

Generation of Diffractive Optical Elements onto Photopolymer using Liquid Crystal on Silicon Displays

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Abstract— In recent years, the optical storage and optical information processing technologies based on holographic and photonic techniques are suffering a huge improvement. On the other hand, Spatial Light Modulators (SLMs) based on LCoS microdisplays (PA-LCoS) open new possibilities to modulate the wavefront of a light beam. PA-LCoS are high resolution reflective devices which make possible the generation of Diffractive Optical Elements (DOE) with many important applications in photonics, communications of optical information processing, whenever it exists the possibility to have a recording material with the optimum characteristics for each application. Recently it is being explored the incorporation of photopolymers, initially used for holographic recording and data storage applications, to fabricate DOEs. Working with a setup based on a LCoS display as a master, we can store complex DOE, such as blazed gratings or diffractive lenses onto the photopolymers. We used a coverplating and index matching system on the material to avoid the influence of the thickness variation on the transmitted light.

Keywords—*Diffractive Optical Element, Photopolymer, Spatial Light Modulator, LCoS, Holography.*

I. INTRODUCTION

In recent years, the optical storage and optical information processing technologies based on holographic and photonic techniques are suffering a huge improvement.

Thanks to the advances on their technologies, the use of Spatial Light Modulators (SLMs) in this kind of applications to modulate the wavefront of a light beam is also being widespread. The use of parallel-addressed liquid crystal on silicon (PA-LCoS) microdisplays [1] has replaced previous liquid crystal display (LCD) based technologies in this field. PA-LCoS are high resolution reflective devices which enable phase-only operation without coupled amplitude modulation, but can be used also as an amplitude master just rotating the angles of two polarizers. These devices make possible the generation of Diffractive Optical Elements (DOE) with many important applications in photonics, communications of optical information processing [2], whenever it exists the possibility to have a recording material with the optimum characteristics for each application. Photoresists [3] have been used classically for

this purpose. Recently it is being explored the incorporation of photopolymers, initially used for holographic recording and data storage applications [4], to fabricate DOEs. The versatility to change their composition and design [5-7] among other very interesting properties, such as the self-processing capability and the low price, makes this material a very promising option in diffractive optics.

One of the most used materials of this type, because of its good properties, are the photopolymer based on polyvinyl alcohol/acrylamide (PVA/AA) monomer [8], which have been demonstrated their high linearity and fidelity working in both high and low spatial frequencies [9]. Although their good properties, these materials present a high level of toxicity [10]. In this sense, we have made efforts to search alternative “green” photopolymers, one of these is called “Biophotopol” [11]. This material uses sodium acrylate (NaAO) as the main monomer and has exhibited, additionally to its high environmental compatibility, a wide dynamic range and a high sensitivity added to its self-processing nature and low cost.

The versatility of photopolymers can even be increased by including new components to their formulations, such as nanoparticles or dispersed liquid crystal molecules. These materials, known as Polymer Dispersed Liquid Crystal (PDLC), open the door to new and interesting additional applications [12], like the control of the DE of a DOE by applying an electrical field. This leads to the possibility of using these DOEs in dynamic applications for beam steering, non-linear optics, and the possibility to obtain optical switching devices [13].

Working with a setup based on a LCoS display as a master, we are able to store complex DOE, such as blazed gratings [14] or diffractive lenses [15] onto the photopolymers. We used a coverplating and index matching system on the material to avoid the influence of the thickness variation on the transmitted light [16].

The material behavior during the recording process for different photopolymer families (AA/PVA, Biophotopol and PDLC) is reproduced using our diffusion model [17]. Experimental data is compared with the simulation results to evaluate the accuracy of our model to reproduce the recording of any kind of complex

DOE onto a photopolymer. This allow us to choose the appropriate characteristics for the material depending on the application and evaluate the influence of different parameters involved in the DOE generation.

II. EXPERIMENTAL

A. Experimental setup

To evaluate the recording of sharp DOEs, the setup shown in Figure 1 was used. A solid-state Verdi laser (Nd:YVO4) with a wavelength of 532 nm (green light), at which the material exhibits maximum absorption, was used during the recording process.

In the setup, we can distinguish two beams, the recording beam and the analyzing beam. The periodic pattern, in this case the blazed grating, is introduced by a Liquid Crystal on Silicon (LCoS) modulator placed along the recording arm of our setup and sandwiched between two polarizers (P) oriented to produce amplitude-mostly modulation. Then, with a 4f system the intensity distribution generated by the LCoS is imaged onto the recording material. In this work, we have used a recording intensity of 0.25 mW/cm², because the different photopolymers tested present an acceptable response and we can analyze the diffraction efficiencies in real time.

The analyzing arm is made up of a He-Ne laser at a wavelength of 633 nm, at which the material exhibits no absorption, used to analyze in real time the elements formed on the material. This arm is designed to collimate the light incident on the recording material and a diaphragm (D1) was used to limit the aperture of this collimated beam of light.

A non-polarizing beam splitter (BS) was used to make the two beams follow the same path up to the red filter (RF) placed behind the recording material to ensure that only the analyzing beam is incident on the CCD placed at the end of the setup. In the case of the recording of diffractive lenses, we image directly 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. In the case of the blazed gratings, to separate the different diffraction orders, we placed a lens behind the material, obtaining the Fraunhofer diffraction pattern on the camera. We used a high dynamic range CCD camera model pco.1600 from pco.imaging. This camera has a resolution of 1600 × 1200 and a pixel size of 7.4 μm × 7.4 μm. The camera was also used in the plane of the recording material to evaluate the intensity pattern actually imaged from the LCD plane, as is shown in Figure 2.

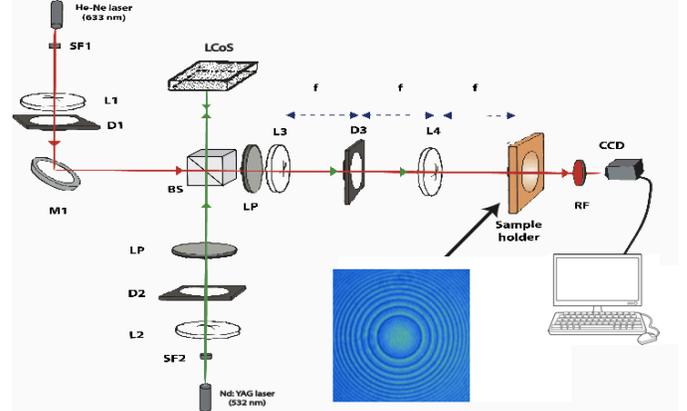


Fig. 1. Experimental setup used to register and analyze in real-time the DOEs (diffractive lenses) D, diaphragm, L, lens, BS, Beam splitter, SF, spatial filter, LP, lineal polarizer, RF, red filter.

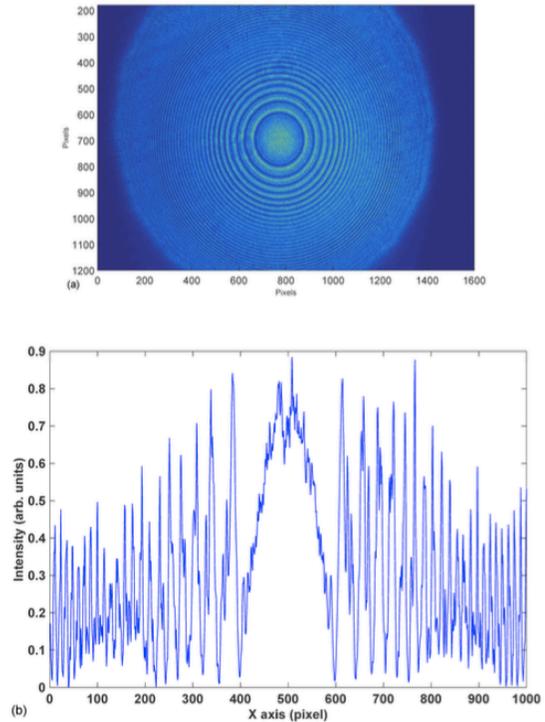


Fig. 2. (a) The image on the photopolymer provided by the LCoS and captured by the CCD camera and (b) the intensity profile provided by the LCoS across a vertical line passing through the center of the lens.

B. Materials

Three different materials have been used and their compositions are shown in Tables 1 and 2.

One is the PVA/AA based photopolymer one of the most studied in the literature. The main problem of this type of photopolymers is the important toxicity of the main monomer, AA. Some efforts have been made to substitute this component in the chemical formulations so as to design highly compatible environmental photopolymers: one of the greenest photopolymers is called Biophotopol, A photopolymer based in this material is the second material analyzed, we study some

different chemical variations of Biophotopol incorporating different crosslinker monomers in order to study the optimum thickness to fabricate 2π phase depth elements. The last material analyzed is one with dispersed liquid crystal molecules, PDLC, for recording DOEs in the low spatial frequency range, as this material is commonly used for the high frequency range. The orientation of the liquid crystal produces a refractive index variation which changes the diffraction efficiency. Therefore, the grating develops a dynamic behavior that may be modified by electronic means. In this manner, it is possible to make dynamic devices such as tunable-focus lenses, sensors, phase modulators or prism gratings. PDLCs are characterized by high values of refractive index modulation that provide diffraction efficiencies close to 100% for an optical thickness around $10\ \mu\text{m}$, but the main drawback is the high value of scattering.

TABLE I. AA AND BIOPHOTOPOL FORMULATIONS

Composition name	AA1	AA2	BIO1	BIO2	BIO3
NaAO (g)	-	-	1	1.5	1.5
TEA (ml)	2.0	2.0	2	3.0	3.0
PVA (ml) (8% w/v)	25	25	30	25	25
YE (0.8% w/v) (ml)	0.6	0.6	0.84	0.6	0.6
DHEBA (g)	-	-	-	0.18	-
BMA (g)	-	0.2	-	-	0.18
AA (g)	0.96	0.84	-	-	-
Thickness $\pm 4\ (\mu\text{m})$	90	90	90	90	90

TABLE II. PDLC FORMULATION

Photopolymer	DPHPA	BL036	YEt	NPG	NVP	OA
H-PDLC	48.4	29.2	0.1	1.5	16.4	4.4

III. RESULTS

Thanks to the addition of the index matching system on the material, we can avoid the influence of the thickness variation on the transmitted light and separate between the “apparent” diffusion due to this thickness variation and the “real” diffusion, the internal monomer diffusion. The values measured for both diffusions in the three different materials are shown in Table 3. In the case of the PDLC materials, this family of polymers is always enclosed between two ITO glasses, and the properties of the hologram or diffracted elements can be switched by the application of an electric field. This special experimental geometry makes impossible to use the index matching method applied for AA and BIO materials. Therefore, for this kind of materials only the “apparent” diffusion can be fitted and the value measured in this case is not appropriate for sharp DOEs recording, as the sharp profiles suffer a smoothing due to this fast diffusion.

TABLE III. FITTED VALUES FOR MONOMER DIFFUSION WITH AND WITHOUT THE INDEX MATCHING SYSTEM

Composition name	AA	BIO	H-PDLC
“apparent” diffusion (cm^2/s)	$2 \cdot 10^{-8}$	$2 \cdot 10^{-9}$	$1 \cdot 10^{-8}$
Internal diffusion (cm^2/s)	$2 \cdot 10^{-10}$	10^{-10}	-

Using the other two materials, suitable for sharp DOEs recording obtaining a phase depth modulation of 2π with the appropriate thickness, we analyzed the recording of diffractive lenses and blazed gratings on them testing not only the suitability of these materials to store this type of DOEs but also the capability of our simulation model [17] to reproduce the recording of these DOEs in the different materials.

Figures 3 and 4 show the intensity at the focal point of a spherical diffractive lens recorded onto the AA/PVA material and the Biophotopol material respectively. To reproduce this, once we have obtained the refractive index distribution using the diffusion model, we used Fresnel propagation to obtain the intensity at the focal point. The results show not only the suitability of these materials to store diffractive lenses and the high focalization power, but also demonstrate the good agreement between the diffusion model and the experiments, that opens an interesting way to produce cheap and manageable diffractive lenses onto photopolymers.

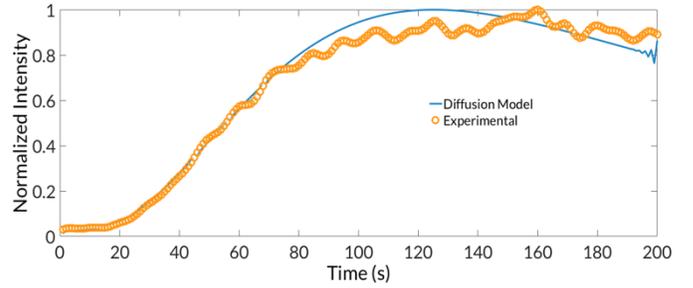


Fig. 3. Intensity at the focal point as a function of the experimental recording and the theoretical simulation for spherical lens $f = 0.5$ recorded on PVA/AA material

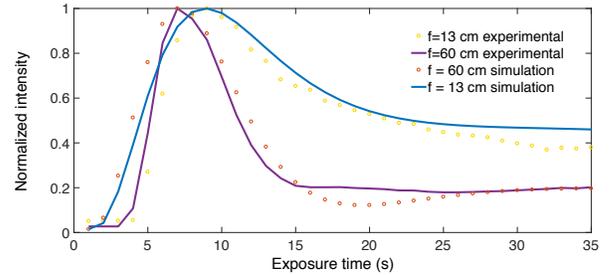


Fig. 4. Intensity at the focal point as a function of the experimental recording and the theoretical simulation for spherical lens $f = 13\ \text{cm}$ and $f = 60\ \text{cm}$ recorded on Biophotopol material

These materials also were used to analyze the blazed gratings recording, as can be shown in Figures 5 and 6. In these figures it can be seen the validity of the model also to reproduce the recording of this type of gratings and the good values of DE achieved, near the 70 % in both cases. These values are near the maximum reachable taking into account the impossibility of obtain 100 % DE due to the low pass filtering introduced by the experimental setup, specially by the diaphragm placed to eliminate the pixilation of the LCoS screen of the Spatial Light modulator.

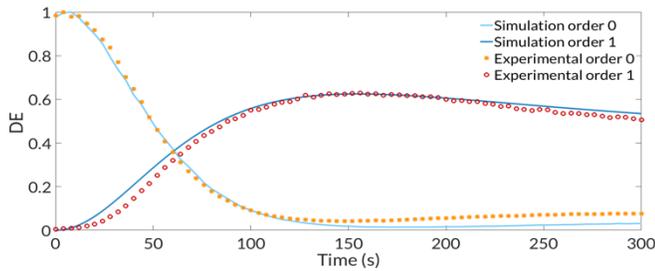


Fig. 5. Comparison of the simulated and experimental DE of a 672 μm period blazed grating recorded onto PVA/AA material.

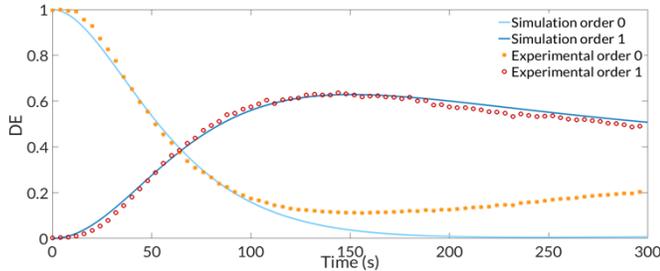


Fig. 6. Comparison of the simulated and experimental DE of a 672 μm period blazed grating recorded onto Biophotopol material.

IV. CONCLUSIONS

The setup based on a LCoS spatial light modulator provide us an alternative way to record complex DOEs with good properties and good resolution allowing us also to characterize the different material properties. We have analyzed different photopolymers and their compositions for low spatial frequency recording and recorded complex DOEs such as diffractive lenses and blazed gratings showing not only the good results provided by materials used but also the capabilities of our diffusion model to simulate and predict the behavior of these materials with good agreement between experimental and simulation results.

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