

Research Article

Overmodulation Control in the Optimization of a H-PDLC Device with Ethyl Eosin as Dye

**Manuel Ortuño,^{1,2} Marina Riquelme,¹ Sergi Gallego,^{1,2} Andrés Márquez,^{1,2}
Inmaculada Pascual,^{1,3} and Augusto Beléndez^{1,2}**

¹ *Instituto Universitario de Física Aplicada a las Ciencias y las Tecnologías, Universidad de Alicante, Apartado 99, 03080 Alicante, Spain*

² *Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal, Universidad de Alicante, Apartado 99, 03080 Alicante, Spain*

³ *Departamento de Óptica, Farmacología y Anatomía, Universidad de Alicante, Apartado 99, 03080 Alicante, Spain*

Correspondence should be addressed to Manuel Ortuño; mos@ua.es

Received 9 September 2013; Accepted 22 October 2013

Academic Editor: Michael J. Bojdys

Copyright © 2013 Manuel Ortuño et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The response of a H-PDLC device is improved by means of a two-step method. First, component optimization—initiator system, crosslinker, and cosolvent—enables the diffraction efficiency of the hologram to be maximized. Second, the use of N-methyl-2-pyrrolidone in combination with N-vinyl-2-pyrrolidone prevents the overmodulation in photopolymers containing ethyl eosin.

1. Introduction

Nowadays, photopolymers are used in holographic applications due to their properties: higher diffraction efficiency with an acceptable energetic sensitivity. They are easily made at a reduced cost and have great flexibility as holographic recording materials [1–4]. The incorporation of liquid crystals adds a special characteristic—the capacity to vary the electrooptical properties by means of an electric field. The liquid crystal molecules add optical anisotropy to the photopolymer, and therefore it is possible to change the photopolymer response modifying the electric field applied [5–10].

Holographic polymer dispersed liquid crystals are known as H-PDLC. They are made by holographic recording in a photopolymerization induced phase separation process (PIPS) in which the liquid crystal molecules diffuse to dark zones in the diffraction grating where they can be oriented by means of an electric field. 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 means of an electronic device. In this manner, it is possible to make dynamic devices such as tunable-focus lenses, sensors, phase modulators, or prism gratings [11–17].

There are many starting criteria for photopolymer optimization: high or low diffraction efficiency, energetic sensibility, low scattering, and so forth. The objective of a H-PDLC material is to act as a support for an electrooptical dynamic device. Bearing this in mind, the material must have the following properties: low thickness for a low electric field, high diffraction efficiency in order to obtain a wide range of responses when the electric field is applied, and low scattering to prevent optical deformations. In order to achieve these properties, we propose a two-step method that may help other researchers to obtain an optimized material quickly and easily. This optimization method takes into account all the previous considerations.

The first step is to optimize the component concentrations so as to obtain a high maximum diffraction efficiency (DE_{\max}) during the recording of the diffraction grating. Initially, the monomer, liquid crystal, and thickness of the layer are selected. The liquid crystal concentration is then set to a fixed value and the concentrations of dye, initiator, crosslinker, and cosolvent are optimized in order to obtain a high DE_{\max} . The variation in each component concentration within a specific range allows the influence of that particular component on the photopolymer to be studied. The components are optimized in the following order: dye, initiator, crosslinker,

TABLE 1: Viscosity of the liquid components at 20°C.

Component	Viscosity 20°C (mPa s)
DPHPA	16000
BL036	23
OA	5
NVP	2.4
NMP	1.67

and cosolvent. When the adequate dye concentration is obtained, the initiator concentration is optimized and so on.

In the second step, the electrooptical properties of the optimized composition with a high DE_{\max} are evaluated. We use N-methyl-2-pyrrolidone (NMP) in combination with N-vinyl-2-pyrrolidone (NVP) since the first additive prevents the overmodulation and this improves the electrooptical response of the device. Thus, we optimized the behavior of the device without detriment to the DE_{\max} optimization achieved in the first step. NVP is a standard component in H-PDLC materials but we found that NVP and NMP have a complementary function in photopolymers with ethyl eosin as dye.

2. Experimental Section

The monomer used was dipentaerythritol penta-/hexaacrylate (DPHPA) with a refractive index $n = 1.490$. We used the nematic liquid crystal Licristal BL036 from Merck. It is a mixture of 4-cyanobiphenyls with alkyl chains of different lengths. It has an ordinary refractive index $n_0 = 1.5270$ and a difference between extraordinary and ordinary index $\Delta n = 0.2670$ [18]. There is a difference of 0.037 between the ordinary refractive index of the liquid crystal and that of the monomer. This implies that the minimum DE will not reach zero when an electric field is applied to the device. But this difference will be less if we consider that $n > 1.5$ for the prepolymer syrup according to the data included in [19] and may be close to 1.52 for the polymerized material according to the previous experiments performed with photopolymers that contain the same monomer [20].

The liquid crystal concentration was set at 28 wt% as the starting point for component optimization. This value falls within the optimum interval obtained by Liu in [19] and remained practically unchanged during the component optimization.

N-Vinyl-2-pyrrolidone was used as crosslinker, N-phenyl glycine (NPG) as radical generator, and octanoic acid (OA) as cosolvent [5]. We used ethyl eosin (YEt) as dye due to the wide experience of our research team in hydrophilic photopolymers with yellowish eosin [21]. N-Methyl-2-pyrrolidone is used in combination with NVP in order to control the overmodulation during the hologram recording.

Table 1 shows the viscosity of the liquid components at room temperature.

The concentrations of dye, initiator, crosslinker, and cosolvent were optimized in order to obtain a high DE_{\max} . The components were optimized in the following order: dye,

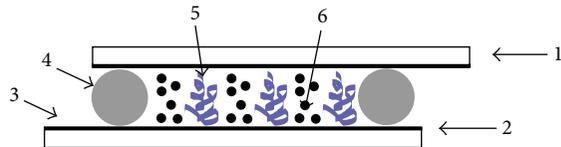


FIGURE 1: Scheme of the H-PDLC device—1: glass plate, 2: ITO coating on glass plate, 3: electric connection zone, 4: glass microspheres, 5: polymer rich zone, and 6: liquid crystal rich zone.

initiator, crosslinker, and cosolvent. The results are included in the following section.

The prepolymer solution was made by mixing the components under red light where the material is not sensitive. The solution was sonicated in an ultrasonic bath, deposited between two conductive ITO glass plates 1 mm thick, and separated using $\sim 13 \mu\text{m}$ glass microspheres. The device was exposed to a laser beam ($\lambda = 532 \text{ nm}$) in a holographic setup in order to record a diffraction grating in the photopolymer layer. A photopolymerization reaction takes place in the bright zones of the diffraction grating and a highly reticulated polymer network is generated. The liquid crystal molecules diffuse to the unexposed region where they remain as droplets.

After recording, the diffraction grating in the H-PDLC is reconstructed ($\lambda = 633 \text{ nm}$) and the diffraction efficiency obtained. The device with the optimized composition is exposed to a variable electric field in order to evaluate the electrooptical properties that the liquid crystal introduces in the photopolymer. We consider a bipolar square waveform, which is generated by a waveform generator connected to a voltage amplifier [5]. Figure 1 shows a scheme of the H-PDLC device. The polymer rich zone and liquid crystal rich zone are separated in the graph but the polymer network penetrates into the liquid crystal rich zones.

2.1. Holographic Setup. We obtained diffraction gratings using a holographic setup to study the behavior of these photopolymers as a holographic recording material. The experimental device is shown in Figure 2. An Nd:YAG laser tuned at a wavelength of 532 nm was used to record diffraction gratings by means of continuous laser exposure. The laser beam was split into two secondary beams with an intensities ratio of 1:1. The diameter of these beams was increased to 1 cm by means of lens, while spatial filtering was ensured. The object and reference beams were recombined at the sample at an angle of 16 degrees to the normal with an appropriate set of mirrors, and the spatial frequency obtained was 1036 lines/mm. The working intensity at 532 nm was 7 mW/cm^2 . The diffracted and transmitted intensity were monitored in real time with a He-Ne laser positioned at Bragg's angle (19.1°) tuned to 633 nm, where the material does not polymerize. The diffraction efficiency was calculated as the ratio of the diffracted beam (I_D) to the incident power (I_0).

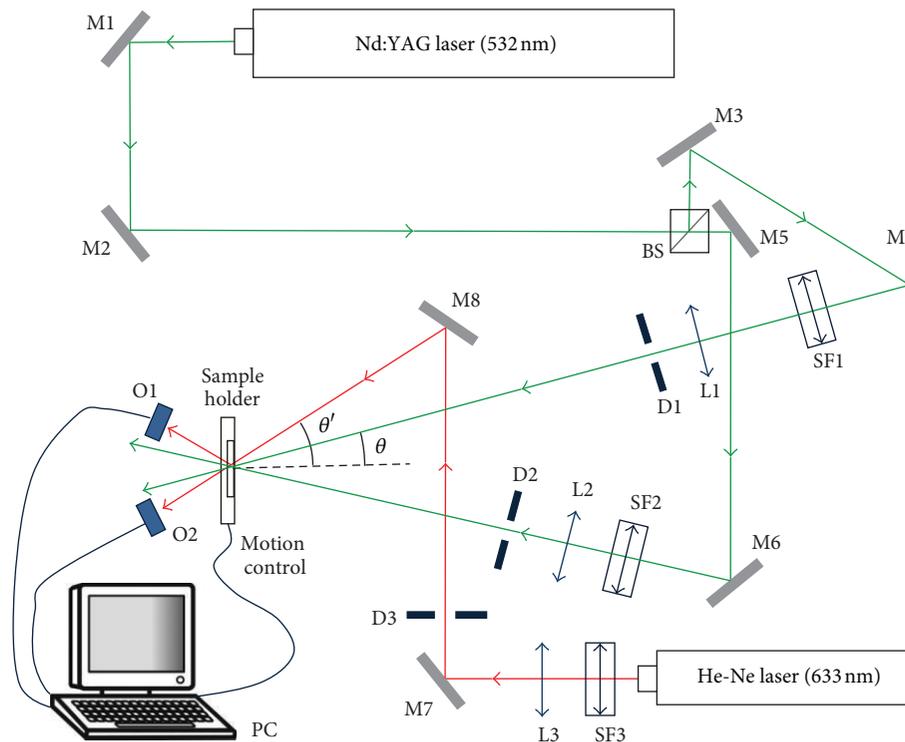


FIGURE 2: Experimental setup. BS: beamsplitter, Mi: mirror, SFi: spatial filter, Li: lens, Di: diaphragm, Oi: optical power meter, PC: data recorder.

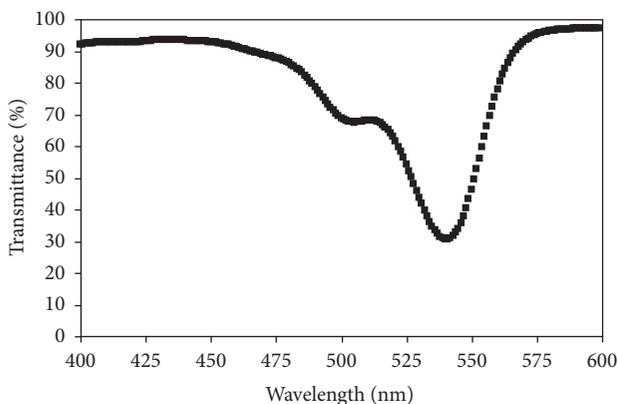


FIGURE 3: Transmission spectrum for the H-PDLC containing YEt dye.

3. Results and Discussion

3.1. Dye Optimization. Figure 3 shows the transmission spectrum before recording H-PDLC layer containing YEt dye. The minimum transmittance is placed into the interval 525–550 nm. The wavelength of the laser recording is 532 nm.

Standard photopolymers without liquid crystals such as poly(vinyl alcohol)/acrylamide materials or acrylic polymers usually contain monofunctional and optionally bifunctional reactive monomers. These materials need a relatively high monomer to polymer conversion in order to reach a high

diffraction efficiency. Therefore, sufficient dye content is necessary, bearing in mind that the typical xanthene dyes are bleached during the photo-initiation process [21].

H-PDLC materials contain mainly polyfunctional monomers in order to get an effective PIPS effect. Polyfunctional monomers obtain a quick and high reticulation of the polymer chains and therefore high refractive index modulation at a lower exposure than standard photopolymers without liquid crystals. For this, the dye content in H-PDLC materials must be very small.

In Figure 4 the concentration of the dye YEt is changed in the range 0–0.7% normally used when a dye is optimized in standard photopolymers. But this photopolymer is a H-PDLC material, and thus we obtain better results with low dye concentrations around 0.1% due to the polyfunctional monomer. A low dye concentration is sufficient to polymerize the polyfunctional DHPA monomer and obtain a high reticulation.

A $DE_{\max} = 67\%$ is obtained with a dye concentration of 0.05–0.1%. A concentration higher than 0.1% obtains a progressively lower DE_{\max} .

3.2. NPG Initiator. NPG is a standard initiator used in H-PDLC materials. The NPG content must be sufficient to produce the photoinitiation reaction between the dye and the initiator. NPG is a solid substance and therefore a high content is related to an increase in viscosity of the solution. The DE_{\max} versus initiator concentration is shown in Figure 5. A concentration of 0.85–1.51% obtains a $DE_{\max} = 62\%$.

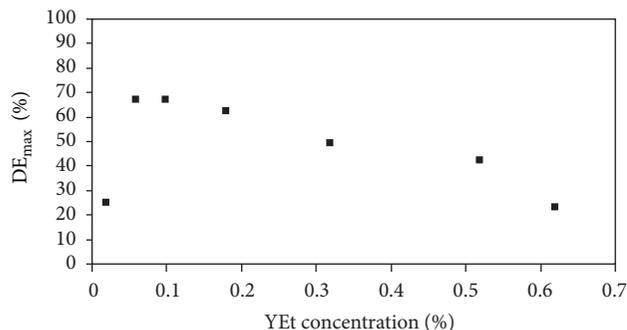


FIGURE 4: Dye content optimization.

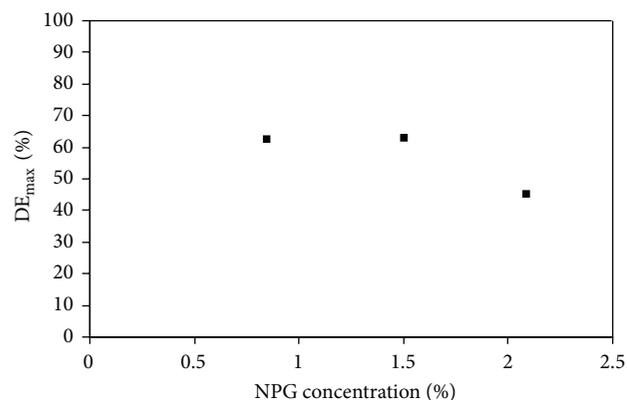


FIGURE 5: Initiator content optimization.

An excessive content of NPG affects the photopolymer indirectly due to the increase in viscosity.

3.3. NVP Crosslinker. NVP is a liquid substance with low viscosity (Table 1) that acts as crosslinker and chain terminator agent. It is a reactive monomer and so not just a simple thinner. It is a critical component in improving acrylate-based H-PDLC materials by reducing the liquid crystal droplet size. NVP causes an increase in the rate of polymerization with increasing concentration. Formulations containing up to 15 wt% demonstrate complete NVP conversion [5].

Figure 6 shows DE_{max} versus NVP concentration. The DE_{max} is not very sensitive to the variation in a specific interval of NVP concentration. It is around 60% with a NVP concentration of 13–20%. This result is very interesting because we could modify the NVP concentration to change the viscosity or to adjust concentrations when the electrooptical response is studied.

3.4. OA Cosolvent. OA is a standard cosolvent that helps to homogenize the prepolymer mix preventing phase separation. This role depends on the specific components in the photopolymer. OA also improves the thermal stability of the prepolymer solution.

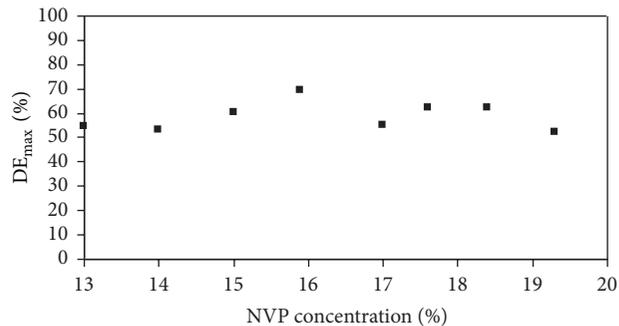
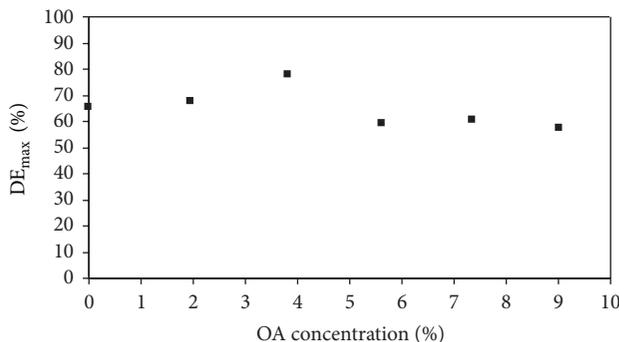


FIGURE 6: Crosslinker content optimization.

FIGURE 7: DE_{max} is slightly reduced when the OA concentration is increased.

OA is a liquid substance with low viscosity (Table 1), and therefore it decreases the viscosity of the prepolymer solution and this implies a better diffusion of the components during the PIPS process.

Also, it helps to obtain the adequate size of liquid crystal droplets during the PIPS process. Additionally, OA acts as a surfactant decreasing the driving voltage improving the electrooptical dynamics of the H-PDLC device. OA forms an intermediate layer between the binder and the liquid crystal reducing the anchoring energy at the interface and favoring the orientation of the liquid crystal molecules at a low voltage [5].

In Figure 7, we obtain a DE_{max} = 65–67% with OA concentration of 0–2%. Bearing in mind that OA is not a reactive component, at high concentrations a low DE_{max} is obtained, since the concentrations of the active components are decreased due to the dilution effect.

A photopolymer without OA obtains a high DE_{max} = 67%—first dot in the figure. This implies a homogeneous phase in the photopolymer for a recently prepared solution. In this situation, OA is not necessary to obtain a homogenous mix with the specific components of this formulation. But this solution is unstable over time or when the temperature changes.

The addition of OA in a percentage lower than 10% prevents phase separation. With 2% OA the DE_{max} is slightly

TABLE 2: Composition for photopolymers 1 and 2 in wt%.

Photopolymer	DPHPA	BL036	YEt	NPG	NVP	OA	NMP
1	48.4	29.2	0.1	1.5	16.4	4.4	0.0
2	46.9	28.3	0.1	1.5	15.8	4.2	3.1

improved. This is related to the low viscosity and surfactant character of OA.

3.5. *Effect of the Incorporation of NMP.* Volume gratings recorded in photopolymers follow Kogelnik's equation (1) [24] as follows:

$$DE(t) = \frac{I_D}{I_0} = \Gamma \sin^2 \frac{\pi n_1(t) d}{\lambda' \cos \theta'_i}. \quad (1)$$

In this equation Γ is the absorption, diffusion, and reflection losses factor. θ'_i is the reconstruction beam angle (Figure 2), measured into the material, which is calculated with refraction Snell law. λ' is the reconstruction beam wavelength. $n_1(t)$ is the refraction index modulation and d is the diffraction grating thickness [25].

In layers with high value for the product $n_1(t)d$ an index refraction overmodulation takes place [26, 27]. The main effect is the quick decreasing of the diffraction efficiency with the exposure that affects negatively the performance of the grating.

The H-PDLC devices with the compositions shown in Table 2 are used as holographic media for the recording of unslanted diffraction gratings. Photopolymer 1 has the optimized composition obtained from the previous experiments. Photopolymer 2 also has NMP and the component concentrations are slightly changed to prevent a dilution effect. The NMP wt% was increased from zero up to the optimized value.

Figure 8 shows the DE versus exposure (E) during the hologram recording.

Photopolymer 1 starts an overmodulation at 110 mJ/cm^2 . This implies low diffraction efficiency at the end of recording and a poor performance for the electrooptical response (Section 3.6).

In the case of photopolymer 2 with NMP there is no overmodulation and its DE_{\max} is stable when the energy exposure is increased. This allows a more complete diffusion of the liquid crystal molecules to the dark zones when the energy is increased. Therefore, NMP acts as an unreactive solvent preventing overmodulation and allowing the best result for the electrooptical response to be obtained.

Figure 9 shows the hologram reconstruction after recording. Photopolymer 1 obtains a $DE_{\max} = 49\%$ and photopolymer 2 a $DE_{\max} = 62\%$. The lower value for photopolymer 1 is due to overmodulation.

The angular response curves are fitted by an algorithm developed by our research team based on the rigorous coupled wave theory [22, 23]. The parameters obtained are included in Table 3. The refractive index modulation Δn is similar for both photopolymers. The absorption and scattering coefficient α_2 for photopolymer 1 is higher than for

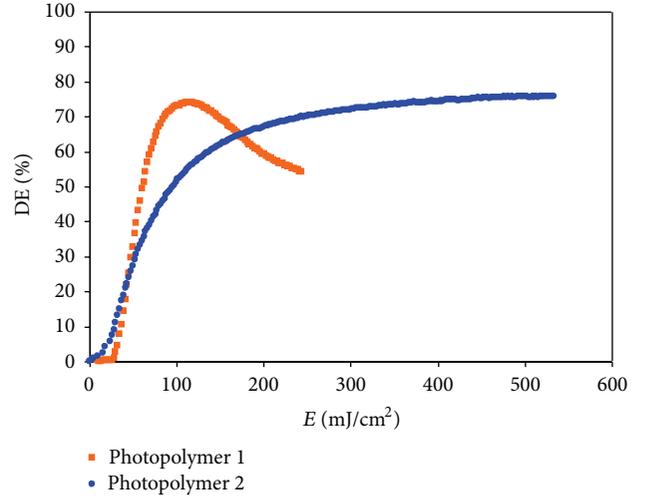


FIGURE 8: Overmodulation control in the photopolymer 2 during hologram recording, photopolymer 1 without NMP and photopolymer 2 with NMP.

TABLE 3: Parameters obtained from the fitting of the angular response by means of the rigorous coupled wave theory detailed in [22, 23].

Angular response fitting parameters	Photopolymer 1	Photopolymer 2
Refractive index modulation Δn	0.0155	0.0154
Estimated optical thickness (μm)	22.0	22.2
Depth attenuation coefficient α_1 (μm^{-1})	0.0670	0.0450
Absorption and scattering coefficient α_2 (μm^{-1})	0.021	0.011

photopolymer 2 as a result of the overmodulation that takes place with the former (Figure 8). The same occurs with the depth attenuation coefficient α_1 .

3.6. *Electrooptical Response.* The devices are exposed to an electrical field in order to evaluate the electrooptical response. Figure 10 shows the electrooptical setup. It includes a Tektronix TDS1012B oscilloscope (A), Tektronix AFG3022B dual channel arbitrary function generator (B), N4L voltage amplifier (C), and an impedance control circuit designed in our laboratory (D) to reach a high voltage avoiding the protection circuit of the amplifier.

Figure 11 shows the relative diffraction efficiency (DE_r) as a percentage versus rms voltage ($V/\mu\text{m}$). We consider the estimated optical thickness in Table 3. When the voltage

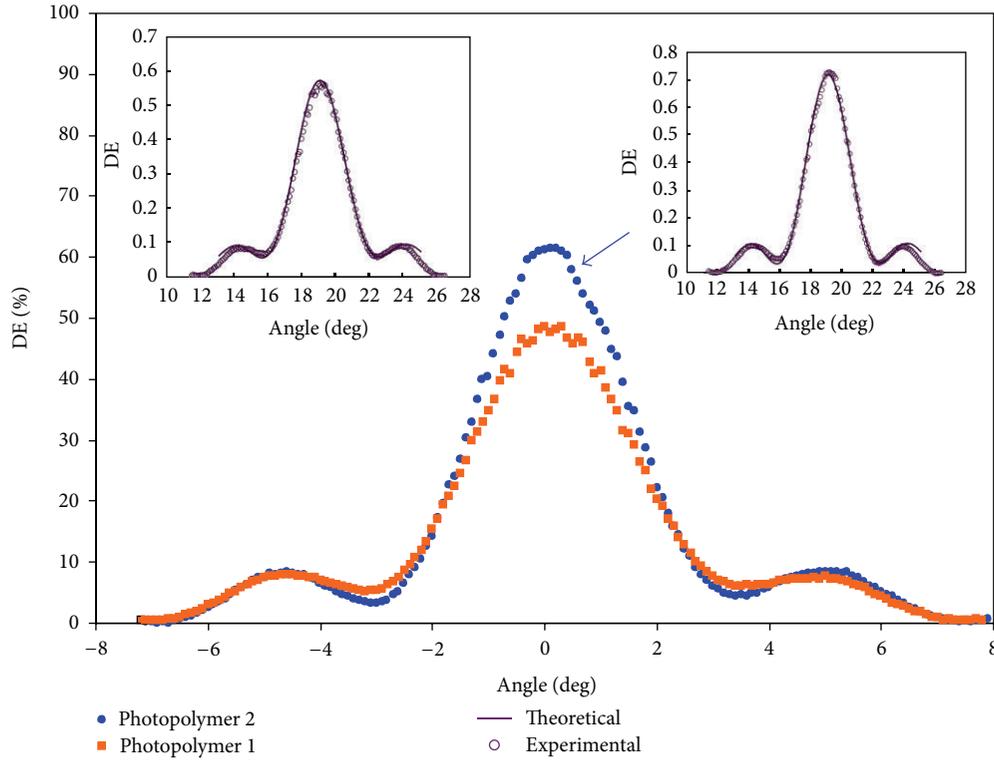


FIGURE 9: Photopolymer 2 with NMP obtains a DE_{\max} higher than photopolymer 1. The two smaller figures show the fitting of the angular responses. Top right figure corresponds to photopolymer 2 and top left figure to photopolymer 1.

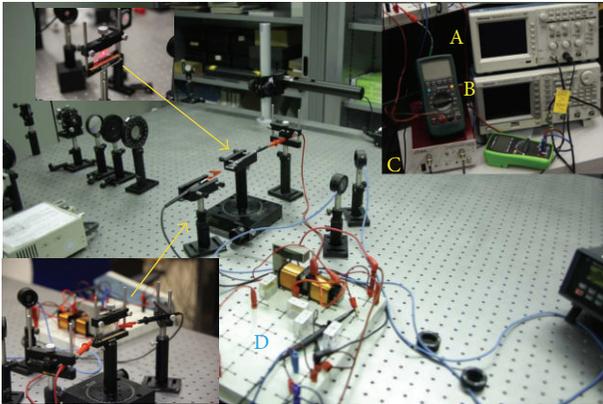


FIGURE 10: Electrooptical setup: the upper arrow shows the diffraction when the hologram is reconstructed. The bottom arrow shows the H-PDLC device plate with the electric connections.

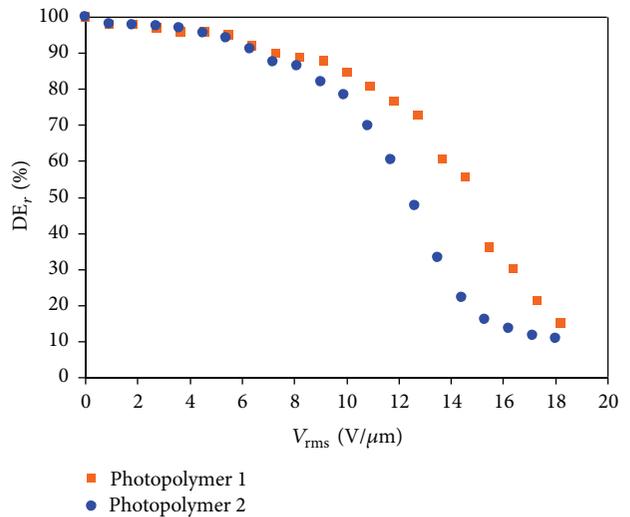


FIGURE 11: Relative diffraction efficiency versus rms voltage.

is applied, the liquid crystal molecules are oriented in the direction of the electric field. The index of the dark zones is now higher than that of the bright zones due to the liquid crystal fraction. Therefore the index modulation decreases when the voltage increases.

For photopolymer 2 the decrease in DE_r is greater than that in photopolymer 1 and this improves the electrooptical response. For $DE_r = 50\%$, photopolymer 1 needs a $V_{\text{rms}} =$

$15 \text{ V}/\mu\text{m}$ and photopolymer 2 a $V_{\text{rms}} = 13 \text{ V}/\mu\text{m}$. This difference could be explained by several reasons. First, the DE_{\max} stabilization of photopolymer 2 makes it possible to increase the exposure energy and the liquid crystal diffusion to the dark zones of the diffraction grating is improved. Second, the viscosity of NMP is lower than that of the other components of the formulation (Table 1). Therefore, photopolymer 2 with NMP has a lower viscosity than photopolymer 1. Third,

the polymerization rate of photopolymer 1 is higher than that of photopolymer 2 (Figure 8) and this affects the LC droplet size.

4. Conclusions

The optimization process carried out in this paper makes it possible to obtain an improved H-PDLC material with a sequence of experiments consisting of a small number of steps and combines NVP with NMP in the same formulation. The diffraction efficiency was optimized starting with a specific monomer and liquid crystal. The liquid crystal concentration was set at a specific value and the components were optimized in the following order: dye, initiator, crosslinker, and cosolvent. As a result of this process, the next concentration intervals were obtained. This methodology could be applied to other monomers and liquid crystals.

The NPG concentration may be between 1 and 1.5% if the viscosity of the liquid layer must be regulated. The concentration of NVP may vary within a wide interval (13–20%) with only a small variation in diffraction efficiency. This also allows the prepolymer viscosity to be modified so as to adjust the electrooptical response of the device. Moreover, the NVP variation enables the concentration of any component to be adjusted without modifying the DE_{\max} . The OA concentration must be maintained at a low value between 1 and 2% to obtain a high DE_{\max} . OA concentration higher than 6% implies a decrease in the DE_{\max} due to dilution.

The incorporation of 3% NMP in the H-PDLC formulation leads to an improved result. It stabilizes the diffraction efficiency curve preventing overmodulation during the hologram recording. This makes it possible to obtain a high DE_{\max} and therefore a better performance in photopolymers with ethyl eosin as a dye. Another interesting effect is related to the electrooptical response: the photopolymer with NMP needs a lower voltage to obtain the same decrease in diffraction efficiency. This is an interesting aspect bearing in mind the practical applications of these devices because less electric power is necessary, and therefore it is possible to use simpler equipment.

Acknowledgments

The work was supported by the Ministerio de Economía y Competitividad of Spain under Projects FIS2011-29803-C02-01 and FIS2011-29803-C02-02 and by the Generalitat Valenciana of Spain under Projects PROMETEO/2011/021 and ISIC/2012/013.

References

- [1] A. B. Samui, "Holographic recording medium," *Recent Patents on Materials Science*, vol. 1, pp. 74–94, 2008.
- [2] R. A. Lessard, "Polymer used as holographic recording materials: a review," in *Interactive Paper*, vol. 3227 of *Proceedings of SPIE*, pp. 199–211, Guadalajara, Mexico, October 1997.
- [3] M. Ortuño, E. Fernández, S. Gallego, A. Beléndez, and I. Pascual, "New photopolymer holographic recording material with sustainable design," *Optics Express*, vol. 15, no. 19, pp. 12425–12435, 2007.
- [4] E. Fernández, M. Pérez, R. Fuentes et al., "Analysis of holographic reflection gratings recorded in polyvinyl alcohol/acrylamide photopolymer," *Applied Optics*, pp. 1581–1590, 2013.
- [5] Y. J. Liu and X. W. Sun, "Holographic polymer-dispersed liquid crystals: materials, formation, and applications," *Advances in OptoElectronics*, vol. 2008, Article ID 684349, 52 pages, 2008.
- [6] S. Massenot, J. Kaiser, R. Chevallier, and Y. Renotte, "Study of the dynamic formation of transmission gratings recorded in photopolymers and holographic polymer-dispersed liquid crystals," *Applied Optics*, vol. 43, no. 29, pp. 5489–5497, 2004.
- [7] S. Meng, H. Duran, J. Hu et al., "Influence of photopolymerization reaction kinetics on diffraction efficiency of H-PDLC undergoing photopatterning reaction in mixtures of acrylic monomer/nematic liquid crystals," *Macromolecules*, vol. 40, no. 9, pp. 3190–3197, 2007.
- [8] M. De Sarkar, N. L. Gill, J. B. Whitehead, and G. P. Crawford, "Effect of monomer functionality on the morphology and performance of the holographic transmission gratings recorded on polymer dispersed liquid crystals," *Macromolecules*, vol. 36, no. 3, pp. 630–638, 2003.
- [9] M. Mucha, "Polymer as an important component of blends and composites with liquid crystals," *Progress in Polymer Science*, vol. 28, no. 5, pp. 837–873, 2003.
- [10] L. V. Natarajan, D. P. Brown, J. M. Wofford et al., "Holographic polymer dispersed liquid crystal reflection gratings formed by visible light initiated thiol-ene photopolymerization," *Polymer*, vol. 47, no. 12, pp. 4411–4420, 2006.
- [11] J. Yan, L. Rao, M. Jiao, Y. Li, H. Cheng, and S. Wu, "Polymer-stabilized optically isotropic liquid crystals for next-generation display and photonics applications," *Journal of Materials Chemistry*, vol. 21, no. 22, pp. 7870–7877, 2011.
- [12] T. J. Bunning, L. V. Natarajan, V. P. Tondiglia, and R. L. Sutherland, "Holographic polymer-dispersed liquid crystals (H-PDLCs)," *Annual Review of Materials Science*, vol. 30, pp. 83–115, 2000.
- [13] H. Ren, S. Xu, and S. T. Wu, "Gradient polymer network liquid crystal with a large refractive index change," *Optics Express*, vol. 20, pp. 26464–26472, 2012.
- [14] V. K. S. Hsiao, C. Lu, G. S. He et al., "High contrast switching of distributed-feedback lasing in dye-doped H-PDLC transmission grating structures," *Optics Express*, vol. 13, no. 10, pp. 3787–3794, 2005.
- [15] S. Massenot, J. Kaiser, M. C. Perez, R. Chevallier, and J. B. Tonnay, "Multiplexed holographic transmission gratings recorded in holographic polymer-dispersed liquid crystals: static and dynamic studies," *Applied Optics*, vol. 44, no. 25, pp. 5273–5280, 2005.
- [16] M. S. Li, S. T. Wu, and A. Y. Fuh, "Sensor for monitoring the vibration of a laser beam based on holographic polymer dispersed liquid crystal films," *Optics Express*, vol. 18, no. 25, pp. 26300–26306, 2010.
- [17] M. Infusino, A. D. Luca, V. Barna, R. Caputo, and C. Umetton, "Periodic and aperiodic liquid crystal-polymer composite structures realized via spatial light modulator direct holography," *Optics Express*, vol. 20, pp. 23138–23143, 2012.
- [18] "Licristal datasheet from Merck," <http://www.merckgroup.com>.
- [19] Y. Liu, B. Zhang, Y. Jia, and K. Xu, "Improvement of the diffraction properties in holographic polymer dispersed liquid

- crystal Bragg gratings," *Optics Communications*, vol. 218, no. 1–3, pp. 27–32, 2003.
- [20] S. Gallego, A. Márquez, M. Riquelme et al., "Analysis of PEA photopolymers at zero spatial frequency limit," in *Optical Modelling and Design II*, vol. 8429 of *Proceedings of SPIE*, pp. 1–8, Brussels, Belgium, 2012.
- [21] M. Ortuño, E. Fernández, R. Fuentes, S. Gallego, I. Pascual, and A. Beléndez, "Improving the performance of PVA/AA photopolymers for holographic recording," *Optical Materials*, vol. 35, pp. 668–673, 2013.
- [22] S. Gallego, M. Ortuño, C. Neipp et al., "3-dimensional characterization of thick grating formation in PVA/AA based photopolymer," *Optics Express*, vol. 14, no. 12, pp. 5121–5128, 2006.
- [23] S. Gallego, C. Neipp, L. Estepa et al., "Volume holograms in photopolymers: comparison between analytical and rigorous theories," *Materials*, vol. 5, pp. 1373–1388, 2012.
- [24] H. Kogelnik, "Coupled wave theory for thick hologram gratings," *Bell System Technical Journal*, vol. 48, no. 9, pp. 2909–2947, 1969.
- [25] S. Gallego, M. Ortuño, C. Neipp et al., "Physical and effective optical thickness of holographic diffraction gratings recorded in photopolymers," *Optics Express*, vol. 13, no. 6, pp. 1939–1947, 2005.
- [26] S. Gallego, M. Ortuño, C. Neipp, C. García, A. Beléndez, and I. Pascual, "Overmodulation effects in volume holograms recorded on photopolymers," *Optics Communications*, vol. 215, pp. 263–269, 2003.
- [27] C. Neipp, I. Pascual, and A. Beléndez, "Theoretical and experimental analysis of overmodulation effects in volume holograms recorded on BB-640 emulsions," *Journal of Optics A*, vol. 3, no. 6, pp. 504–513, 2001.



Hindawi

Submit your manuscripts at
<http://www.hindawi.com>

