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Programmable CGH on photochromic plates coded with DMD generated masks

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Abstract: Computer Generated Holograms (CGHs) are used for wavefront shaping and complex optics testing. Present technology allows for recording binary CGHs. We propose a Digital Micro-mirror Device (DMD) as a reconfigurable mask, to record rewritable binary and grayscale CGHs on a photochromic plate. Opaque at rest, this plate becomes transparent when it is illuminated with visible light of suitable wavelength. We have successfully recorded the very first amplitude grayscale CGH, with a contrast greater than 50, which was reconstructed with a high fidelity in shape, intensity, size and location. These results reveal the high potential of this method for generating programmable/rewritable grayscale CGHs, which combine DMDs and photochromic substrates.

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1. Introduction

Computer Generated Holograms (CGHs) are useful for wavefront shaping and complex optics testing, including aspherical and free-form optics [1]. CGHs are classified as phase holograms, which are obtained by recording a phase variation in a material having a modulated refractive index or thickness, and amplitude holograms, where an intensity pattern is recorded in a material whose transparency can be locally controlled. Phase and amplitude holograms provide the same performances in terms of image reconstruction quality, but different diffraction efficiency. For instance, binary phase holograms, show 40% diffraction efficiency in the first order, whereas efficiency is limited to 10% for binary amplitude holograms [2]. Therefore, amplitude holograms are usually applied in interferometry, which is not intensity limited.

Grayscale holograms (both amplitude and phase) are known to give a higher reconstruction quality than binary holograms [2], but they require a more complex production process. Specifically, the production of phase grayscale CGHs is complex since a series of masks has to be consecutively aligned, and a developing step is required after each exposure step to obtain the final hologram.

To our best knowledge, only grayscale phase CGHs have been obtained so far by micro-lithography [3], the uniformity of the material thickness being the main limiting parameter [4]. Concerning amplitude CGHs, they are nowadays produced in chrome on glass by means of lithographic techniques, either mask or maskless (by direct writing) lithography. Due to the binary nature of the chrome developing process, these techniques allow for easily writing binary CGHs, but they cannot provide grayscale CGHs.

Here we demonstrate an original recording technique, which makes use of a programmable mask and a non-threshold photosensitive material, to produce ready to use grayscale CGHs in a one exposure process without requiring any developing step. Indeed, a set-up based on a Digital Micro-mirror Device (DMD), which has been originally developed to generate programmable slit masks in multi-object spectrographs [5], is considered. DMDs are programmable devices, composed of millions of micro-mirrors reconfigurable in real time. Actually, DMDs have been extensively used to generate dynamic binary or grayscale holograms [6], by exploiting the fast switching of the mirrors at frequencies higher than the human vision frame rate. The grayscale originates as a dynamic effect and not as a steady state effect. However, the discrete structure of the device induces a high scattering and background noise from the mirrors edges when illuminated with laser light [7], making such holograms useless for interferometry and metrology. Nevertheless, DMDs perfectly reproduce binary masks to be projected with incoherent light on photosensitive plates, thus producing amplitude CGHs. In this work, such plate consists in a photochromic film that can be reversibly converted from an opaque and colored form to a transparent form upon exposure with light of suitable wavelengths [8].

Actually, reversible holograms have been already obtained with photochromic materials [9, 10] and real-time photochromic holograms were shown, by exploiting the fast transition of imidazole dimers [11, 12]. Moreover, photochromic binary CGHs for optical testing have been recently demonstrated [13]. In photochromic materials, a ready to use hologram is generated just after the light exposure, and the reversibility of the photoconversion makes devices rewritable. Even more interesting, the transparency of a photochromic layer can be tuned by the dose of light absorbed, which opens to the development of grayscale patterns

[14]. In fact, the DMD set-up allows for easily recording grayscale CGHs with equidistant transparency levels, named as *stepped CGHs*, in a single exposure process. The lower diffraction efficiency of grayscale amplitude holograms with respect to binary amplitude holograms (6% vs. 10% [2]) is here compensated by a better image reconstruction quality, an easy exposure process and no developing steps, which are the limiting factors in the production of grayscale phase holograms.

In this paper, we report on the first stepped CGHs and results are compared to binary CGHs. We read the recorded information using a low power 632.8 nm laser, and the whole hologram is erased with a UV flash, for a reusable substrate.

2. Recording set-up

Figure 1 shows the set-up used to record the photochromic CGH. The DMD is the largest device produced by Texas Instruments and consists of 2048x1080 micro-mirrors with a pitch of 13.68 μm [15]. It is homogeneously illuminated by a collimated beam from a white source limited by a high bandpass filter (cutoff at 515nm) and redirects the light toward the plate, through an Offner relay with a magnification of 1:1, which warrants an almost aberration free projection. The set-up resolution is 2-3 μm and the size of a micro-mirror is 13 μm , hence the CGH resolution is not limited by the optics but by the DMD. Finally, a post-CGH imaging system is placed right after the CGH plate, and consists of two achromatic doublets, a filter centered around 600 nm and a CCD camera. This afocal assembly allows for CGH imaging during writing, both *in situ* and in real time. DMD, CGH and camera planes are conjugated, accordingly.

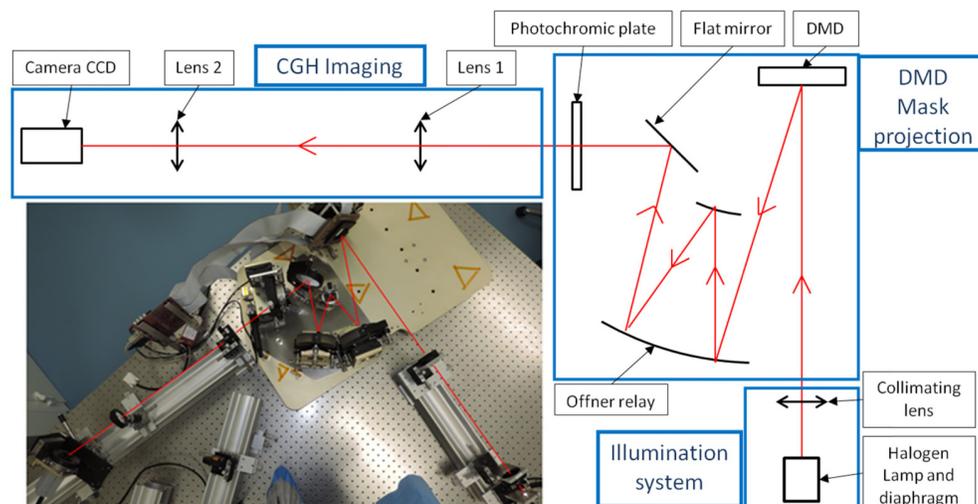


Fig. 1. Set-up for recording CGHs; it is based on an illumination unit towards the DMD, an imaging optical system based on a 1:1 magnification Offner relay from the DMD plane to the CGH plane, and a post-CGH imaging system. In red, the path of the optical beam.

3. Photosensitive plates

The photosensitive material is a diarylethene-based polyurethane [16]. Such kind of photochromic substrate contains a large content of photochromic units (i.e. 50% wt. in this work) that turns into a high contrast between the colored and uncolored forms, also for thin films. Moreover, the optical quality in terms of transparency and scattering is very good. The photochromic plate is 3 μm thick and the film is set uniformly to the opaque state by a UV exposure. The conversion under light illumination of the photochromic film has been previously determined by a kinetic model that provides the degree of transparency as function of the film features and illumination conditions [14].

4. Amplitude Fresnel CGH calculation

Fresnel holograms are directly calculated with the light propagation equations, and they can be modeled by the Rayleigh-Sommerfeld diffraction integral [17]. Being much greater than sensor and CGH dimensions, the distance z between the hologram and the screen can be approximated by the 2D convolution product in Eq. (1):

$$A_z(x, y) = A_0 e^{ikz} t * h_z \quad \text{where } h_z(x, y) = \frac{1}{i\lambda z} e^{i\pi \frac{x^2 + y^2}{\lambda z}}. \quad (1)$$

The resulting complex wave A_z is estimated by calculating the sum of the contributions of each pixel of the hologram anywhere on the screen located at a distance z ; therefore the image physical size and the focus are fixed. Each pixel is considered as a secondary spherical wave source weighted by the transmittance $t(x, y)$ of the hologram. These secondary waves are generated when the incident wave, characterized by its complex amplitude A_0 and its wavelength λ (or the wave number $k = 2\pi/\lambda$), reaches the hologram.

Figure 2(a) shows the image to be encoded, namely a 200x200 pixels "Z". The size of the CGH has been limited to 10x10 mm², which leads to a CGH resolution of 720x720 pixels. In order to be sure that all the fringes in the CGHs are resolved, hence well-encoded, the image physical size and the focus have been adapted and fixed at 2x2mm² and 2m respectively. The continuous CGH, calculated with these parameters, is shown in Fig. 2(b).

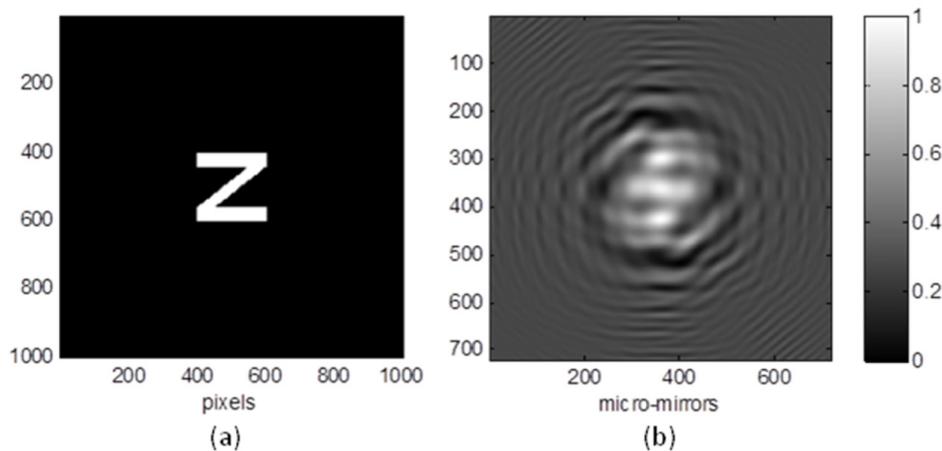


Fig. 2. (a) Original image to be encoded; a 200x200pixels "Z" (b) Magnitude of the 720x720 pixels calculated continuous complex CGH for an object dimension of 2x2mm² at a focus of 2m.

Once this continuous complex pattern is obtained, its magnitude can be binarized or discretized. The complex CGH is binarized by fixing pixel transmittance according to its magnitude value: pixels with a magnitude smaller than the mean level is fixed at 0 and the others at 1. Figure 3(a) shows the binary CGH of "Z" and the simulation of the reconstruction at 2m.

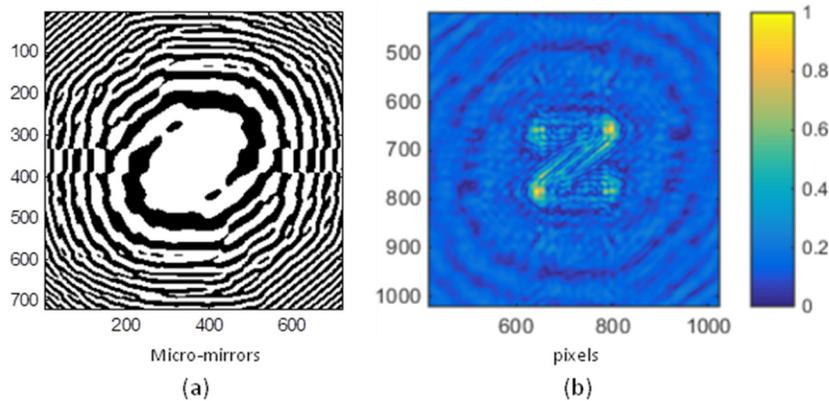


Fig. 3. (a) 720x720 pixels calculated binary CGH of a 200x200 pixels “Z” of 2x2mm² at a focus of 2m (b) Simulated reconstruction of the object.

As shown in Fig. 3(b), the obtained image does not completely resemble the original one (Fig. 2(a)), since binary CGHs do not well suit the shape and the intensity of the calculated continuous CGH. It follows that reconstructed images from a binary CGH are either pixelated or empty with a thin boundary, depending on the ratio between the focus and the image size.

In the present configuration, recording a binary CGH requires the projection of a single mask set on the DMD to the photochromic plate, for an exposure time large enough to produce the full conversion of the opaque form into the transparent form of the illuminated pixels. The use of a series of defined binary masks, which are sequentially projected on the photochromic plate, creating for each step a new degree of transparency, allows for obtaining stepped CGHs. It is worth noting that the production of grayscale CGHs does not require longer time than recording binary CGHs since the maximum transparency that can be achieved in a grayscale CGH corresponds to the full transparency in the binary CGH.

Here, we discretized the CGH in 20 gray levels; this number of steps is sufficient as the difference between the continuous and stepped CGH shapes calculated with the least mean square method is below 1%. Twenty binary masks are calculated by binarizing the continuous CGH pattern with thresholds ranging from 0 to 1 in steps of 0.05. Adding all these masks leads to the designed stepped CGH, as shown in Fig. 4(a). Figure 4(b) reports the calculated reconstructed image of this CGH. The reconstruction fidelity expected from a grayscale CGH is much higher than in the previous case. The image is fulfilled and well defined, namely almost identical to the original one.

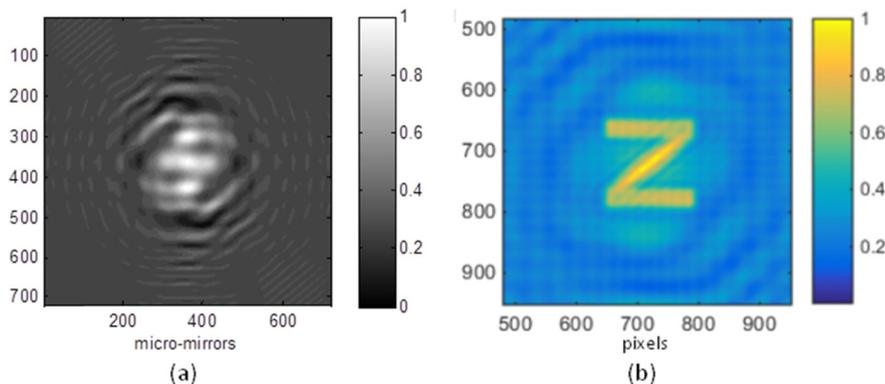


Fig. 4. (a) 720x720 pixels calculated stepped CGH of a 200x200 pixels “Z” of 2x2mm² at a focus of 2mm (b) Simulated reconstruction of the object.

5. Recording of amplitude CGHs

In the experimental recording, the photochromic plate is in the opaque state and it is exposed to visible light through the DMD set-up, with a progressive bleaching to the complete transparency. The imaging camera of the test set-up allows to record different images during the CGH exposure, thus to determine the exposure time. From the recorded images, the illumination law can be built, which provides the transparency of the plate as a function of the exposure time. Specifically, we recorded a calibration pattern including black and white areas as well as fine patterns (Fig. 5(a)), and we took images every thirty seconds.

Once determined the total exposure time, the plate was erased with UV light, and our first binary CGH, coding a 10x10 pixels “Z” of 2x2mm² at a 2m focus, was written (Fig. 5(b)). It resulted similar to the designed binary CGH reported in Fig. 3(a), confirming the reliability of the writing system. Clearly, to write binary CGHs, the plate is just exposed until the complete transparency in the desired regions is obtained. Several writing runs are actually possible using the same plate, although, an aging effect due to photofatigue is revealed, leading to a progressive decrease of the sample dynamics. This effect is well known in the photochromic witches, and strategies to prolong the lifetime of our photochromic plates are currently under investigation.

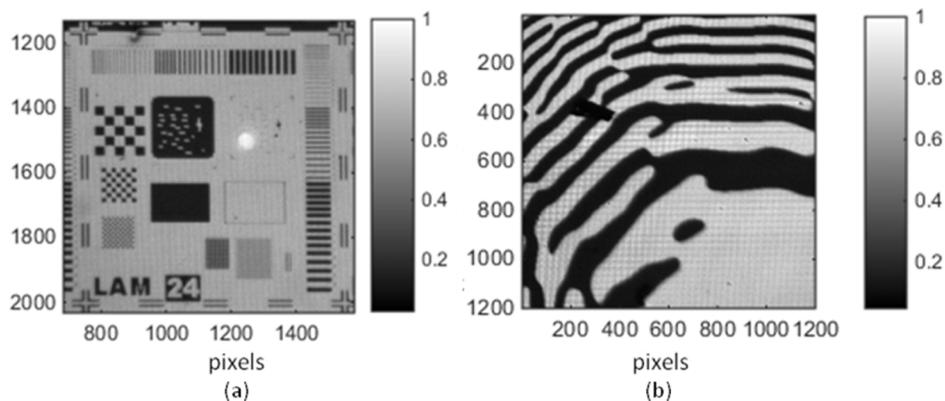


Fig. 5. (a) Close up view of the calibration pattern written on the photochromic substrate (b) close up view of a 720x720 pixels recorded binary CGH of a “Z” (10x10 pixels, 2x2mm² at a focus of 2m) on the same photochromic substrate after the UV initialization.

Since we are mainly interested in considering now grayscale CGHs, a linear gray scale is mandatory to precisely address the transparency level. Because of the nonlinear response of the photochromic materials, i.e. the transparency is not proportional to the absorbed dose, each mask has to be projected for a different time in order to get equal transparency degree in the CGH.

To linearize the transparency scale we considered the illumination law calculated with the calibration pattern, and shown in Fig. 6(a). The resulting curve resembles very well the bleaching equation described in the literature [14], and it allows for drawing the curve showed in Fig. 6(b), which gives the exposure time required for each mask. Four of the masks are shown on the top of the Fig. 6 as an example. The initial binary masks are essentially white because the CGH mean value of transparency has to be reached; then, only the most transparent areas of the CGH have to be written and the last masks look darker time after time. Finally, Fig. 6(c) represents the mean value for each obtained levels and its linearity proves that our illumination law generates equidistant levels.

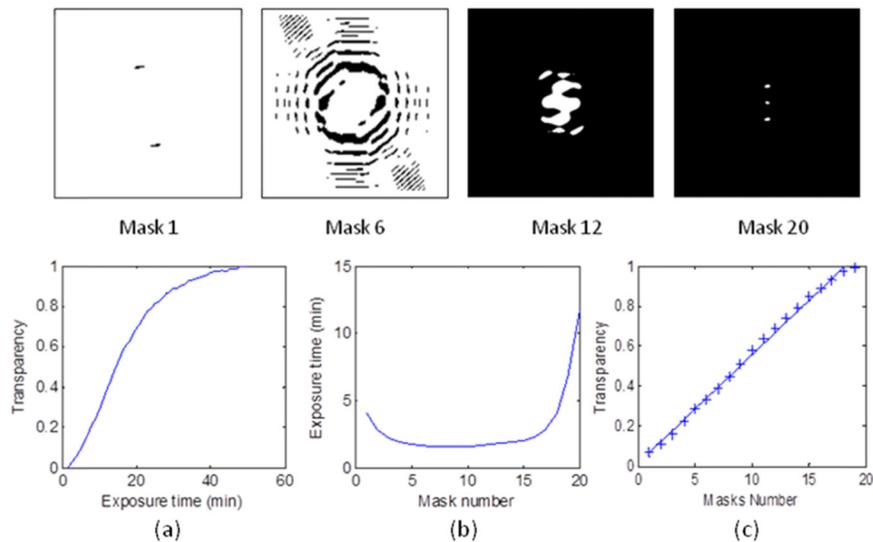


Fig. 6. (a) Illumination law of the photochromic plate (b) Exposure time of each mask for a CGH stepped in 20 levels (c) Linearity of the command law.

The total exposure time is proportional to the illumination intensity, and we have margins to reduce it up to few minutes by using a more powerful light source. In fact, DMDs are usually used for display application, and are adapted to strong illuminations, shortening drastically the exposure time. Moreover, the law obtained for a given light power is valid at different light powers, by a rescale with a homothetic transformation [14].

6. Results and CGHs comparison

Using the calculated exposure times for the different masks, the amplitude grayscale CGH has been actually written on the same photochromic substrate (Fig. 7(a)). As for the binary CGH of Fig. 5(b), it corresponds to the calculated 200x200 pixels “Z”, of a size of 2x2mm located at 2m, and stepped into the 20 levels. Interestingly, the recorded CGH (Fig. 7(a)) is almost identical to the predicted stepped CGH reported in Fig. 4(a).

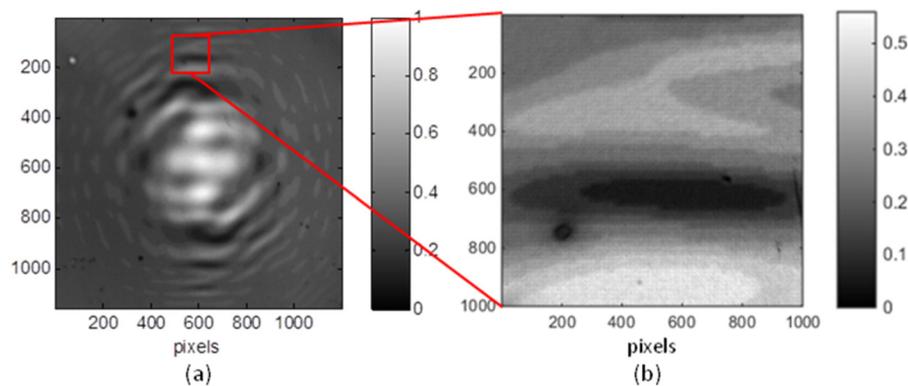


Fig. 7. (a) 720x720 pixels recorded stepped CGH of a 200x200 pixels “Z” of 2x2mm² at a focus of 2m stepped in 20 levels (b) Magnification of a part of the written CGH.

An area of the CGH obtained with an optical magnification of 3.75 is shown in Fig. 7(b), demonstrating the accuracy of this recording method in terms of definition of the grey levels and edges between levels. As already pointed out in section 2, the recording resolution is not

limited by the optical set-up but by the DMD pixels and then each micro-mirror trace is recorded on the plate. Each level is therefore perfectly defined and so the CGH is stepped.

The contrast of the CGH, which is closely related to the diffraction efficiency of amplitude holograms [13], has been evaluated directly with the imaging set-up on the CGH plate. The contrast is calculated as the ratio between the transmittance of the transparent areas over the transmittance of the colored areas measured by the CCD. The linearity of CCD has been checked and light intensity has been calibrated in order to have a good S/N for all the recorded images independently from the transparency degree. A contrast equal to 50 was obtained at 610 nm (10 nm bandwidth), which turns into a diffraction efficiency of the order of 75% of the maximum diffraction efficiency (achieved for infinite contrast). It is worth noting that higher contrasts can be reached by optimizing the photochromic plate (i.e. thickness, content and structure of the photoactive units).

Figure 8 reports the reconstructed image of the recorded CGH, which was obtained by illuminating the CGH with a collimated 632.8 nm He-Ne laser beam.

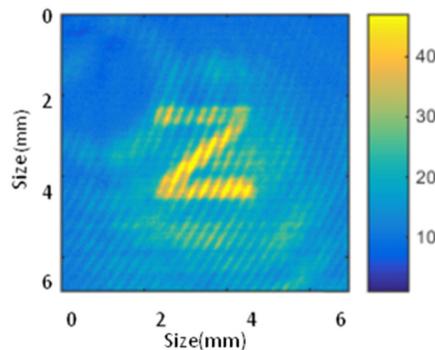


Fig. 8. Reconstruction of the recorded stepped CGH of a 200x200 pixels “Z” of 2x2mm at a focus of 2m and stepped in 20 levels.

The image was reconstructed at 2m, which was the designed focal distance. The physical size of the “Z” is 2x2mm², as expected.

We can notice a shadow on the upper left hand side of this reconstructed image that is ascribed to the diffraction caused by a defect on the CGH plate, which is visible in Fig. 7(a) (see the upper left hand side in the central area). Fresnel CGHs are very sensitive to defects and cannot be reconstructed correctly if the most transparent areas are altered. The image size and the focus chosen for the calculation also depend on the quality of the illumination. If the laser beam converges instead of being well collimated, the focus will be shorter and the size of the image smaller, and vice versa if the laser beam is diverging. The interferences fringes in Fig. 8 are probably due to multiple reflections in the plate itself.

As resulting from the simulation, the reconstructed image (Fig. 8) is very faithful to the original image (Fig. 2(a)), meaning that grayscale CGHs clearly give better reconstructed images than binary CGHs.

7. Conclusion

In this paper we demonstrated the realization of grayscale stepped amplitude CGHs. The combination of a DMD based writing set-up and a photochromic plate enables the design of complex holograms with good reconstruction quality.

We successfully recorded Fresnel CGHs, both with binary and stepped coding. The high optical resolution of our set-up allowed making high quality CGHs and the desired grayscale were properly produced. The reconstructed images using stepped holograms were very faithful to the original image without being pixilated as for binary holograms.

Finally, with our method, it is also possible to create any object of locally varying transmission (e.g. optical equalizers or apodizers), using the same protocol followed for stepped CGHs.

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