

Colorful reconstructions from a thin multi-plane phase hologram

Michał Makowski,* Maciej Sypek and Andrzej Kolodziejczyk

Faculty of Physics, Warsaw University of Technology, 75 Koszykowa, 00-662 Warsaw, Poland

*Corresponding author: mcovsky@if.pw.edu.pl

Abstract: A new technique of design and reconstruction of a color hologram is presented. The design is based on an iterative multi-plane optimization algorithm. It allows to encode three different images for a reconstruction at various distances measured from the hologram plane. The distances are calculated in order to obtain a fine color compound image when the hologram is illuminated by three laser beams of RGB colors. A single light phase modulator is used instead of three. The reconstructed red, green and blue component images remain in an exact match in size and position. The 2-D color image is reconstructed at a pre-assumed distance and its color pattern can be easily controlled by the choice of the three input component images.

©2008 Optical Society of America

OCIS codes: (090.1705) Color holography; (090.1760) Computer holography; (090.2870) Holographic display.

References and links

1. E. N. Leith, A. Kozma, J. Upatnieks, J. Marks, and N. Massey, "Holographic data storage in three-dimensional media," *Appl. Opt.* **5**, 1303–1311 (1966).
2. T. Yamaguchi, G. Okabe, and H. Yoshikawa "Real-time image plane full-color and full-parallax holographic video display system," *Opt. Eng.* **46**, 125801 (2007).
3. M. Makowski, G. Mikula, M. Sypek, and A. Kolodziejczyk "Three-plane phase-only computer hologram generated with iterative Fresnel algorithm," *Opt. Eng.* **44**, 125805 (2005).
4. M. Makowski, M. Sypek, A. Kolodziejczyk, G. Mikula, and J. Suszek "Iterative design of multi-plane holograms: experiments and applications," *Opt. Eng.* **46** (2007).
5. G. C. Larsen and T. S. Gleghorn, "Hologram methods for signature security consolidated content and an accelerometer," US Patent Application Publication, Pub. No.: US 2007/0127096 A1 (2007).
6. I. Yamaguchi, T. Matsumura, and J. Kato, "Phase-shifting color digital holography," *Opt. Lett.* **27**, 1108–1110 (2002).
7. T. Ito and K. Okano, "Color electroholography by three colored reference lights simultaneously incident upon one hologram panel," *Opt. Express* **12**, 4320–4325 (2004).
8. R. W. Gerchberg and W. O. Saxton "A practical algorithm for the determination of phase from image and diffraction plane pictures," *Optik* **35** (1972).
9. R. Dorsch, A. Lohmann, and S. Sinzinger "Fresnel ping-pong algorithm for two-plane computer-generated hologram display," *Appl. Opt.* **33** 869–875 (1994).
10. M. Sypek, "Light propagation in the Fresnel region: new numerical approach," *Opt. Commun.* **116**, 43–48 (1995).

1. Motivation

The holography designed to form a color image can be divided into two categories. First is the thick holography [1]. It assumes the object wave interfering with a reference beam and then the fringe pattern recorded into a volume thick medium. During a reconstruction in a white light the hologram works like a large set of interferometric spectral filters, thus creating a color reproduction of the recorded three dimensional scene. The second category assumes using three spatial modulators and illuminating each of them with a red, green or blue reconstruction beam [2]. The former method has a certain advantage of white light

reconstruction yielding a fine full-parallax viewing experience. On the other hand the used recording media (e.g. polymers) are relatively expensive and make difficulties in a massive reproduction, which limits the possible applications. Additionally, the recorded scenes are static. The latter method provides a real-time animated holography using a set of three Spatial Light Modulators (SLMs) [2]. Each of the modulators alters the phase of a red, green or blue beam separately to compose a final dynamic color hologram. The main problem is the price of the used three SLM devices. This paper shows how the holographic design method [3,4] can be applied a full color reconstruction of a 2-D object. The proposed technique differs from the holographic video display system [2] since it assumes the use of only one SLM instead of three to project a 2-D color real image, thus sacrificing the parallax effect and a 3-D depth. Additionally it does not involve a segmentation or a multi exposure technique. Thus the full dynamic range of the hologram is used and there are no viewing obstructions or ghost images due to the use of a segmentation function [5-7].

2. The design of a multi-plane hologram

The transmittance of a multi-plane hologram is calculated in the computer memory by using a dedicated software. The detailed description of the design method has been previously published [3,4]. It is based on a Gerchberg-Saxton algorithm [8] and involves an iterative loop of propagations [9] between the three image planes and the hologram plane, as shown in Fig. 1.

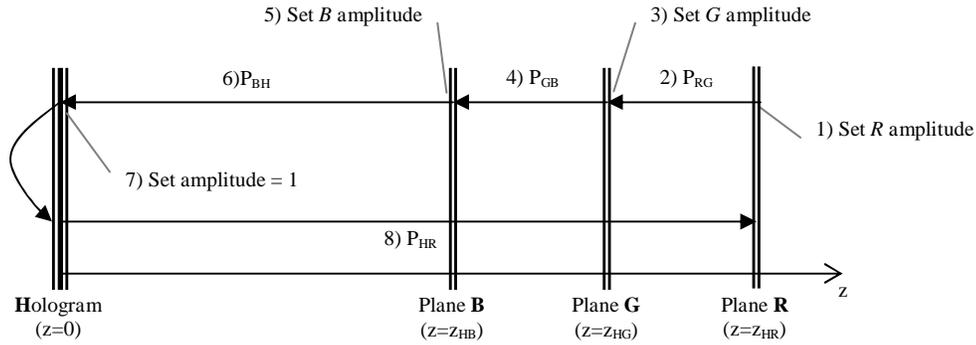


Fig. 1. Ideal scheme of the design of a three-plane phase hologram. P denotes a propagation operation.

The algorithm starts at the distance z_{HR} with a random initial phase and an amplitude imported from *Image R* (step 1 in Fig. 1). The wavefront constructed in such way is then propagated backwards to *Plane G*. There the amplitude is overwritten by importing from *Image G* without altering the phase. The wave front is propagated to *Plane B*, where the *Image B* is forced as an amplitude, again with no change in the phase. Afterwards the propagation to the hologram plane occurs. There the amplitude is equalized to a value of 1 in order to achieve a phase only structure. Propagation to *Plane R* closes the iterative loop. Therefore the complex amplitude U of the wavefront after n iterations can be expressed as:

$$U_n = P_{HR} \{ A_1 \{ P_{BH} \{ A_B \{ P_{GB} \{ A_G \{ P_{RG} \{ A_R \{ U_{n-1} \} \} \} \} \} \} \} \} \} \quad (1)$$

Where P denotes a propagation between two planes given in the lower index, A denotes an amplitude import from an image given in the lower index. The loop is repeated pre-assumed number of times. Such optimization remarkably increases the contrast ratio and decreases the speckles visibility [4]. Increasing of the number of iterations causes an asymptotic

improvement in the quality of a final reconstruction [3]. However, when real time projection applications are considered, the computational cost must be taken into account. Therefore in this work 30 iterations were chosen as a trade-off between the quality and the computational cost. In the color display application it is critical to maintain an equal average intensity of each of the images. This is successfully maintained because in the iterative loop every image is enforced as amplitude with the same frequency, i.e. once per loop. The distance from the hologram to the *Plane R* plane was established so that the red component, i.e. *image R* is reconstructed at the distance of 100 mm when using a red beam of a wavelength of 632.8 nm. This wavelength was chosen intentionally for the convenience of future experiments using a He-Ne laser. The distance from the hologram to the *Plane G* was established so that the green image is reconstructed at the same distance of 100 mm when using a wavelength of 570 nm. The distance from the hologram to the *Plane B* was established so that the blue image is formed at the same distance of 100 mm when using a wavelength of 490 nm. In this way we obtain a hologram which produces a sharp image at a fixed distance of 100 mm when illuminated with a beam of any of the three mentioned wavelengths. Thus when illuminated by the three beams simultaneously, it shall produce a sharp colorful image at the distance of 100 mm. The ideal scheme of the reconstruction process is shown in Fig. 2.

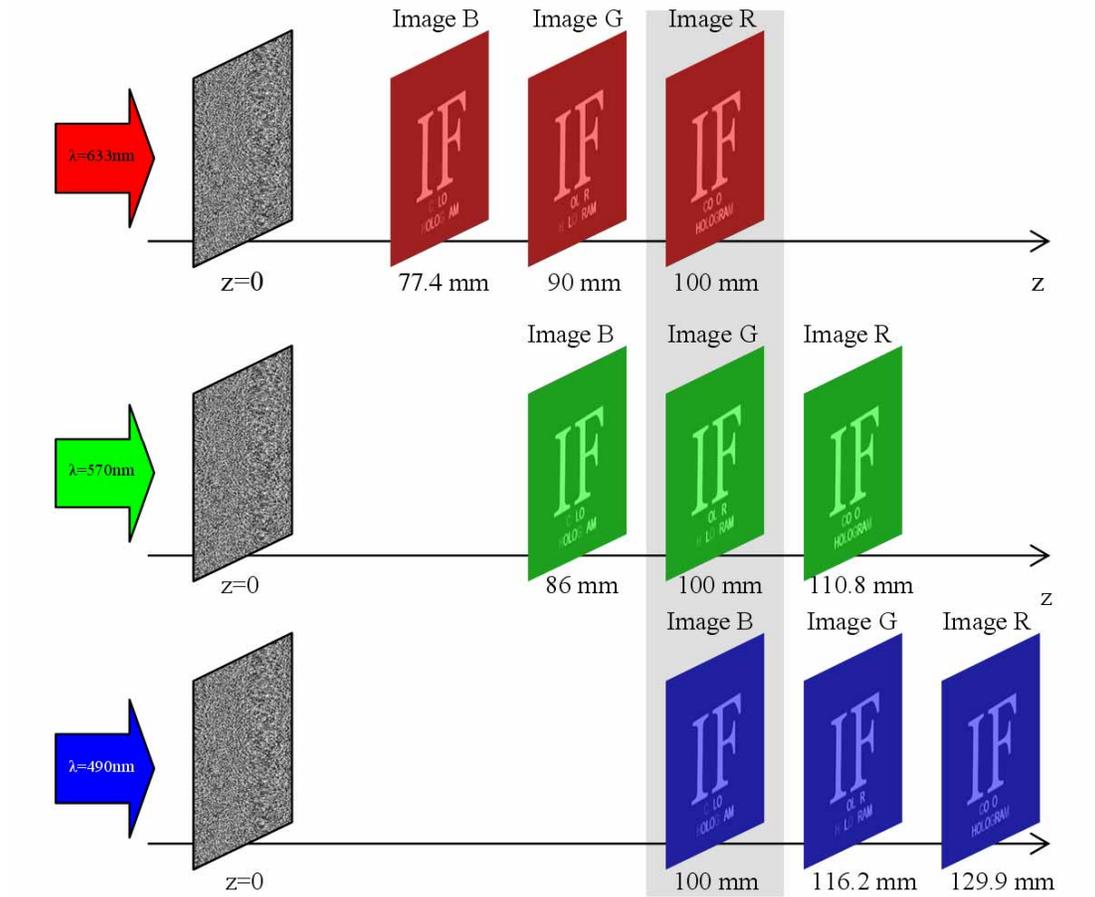


Fig. 2. Ideal scheme of a reconstruction of a three-plane hologram using beams of three different wavelengths. The distance of 100 mm, where all three RGB beams reconstruct a sharp image is marked.

When a hologram designed for $\lambda=632.8$ nm is reconstructed with plane waves of different wavelengths, the longitudinal displacement of the image planes occurs, as shown in Fig. 2. The presented method assumes an object reconstruction by a plane wave illumination. The use of such an illumination guarantees that the transverse size of every image is wavelength independent and remains unchanged. The used propagation method [10] based on FFT assumes the same array size and sampling values for both hologram and image planes during the calculations. Nevertheless the final structure belongs to the class of diffuse holograms hence the object information is recorded globally in every fragment of the structure surface. Therefore in the reconstruction stage the dimensions of the hologram can be much smaller than the dimensions of the object. For example one could design a hologram on a large array, e.g. 65536 by 65536 points and use only its central region of 1024 by 1024 points for a reconstruction. In this way one could obtain an image 64 times larger than the hologram, although for the price of a high computational cost. The established object distances were 77.4 mm, 90 mm and 100 mm for the red light for R, G and B components respectively when an illumination with a red light is assumed. Those values were used in the iterative optimization algorithm. The content of images *R*, *G* and *B* was chosen arbitrarily in order to demonstrate the capabilities of reproducing images of wide color range and high contrast. The two sets of exemplary input images are shown in Fig. 3. In the Set 1 the “IF” letters are at maximal brightness in all three components, which shall reproduce as a white color in the final composition. The small letters “COLOR HOLOGRAM” have variable gray levels in the three RGB components, which shall reproduce as a colorful sign. Sets 2 and 3 are supposed to reproduce skin tones and fine color transitions. The results of numerical reconstructions from the obtained phase distributions after 30 iterations of the iterative algorithm are presented in the following section.

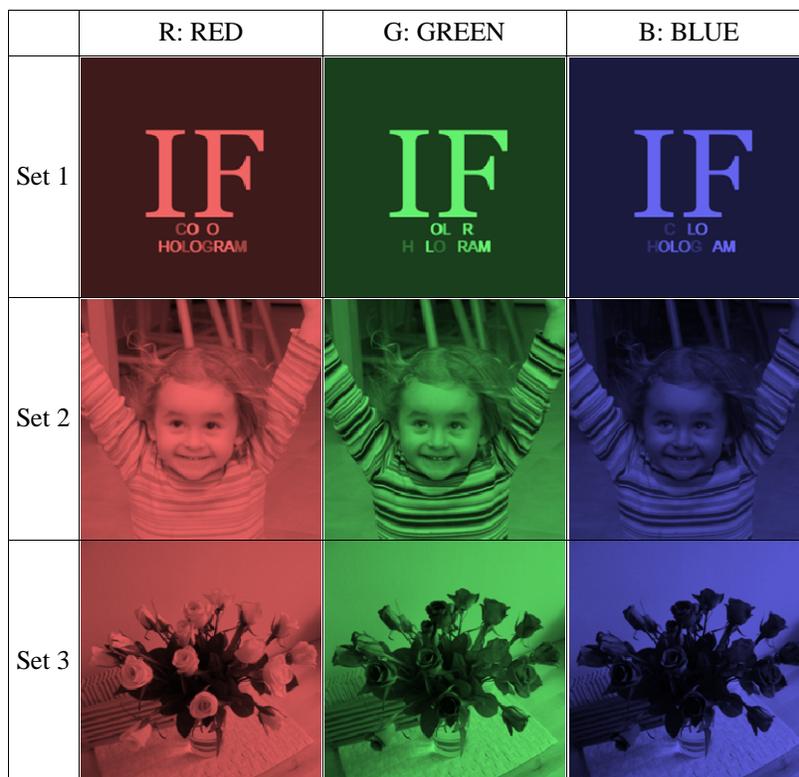


Fig. 3. Exemplary input images split into RGB components. Set 1: "color hologram", Set 2: "child", Set 3: "roses".

3. Numerical reconstruction

The obtained phase distribution was multiplied with a constant amplitude and then numerically propagated [10] to the distance of 100 mm using $\lambda=632.8$ nm, then 570 nm and 490 nm. These operations were performed using a dedicated software on arrays of 1024 by 1024 points with the sampling equal to 10 μm , thus the image size was 10.24 mm by 10.24 mm. The arrays contained a continuous phase without any quantization. Fig. 4 shows the obtained intensity distributions at 100 mm for each used wavelength. The three obtained images exhibit an equal average intensity and the visible shapes exactly match in size. This is important, since any mismatch in a size shall result in chromatic aberrations. In the work [2] this negative effect required a manual rescaling of the reconstructed images by zero-padding. In our case any manual size-matching is not necessary.

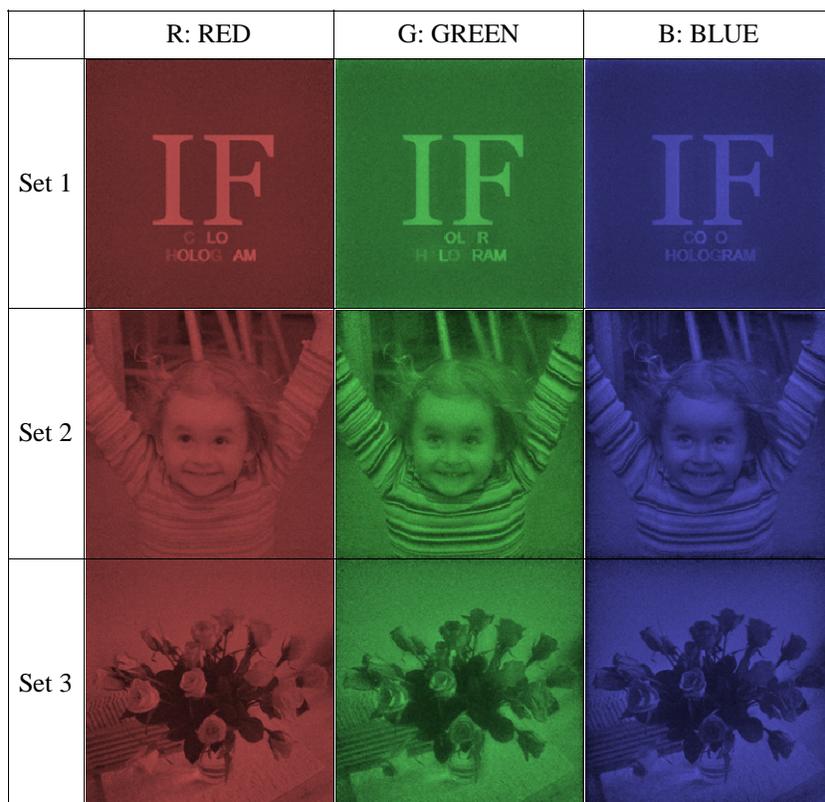


Fig. 4. Results of a numerical reconstruction of the hologram at the distance of 100 mm using wavelengths of a red, green and blue light.

The obtained grayscale images were colored red, green, blue and combined using a photo editor software. The result of this merge compared to the combination of the input images is shown in Fig. 5. This numerical operation is equivalent to observing a screen placed at the distance of 100 mm if the hologram is simultaneously illuminated with three RGB plane waves from laser sources. As can be seen, the color range was reconstructed with a good synchronization of RGB patterns. On the other hand, the color noise surrounding the characters is visible. Its appearance is a result of the combination of three randomly localized speckle patterns from RGB components. The visibility of the speckles can be further reduced

by increasing the number of iterations of the optimization algorithm. The colors reproduced from the hologram look less saturated due to the decreased contrast ratio in the reconstruction compared to the contrast ratio of the input images. The obtained RGB component images are equal in size, thus no aberrations or overlapping in colors are visible. It is an important advantage of the present design of a multi color hologram. Some less noticeable intensity variations [4] and thus color shifts can be observed in Fig.5 b), nevertheless this can be further suppressed by using larger arrays in the iterative process.

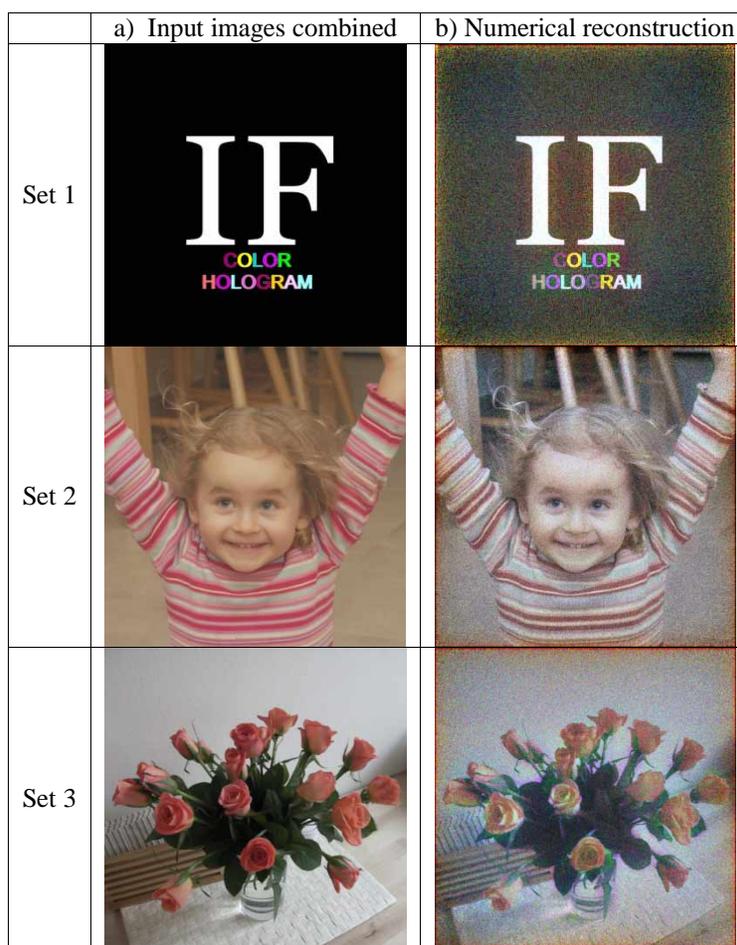


Fig. 5. Color combination of: a) the input grayscale component images; b) the output grayscale images numerically reconstructed from the hologram.

4. Conclusions

We have presented a new technique of a color reconstruction from a single thin phase-only hologram. The method was tested numerically with good result obtained for three sets of input images containing some characters and colorful pictures. The performed numerical simulations have proven that the new technique allows one to successfully display a full color 2-D image at a fixed distance by using only a single phase modulator instead of three. The current research is focused on the experimental confirmation of the conclusions conceived from numerical simulations.