Hybrid ternary modulation applied to multiplexing holograms in photopolymers for data page storage

Elena Fernández, Andrés Márquez, Sergi Gallego, Rosa Fuentes, Celia García, and Inmaculada Pascual

***Abstract*— Holographic data storage is a new optical technology which allows an important number of bits to be stored in a recording material. In this work, holographic data pages were stored in a PVA/acrylamide photopolymer layer using a peristrophic multiplexing method. This material is formed of acrylamide photopolymers, which are considered interesting materials for recording holographic memories. Moreover, a hybrid ternary modulation (HTM) was used to reduce the zero frequency of the Fourier Transform (FT) of the object. A liquid crystal device (LCD) was optimized to modify the object beam in order to obtain data pages with the HTM.**

***Index Terms*— Liquid-crystal devices, multiplex holography, optical storage and recording materials.**

I. Introduction

TWO-dimensional memory technologies like CD-ROM and DVD have reached the limits of their capacity and so there is a need for new technological systems capable of storing more information. Holographic data storage (three-dimensional technology) is a new optical memory technology that allows an important number of bits to be stored in a recording material with greater capacity, higher density and faster readout rates than two-dimensional technology.

A photopolymerizable material was used to store the holograms. These materials have excellent holographic characteristics, such as high refractive index modulation [1,2], large dynamic range [3-5], good light sensitivity, real time image development, high optical quality, low cost, and have been used as the basis of new 3-D holographic disks. In addition, their properties like energetic sensitivity or spectral sensitivity can be easily changed by modifying their composition [1,3,6]. The photopolymer is composed of acrylamide (AA) as the polymerizable monomer, triethanolamine (TEA) as radical generator, N,N'methylene-bis-acrylamide (BMA) as crosslinker, yellowish eosin (YE) as sensitizer and a binder of polyvinyl alcohol (PVA). Layers of this material about 80±10, 250±10 and 500±10 μm thick were used to store the holograms.

Twisted-nematic liquid crystal displays (TN-LCDs) have been used in recent years as spatial light modulators (SLMs) to modify in real time the amplitude or phase of a light beam [7-10]. This LCD can be used to design programmable optical elements, such as lenses and data pages, or in holographic data storage.

In holographic data storage systems (HDSS), LCDs are normally used as binary amplitude transparencies to display the data page, and the Fourier transform (FT) of the data page is then holographically recorded on a photosensitive material. However, amplitude modulation produces a high zero frequency which may saturate the dynamic range of the material, thus limiting the accessible dynamic range. The problems caused by the lack of homogeneity of the FT can be solved by using some other modulation schemes, such as random phase masks [11], binary π radians phase-only modulation (πBPM) [12-15], full multi-phase scheme [16,17] or hybrid ternary modulation (HTM) [13,15,18-20].

In this study, the data pages were sent to the LCD and stored in the material using HTM. The main reason is that this study was initiated by us using the binary intensity modulation, and the HTM uses exactly the same experimental scheme; this enables us to compare the results of two modulations. The difference between binary intensity modulation and the HTM is only that the type of codified object that is sent to the LCD changes, without any additional adjustments in the setup. Therefore, it is straightforward to implement this new scheme. In comparison, the use of modulation schemes such as full multi-phase modulation involves using interferometric methods in the reconstruction. This adds additional complexity to the experimental setup.

With the HTM, some bits are represented on the data page by two different gray levels that produce a maximum transmission and have a phase difference of π rad (the "one"

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bits). The other bits are represented by a gray level with a minimum transmission (the "zero" bits). Using this method, if half of the bits with the maximum intensity have a phase difference of π rad compared with the other half, the intensity of the high zero frequency of the FT can be reduced [15].

Moreover many holograms were superimposed at the same position in the material using peristrophic multiplexing in order to store information with holographic techniques, and the object beam was modulated using HTM so as to reduce the zero frequency.

Different objects were stored in three layers of photopolymer of different thicknesses. Once the holograms were stored, they were illuminated in the reconstruction stage by the same plane wave as in the recording process in order to prevent the appearance of aberrations in the reconstructed image. Using an optical system, the stored information was imaged onto a CCD camera connected to a personal computer, where the images were analyzed and processed.

Once the images have been obtained, a criterion is needed to assess the quality of the different images and to compare them with the original object. In order to evaluate the image quality, its histogram was used to calculate the bit error rate (BER) [21-23] and determine the contrast between the pixels. BER values of each image were calculated to decide which parameters provide the best image quality (greater contrast and less noise).

The study undertaken in this paper combines three of the basic elements needed for a realistic realization of a holographic data storage system. Firstly, the recording material, which is a photopolymer, Secondly, the codification scheme for the data pages, which is HTM. And thirdly, the multiplexing methodology, which is peristrophic. Each of these three elements alone has already been introduced and studied in the literature. However, their combined implementation, which is not a trivial task, has not yet been done and this is our main interest in this paper. A widely tested material is used so that we can actually verify, and with a large amount of experimental measurements to support it, the feasibility of this HDSS proposal.

II. Experimental

A. Preparation of the material

The photopolymer in which the holograms were recorded was composed of acrylamide (AA) as the polymerizable monomer, triethanolamine (TEA) as radical generator, N,N'methylene-bis-acrylamide (BMA) as crosslinker, yellowish eosin (YE) as sensitizer and a binder of polyvinyl alcohol (PVA). Table 1 shows the component concentrations of the photopolymer compositions 1, 2 and 3 used to obtain layers about 80, 250 and 500 µm thick, respectively.

A solution of PVA in water forms the matrix and this is used to prepare the mixture of AA, BMA, and photopolymerization initiator system composed of TEA and YE. The mixture is made under red light, deposited by gravity on a 22 cm x 40 cm glass plate and left in the dark for one day to allow the water to evaporate in conditions of temperature, T, between 20 ºC and 25 ºC, and relative humidity, RH, 40%-60%. These conditions of drying time, temperature and relative humidity are optimized to obtain the maximum diffraction efficiency of the gratings. Once dry, the glass is cut into squares of 5x5cm."

TABLE I
Concentrations of the photopolymer composition

	Composition 1	Composition 2	Composition 3
Polyvinylalcohol	6.6% m/v	13.4% m/v	13.3% m/v
Acrylamide	0.33M	0.34M	0.35M
Triethanolamine	0.17M	0.15M	0.15M
Yellowish eosin	2.4x10-4M	1.4x10-4M	0.9x10-4M
N,N'methylene-bis-acrylamide	0.027M	0.037M	0.04M

B. Holographic set-up

Holographic data pages were stored using a Nd:YV0$_4$ laser (Coherent Verdi V2) with a wavelength of 532 nm, which was sensitive to the material. The set-up is shown in Fig. 1. The polarized beam emitted by the laser was split into two beams with a beam-splitter. Each beam was expanded and filtered using a microscope objective and a pinhole. Then the beams passed through a series of lenses and diaphragms in order to obtain collimated beams with the desired diameter. The total intensity of the recording beams was 3.3 mW/cm^2 with an intensity ratio of 100:1. The two laser beams were spatially overlapped at the recording medium intersection at an angle of 17.4º (measured in air).

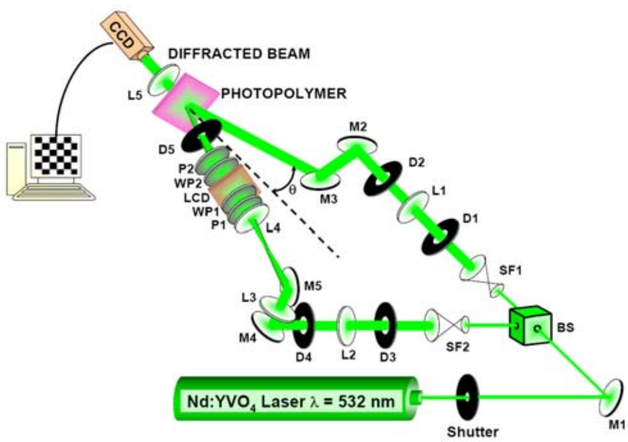


Fig. 1. Experimental setup: BS beam splitter, Mi mirror, Li lens, Di, diaphragm, SFi, microscope objective lens and pinhole, SLM spatial light modulator, Pi polarizer, WPi quarter wave plate, CCD charge coupled device.

An LCD was placed in the object beam between two polarizers and two quarter wave plates, one to each side of the LCD. The LCD, polarizers and quarter wave plates were used as an SLM. In addition, a lens (L4) was placed in front of the SLM to do the Fourier transform (FT) of the data page which was sent to the SLM.

A diaphragm was placed just in front of the photopolymer to block all the orders that leave the LCD except the central order. If the other orders were not blocked, they would also be stored in the material, and during reconstruction, interference patterns would be observed on the image, thus worsening its quality. The reference beam was a plane wave that interferes with the object beam at the surface of the material. In previous papers we studied how the beam ratio between object beam and reference beam affects the quality of the stored images [24]. These beam intensities were measured at the position where the photopolymer must be placed when the holograms are stored.

Once the object was stored, the hologram was illuminated in the reconstruction step with the same reference beam used in the recording, but at a very low intensity so as not to deform the hologram because the material is sensitive to this wavelength [7]. Another lens (L5) was placed behind the photopolymer to do the inverse Fourier transform (IFT) of the diffracted beam on the surface of the charge coupled device (CCD). A computer sent the data pages to the LCD and another computer captured images reconstructed by the CCD.

III. Results

In this paper holograms were multiplexed in layers about 80, 250 and 500 µm thick using the compositions 1, 2 and 3 in Table 1 respectively. Binary data pages with a random pixel form were stored. These objects have a different number of pixels: 300x300, 400x400, 500x500 and 800x600, thus allowing us to study the behavior of the photopolymer material when data pages with different numbers of pixels are multiplexed.

These objects were stored at the same position in the material using peristrophic multiplexing because previous papers showed that when a not very large number of holograms (fewer than 200) are stored, higher diffraction efficiency is obtained with peristrophic multiplexing [25].

The holograms were stored with an angular separation of 3°. Reference [26] shows the method which with angular selectivity for the peristrophic multiplexing was obtained. The angular selectivity calculated theoretically was 2.6°. Moreover angular selectivity was measured experimentally and a value of 2.5±0.1° was found. Therefore, an angular separation of 3° is more than sufficient to prevent the holograms from overlapping. The holograms were recorded with a reference to object beam ratio of 100 and a reading beam intensity of 0.03 mW/cm^2. In previous studies of the influence of these parameters on the quality of the stored images [24,27], these values were found to give a greater image quality and, therefore, a lower BER.

A. Optimization of the LCD

As described in the Holographic set-up section, an LCD was placed in the object beam to modify the wavefront and store this variation in the photopolymer. In particular we use the LCD kit LCD2002 distributed by Holoeye, which actually corresponds to a SONY LCD model LCX016AL-6, with 800x600 pixels and with a pixel size of 32 µm. The variation may be in phase, amplitude or both. In the introduction section we explained that HTM was used to reduce the zero frequency of the FT. In order to use HTM we need to obtain three states with the LCD: two states with maximum transmission and a phase difference of π rad, and a third state with minimum transmission. However, to achieve this, the LCD, polarizers and quarter wave plates must be calibrated correctly [8,10,28], which means that the angles at which the latter are to be placed must be optimized in order to obtain these states.

TABLE II
LCD Calibration parameters independent of the voltage applied

α	Ψ_D	β_{max} (λ_0=633 nm)	β_{max} (λ_0=532 nm)	β_{max} (λ_0=442 nm)
94º±1º	45º±1º	118º±1º	168º±1º	199º±1º

The calibration process consists of two calibration steps. In the first step, the LCD is turned off and no voltage is applied. In this step, three parameters that are independent of the voltage are calculated: the total twist angle *(α)*, the orientation of the molecular director at the input face *(Ψ_D)* and the maximum birefringence *(βmax)* versus the wavelength. These parameters are obtained from a fit of experimental measurements to the theoretical equations for different polarizer angles. To reduce the freedom degrees the intensity has been measured with different wavelengths. The parameters obtained with the LCD calibrated while turned off are shown in table 2.

In the second step, the parameters dependent on voltage are measured. These are related to the variation in optical anisotropic properties throughout the thickness of the cell as a function of the voltage applied. The model attempts to take into account the fact that the liquid crystal molecules near the glass are practically adhered to its surface and cannot reorientate themselves when the voltage is applied. Thus, the total thickness d of the LCD may be decomposed into two lateral regions of width d_1 and a central region of width d_2. In this way, the anisotropic properties of the LCD may be modeled using two voltage-dependent parameters – birefringence β and δ – which are expressed in Eq. 1.

$$\begin{aligned}\beta(V) &= \pi\Delta n\, d_2/\lambda_0 \\ \delta(V) &= \pi\Delta n_{\max} d_1/\lambda_0\end{aligned} \quad (1)$$

where λ_0 is the wavelength of the light, Δn is the difference between the ordinary and extraordinary index, with Δn_{max} being the maximum value.

From the curves of $\beta(V)$ and $\delta(V)$, we can find the angles at which the polarizers must be placed in the experimental setup to modulate the incident beam. In our study, our aim is to obtain the maximum contrast between maximum intensity bits and minimum intensity bits, so there must be a phase difference of π rad between half of the bits with maximum intensity and the other half. To find these states, the two figures of merit in Eq. 2 were combined.

$$f_1 = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (2)$$

$$f_2 = \frac{Max[phase] - Min[phase]}{360}$$

The configuration found to satisfy the two figures of merit is shown in Fig. 2. This configuration was obtained with the angles φ_1=178º and η_1=73° for the polarizer and the wave plate placed in front of the LCD and φ_2=93º and η_2=87° for the polarizer and the wave plate placed behind it.

In Fig. 2 black circles represent the intensity that can be obtained in the configuration with the angles φ_1, η_1, φ_2 and η_2 depending on the gray level. White circles represent the phase obtained with the same angle configuration depending on the gray level. With this configuration, the three states chosen to apply HTM have been circled in Fig. 2. These three states are summarized in Table 3.

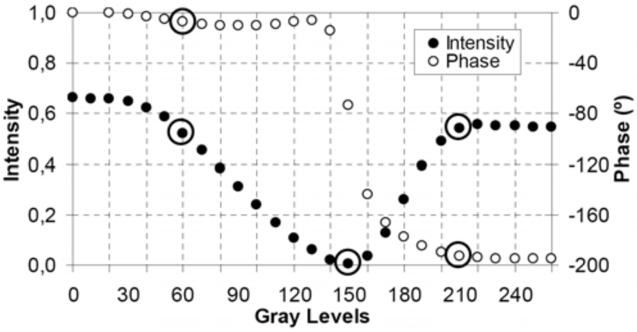
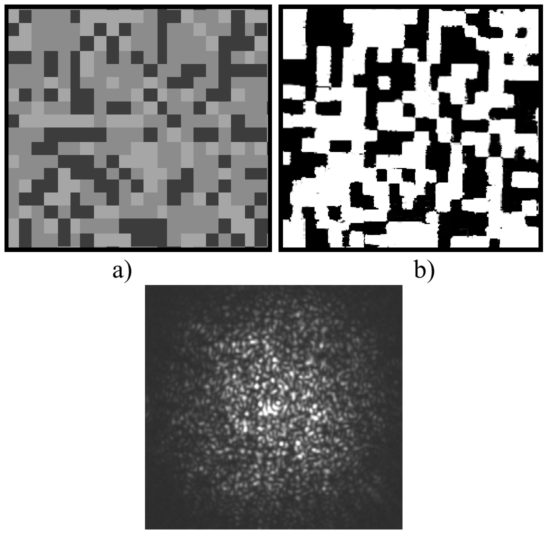


Fig. 2: Black circles represent the intensity obtained with the polarizers at angles φ_1=178º and φ_2=93º and with the quarter wave plates at angles η_1=73° and η_2=87°, and white circles represent the phase obtained depending on the gray level with the same polarizer and wave plate angles.

TABLE III
GRAY LEVEL, INTENSITY AND PHASE OF THE STATES OBTAINED WITH φ_1=178º, φ_2=93º η_1=73° AND η_2=87°

	White 1	White 2	Black
Gray Level	60	200	150
Intensity	0.54	0.52	0.006
Phase	-192°	-7°	-14°

Fig. 3a represents a model of the data page which was created with the gray levels in Table 3. Fig. 3b was obtained when the data page in Fig. 3a was sent to the LCD. The angles of the polarizers were those mentioned above in order to obtain the HTM configuration. They were illuminated with the laser and a CCD camera captured the image formed. Fig. 3c shows the FT of the image represented in Fig. 3a. As can be seen, the frequencies were distributed over the entire FT plane and the zero frequency had no more intensity than the other frequencies [29].



a) b) c)

Fig. 3: a) Data page created with the gray levels 60, 200 and 150. b) Image obtained with the HTM configuration binarized. c) FT of the image 3a.

B. *Thickness of 80 µm*

In section 3.1 the SLM was optimized for storing data pages with the HTM method, which reduces the zero order of the TF of the objects. The data pages mentioned in that section were stored in an 80 µm thick material with four different pixel sizes: 300x300, 400x400, 500x500 and 800x600. Each of the four objects was multiplexed at the same position in the material with an angular separation of 3° by peristrophic multiplexing. In addition, they were stored with a beam ratio of 100 and reconstructed on the CCD with a reading beam intensity of 0.03mW/cm^2 [24]. As the holograms are stored in the material, the dynamic range is consumed [21-23,25]; therefore, the exposure must be increased in order to store more holograms. Of course, when all the dynamic range is consumed, no more holograms will be formed in the material even if the exposure is increased.

After one of the objects has been stored in the photopolymer, the hologram formed is reconstructed illuminating it with the reference beam. The diffractive beam obtained is imaged onto the CCD. However, the image may be distorted for many reasons; therefore, it is advisable to measure a parameter that quantifies the image quality. This parameter is the bit error rate (BER) which is defined as the probability of having erroneous bits in the image. References [23,24,27,30] explain how to calculate the BER. The lower the BER of the stored images, the greater their quality. But how can we tell if an image is of good quality? In a previous study [30] it was found that images with a value of BER less than or equal to 0.2 still had good contrast and well-defined edges, that is, they were images of acceptable quality. Therefore, a BER of 0.2 is taken as the threshold value below which the images obtained are considered to be of good quality.

Data pages were multiplexed with the four bit sizes with the exposure (*E=I·t*) represented in Fig. 4 by purple triangles as a function of the number of holograms. First data pages with 300x300 bits were stored. Once stored the holograms were illuminated with a reference beam intensity of 0.3mW/cm^2. The reconstructed images were captured by a CCD camera.

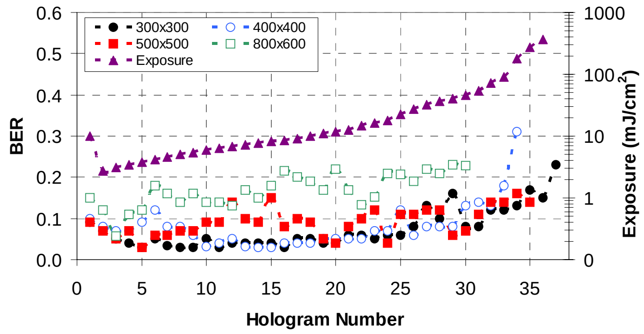


Fig. 4: BER of the 300x300 pixel (solid black circles), 400x400 pixel (empty blue circles), 500x500 pixel (solid red squares) and 800x600 pixel (empty green squares) objects stored with the HTM configuration in a 80 µm thick material, and exposure (solid purple triangles).

The next step was to calculate the BER of the images. The BER results obtained for the 300x300 bit object are represented in Fig. 4 by solid black circles as a function of the number of holograms. As can be seen, 36 holograms with a BER less than 0.2 were stored. When more holograms are stored the image is almost all noise. Holograms between 1 and 26 have a BER value below 0.1 and the BER average of this 36 holograms was 0.08.

The next object to be multiplexed was the 400x400 bit object. It was stored with the same exposure represented by solid purple triangles in Fig. 4. Once stored, the holograms were reconstructed with the reference beam, the images were captured by the CCD camera and their BER was calculated. BER values obtained for this object are shown in Fig. 4 (empty blue circles). In this case 33 holograms with a BER less than or equal to 0.2 were obtained.

Then, the 500x500 bit object was stored in the photopolymer. The BER of the images corresponding to this object is represented in Fig. 4 by solid red squares. In this case 35 holograms were also obtained with a BER of less than 0.15.

And finally, the 800x600 bit object was multiplexed in the material and the BER values obtained are represented in Fig. 4 by empty green squares. 30 holograms with a BER values near 0.2 were stored and the BER average of this 30 holograms was 0.17.

Fig. 5 shows the images with the lowest BER for each object. Fig. 5a shows the image of hologram 1 of the 300x300 pixel object which has a BER = 0.01; Fig. 5b represents the image of hologram 4 of the 400x400 pixel object with a BER = 0.03; Fig. 5c shows hologram 1 of the 500x500 pixel object with a BER = 0.02, and Fig. 5d shows hologram 1 of the 800x600 pixel object with a BER = 0.03. As can be seen, there is a greater contrast between the white and black pixels and the edges are well-defined in the images.

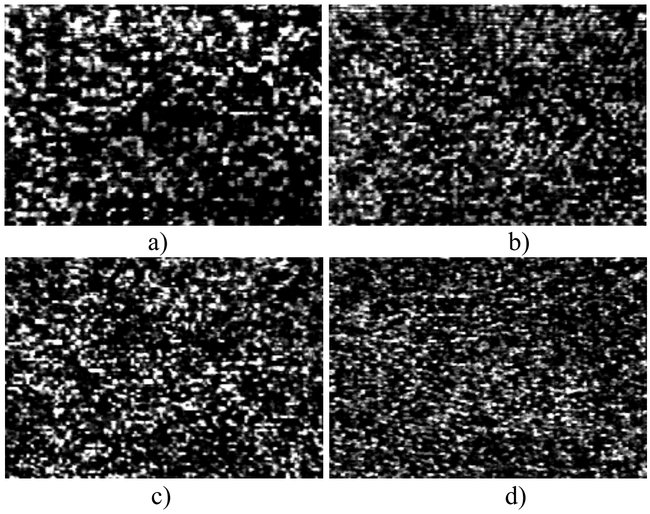


Fig. 5: Best images obtained in an 80 µm thick material for the a) 300x300 bit, b) 400x400 bit, c) 500x500 bit and d) 800x600 bit objects.

To demonstrate the advantages of the use of HTM over other types of modulation as binary intensity modulation, the results obtained with the HTM have been compared with the results obtained using binary intensity modulation [30].

The main advantage to use the HTM is that a larger number of data pages have been stored using it. For the thickness of 80 µm, with binary intensity modulation 15 holograms were stored with BER values near zero [30], while 25 holograms have been stored with the HTM. Moreover, with the HTM we obtained an image quality as good as the quality obtained with binary intensity modulation because the BER values have the same order of magnitude.

As mentioned in the introduction, when binary intensity modulation is used, the zero order of the FT is very intense. This fact makes that the material saturates storing only a few holograms. However, the HTM minimizes the intensity of the zero order and therefore a greater number of holograms can be stored before the material is saturated.

The main application of the study undertaken in this paper is to produce a holographic memory device for storing information. This requires a study of stability and multiple reading degradation of the stored information.

To obtain long term stability of stored holograms, once registered they are illuminated with white light to consume the remains of dye that may be left. Once the dye has been consumed, the stored information maintains over time. It is not erased by the subsequent multiple readings, since the material does not react when illuminated.

The BER values measured immediately after registration, when multiplexing data pages, are shown in Fig. 4. In Fig. 6 we show the BER values measured after the material has been bleached with white light all the dye has been consumed.

If results of Fig. 4 and 6 are compared, we see that BER values in Fig. 6 are slightly higher than in Fig. 4. For the objects 300x300 and 400x400 the average BER values are 0.13 and 0.11 respectively. For the object with 500x500 pixels the average BER value is 0.15 and for the object with

800x600 pixels is 0.2.

When bleached, the quality of the stored images degrades. However, since the material no longer reacts under illumination, the stored information will not suffer further degradation in the case of multiple readings.

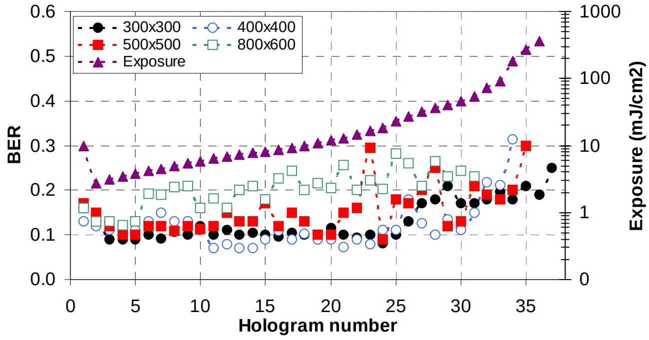


Fig. 6: BER of the 300x300 pixel (solid black circles), 400x400 pixel (empty blue circles), 500x500 pixel (solid red squares) and 800x600 pixel (empty green squares) objects stored with the HTM configuration in a 80 μm thick material bleached, and exposure (solid purple triangles).

C. *Thickness of 250 μm*

In the next step, data pages with the four pixel sizes mentioned before were stored in a 250 μm thick material. Fig. 7 shows exposures used to store the multiplexed holograms (purple triangles). Furthermore, the same figure shows the BER values measured for the images obtained after reconstructing the holograms with the reference beam.

For the 300x300 bit object, 41 holograms were stored with a BER less than 0.2. The BER values are represented in Fig. 7 by solid black circles versus the number of holograms. As can be seen, The BER values are around the average BER of 0.13, which was obtained for all the holograms with this pixel size. Only the first and the last holograms have BER values around 0.2.

The BER of the objects with 400x400 bits, 500x500 bits and 800x600 bits are represented in Fig. 7 by empty blue circles, solid red squares and empty green squares respectively. For the 400x400 bit object, 30 holograms were stored with a BER less than 0.2. The average BER for these holograms was 0.15. The last five holograms had BER values higher than 0.7. About 35 holograms were recorded when the 500x500 bit object was multiplexed in the photopolymer and the BER of these holograms was around 0.13. Once again the last holograms had BER values higher than the first. This indicates that the last holograms are not well formed because the monomer and/or dye in the material have been consumed. The BER of the first holograms is also slightly higher than that of the rest because they were stored with insufficient exposure. However, we chose not to increase the exposure when storing these first holograms, otherwise the material components would be consumed and it would not then be possible to eventually store a greater number of holograms. And finally the 800x600 bit object was recorded and 37 holograms were obtained with a BER value of around 0.13.

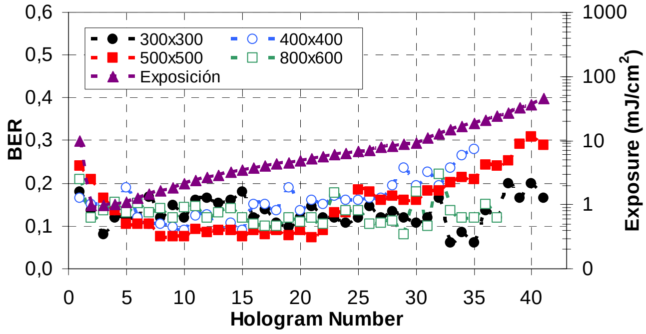
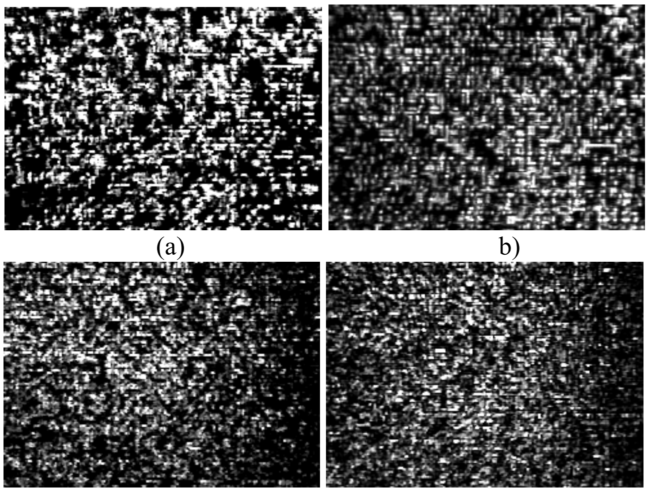


Fig. 7: BER of the 300x300 pixel (solid black circles), 400x400 pixel (empty blue circles), 500x500 pixel (solid red squares) and 800x600 pixel (empty green squares) objects stored with the HTM configuration in a 250 μm thick material, and exposure (solid purple triangles).

Fig. 8 shows the best pictures with the lowest BER corresponding to the four objects stored for this thickness. The image quality was good and this was reflected in the BER values which were below 0.1. Their quality is less than that of objects stored in the 80 μm thick material although the contrast between the bits is good.



(a) b)

(c) (d)

Fig. 8: Best images obtained in a 250 μm thick material for the objects a) 300x300 bits, b) 400x400 bits, c) 500x500 bits and d) 800x600 bits.

In this thickness, 40 holograms with BER values lower than 0.2 have been obtained using the HTM. With the binary intensity modulation only 28 holograms were stored [30]. So, again with the HTM a greater number of holograms have been stored, though it is true that the BER average is higher for the HTM compared to binary intensity modulation.

For thicknesses that are becoming high, as it is the case for 250 μm, when we use the binary intensity modulation, distortions appear in the images due to the defects found in the material. By using the HTM to modulate the object beam, this fact was not observed. Therefore, the use of HTM enhance the quality of the images and they are not dependent on the presence of possible defects in the material. In reference [30] it can be observed that there were distortions in the images due to the defects found in the material. As can be seen, these distortions do not appear in the images presented in this paper using HTM.

D. Thickness of 500 µm

Finally, for the thickness of 500 µm the four objects were stored with the exposure values represented in Fig. 8 by purple triangles. This figure also shows the BER values obtained for each object.

As can be seen in Fig. 9, for the 300x300 bit object, 71 holograms were multiplexed with an average BER of 0.11. For the 400x400 bit object, the average BER of the 80 holograms multiplexed was 0.16. Sixty eight holograms were stored with the 500x500 bit object and the average BER was 0.21. Finally the 800x600 bit object was multiplexed and 72 holograms were reconstructed with an average BER of 0.23. As can be seen, with this thickness the average BER values are higher than those obtained with the other thicknesses. This is due to the fact that when the thickness of the material is increased it becomes translucid and this one results in the final image being slightly out of focus, which reduces the quality of the stored images.

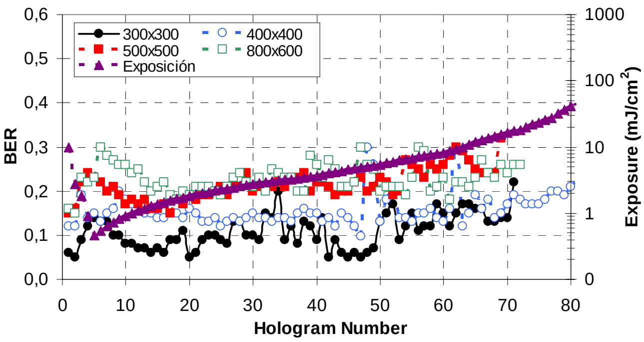


Fig. 9: BER of the 300x300 pixel (solid black circles), 400x400 pixel (empty blue circles), 500x500 pixel (solid red squares) and 800x600 pixel (empty green squares) objects stored with the HTM configuration in a 500 µm thick material, and exposure (solid purple triangles).

Fig. 10 shows the images with the lowest BER of each object. Image (a) corresponds to the 300x300 bit object with a BER value of 0.05 and, as can be seen, the bits are clearly distinguishable from each other. Image (b) has a BER value of 0.09. Images (c) and (d) both have the same BER, 0.15.
The BER increased significantly for these two objects, which have a smaller pixel size than that of the objects of the images (a) and (b).

Finally, if we compare the results obtained from the HTM with binary modulation in intensity, it can be seen that with the binary intensity modulation between 40 and 50 holograms were stored while 80 holograms were recorded with the HTM. The number of holograms stored with HTM is much higher than with the binary intensity modulation.

In addition, BER values are more uniform in the case of HTM as the highest value of BER obtained with the HTM for this thickness is 0.3, while for binary intensity modulation BER values up 0.8 were obtained.

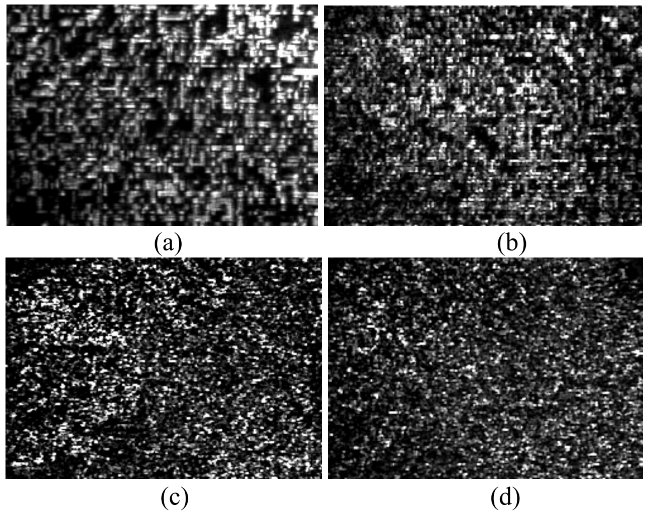


Fig. 10: Best images obtained in a 500 µm thick material for the objects a) 300x300 bits, b) 400x400 bits, c) 500x500 bits and d) 800x600 bits.

Therefore, from Figs. 4, 6 and 8, it may be concluded that:

For the 80 µm thick layer, it was possible to store 35 holograms with a BER of less than 0.2 using HTM. Moreover, holograms have BER values are around 0.1. The 800x600 pixel object has values of BER close to 0.2 for holograms.

For the 250 µm thick layer, we were able to store 40 holograms with a BER value below 0.2 for some objects. However, the quality of the images was inferior to that obtained with the 80 µm thick layer and although the contrast between the bits was good, the edges were not so well defined, and were slightly unfocused. To reconstruct the hologram, the laser beam must pass through all the thickness of a translucent material, which results in a slight blurring of the image.

For the 500 µm thick layer, we were able to store 70 holograms with a BER value less than 0.2, but the BER of the images increases and the image quality decreases when the number of bits in the objects increases. As happened with the thickness of 250 µm, when the bit size is larger, the effects of blurring due to the high material thickness were not remarkable. However, when the bit size was reduced, blurring appeared in the image, decreasing its quality.

It may be seen that when the thickness increases, the number of holograms that may be stored increases, which is important for material which is to be used as a holographic storage memory. However, increasing the thickness the transmittance of the material decreases, and this fact makes to obtain images with a lower quality.

IV. Conclusion

In this study, four different data pages with a different pixel size were multiplexed in layers of PVA-acrylamide photopolymer of three different thicknesses. In order to reduce the zero frequency of the FT of the data pages, HTM was used to modulate the object beam which was introduced in the holographic set-up with a TN-LCD. Amplitude modulation produces a high zero frequency which may saturate the dynamic range of the material and limit the accessible dynamic range. If this zero frequency is reduced many holograms may be superimposed at the same position in the material. Once the holograms were stored by peristrophic multiplexing, the BER of the images was calculated to quantify the quality of the images as a function of the number of multiplexed holograms.

In addition, results obtained with HTM and binary intensity modulation have been compared and the main advantage of HTM versus binary intensity modulation is to be able to store a greater number of holograms because the intensity of the zero order of the FT was reduced. Furthermore, storing data pages with HTM makes the storage of them less sensitive to possible defects in the material.

This study shows the possibilities of this photopolymer as a holographic memory.

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