Multi SLMs holographic display with inclined plane wave illumination

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ABSTRACT

Holography can store full wide angle information about a registered object, since during registration process information about amplitude and phase of an optical wave scattered from an object is captured. Because of this unique feature people put hope in holography as the method which can be utilized in a 3D imaging display. In the paper we present the design of a wide viewing angle display system utilizing multiple Spatial Light Modulators (SLMs). The system is capable of displaying objects from both virtual and real worlds. In our system we are using phase only reflective SLMs based on liquid crystal on silicon (LCoS). There are designed to work with normal illumination. However in order to simplify an optomechanical system of the display here the SLMs are used with an inclined plane wave illumination. Therefore in the paper at first we focus on determination of a tilt depended SLM calibration, so thus SLM even with highly off axis inclined illumination is capable of an accurate wave reproduction. Then we focus on obtaining high quality reconstruction of objects from virtual world. We present an algorithm based on Gerchberg-Saxton scheme and diffraction computing between tilted and parallel planes. All of the paper discussions are accompanied with experimental results obtained in the multi SLMs display.

Key words: digital holography, LCoS SLM, holographic display, 3D display, tilted plane algorithm

1. INTRODUCTION

In visual multimedia technology rapid progress of creation and display 3-D data is mainly represented by a stereoscopic and pseudostereoscopic techniques [1]. However one of the most promising future ideas is holography. In this sophisticated method a full object wavefield information can be captured and then optically reconstructed giving true 3-D effects. Constant development of CCDs and spatial light modulator (SLM) technology in last decades, gave new possibilities of recording and data presentation and contributed to form digital holography based concepts of 3-D displays[2].

Main issues for such a system, relatively to conventional holography, are big pixel size, small apertures and periodic structure for both CCD detectors and commercially available SLMs. In consequence we have limited angular field of view, low image resolution, closeness of aliasing images, high speckle noise, difficult conditions of observation and almost impossible binocular, that is 3-D, vision [3]. All these attributes gathered together cause problems, which have to be overcome to build a holographic display.

Waiting for a technological progress, we learn to take full advantage of current solutions, to better exploit capacities of their future counterparts. So far SLMs based on Liquid Crystal on Silicon (LCoS) technology have been recognized as the most feasible devices for holographic displays [4]. They work in reflection and enable phase modulation of illuminating wave in the range of 0-2π (and more). This allows to get high diffraction efficiencies (close to 90%) and address them directly with the phase of an object wavefront.

Limited viewing angle seems to be one of the most important features affecting the experience of observing optically reconstructed holographic images. It is limited by a finite pixel size of the SLM device. Recently several attempts have been made to enhance these features by employing innovative optoelectronic modules which are adopted to generate a large number of data points [5] and to increase holographic display angular viewing ability [6,7].

In this paper we present a holographic display configuration, based on synthetic aperture method, where multiple SLMs aligned in circular configuration are put to work together. This technique allows to increase the viewing angle in horizontal direction and thus the horizontal parallax. The system is based on LCoS high definition spatial light modulators. We discuss the linking of multi CCD digital holographic capture with display system, allowing in future to

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display holograms captured for real world objects (Section 2). Finally we present the setup arrangement as well as the results obtained from a six SLMs (section 5). However to put the system to its full operation several theoretical and practical problems have to be addressed including: SLMs calibration (pixel response and wavefront aberration) (section 3), and necessary hologram processing (order removal and tilt correction algorithm) (section 4).

2. SYSTEM CONCEPT

Multi SLMs display configuration is closely linked to capture system. In this section the main dependencies between these setups, caused issues and proposed solutions are presented.

The capture system is based on principals of digital holography [8]. Spherical coherent wave illuminates the imaged object and creates an object wave. The holographic fringes as a result of interference of an object wave with a plane reference wave are captured by CCDsa. Although a progress has been made in a CCD technology, a single camera is still unsufficient to register an object wave scattered from different object perspectives. In order to increase viewing angle, a multi camera system is proposed to register separate perspectives. The CCDs are positioned with their normals pointing toward an object, to fill the whole detector area and capture microinterferogram due to its high frequency content, what minimizes the loss of information. The circular configuration for multi camera system fits the best to our requirements (Fig.1) and allows to use optimally entire CCD area.

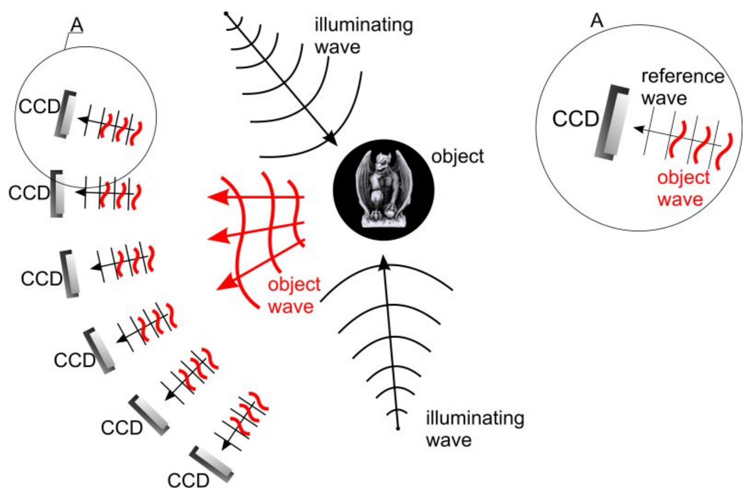

Fig.1. The setup of a multi CCD digital capture system.

From a reconstruction point of view, the knowledge of geometry of capture setup (e.g. angular separation of CCDs, pixel size, wave length, registration distance etc.) is very important because of necessity of copying it during a reconstruction process. It means that each SLM should recreate the same wave field part as captured by a corresponding CCD camera with proper magnification and its position in space.

For the possible results a type of registered hologram is also very important. At our system we applied Fresnel, on axis, phase shifted digital holograms (PSDH). Other techniques have additional holographic orders, twin images which on the whole result, like in the case of Fourier holograms, in the lack of 3D perception. Phase shifting method allows to remove zero order (which for example in Fourier holograms have strong influence on a quality of reconstructions) and a twin image [9]. Moreover previous experiments [10] had clearly shown that such holograms allow to utilize in the best way a field spatial bandwidth product.

As mentioned before the reconstruction system should comply with a registration one. Thus the first assumption about the SLMs' configuration was to illuminate them along their normals (Setup1) (Fig.2a). In such case the direction of reflected beams from SLMs is the same as of a wave field recorded by CCDs. As a result a holographic image with multiple perspective (multiple SLM) is reconstructed accordingly to the capture system.

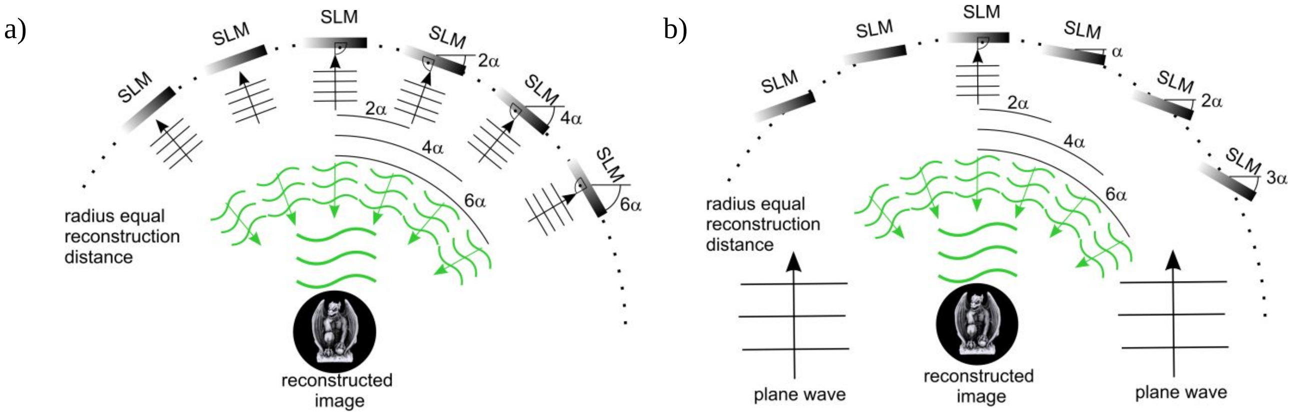

Fig.2. The scheme of a reconstruction configuration with illumination along LC SLMs' normals (setup 1) (a) and with parallel illumination (setup 2) (b)

However this type of solution occurred to be complicated in its experimental realization, since it was necessary to direct each illumination beam at a specific angle. Second method is to illuminate SLMs with parallel beams (Setup 2) (Fig.2b). This approach gives system more flexibility to reconstruct holographic images from different capture setups (distances and angular separation). In this configuration SLMs are arranged on an arc which radius is equal to the reconstruction distance with illumination going along its optical axis. To make all images appear in the same point, SLMs must be tilted to the normals like for an arrangement on arc with twice more longer radius (principle of work spherical mirror). In practice this means that this tilt angle (α) is the half of the angular separation between tilted and normally illuminated SLM in the setup.

As it can be seen from Fig.2, the angle of the marginal SLM in the first configuration is two times bigger than in the second one, which in the final result effects in bigger dimensions of the setup. This feature as well as simpler illumination decided of applying the setup 2. However the preferred setup 2 differs essentially from registration configuration. The SLM planes do not coincide with capturing CCD matrixes, therefore we have to recalculate holograms so that they will fit the new geometry. To do this we have developed a tilted plane algorithm, which is described in section 4.

The reconstruction system (display) utilizes six Liquid Cristal on Silicon Spatial Light Modulators (LCoS SLM, model HEO 1080P) which are illuminated by plane waves. The LC SLMs used in our setup are phase modulators working in high definition and with a pixel pitch of 8μm square. CCDs' pixel sizes are usually smaller and the resolutions differ from SLMs', hence some other geometrical and optical parameters of both systems are different. Also using other wavelengths gives consequences to reconstruction. We have to consider these effects while linking both systems. These mismatches between hologram's properties and our system affects on optical reconstruction in two ways [11]:

- modification of the distance of reconstruction plane to SLM plane according to the equation:

$$z_{rek} = z_{reg} \frac{\lambda_{reg} {\Delta^2}_{rec}}{\lambda_{rec} {\Delta^2}_{reg}} \qquad (1)$$

where z_{reg} is distance between object and detector, $\lambda_{reg/rec}$ is a wave length used during registration and reconstruction respectively, $\Delta_{reg/rec}$ is a pixel size of CCD and SLM respectively.

- modification of the transverse magnification by the factor of:

$$M = \frac{\Delta_{rec}}{\Delta_{reg}} \qquad (2)$$

Real objects holograms may have some errors which can be introduced due to instability and phase shift step during the capture. To avoid them and evaluate optimal reconstruction results, we study the computer generated holograms, designed to match the features of our setup.

3. SLM CALIBRATION

The quality of holographic reconstruction using LCoS SLM is connected with nonlinearity (and range) of phase shift and its surface curvature (wavefront aberration). Both factors depend on SLM tilt angle, so calibration procedure should be used for every SLM position. There are many approaches that can be applied for the tasks. For characterization of the nonlinearity of phase response we use double slit experiment [12] (Fig.3a), while for calibration of wave aberration we apply Twyman-Green based interferometric method [13](Fig.3b).

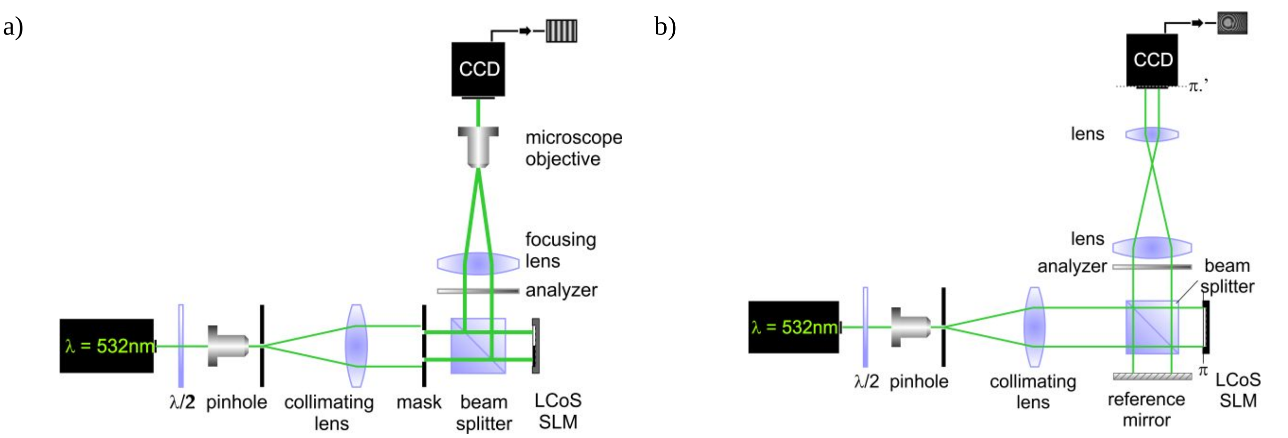

Fig.3 Setups for phase response (a) and wavefront aberration (b) measurements

The expected pixel response of LCoS SLM is 2π linear phase modulation and is coded as grayscale level at 8-bit image. Nature of this characteristic depends on used voltage range, input gamma curve and varies for different wavelengths and angles of incident beam. The utilized HEO 1080P system supports using independent settings for a single SLM. Modulation depth is set with voltages range corresponding to grayscale level. In the first step natural characteristic of display phase shift is measured. For this purpose a linear voltage change (i.e. linear gamma curve) is needed. Phase nonlinearities are corrected by using calculated new gamma curve. The exemplary measured phase shift characteristics and gamma curves are presented on Fig.4.

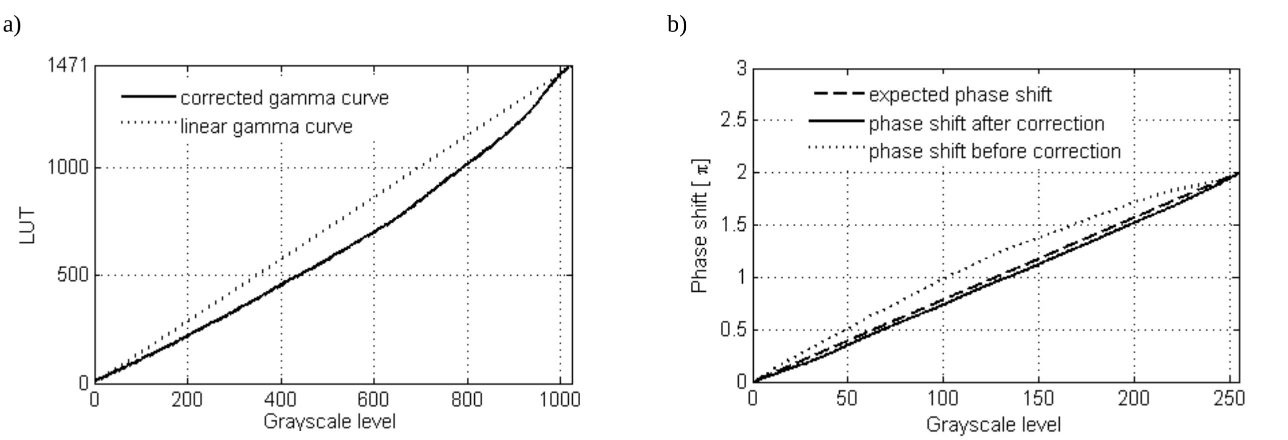

Fig.4 Gamma curves (a) and obtained phase shift characteristics (b) for example LCoS SLM

We need to remember that LCoS SLM is based on nematic LC and is designed for normal illumination. It gives however a phase modulation also for inclined one, but in this case, it is necessary to calibrate SLM for every tilt angle. The results of calibrations for SLM tilts $\alpha = 0, 10, 20, 30, 45°$ for voltages 0.9 – 2.59 [V]are presented in Fig. 5. The value of 2.59 [V] is a minimal voltage for which 2π modulation is obtained for 45° tilt. For comparison, normally illuminated SLM generates phase modulation of $3.062\ \pi$ in this voltage range. It is easy to notice that to obtain a phase difference of 2π for normal illumination, the sufficient voltage range is the smallest, and increases with the tilt angle. The experimental results pointed out, that for small tilts (e.g. 10°) phase shift difference is 1.97π, and the error is negligible, but for 20°, it is about 1.86π, what must be corrected, by using proper gamma curve and the extension of voltage range. We decided to use basic calibration (for normal illumination) in the range of tilt angles α = 0-10°, and tilted gamma curves for α>10°.

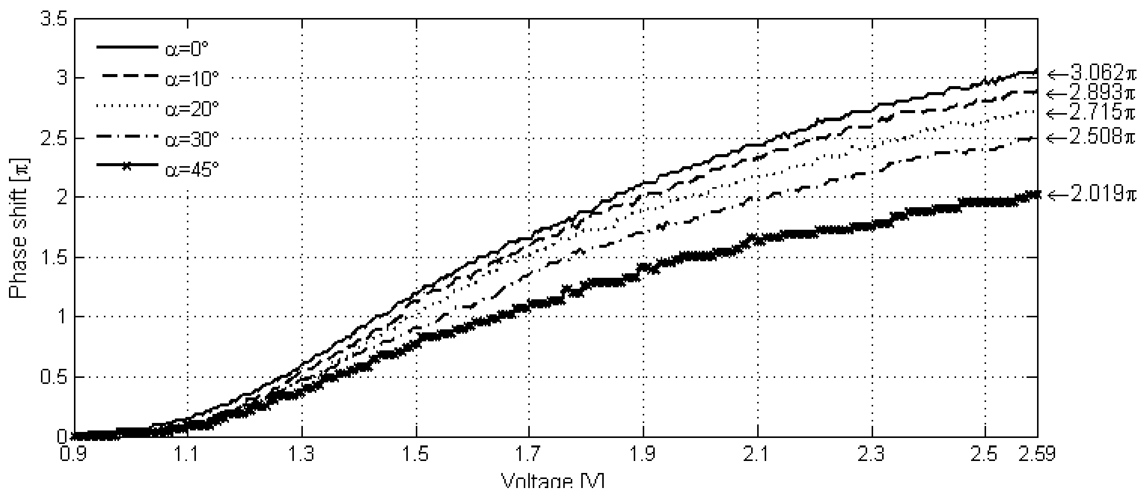

Fig. 5 Experimental pixel phase shift characteristics for series of tilted SLMs

Proper SLMs pixel phase shift calibration is important for good image intensity and contrast. Apart of that in PSDH method it has great influence for zero order removal. Experimental results of images reconstructed before (about 3π nonlinear phase shift) and after calibration (2π linear phase shift) are presented in Fig.6.

a) b)

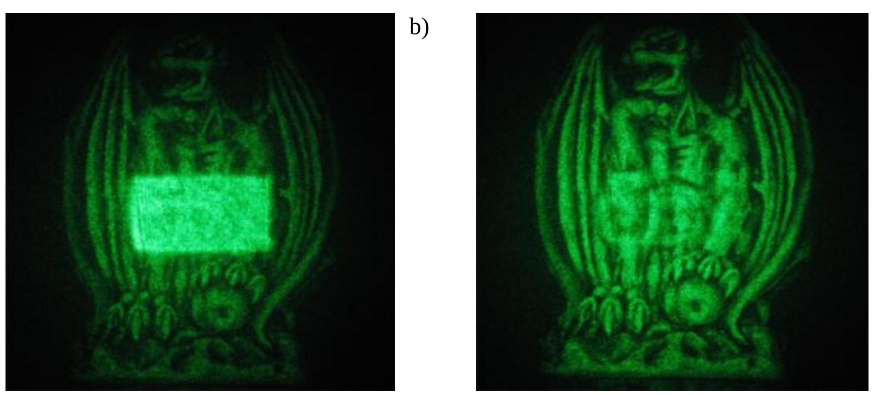

Fig.6: Fresnel PSDH hologram reconstructed before (a) and after SLMs phase shift calibration (b)

The second SLM correction is connected with a presence of wavefront aberration in the reconstruction. This the effect of SLM surface curvature and eventual aberrations of other optical elements. The main goal of this measurement is to obtain information about used display. This kind of correction must be introduced on the whole surface of SLM, which is the only way to add it to a currently displayed hologram. Example of experimental results of measured aberration and its phase correction image are presented in Fig.7a-b.

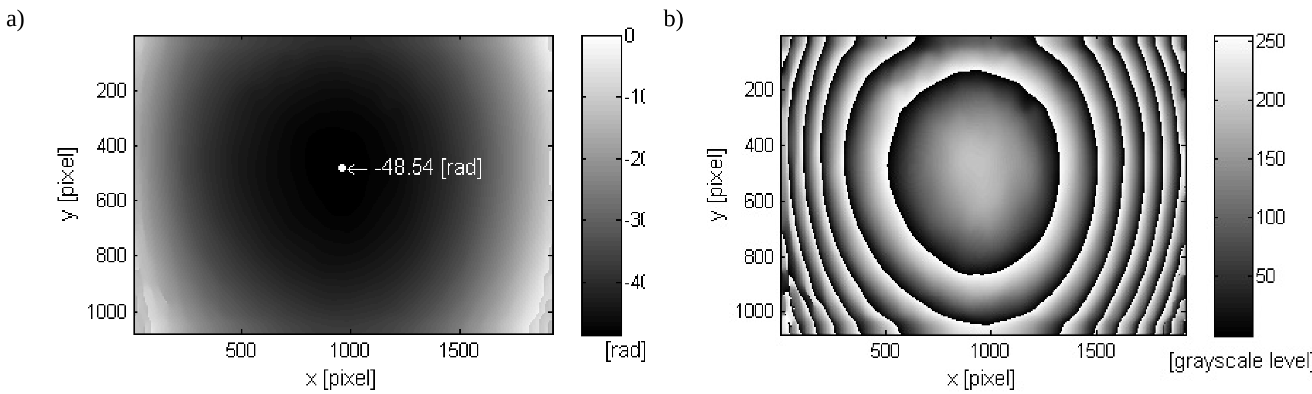

Fig.7: Experimental results of measured wavefront aberration (a) and its correction (b)

In the exemplary measured aberration we obtain P-V value 48.54[rad], what gives half of this value surface nonflatness (2.05µm for used wavelength 532nm). According to technical specification of HEO 1080P, SLMs' surface is almost spherical and do not exceed 2.53µm, what is consistent with our results. The effects of wave aberration correction are presented in Fig.8, as the images of spots for a displayed phase lens of focal length 462mm displayed by SLM. We can notice great improvement of spot shape after introducing the correction.

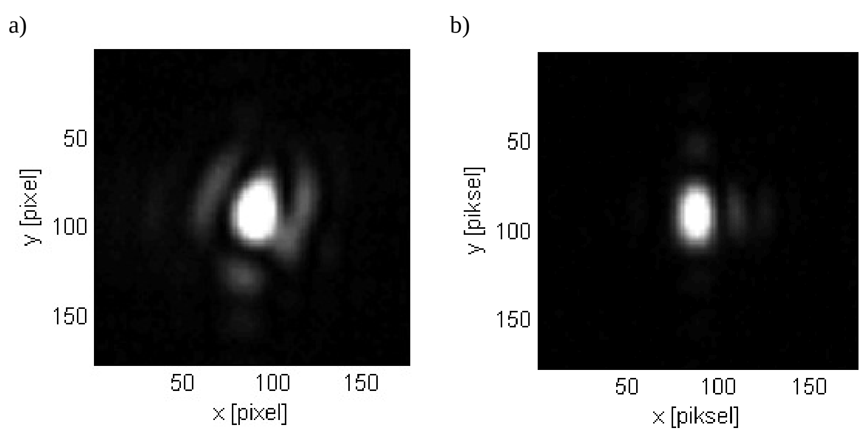

Fig.8: Spot images for 462mm focal length before (a) and after applying correction (b)

Likewise on phase shift characteristic, the tilt of the SLM has the influence on wave aberration. Because of the finite optical elements dimensions in setup, the aberration measurement can be troublesome for larger tilt angles. Moreover characterization for every angle is time consuming. Therefore we propose to characterize SLM curvature for normal orientation only and then recalculate its height function to inclined plane. Locally refracted plane wave components are computed and then assembled into output field. To avoid long computation time of propagation, we propose to use thin elements approximation (TEA) for tilted SLM. Due to SLM curvature, only phase of illuminating plane wave is altered. This gives us the distribution of tilt dependent SLM wave aberration at plane X':

$$u(x') = \exp\{ik2h(x')\cos\alpha\} \tag{3}$$

where h(x') is a SLM height function.

4. HOLOGRAM PROCESSING

It was presented in section 2 that both capture and display systems are different. Therefore we cannot display directly registered digital holograms. Prior to display holograms have to be processed with: order removal and tilt correction algorithm.

We address SLM pixels with an object wave phase values, which may be delivered by means of digital holographic acquisition system as well as by numerical generation of synthetic holograms. Real object wave captured with digital holography by a CCD matrix is the intensity pattern. To optimally reconstruct a hologram with a phase only modulator, we filter a complex object beam using numerical techniques [15] or phase shifting digital holography [16]. Then, in reconstruction we use the phase of an object beam only.

In digital holography we capture complex wave propagating normally to CCD plane (section 2, Fig.1), what in Fig. 9 corresponds to plane X. Therefore, the captured complex wave has to be converted using tilt correction algorithm, before it is loaded onto SLM and displayed. The developed algorithm is based on a plane wave spectrum decomposition between tilted planes [17]. Normally it would result in an increase off spatial bandwidth product, since we get decreased pixel size and increased number of pixels, which effects on getting off axis field. In our case there is no necessity of spectrum field extension [18], so we process only the on-axis field and as a result we obtain field of the same spatial bandwidth product as the input one. This gives nonlinearly distributed plane wave spectrum components at plane X'. To get the object wave we have to compute Discrete Fourier Transform, which requires evenly spaced frequency samples delivered after interpolation.

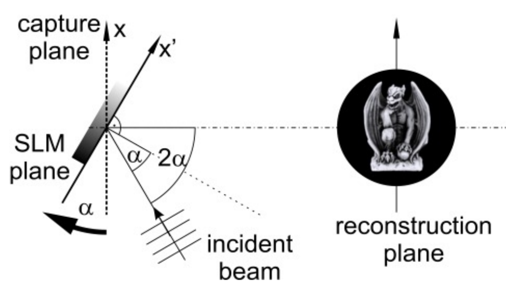

Fig.9: System geometry with the inclined illumination

Experimental results for tilt angles α = 0, 10, 20, 30, 40° are presented on Fig.10. We can clearly notice the great improvement of the image reconstruction quality. Both the effects of defocusing and tilt of holograms are satisfactory for all measured tilt angles.

5. MULTI SLM HOLOGRAPHIC DISPLAY IMPLEMENTATION

The system consists of six SLMs in the circular configuration with parallel illumination. Each hologram was processed and the display was calibrated to work optimally in tilted illumination conditions. As the object we used computer generated holograms of the 40mm height gargoyle statue at reconstruction distance of 693mm and angular separation of 2°.

Multi SLM display system (Fig.11) may be divided into illumination and reconstruction modules. The task of the first one is to illuminate six SLMs with homogeneous, parallel beams with the same intensity. For this we use a single laser beam, where plane wave is obtained by a large diameter collimating lens. This beam is divided into six parts by means of three beam-splitter cubes. SLMs are illuminated with a set of independent mirrors by a vertically tilted beams. It is necessary to separate incident and reflected beams, however, because of the setup configuration this tilt is not larger than 1.5-2°, so the negative effects of it might be neglected.

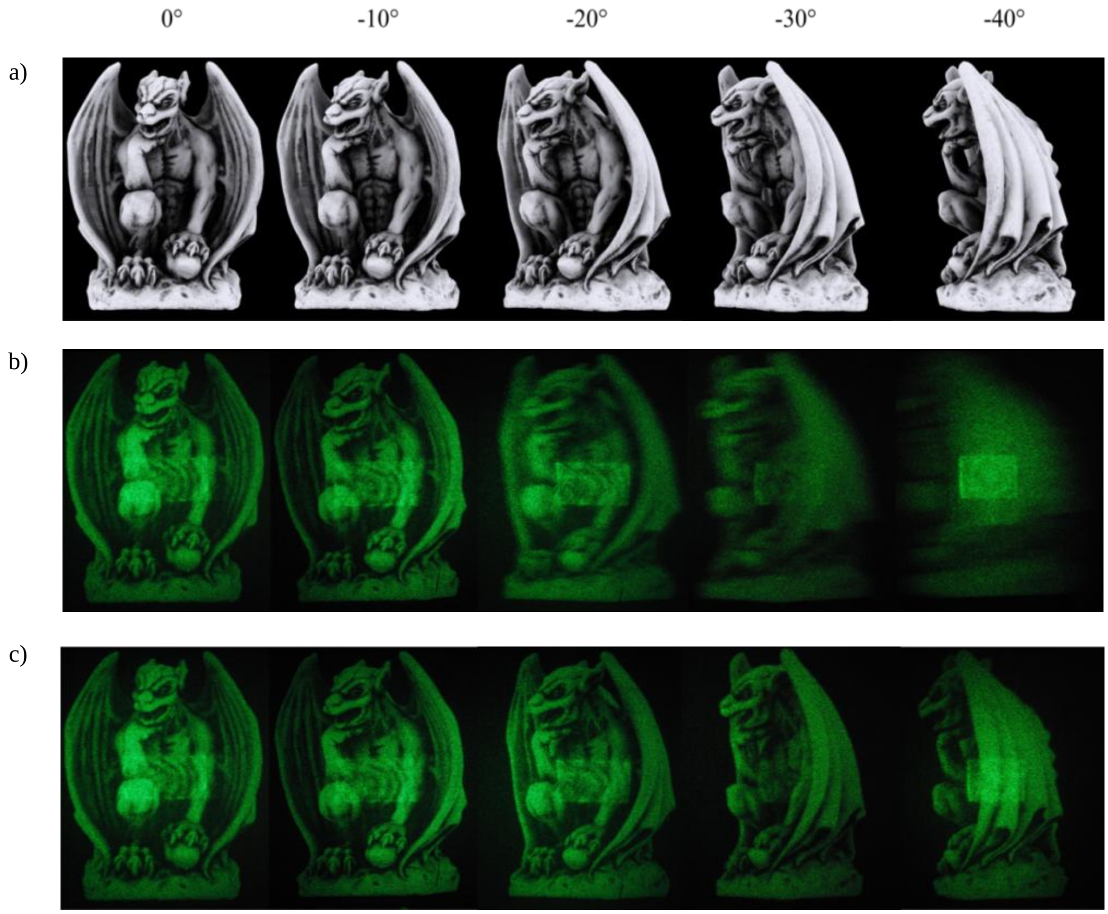

Fig.10: Object (a) and its reconstruction for an inclined illumination without (b) and with tilted planes algorithm use (c) for a tilt angles α = 0, 10, 20, 30, 40° registered on symmetrically diffusing screen

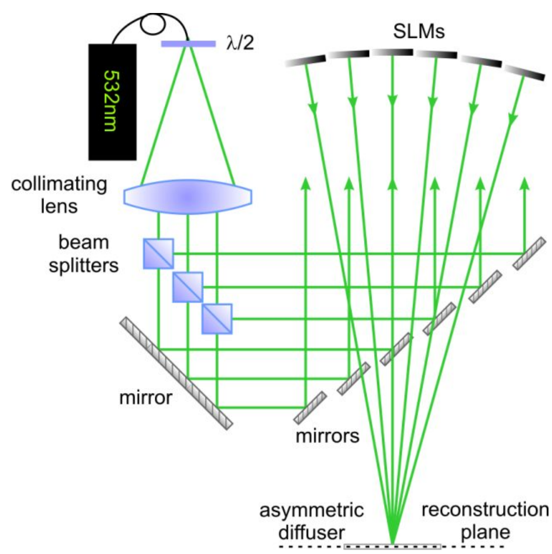

Fig.11: Multi SLM holographic display setup

Reconstructed images are observed with an asymmetric diffuser, where the angle of a vertical diffuse is equal 40° and horizontal 0.2°. It lets us to enlarge aperture mostly in vertical direction and save horizontal parallax, so we can observe the image as a stripe which moves with observer and forms a kind of viewing window (a vertical key-hole). The images reconstructed and observed from a single LCoS SLM are shown in Fig.12. The angular field of view of a single LCoS SLM is 4°, and limits the reconstruction size.

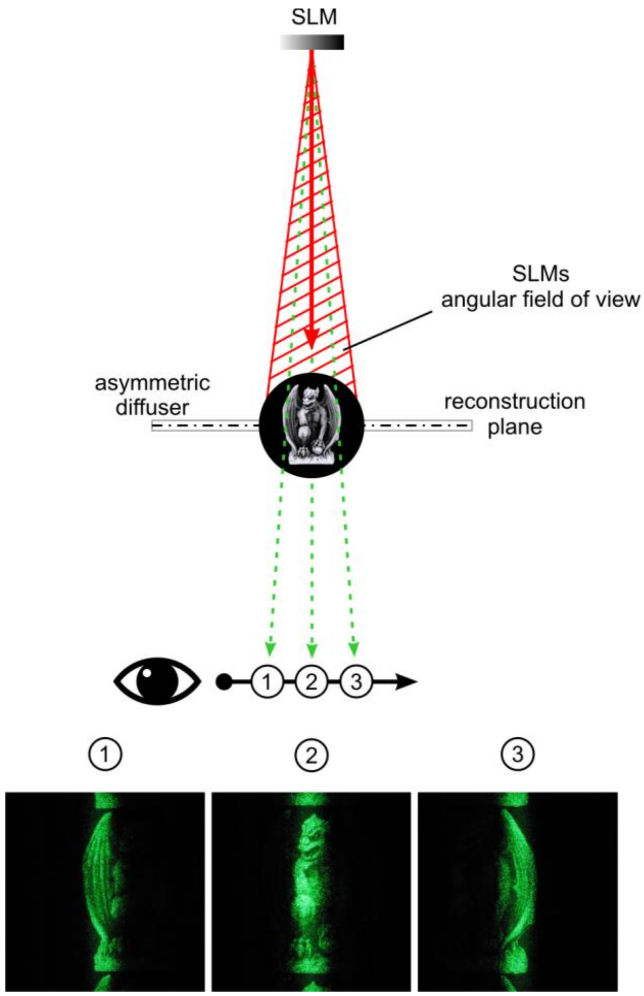

Fig.12: The principle and effects of observation for single SLM with asymmetric diffuser

The full setup configuration(with 6 SLMs) allows us to see a final effect as an image composed of several stripes (one from each SLM), that shows the different views of the object relatively to the observer's position with the viewing angle 20° and bigger aperture (Fig.13). An effect of local decrease of intensity between the stripes reconstructed for sequence of SLMs is caused by discontinuity of obtained synthetic aperture, i.e. modulator geometry. This is partially reduced by the scattering effect of the asymmetric diffuser, and may be further minimized by an enlargement of reconstruction distance, what decrease separation angles (2α). In future the hardware method for removing the gaps will be developed.

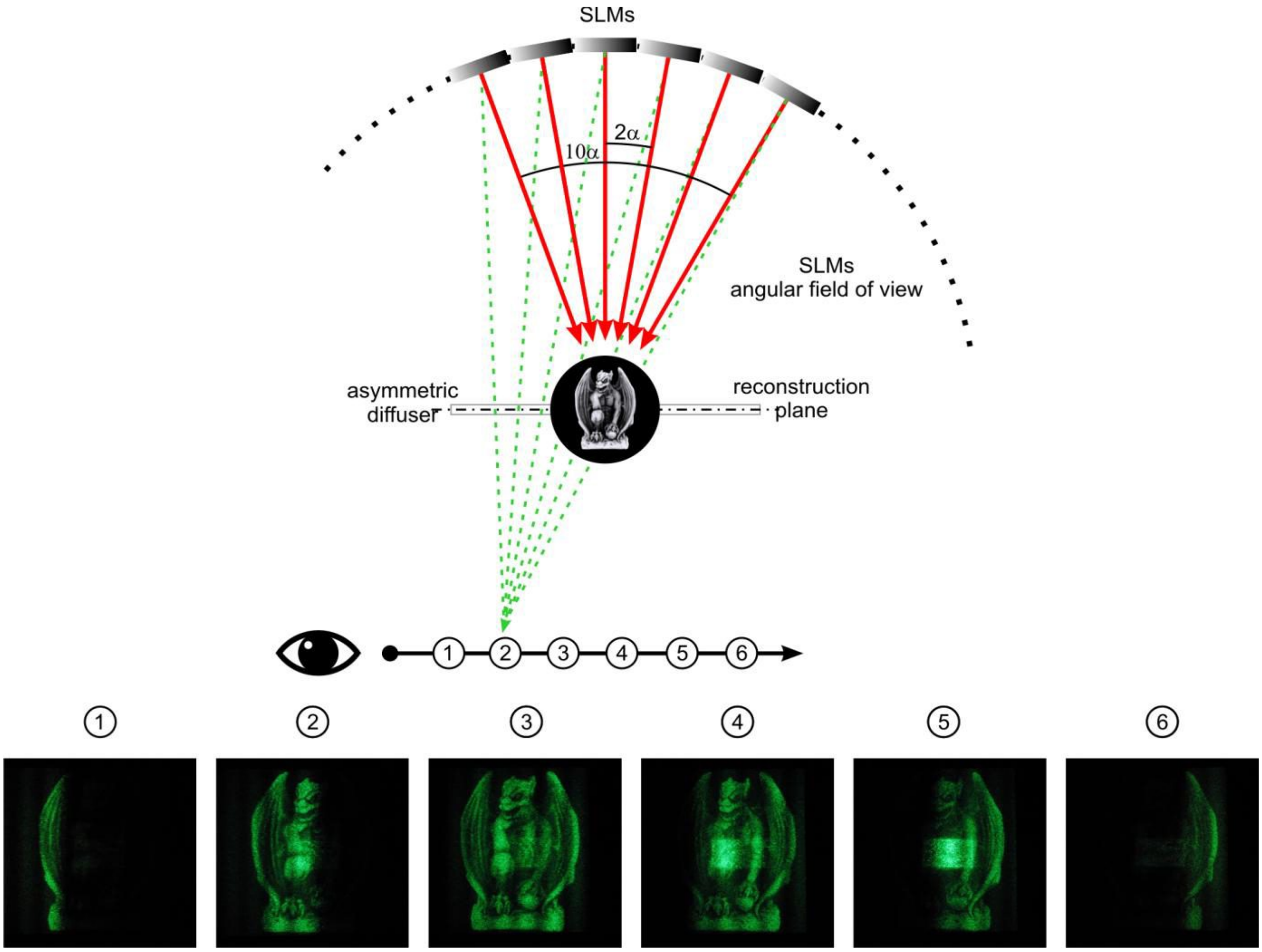

Fig.13: The principle and effects of observation of six SLMs with asymmetric diffuser for different observers position

6. CONCLUSIONS

In the paper we have presented the design of a wide viewing angle display system capable of displaying digital holograms captured in a multi CCD configuration. We have discussed the two possible configurations of multi LCoS SLM system. The first one with a normal illumination and the second one with tilted SLMs and parallel illumination. The second solution gives a simpler setup, however it requires processing of captured holograms. Therefore we have developed a tilted plane algorithm, necessary for holograms recalculation. In order to increase the quality of reconstructed object we proposed LCoS SLMs calibration procedure including pixel response and wavefront aberration correction. The calibration and implemented tilt procedure allows to work with SLMs tilted up to $\pm 30°$. Finally we have presented the wide angle object reconstruction with inclined six LCoS SLMs display and discussed the visual perception of holographic images observed with an asymmetric diffuser.

7. ACKNOWLEDGMENTS

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8. BIBLIOGRAPHY

[1] L. Onural, T. Sikora, A. Smolic, J. Ostermann, J. Watson, *„An assessment of 3DTV Technologies"*, NAB BEC Proceedings, 2006

[2] T.-Ch. Poon, *"Digital Holography and Three-Dimensional Displays"*, Springer, Berlin 2006

[3] T. Kozacki, *"On resolution and viewing of holographic image generated by 3D holographic display"* Opt. Express 18, 27118-27129 (2010).

[4] D.P. Kelly, D.S. Monaghan, N. Pandey, T. Kozacki, A. Michałkiewicz, B. M. Hennelly, M. Kujawinska, *"Digital Holographic Capture and Optoelectronic Reconstruction for 3D Displays"*, International Journal of Digital Multimedia Broadcasting, Article ID 759323 (2010)

[5] K. Maeno, N. Fukaya, O. Nishikawa, K. Sato, and T. Honda, *"Electro-holographic display using 15 mega pixels LCD*", *Proc. SPIE* 2652, 15-23 (1996).

[6] C. Slinger, P. Brett, V. Hui, G. Monnington, D. Pain, and I. Sage, *"Electrically controllable multiple, active, computer-generated hologram"*, *Opt. Lett*. 22, 1113-1115 (1997).

[7] S. B. Hasan, T. Kozacki, *"Method for enhancing resolution of holographic displays"*, Photonics Letters of Poland, vol.1(4), 193-195 (2009), doi: 10.4302/plp.2009.4.17

[8] T. M. Kreis, M. Adams, and W. P. O. Juptner, *"Methods of digital holography: a comparison"* in *Optical Inspection and Micromeasurements II*, vol. 3098 of *Proceedings of SPIE*, pp.224–233, Munich, Germany, June 1997.

[9] U. Schnars and W. P. Juptner, *"Digital Holography: Digital Recording, Numerical Reconstruction and Related Techniques"*, *Springer*, Berlin, Germany, 2005.

[10] I. Yamaguchi and T. Zhang, "Phase-shifting digital holography", *Optics Letters*, vol. 22, no. 16, pp. 1268–1270, 1997.

[11] D. P. Kelly, D.S.Monaghan, N. Pandey, T. Kozacki, A. Michalkiewicz, G. Finke, B.M. Hennelly, and M. Kujawinska, *"Digital Holographic Capture and Optoelectronic Reconstruction for 3D Displays"*, *Hindawi Publishing Corporation, International Journal of Digital Multimedia Broadcasting*, vol. 2010, Article ID 759323, 14 pages

[12] A. Bergeron, J. Gauvin, F. Gagnon, D. Gingras, H. H. Arsenault and M. Doucet, *"Phase calibration and applications of a liquid-crystal spatial light modulator"*, Appl. Opt. **34**, 5133-5139 (1995).

[13] X. Xun and R. W. Cohn, *"Phase Calibration of Spatially Nonuniform Spatial Light Modulators"* Appl. Opt. **43**, 6400-6406 (2004).

[14] A. Rohrbach and W. Singer, *"Scattering of a scalar field at dielectric surfaces by Born series expansion"*, J. Opt. Soc. Am. A **15**, 2651-2659 (1998).

[15] T. Latychevskaia and H.-W. Fink, *"Solution to the twin image problem in holography"*, Phys. Rev. Lett. **98**, 23390-23393 (2007).

[16] I. Yamaguchi and T. Zhang, *"Phase-shifting digital holography"* Opt. Lett. **22**, 1268–1270 (1997).

[17] K. Matsushima, *"Computer-generated holograms for three-dimensional surface objects with shade and texture"* Appl. Opt. **44**, 4607-4614(2005).

[18] T.Kozacki, R. Krajewski, M. Kujawinska, "Reconstruction of refractive-index distribution in off-axis digital holography optical diffraction homographic system", *Optics Express*, 2009, vol. 17, no.16, pages 13758-13767.