# Performance of the 4k phase-only spatial light modulator in image projection by computer-generated holography

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**Abstract**—We present the experimental results of holographic image projection with the use of a newly available Liquid Crystal on a Silicon Spatial Light Modulator with a resolution of 4096 by 2400 pixels and a pixel pitch of 3.74μm. This combination of parameters has allowed the highest resolution and throw angle of projected images formed by the reconstruction of computer-generated Fourier holograms. Additionally, we present the interferometric measurements of the flatness of the panel and evaluation of its diffractive efficiency in the case of displayed binary and saw-tooth diffractive gratings.

Liquid Crystals on Silicon (LCoS) Spatial Light Modulators (SLM) are the main tools allowing progress in display devices based on Computer-Generated Holograms (CGHs). Nevertheless, their performance in the diffractive redirection of light rays is inevitably limited by the pixel pitch. The maximal angle of diffraction (α) in the first order is proportional to the wavelength (λ) and inversely proportional to the pixel pitch ($p$):

$$\alpha = \arcsin\left(\frac{\lambda}{2p}\right) \tag{1}$$

In this work we used a newly available Jasper Display JD8715 Quad-HD 0.70" phase-modulating microdisplay with a pixel pitch of 3.74μm and fill factor of 90% (see Fig. 1). The panel modulates the phase in a full 2π range for the visible light, in contrast to previous attempts with amplitude-modulating 4k panels [1-2]. These parameters allow the diffraction angle of 4.85°, according to Eq. (1) for λ=632.8nm, which is a significant improvement compared to 2.3° of the Holoeye Pluto [3] (8μm pixel pitch) used in our previous works [4-5].

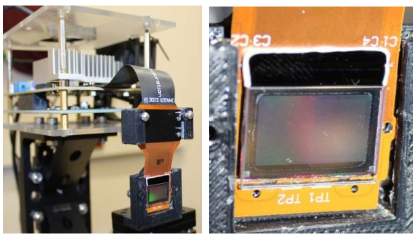

Fig. 1. Photographs of the Jasper Display JD8715 SLM.

The total throw angle of holographic projection realized on JD8715 is therefore equal to 2α=9.7°, which yields a diagonal size of 24cm (9.7") of an image projected at a distance of 1m, which is awaited by the pico-projector industry.

The experimental setup built for the evaluation of the throw angle and image resolution is depicted in Fig. 2.

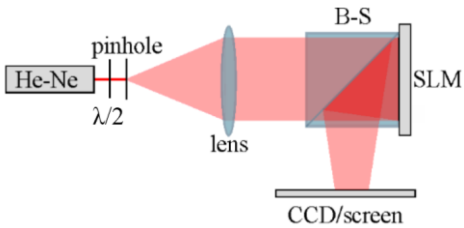


Fig. 2. Scheme of the experimental setup.

The expanded beam from the He-Ne laser (632.8nm) illuminates the SLM at a normal incidence angle and with optimal polarization set by the half-wave plate. The reflected beam is reflected in a non-polarizing 50-50% beam splitter cube and reaches the white sheet of paper with a printed centimeter scale (or optionally is thrown directly onto the CMOS matrix of the camera). The SLM was addressed with iterated Fourier holograms obtained with the Gerchberg-Saxton algorithm, pre-calculated on a matrix of 4096 by 4096 points. The holograms were additionally multiplied with a phase factor of a positive lens in order to focus correctly on the acquisition plane. The focal lengths of the lens factors in $x$ and $y$ directions were slightly different in order to compensate for the measured astigmatism of the SLM panel.

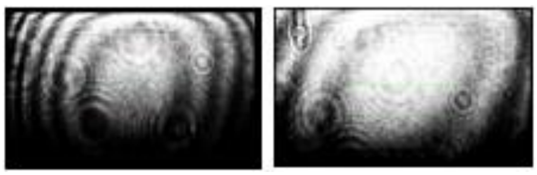

Fig. 3. Interferograms of the SLM panel taken in Mach-Zehnder setup: off-state (left) and on-state (right).

The intrinsic curvature radius of the SLM, measured in the Mach-Zehnder interferometer was 11.7m in the horizontal direction and 12m in the vertical direction, see Fig. 3. The lens focal lengths in [mm] are given in Table 1 for reference.

Table 1. Focal lengths of the lens factors introduced to the holograms displayed on the SLM.

| Distance between the SLM and the acquisition plane [mm] | Focal length of the lens factor in *x* direction | Focal length of the lens factor in *y* direction |
|---|---|---|
| 160 | 173.6 | 173.3 |
| 310 | 324.1 | 324.2 |
| 460 | 474.8 | 475.4 |
| 610 | 626.3 | 634.8 |

The photographs of the projections were taken with a Canon EOS 600D digital camera, which was configured to low sensitivity and lossless RAW encoding. The distance from the SLM to the projection plane was set to the following values: 160mm, 310mm, 460mm and 610mm. Figure 4 shows the obtained photographs for the mentioned distances. As predicted, a 10cm by 10cm image was achieved for a distance of 610mm, which is, to our best knowledge, equivalent to the biggest holographic projection angle to date.

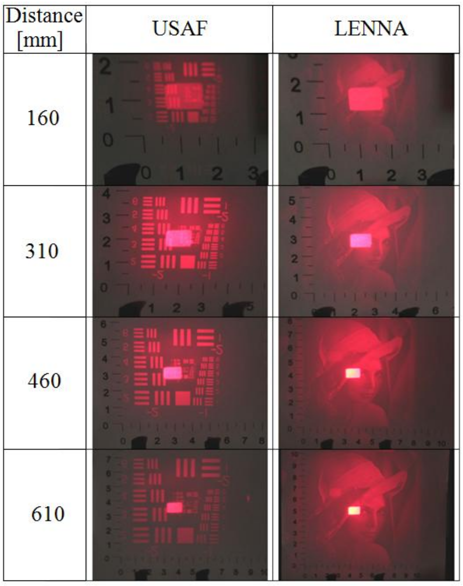


Fig. 4. Experimental projections at variable distances.

In the next step, we assessed the image resolution understood as a number of effective image lines or columns at the projection screen. It is always a function of the number of pixels taking part in the modulation of the wavefront reflected from the surface of the light modulator. Usually, the effective loss of image points compared to the SLM's pixel count is close to 50%. For this reason, up to now it has been impossible to obtain a Full-HD resolution of the final projected image. The use of a 4k by 2k SLM allows that to be achieved.

As the first step, we have performed a series of numerical simulations of the simple holographic reconstruction process depicted in Fig. 5.

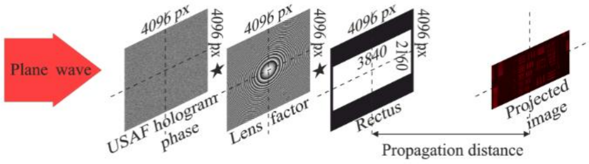


Fig. 5. Numerical simulation projections at variable distances.

We assumed the same reconstruction distances and geometry as in the experiment. The resolution was measured by the analysis of the MTF function. The spatial frequency with a loss of contrast at 50% was selected and multiplied by the transversal size of the projected image, giving a total number of cycles (or line-pairs).

In the experiment, the resolution was assessed from the experimental photographs of the USAF (US Air Force resolution test pattern) projections shown in Fig. 4. The close-up views of the dense groups of the USAF pattern are presented in Fig. 6.

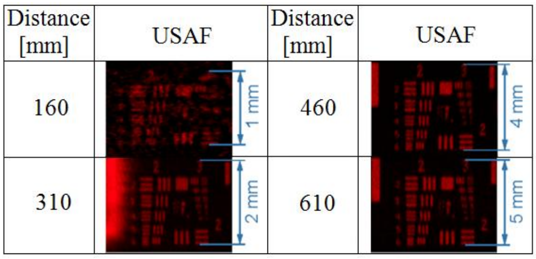


Fig. 6. Details of the projected USAF resolution test pattern.

The analysis was performed by the selection of the most dense resolved element of the USAF pattern and dividing the image size by the size of the smallest resolved element. The recognition of the resolved elements was difficult due to the strong zero-order light visible as a bright rectangular patch of light in Fig. 3. For 160mm, the zero order patch was numerically subtracted in a graphics program.

The numerical and experimental graphs of the resolution are gathered in Fig. 7. Note that the resolution here is taken as the number of effective image lines or columns formed in the projection plane. An increase in experimental resolution with the distance and a decreasing error rate can be attributed to a larger depth of focus for bigger distances, allowing easier image focusing on a CMOS matrix.

 

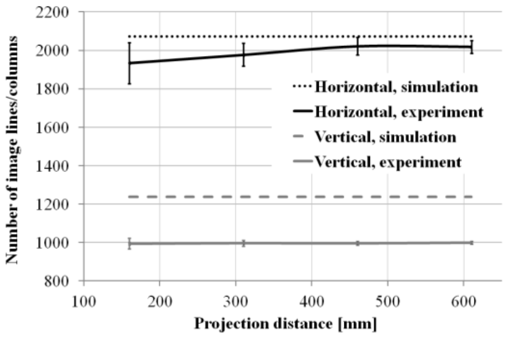


Fig. 7. Resolution of the projected images.

The maximal experimental image resolution was 2019 by 1000 points, which stands in good agreement with the numerical simulations for the horizontal direction. In the case of vertical direction, a discrepancy of c.a. 240 image lines is notable. It can be attributed to a time-domain flicker [6-7] of the SLM due to line-by-line feed, which was not taken into account in the simulations. This leads to the conclusion that the experiment was correctly aligned, but the JD8715 SLM needs a minor calibration of the controller fed by a HDMI signal.

As the last measurement, the diffractive efficiency of the SLM was assessed by experimental measurements of power distribution into three lowest orders of diffraction. The modulator was addressed with the phase factors of diffractive gratings with a period equal to 8 pixels (i.e. 29.92µm). The optical setup is depicted in Fig. 8.

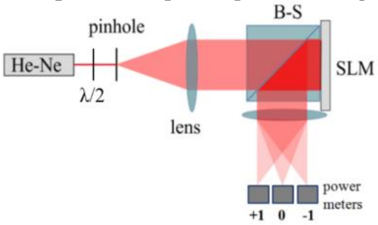


Fig. 8. Experimental setup for the evaluation of diffractive efficiency of the SLM.

The beams reflected from the SLM were focused on the active surfaces of three identical power meters with the help of a refractive positive lens. The SLM was addressed with static bitmaps representing the phase patterns of diffractive gratings. The darkest and brightest grey levels were changed in order to locate the optimal value yielding the best diffractive efficiency (calculated as the light power measured in the +1st order divided by the total power measured in the -1st, 0th and +1st diffractive orders). Higher orders were neglected, which introduces some error to these results. The graphs showing the peak efficiency of approx. 60% for kinoform gratings and binary gratings are shown in Fig. 9 and Fig. 10, respectively. The optimal gray levels for the kinoform gratings and binary gratings were chosen at 220 and 110, respectively.

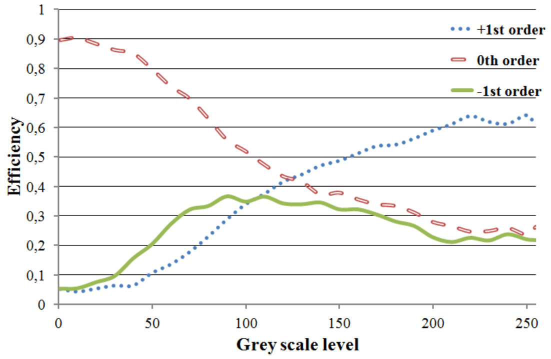


Fig. 9. Diffractive efficiency of the JD8715 SLM in 8-bit phase modulation mode.

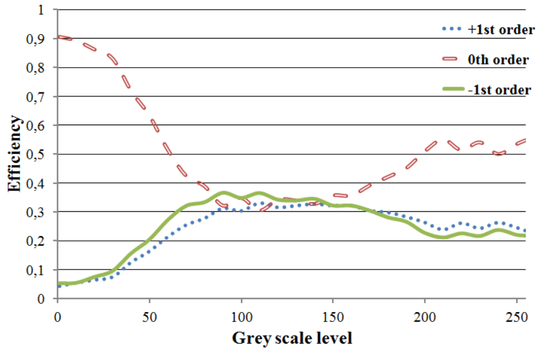


Fig. 10. Diffractive efficiency of the JD8715 SLM in binary phase modulation mode.

To summarize, a new spatial light modulator with a 4k resolution and a 3.74µm pixel pitch was presented and evaluated experimentally. It allows unprecedented [8] high-resolution and high-angle reconstructions from computer-generated holograms.

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