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Influence of the set-up on the recording of diffractive optical elements into photopolymers

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ABSTRACT

Photopolymers are often used as a base of holographic memories displays. Recently the capacity of photopolymers to record diffractive optical elements (DOE's) has been demonstrated. To fabricate diffractive optical elements we use a hybrid setup that is composed by three different parts: LCD, optical system and the recording material. The DOE pattern is introduced by a liquid crystal display (LCD) working in the amplitude only mode to work as a master to project optically the DOE onto the recording material. The main advantage of this display is that permit us modify the DOE automatically, we use the electronics of the video projector to send the voltage to the pixels of the LCD. The LCD is used in the amplitude-mostly modulation regime by proper orientation of the external polarizers (P); then the pattern is imaged onto the material with an increased spatial frequency (a demagnifying factor of 2) by the optical system. The use of the LCD allows us to change DOE recorded in the photopolymer without moving any mechanical part of the set-up. A diaphragm is placed in the focal plane of the relay lens so as to eliminate the diffraction orders produced by the pixelation of the LCD. It can be expected that the final pattern imaged onto the recording material will be low filtered due to the finite aperture of the imaging system and especially due to the filtering process produced by the diaphragm. In this work we analyze the effect of the visibility achieved with the LCD and the high frequency cut-off due to the diaphragm in the final DOE recorded into the photopolymer. To simulate the recording we have used the fitted values parameters obtained for PVA/AA based photopolymers and the 3 dimensional models presented in previous works.

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

1. INTRODUCTION

Photopolymers are very interesting materials that recently are generating a significant interest as holographic recording media due to its good features, the capacity of self-processing and the low price at which can be acquired [1-3].

Photopolymer materials enable modulation of the material's permittivity and thickness and one of the most important properties of these materials, the linearity in their response during recording, namely, the dependence of the refractive index modulation as a function of recording time, can be exploited to record phase diffractive optical elements (DOE). This is achieved due to the relief surface changes and the refractive index modifications [4, 5].

One of the materials of more interest for its good properties, are the photopolymers 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 recording laser used, only changing the sensitizer dye. They also have a high diffraction efficiency, an acceptable resolution and signal/noise ratio [6].

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This work is centered specifically in the use of the PVA/AA compounds due to their low price, easy preparation and that it's not necessary to use complicated developing processes to make them very useful for a wide list of applications [7-9].

In previous works, the parameters involved on the diffractive phase image formation has been determined [10-12] 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 [13-15]. 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 [16], kinetics parameters [17] and dye influence [18-20].

In this work, we simulate some of the effects produced by the setup, like the effect of the visibility achieved with the LCD and the high frequency cut-off due to the diaphragm in the final DOE recorded into the photopolymer. As has been said above, the simulation of the recording has been done using the fitted values of the parameters obtained for PVA/AA photopolymers. We simulate the hybrid optic-digital experimental set-up presented in Figure 1. In order to record phase diffractive gratings we introduced a spatial light modulator (SLM) working in the amplitude only mode [11] to modulate the green beam. The pattern (sinusoidal, binary, blazed, etc.), is introduced by a liquid crystal display (LCD), a Sony LCD model LCX012BL, extracted from a video projector Sony VPL-V500. We use the electronics of the video projector to send the voltage to the pixels of the LCD. To optimize the visibility and obtain a linear variation of the intensity (I) with the level of grays, the LCD is used in the amplitude-mostly modulation regime by proper orientation of the external polarizers (P). The angles of these polarizers are obtained using the model presented in [11] to obtain the maximum visibility on the DOE; then the pattern is imaged onto the material with an increased spatial frequency (a demagnifying factor of 2). The use of the LCD allows us to change the period of the grating recorded in the photopolymer without moving any mechanical part of the set-up. Nevertheless the size of the pixel, $42\text{ }\mu\text{m}$, of this LCD model limits the minimum value of the spatial period in the recording material to $168\text{ }\mu\text{m}$ (i.e. 8 LCD pixels to reproduce a period).

To eliminate the effects of the pixelation, we have introduced the *Stop2* (Fig.1). This diaphragm eliminates the higher harmonics in the Fourier Transform and produces a low pass-filtering in the DOE projected on the material.

We study the influence of the LCD optimization for amplitude-only modulation and the low pass-filtering produced by *Stop2* in the final characteristics of the DOEs fabricated.

Fig.1 Experimental setup 1 to record diffractive optical elements using the LCD as a master.

2. THEORETICAL MODEL

Three dimensional behaviors can be described by the following general equations:

$$\frac{\partial[M](x, z, t)}{\partial t} = \frac{\partial}{\partial x} D_m \frac{\partial[M](x, z, t)}{\partial x} + \frac{\partial}{\partial z} D_m \frac{\partial[M](x, z, t)}{\partial z} - F_R(x, z, t)[M](x, z, t) \quad (1)$$

$$\frac{\partial[P](x, z, t)}{\partial t} = F_R(x, z, t)[M](x, z, t) \quad (2)$$

For a sinusoidal case we have:

$$F_R(x, z, t) = k_R \cdot I^\gamma(x, z, t) = k_R \left(I_0 [1 + V \cos(K_g x)] e^{-\alpha(t)z} \right)^\gamma \quad (3)$$

where $[M]$ is the monomer concentration, $[P]$ is the polymer concentration, D_m is the monomer diffusion coefficient, I is the recording intensity, I_0 its amplitude, K_g the grating number, k_R is the polymerization constant, γ indicates the relationship between intensity and polymerization rate (F_R), V is the visibility of the fringes, this value will be varied between 0.25 and 1 in order to simulate the visibility of the LCD screen, values between 1 and 0.5 can be considered as normal values of visibility for a LCD screen, values below these are extreme cases; α is the coefficient of light attenuation. The initial value of α [$\alpha(t=0)=\alpha_0$] can be obtained if the transmittance and the physical thickness of the layer are known. In this paper we use the finite-difference method (FDM) to solve a 3-dimensional problem using a rigorous method. Therefore eqs. (1) and (2) can be written as:

$$\begin{aligned} M_{i,j,k} = & \frac{\Delta t}{\Delta x^2} D_m M_{i+1,j,k-1} - 2 \frac{\Delta t}{\Delta x^2} D_m M_{i,j,k-1} \\ & + \frac{\Delta t}{\Delta x^2} D_m M_{i-1,j,k-1} + \frac{\Delta t}{\Delta z^2} D_m M_{i,j+1,k-1} \\ & - 2 \frac{\Delta t}{\Delta z^2} D_m M_{i,j,k-1} + \frac{\Delta t}{\Delta z^2} D_m M_{i,j-1,k-1} - \Delta t F_{Ri,j,k-1} M_{i,j,k-1} + M_{i,j,k-1} \end{aligned} \quad (4)$$

For sinusoidal case:

$$F_R(x, z, t) = k_R \cdot I^\gamma(x, z, t) = k_R \left(I_0 [1 + V \cos(K_g x)] e^{-\alpha(t)z} \right)^\gamma \quad (5)$$

In order to guarantee the numerical stability of the equations, the increment in the time domain, Δt , must satisfy the stability criterion

$$\Delta t \leq \frac{1}{2} \frac{(\Delta x)^2}{D_m} \quad (6)$$

In this paper, we choose $\Delta t = 0.4 (\Delta x^2/D_m)$.

Once the monomer and polymer concentrations are calculated, we can obtain the relief surface formed:

$$d = d_b + d_m + d_p \quad (7)$$

Where d_b is the part of the thickness due to the binder, d_m the part due to the monomer, d_p the part due to the polymer and M_0 is the average initial value for the volume fraction of monomer. Using “zero frequency” interferometry, the differences between monomer and polymer volumes can be calculated. If we assume that d_b is constant we can obtain the thickness of the layer as follow:

$$d = d_0(1 - M_0 - M) + d_{0P} \left(1 - \frac{Sh}{100M_0} \right) \quad (8)$$

Where Sh is the shrinkage of the whole layer in μm where all the monomer is consumed and d_0 is the initial physical thickness of the layer, in the cases analyzed in this paper $d_0=100\mu\text{m}$. The final refractive index distribution during the recording process is:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{n_m^2 - 1}{n_m^2 + 2} M + \frac{n_p^2 - 1}{n_p^2 + 2} P + \frac{n_b^2 - 1}{n_b^2 + 2} (1 - M_0) \quad (9)$$

where n_p is the polymer refractive index, n_m is the monomer refractive index, n_b is the binder refractive index. The values used in this work, are the following: $n_m = 1.486$, $n_b = 1.474$, $n_p = 1.505$. The values of n_m and n_b were obtained using the Lorentz-Lorenz equation [22] with calculations based on refractometer measurements by use of water solutions. The value of n_p was obtained with the Zero Spacial Frequency Limit method used in [10].

The final pattern imaged onto the recording material can be expected to be low-pass filtered due to the finite aperture of the imaging system and especially due to the filtering process produced by the diaphragm. To take into account this filtering, we have applied a low pass filter to the DOE following the general procedure and performing the Fourier Transform with adequate scales in order to check the influence of different diaphragm diameters.

The effect of the visibility achieved with the LCD, namely has been simulated obtaining the maximum and minimum values of the incident intensity based on a given visibility value:

$$I_{\min} = 2 \cdot I_0 \cdot \left(\frac{1 - V}{1 + V} \right) \quad (10)$$

$$I_{\max} = 2I_0 \quad (11)$$

Where I_0 is the input intensity and $I_{\max}$, $I_{\min}$ are the max and the minimum values of the intensity achieved by the LCD screen based on a given value of visibility (V). As has been said, we have simulated using normal values and extreme cases.

3. RESULTS AND DISCUSSION

As has been mentioned along this paper, the main idea is taking into account some effects due to the experimental setup in order to obtain a more complex model able to simulate with much more precision the behavior of the real material.

In this way, we have carried out different experiments for several intensity distributions, taking into account separately the low-pass filtering due to the diaphragm, the visibility of the LCD and both simultaneously. These simulations has been compared with the initial model [13-15] witch obviates the above effects to quantify how they affect the final result of the diffraction efficiency (DE).

3.1 Influence of the LCD visibility.

In these tests we have only take into account the influence of different variations of the LCD visibility for different intensity distribution obviating the low-pass filtering. The Fig.1 shows the effects of different visibility variations in the DE curve of a sinusoidal intensity distribution for the four values mentioned, 1, 0.75, 0.5 and 0.25 corresponding to $I_{\max}$ value of 1 and $I_{\min}$ values of 0, 0.6, 0.33 and 0.143 respectively.

Fig 2. a) Influence of different values of visibility in a sinusoidal pattern. On b) the M distribution for a sinusoidal pattern for a visibility of 1 and 0.25 is shown.

For binary and blazed patterns, the effects of the visibility are similar to those on Fig 2, showing a slower evolution of the DE as the visibility is decreased, resulting in a smaller difference between the maximum and minimum intensity values each time. In this case, with blazed patterns, we have changed the values of d and n_p in order to simulate, as has been done by other authors, materials that doesn't attenuate the profiles in its surface and study properly the effects of the visibility of the LCD and, later, the effects of the low pass filtering in a profile with high first orders. The values simulated are $D_m=0.01 \text{ cm}^2/\text{s}$ and $n_p=1.6$.

In Fig. 3 the form of the patterns for blazed intensity distribution for two well differentiated visibility values is shown, and in Fig.4 we can observe the effect of the visibility in the DE of this kind of distributions.

Fig. 3: Blazed pattern distribution for visibility values of 0.25 and 1.

Fig. 4. Influence in the DE of different values of visibility for binary (a) and blazed (b) distribution patterns.

3.2 Influence of the low-pass filtering due to the diaphragm.

In the same way as in the previous paragraph we studied the influence of the LCD visibility on the DOE, in this case we study the effects produced by the low-pass filtering on the initial model, without any visibility effects, and with a given visibility in the binary and blazed DE (Fig.5) for different sizes of the filter simulating different diameters of the diaphragm. In this case, with blazed patterns, we have changed the values of d and n_p in order to simulate, as has been done by other authors, materials that doesn't attenuate the profiles in its surface and study properly the effects of the low pass filtering in a profile with high first orders. As has been said above, the values simulated for the blazed pattern are $D_m=0.01 \text{ cm}^2/\text{s}$ and $n_p=1.6$. The effects of the low-pass filtering in the distribution patterns can be observed in Fig.6 for blazed intensity distribution. A smaller size of the band pass means a smaller aperture of the diaphragm, therefore, the effect of the filtering is more pronounced.

Fig. 5 Effect of the low-pass on the DE of a binary pattern without any visibility effect (a) and in a blazed pattern (b) with a visibility value of 0.5. The percentage that represents the size of the filter indicates the size of the filter relative to the total size of the pattern. For example, for a pattern with 5472 samples, a filter with a size of the 5.5% means a 300 samples filter.

Fig. 6: Effect of the filtering on the distribution pattern. The effect of the filtering is bigger with smaller filter sizes.

4. CONCLUSIONS

Starting with the validated initial model to simulate the formation of gratings in photopolymers, we have constructed a more accurate version to simulate the recording of DOE on photopolymers which takes into account aspects like the effect of the visibility achieved with the LCD and the high frequency cut-off due to the diaphragm. This model now doesn't ignore these factors and the observable changes that they produced in the final DOE recorded. The effects and the importance of the inclusion of these factors have been shown along this paper.

The effect of the calibration of LCD for working in only amplitude has been shown. Similar effects have been shown for the diameter of the diaphragm. The size of this diameter affects significantly to the diffraction efficiency of the order 1 and to the final shape of the DOE stored.

We have demonstrated the importance of an optimal calibration of the optical experimental setup to fabricate DOE with the desired properties.

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