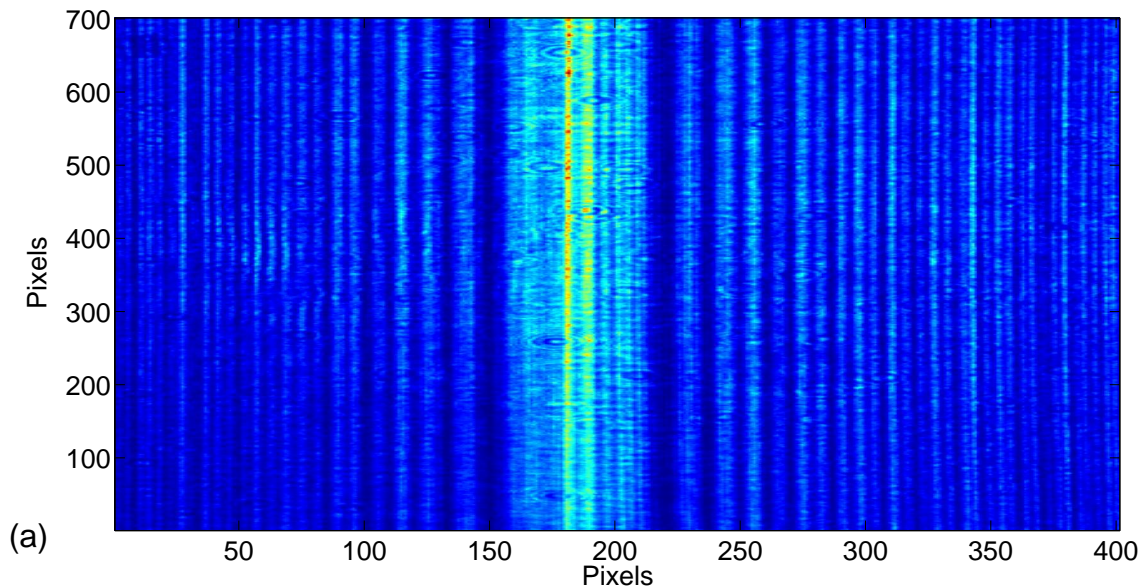


Figure. 2 Theoretical intensity distribution (horizontal cut) projected onto photopolymer for a focal length of 50 cm.

In Fig. 3.a, we show the image obtained using the CCD camera when it is placed in the recording plane. We see the characteristic structure with decreasing period as we move away from the center of the diffractive lens. In Fig. 3.b, we show the intensity plot along the horizontal line passing through the center of the lens. This intensity pattern in Fig. 3 is the exposure pattern that will be recorded on the photopolymeric material. This new spatial light modulation is composed by square pixel of  $8 \mu\text{m}^2$  that provides the opportunity of recording symmetric and asymmetric holographic patterns using a single beam [16] or alternative diffractive optical elements with more resolution. Nevertheless, we can see some important differences between figure 2, ideal intensity distribution, and figure 3 due to the finite size of pixels and the low pass filtering of the optical set-up, these differences are more accused in the boundaries of the lens where the distance between two consecutive peaks is smaller.



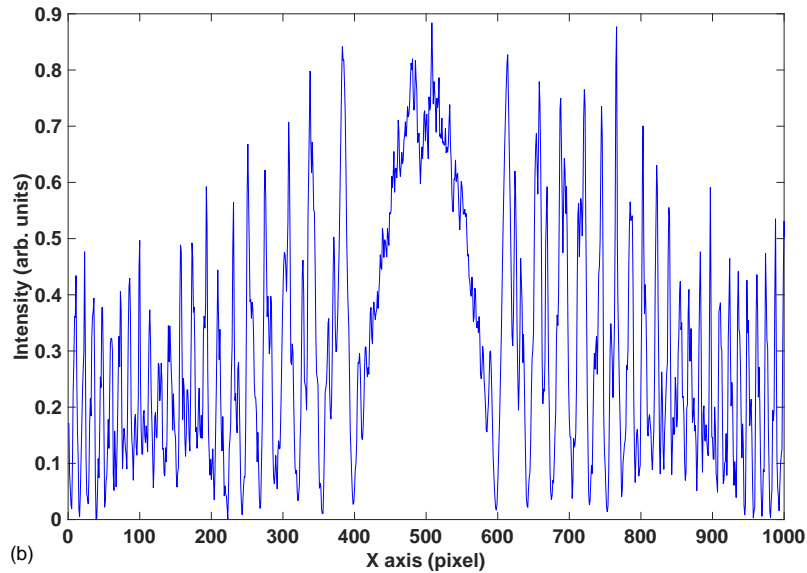


Figure 3. (a) Image of the LCoS at the material plane (where the intensity transmittance equivalent lens is displayed) captured by the CCD camera. This plane is where the photopolymer should be placed. (b) Intensity profile across the horizontal line passing through the center of the lens.

In this work we use a photopolymer composed by acrylamide (AA) as polymerizable monomer, *N,N'*-methylene-bisacrylamide (BMA) as crosslinking monomer, triethanolamine (TEA) as coinitiator and plasticizer, yellowish eosin (YE) as dye, polyvinyl alcohol (PVA) as binder and a small proportion of water as additional plasticizer. Different types of PVA can be used as binder. In this work we have used a PVA 18-88 with  $M_w = 180000$  amu. The particular concentration used in this work is presented in Table 1. To index match the photopolymer, we used a glycerin with refractive index  $n=1.478$ . This value fits perfectly with our pre-exposed photopolymer with a refractive index of 1.477, measured with a refractometer and published in previous works [15]. For the preparation of the layer, 30 ml of solution with water as the solvent is deposited using the force of gravity on a glass substrate (20 cm x 20 cm) and left in the dark (RH = 40–45%, T = 20–23 °C). When part of the water has evaporated (after about 36 hours), the layer has enough mechanical resistance and can be cut without deforming. The final “solid” film has a physical thickness around  $90 \pm 5$   $\mu\text{m}$ . This final thickness can be modified changing the quantity of the syrup deposited on the glass.

**Table 1. Composition of the liquid solution for photopolymer AA.**

TEA (ml)	PVA (ml) (8% w/v)	AA (gr)	BMA (gr)	YE (0.8% w/v) (ml)
2.0	25	0.84	0.2	0.6

## 2. RESULTS AND DISCUSSION

In this section we present we experiments performed to store cylindrical diffractive lenses onto PVA/photopolymers. Taking into account previous results [15] for sinusoidal low spatial frequencies gratings, we expected that the phase depth of  $2\pi$  can be achieved after 150 s of recording for this recording intensity, where the light is focalized along a vertical line. In order to analyze the formation of the cylindrical lens in the photopolymer, we place the CCD camera just in the focal plane. In figure 4, we present the images captured with the camera before recording and after 150 s and in figure 5 the intensity distribution along the middle horizontal axis for recording times: 0, 40, 80, 120, 160 and 200 s. As it can be seen, the red light begins to be focalized along a line, and the intensity of this line is growing during the first 140 s to arise a maximum value for this exposition time, very near to the 150 s expected. After this point, we observe a small defocusing effect, maybe due to the overmodulation, the phase depth, slightly larger than  $2\pi$ , or an increment of the noise.

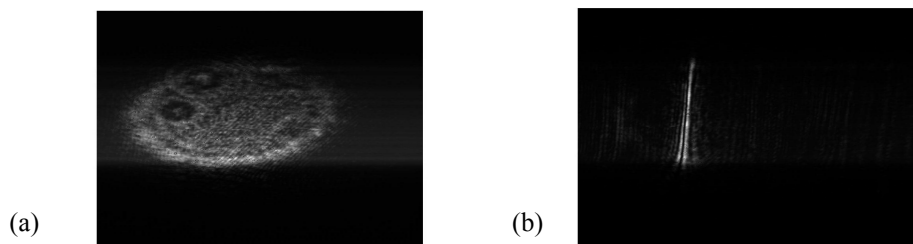


Figure 4. Images of the intensity distribution at the focal plane of the stored cylindrical diffractive lens before and after recording (a) 0 s and (b) 150 s.

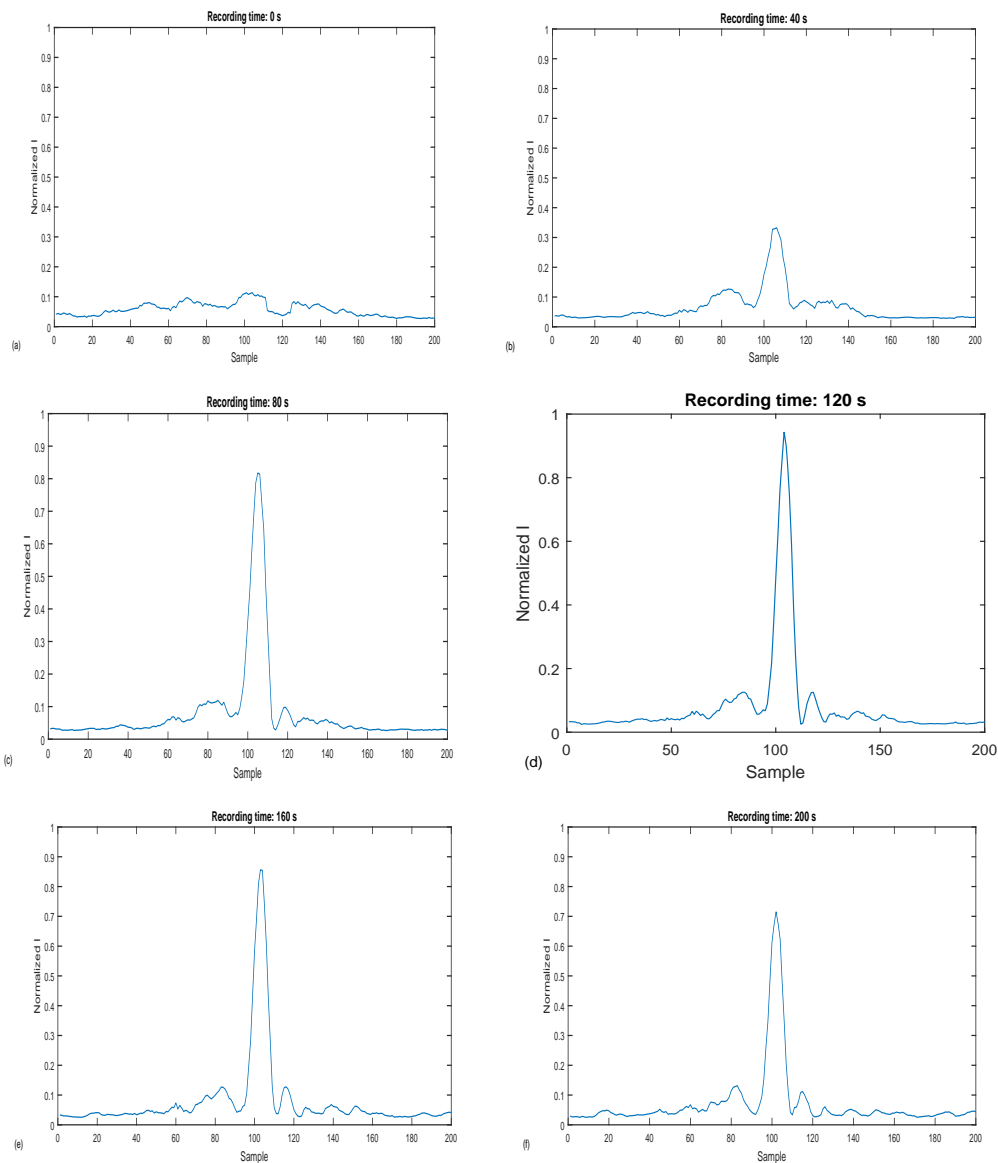


Figure 5.- Intensity distribution at the focal plane along the middle horizontal axis for different recording time (a) 0 s, (b) 40 s, (c) 80 s, (d) 120 s, (e) 160 s and (f) 200 s.

From figure 4 we can see the good focalization of our recorded lens; nevertheless, this focalization is not perfect. In previous works presented two years ago in the same conference [17] we discussed that one of the most important drawbacks of our hybrid digital-optical experimental set ups is the low pass filter due to the diaphragm D3. This component let us to eliminate the effect of the pixilation in the projected image, but on the other hand, smooths our image. In the case of diffractive lenses this effect is especially important due to the sharp profiles required, see Figure 2. In order to obtain more quantitative information about the diffractive lens formation we have used the diffusion model proposed in reference [8]. The idea is to model the intensity in the center of the focal plane as a function of the recording intensity, these results are presented in figure 6, where both experimental and simulation results are presented. As we show in this figure, the simulations and experiments agree perfectly. It is important to remark that all the parameters introduced in our model are previously measured using interferometric and diffractive techniques [15].

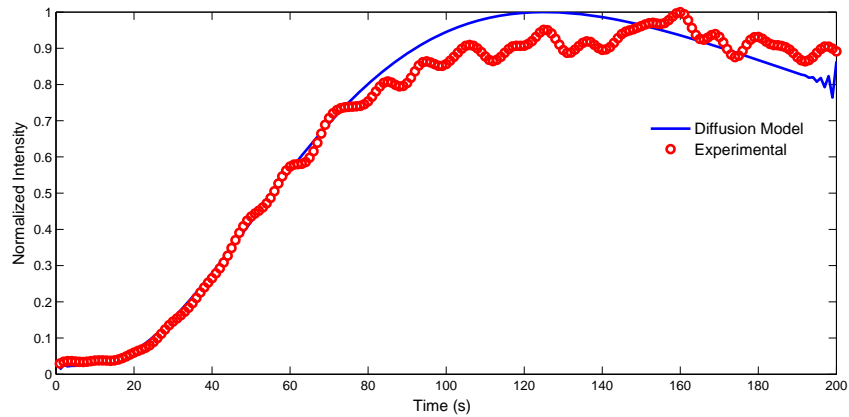


Figure 6. - Intensity at the focal point as a function of the experimental recording and the theoretical simulation for cylindrical lens  $f=0.5$  and layer thickness of  $95\pm 2 \mu\text{m}$ .

#### 4. CONCLUSIONS

To summarize, we have presented a detailed method to record cylindrical diffractive lenses onto photopolymers with good focus power. Firstly, we have proposed a hybrid optical-digital experimental set up using a LCoS display as a master and a PVA/AA photopolymer as diffractive recording material. We have shown as the optimum recording time for the recording intensity of  $0.5 \text{ mW/cm}^2$  is around 160 s. After this time, the intensity focused in the focus line decreases. We have validated the model to reproduce and predict the experimental behavior of the photopolymer in the lenses fabrication. This is a practical and elastic method to fabricate and simulate diffractive lenses in photopolymers. Additional studies can be done analyzing the properties of the recorded lenses, such as the shape of the PSF of these stored lenses.

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