Native frame rate single SLM color holographic 3D display

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Abstract— In this paper we present a single SLM color holographic 3D display with a spatial only multiplexing method. The SLM is illuminated simultaneously with three beams. A color (RGB) filter mask placed in front of the SLM surface distributes illuminating beams to respective component holograms. After propagation, modulated wavefronts overlap in space and create a real color 3D image. The display works with a native SLM frame rate, but with the cost of spatial bandwidth product reduction. In the paper we present the method's capabilities and discuss its limitations. Finally, we present the display implementation and resulting color holographic reconstruction of a computer generated 3D object.

Technological limitations of spatial light modulators (SLM) used for holographic displays (large pixel size, small aperture) forced to seek solutions to increase the imaging dimension and viewing angle. For this purpose monochrome displays employ spatial, temporal or spatio-temporal multiplexing methods [1]. Introducing color in such a display usually requires a further increase in SLM number [2] or refresh rate [3]. Thus, low complexity color reconstruction techniques are required. One of the attractive solutions is an aperture field division method (AFD) [4-5], which utilizes a single SLM and spatial multiplexing for color image reconstruction. In this paper we present a solution for color 3D holographic reconstruction with an AFD method where an individual SLM can be converted into a color holographic 3D display with its native frame rate.

In the AFD solution three beams are simultaneously illuminating the SLM surface (Fig. 1). The active area of a modulator is horizontally divided into three regions corresponding to red, green and blue component holograms. A color filter mask which is placed in front of the SLM surface from approximately a 2mm distance distributes illuminating beams according to the displayed information. Modulated wavefronts pass through the filter mask and after propagation overlap in the region where a real color holographic image is reconstructed. Due to the lateral separation of the channels a triple "keyhole" problem (color channel separation) occurs when looking at the image with the naked eye. Therefore it is necessary to apply an observation method which supports color mixing at the image plane. At this paper we use an asymmetrical diffuser which is placed at the reconstruction plane [6]. This technique provides color mixing by expanding every channel viewing window in a vertical direction and converts our display into horizontal parallax only. The filters are aligned horizontally which allows obtaining a linear Field of View (FoV). What is more important, visual monocular and binocular FoVs in a horizontal direction are equal to those of the display without a color filter mask [7].

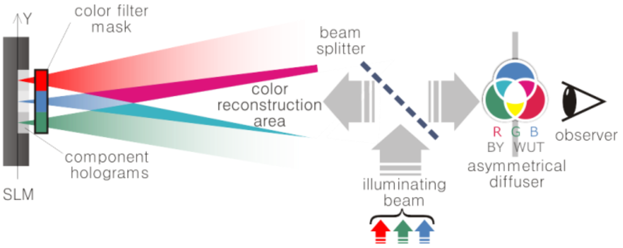

Fig. 1. The scheme explaining the principle of color holographic reconstruction with an aperture field division method

Due to the wavelength diversity of separate color channels and their lateral displacement, the basic reconstruction parameters differ from those of a monochrome display [7]. Individual color holographic reconstruction images overlap properly in a limited cone area only, as shown in Fig.1. In the most general case, the location of this area depends on the dimensions of color mask filers, its position and angular field of view (aFoV) of each color component. A single channel aFoV is determined by the light wavelength λ and the SLM pixel pitch Δ [7]:

$$\mathrm{aFoV} = \alpha \cong \frac{\lambda}{\Delta}\ . \tag{1}$$

The formula shows that the narrowest field of view is obtained for the shortest light wavelength. It means that the blue channel limits the color reconstruction area. Thus, most favorably, from the point of other system parameters, is to place it at the SLM center. As shown in Fig. 2, color mixing occurs as soon as three wavefronts start to overlap at point RG. In Fig. 2 there are two more distinctive points, i.e. BR and BG which define the color holographic imaging area. These imaging areas, which are marked as I, II, and III have the following z_r coordinates:

$$\text{I.}\quad \frac{(h_G+2h_B+h_R)\Delta}{\lambda_R+\lambda_G} < z_r \le \frac{(h_B+h_R)\Delta}{\lambda_R-\lambda_B}\ , \tag{2}$$

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$$\text{II.}\quad \frac{(h_B+h_R)\Delta}{\lambda_R-\lambda_B} < z_r \leq \frac{(h_B+h_G)\Delta}{\lambda_B+\lambda_G}\,, \tag{3}$$

$$\text{III.}\quad \frac{(h_B+h_G)\Delta}{\lambda_B+\lambda_G} < z_r \leq \infty\,, \tag{4}$$

where h_R, h_G h_B are the holograms heights of red, green and blue color filter masks, λ_R, λ_G, λ_R are the corresponding illumination light wavelengths and z_r is the reconstruction distance. In each of these reconstruction areas the linear Field of View (FoV) in a vertical direction is described by a different equation:

$$\mathrm{FoV_I} = \frac{(\lambda_G+\lambda_R)z_r}{2\Delta}+\frac{h_R-h_G}{2}\,, \tag{5}$$

$$\mathrm{FoV_{II}} = \frac{(\lambda_G+\lambda_B)z_r}{2\Delta}-\frac{h_G+h_B}{2}\,, \tag{6}$$

$$\mathrm{FoV_{III}} = \frac{\lambda_B z_r}{\Delta}\,. \tag{7}$$

In areas I and II, the corresponding vertical $\mathrm{FoV_I}$ and $\mathrm{FoV_{II}}$ are not symmetrical with respect to axis Z, different wavelengths, field of view limits. In area III we obtain a symmetrical $\mathrm{FoV_{III}}$ and fully utilize the capabilities of the SLM, due to beams superposition covering the entire blue field of view.

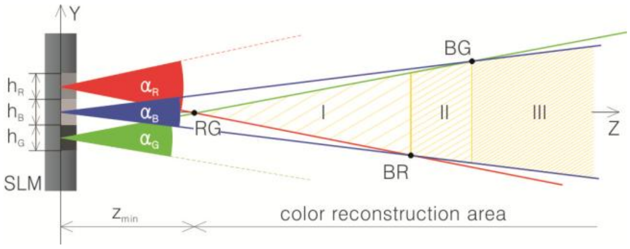

Fig. 2. The principle of a color reconstruction linear Field of View determination.

Since a single color channel of the image is created using a third of the SLM area, the spatial bandwidth product of such a hologram is three times lower than for the whole surface reconstruction. It affects the vertical resolution of holographic image reconstruction. Horizontal (d_H) and vertical (d_V) image resolution in the image central region can be described by the equations [7]:

$$d_H = \frac{\lambda z_r}{\Delta N_x}\,, \tag{8}$$

$$d_V = \frac{\lambda z_r}{\Delta N_y/3}\,, \tag{9}$$

where N_x and N_y are the numbers of SLM pixels in horizontal and vertical directions, respectively. Referring to these equations, the lowest resolution is obtained for the red channel which limits color display resolution.

Precise matching of the filter mask position and component holograms at the SLM plane is a crucial feature of the presented method's high efficiency. For this purpose a positioning method has been developed based on displaying modulator phase patterns and their observation through a filter mask [7]. It should be noticed that this pixel loss depends on filter manufacturing precision as well as the illumination angle in plane YZ. For the experimental setup, normal illumination was chosen, which ensures the smallest possible waste area due to filter mask joints.

Because the SLM pixel phase response characteristic is strongly dispersive [9], each of the masked regions requires the settings corresponding to the used light wavelength. As the modulation range is defined simultaneously for the entire SLM area, we decided to use the highest modulation range characteristic of the device and bit depth reduction phase response compensation for color hologram components [6]. In our experiment the bit depth is equal to 255, 186 and 154, respectively for the red, green and blue channel. It was proven [10] that such a bit depth reduction does not affect significantly the quality of image reconstruction.

The input data for the color display are separate holograms produced for selected wavelengths. The necessary data processing of such a hologram is presented in Fig. 3. We can distinguish two basic processing steps: (1) application of spatial masking found during the calibration process and (2) modulation bit depth scaling. In practice, the correction of bit depth information can be stored in the color distribution mask and applied by multiplying the mask over a set of holograms on a scale 8-bit image saved as a 24-bit color.

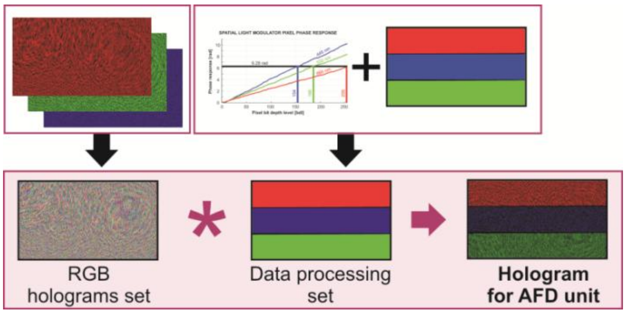

Fig. 3. Data processing scheme at aperture field division method.

To generate the 3D holographic content we have used an object based on a 3D computer graphics representation [11] in the form of cloud of points with 91000 points per color. In Fig. 4, a 3D object model and its optoelectronic reconstruction is presented. The reconstructed 3D holographic image covers approximately the volume 25mm×25mm×35mm and the distance of a central reconstruction plane is 750mm. Color mixing supported by an asymmetrical diffuser (0.4°x60°) creates satisfying observation conditions (Fig. 4b). The area marked with a white rectangle was additionally captured with a CCD matrix placed in the reconstruction plane of a front vase surface. In the image we observe image defocus gradually changing from the vase center (clearly visible object points) to the edge (random speckle structure and blurring) due to object three dimensionality.

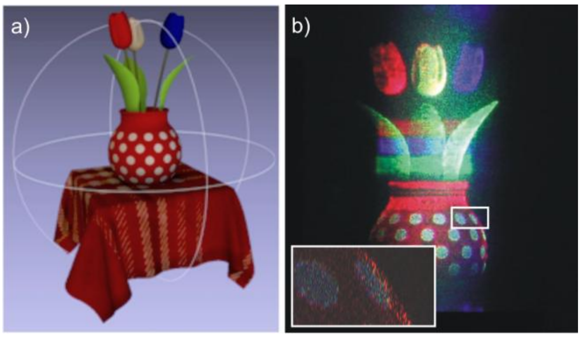

Fig. 4. The synthetic 3D object view (a) and its holographic reconstruction asymmetrical diffuser with the use of an aperture field division method (b).

Table 1. A set of basic parameters of a color holographic 3D display with spatial only multiplexing and asymmetrical diffuser screen.

PARAMETER NAME	PARAMETER VALUE
Vertical FoV= Horizontal FoV	41.71mm
Vertical resolution d_V	32µm
Horizontal resolution d_H	172µm
Horizontal VFoV	19.48mm
Vertical VFoV	41.71mm
Horizontal aFoV	3.19° + 0.4°
Vertical aFoV	3.19° + 60°
Color image display frame rate	60Hz (native)

The presented solution provides a 3D color holographic reconstruction. Display parameters are listed in Table 1. The values are calculated for the following experimental setup parameters: high definition SLM with the pixel pitch Δ=8µm and the frame rate 60Hz, the light sources wavelengths: 660nm, 532nm and 445nm, central plane reconstruction distance z_r=750mm (area III) and calculation observation distance z_o=1000mm. Despite using one third of the SLM surface all horizontal parameters of the setup stay unchanged (compared to the whole SLM reconstruction). Especially important are visual monocular and angular fields of view (VFoV and aFoV) which define image observation conditions [8]. A viewing window decrease in the vertical direction does not affect field of view parameters, as we work in a display configuration of horizontal parallax (i.e. with an asymmetrically diffusing screen) and VFoV is equal to the scene size. However, the three times lower spatial bandwidth product causes a vertical resolution decrease. The method's advantage is giving us an opportunity of channels resolution difference compensation. By developing more complex filter mask patterns, we would take into account light wavelengths ratio and SLM dimensions and in this way affect color image resolution. With all these parameters values, the most important advantage of the presented solution is the native operating frequency of the SLM. This allows for widening an angular field of view or image quality improvement by using a number of multiplexing solutions.

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