Novel reflective SLM in real holographic 3D HUD displays and their impact on quality

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ABSTRACT

Market penetration of automotive head-up displays (HUD) is increasing and extending from higher-end models to mid-range and even compact cars. New HUD use cases will be motivated by autonomous driving as well as improved HUD abilities. Holographic 3D (H3D) HUD will contribute to further improve the usability and attractiveness, specifically by presenting images with a full consistency of all depth cues. Based on results from H3D-HUD implementations, it is explained how H3D images are created and how viewers benefit from the unique 3D solution that eliminates ambiguity of the presented information and improves safety by properly overlaying virtual 3D objects with the real world. The difference between possible SLM options is explained, including references to ongoing development of high-resolution phase-modulating micro-mirror-based SLM (micro mirror arrays, MMA). It is compared how use of MMA vs. LCoS can improve selected features and the user experience. Ongoing development of MMA in a consortium of expert companies and institutions and results of already manufactured MMA are presented.

Keywords: Holography, Head-up Display, phase-modulation, Micro mirror array

1. INTRODUCTION

Automotive HUD started with first implementations into cars back in the late 1980ies[1]. These first devices had very limited functionality showing only basic symbols like speed. In recent years HUD systems started to become more advanced. Augmented Reality HUDs are now displaying content on the street in context with the real environment of the driver[2]. A deficit of current products is however the limitation to one or at maximum two image planes located at fixed distances from the driver. HUD content and real world in this case are not perfectly matched. SeeReal has developed a HUD system based on holographic 3d, which allows to place HUD symbols at any distance from the car driver. A previous version of that system has been described in[3]. This system has been improved and a new, more compact prototype with a larger Field of view (FOV) of 9x5° has been set up. The experimental configuration is currently using an LCoS as modulator for generating the hologram. Such a device would be available for a first generation of HUD products. On the other hand, use of LCoS also has drawbacks including crosstalk in the small liquid crystal pixels and limitations of LC response at high framerate. A micro mirror array (MMA) avoids these drawbacks as it allows for modulation of individual mirrors independent from their neighbors and is also capable of frame rates in the kHz range.

In section 2 of the paper the use case for holographic HUD and the current prototype are explained in more detail. The following sections give a comparison of LCOS vs MMA parameters and their expected impact on HUD performance. Some simulations as well as experimental results from MMA samples are shown. These samples do not yet have a backplane for full driving but already allow addressing and characterization of individual mirrors.

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Proceedings Volume 12913, Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR) V; 1291303 (2024) https://doi.org/10.1117/12.3001348
Event: SPIE AR | VR | MR, 2024, San Francisco, California, United States

2. HOLOGRAPHIC HUD

Figure 1. Schematic view of HUD set-up at SeeReal. The driver can see objects at different distances in front of or even inside the car, that are generated by a holographic HUD. Photos in the following figures are made with a camera located at the position of the driver`s head.

2.1 Holographic HUD use case

Existing HUD products have either a single image plane located at a fixed distance from the car or a maximum of two planes. In the latter case some basic symbols like speed or similar are visible in the lower part of the field of view at approx. 3 m distance and more complex content is visible in the upper part of the field of view at a distance of approx. 10 m[4]. There exist also “varifocal” HUD systems with a tilted 2d image plane which means that there is a continuous change of image distance with the vertical position in the FOV which is nevertheless fixed.

In a real environment important incidence can take place inside the range of 3 to 10 meters. The following figure 2 gives an example of a street scene. The photos are taken with a camera located at the position of the driver in the set-up that is schematically shown in figure 1. A real holographic 3d reconstruction is shown, where the camera lens setting is equivalent to a focal distance an eye would be accommodating at. The photos were however taken inside a lab and not on a real street. The street scene in the background is therefore not real but located on a screen placed at some distance from the HUD set-up.

In this example a crosswalk is located directly in front of the car and another one further away. In addition, other road users like cyclists and parking cars may be located on the street still close to the car but at different distances compared to both crosswalks. In the upper part of the figure the camera focus is located on the front. Information like current speed, allowed maximum speed or navigation information are in focus. In this case both the symbols in the background and the street in the background are out of focus. In the lower part of the figure the camera focus is changed to the more distant elements but with the same holographic reconstruction. A symbol in context with the second crosswalk is shown at the same distance, where this crosswalk is located. A warning related to the cyclist can be shown at the correct distance. Turn right signs are shown at the distance where the car is expected to turn. The whole 3d scene is shown at once and only the focus of the camera or the accommodation of the driver’s eye lens decides, which part is blurred and which part is clearly visible. The advantage of the holographic 3d HUD is that both the relevant HUD symbols and the corresponding real world content are at the same focal distance.

For a 2d HUD there would be motion parallax between HUD symbols at a 10 meters image plane and a real object at closer distance if the observer moves his head inside the HUD box. For a single object of interest in the 2d HUD, if a camera tracks the observers head position within the eye-box, it may still be to some degree possible to compensate for the motion parallax in the HUD content, but already keeping some accommodation-vergence conflict. This would however be more complex for several objects at different distances. The holographic HUD has the advantage that it can generate natural motion parallax as placing all the HUD symbols at their correct depth.

In today's cars warnings and navigation symbols provide the main content of a HUD. For future use cases like autonomous driving, it will be important to confirm to the passengers that the car has the correct assessment of its environment, for example has detected and will take other road users into account. In addition, information to the passengers about points of interest may be relevant, or even advertisement.

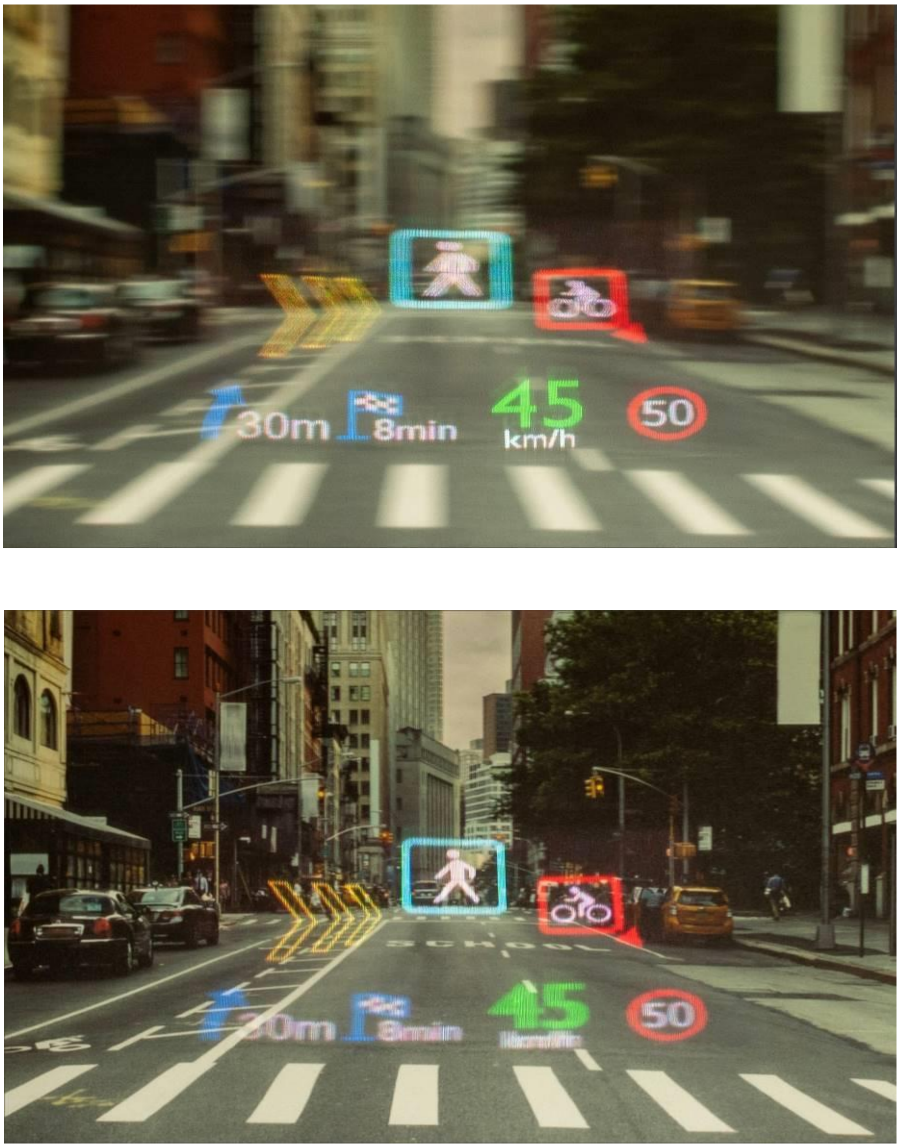


Figure 2. Street scene with HUD symbols and camera focus either on front or back (real holographic reconstruction – photos taken by camera, but in an indoor environment, not on a real street).

2.2 Requirements

Spec sheets for HUD products from car manufacturers include parameters like brightness range for use of the HUD both under bright sunlight conditions as well as at dark night, white balance and contrast[5]. Any sunlight reflection from the HUD box that distracts the driver must be strictly avoided. What is also important is a compact system volume, as the HUD needs to fit into the limited space within a car. In the era of electric cars low power consumption of the HUD is also getting more and more important. Some HUD developments especially focus on such selected aspects like compactness[6] and light efficiency[7].

A 3d holographic HUD product needs to implement the advantages of holographic 3d but at the same time needs to meet all the specifications that are common for state-of-the-art 2d HUD systems. A prominent example for the difference between holographic and conventional HUD systems is the use of laser light sources in the holographic set-up which includes the need for implementing methods for speckle reduction. SeeReal has put a lot of effort in optimizing image quality by both hardware and software methods[8]. Another difference is the need for generating a small viewing window for each eye within the larger HUD eye box and tracking of the observer’s eye positions. This also leads to an important modification of the optical functionality, while at the same time still keeping a similar free-form mirror optical system as in a 2d HUD. Developments at SeeReal inhouse as well as in cooperation with partners include components like compact laser modules, devices for observer tracking, optical designs suitable for holography, hologram computation as well as hardware/ software methods for improvement of image quality.

2.3 Optical set-up of 3d holographic HUD

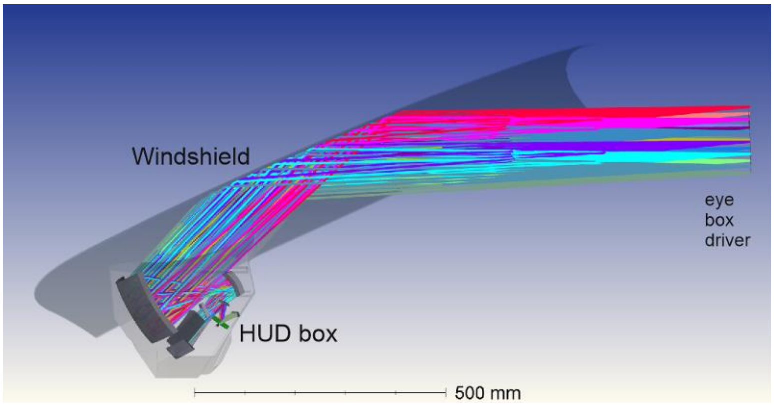


Figure 3. Example of a Zemax optical design of a holographic HUD. This design is more compact than the current experimental implementation and shows the potential of future integration of the HUD into a car. The lab-setup already uses a similar arrangement of components but the size and distance of some parts is still larger.

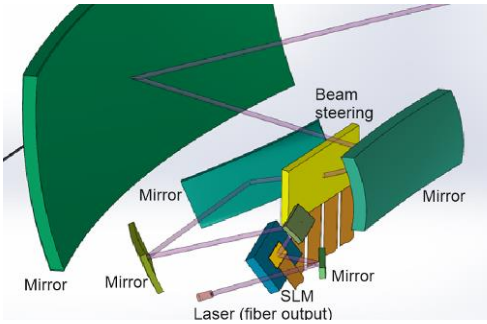


Figure 4. Details of the HUD design: components in the HUD box.

The HUD system includes a laser illumination. RGB lasers (not shown in the figure) are coupled to an optical fiber. From the fiber output illumination of the spatial light modulator (SLM) is generated with a collimated beam by either lenses or in this case a mirror. The SLM is then imaged with additional mirrors which also do a folding of the optical path to an intermediate image plane, where beam steering elements are located that deflect the light towards the detected eye positions. A free-from mirror optics in combination with the car´s windshield generates a magnified virtual image of both the SLM and the beam steering elements in front of the car, and in addition generates small viewing windows. The position of these viewing windows for the left and right eye inside the eye box is controlled by the beam steering elements. The holographic 3d scene reconstruction is then located both in front of and behind the virtual image plane. For example, the image plane can be located at a distance of 4 meters from the driver and the 3d scene generated from the hologram on the SLM can be located between 2 meters and infinity.

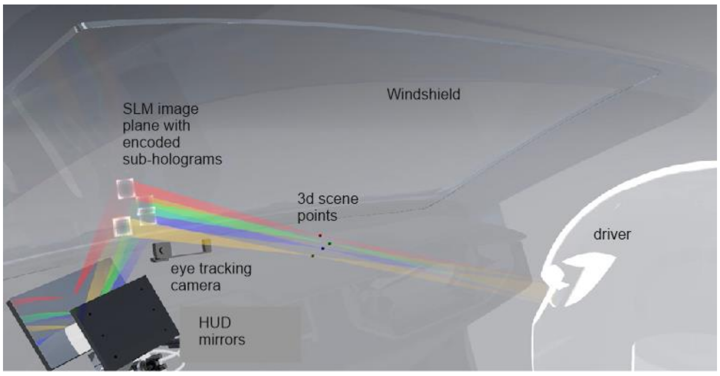


Figure 5. Schematic: Hologram reconstruction from the SLM virtual image plane generated by the HUD optics, that is visible for the driver. Sub-holograms are encoded on the SLM, an image of the sub-hologram is then located also in the SLM´s virtual image plane. The sub-holograms generate 3d scene points in space. For easier visualization the figure shows the scene points close to the driver and only in front of the virtual image. In order to display HUD content typically both the virtual image plane as well as the 3d scene points would be located outside the car at several meters distance to the driver's head. The scene points may also be behind the virtual image plane.

Figure 5 schematically shows the individual sub-hologramms that generate the scene points of the 3d scene in space. Each sub-hologram equals a small lens function, similar to a fresnel lens, which is encoded into the SLM. Many overlapping sub-holograms sum up to a complex valued hologram. Whereas transmissive direct view displays with large pixels can make use of a sandwich of amplitude and phase SLM to represent the complex values, the best solution for a reflective microdisplay is phase-only encoding where iterative methods like Gerchberg-Saxton are used to transform the complex valued sum-hologram to phase only data. Each sub-hologram generates a 3d object point in space equivalent to light propagation from the virtual image plane through the object point towards the eye.

A key component of the holographic HUD system is the SLM to which the Sub-holograms are encoded as phase functions. The impact of SLM features on HUD performance which will be explained in more detail in the following sections.

2.4 Trade-off for using LCOS in HUD, parameter: contrast

A deviation of SLM phase modulation from ideal behavior can have large impact on quality of the 3D scene reconstruction for example on parameters like contrast. Contrast is important in a HUD as only a small part of the FOV is actually filled with HUD symbols, whereas visibility of the real world environment surrounding these HUD symbols is also crucial for the driver. Bad contrast does not only affect the appearance of the desired content but has the consequence of lower visibility of the real world. In worst case this might cause safety issues.

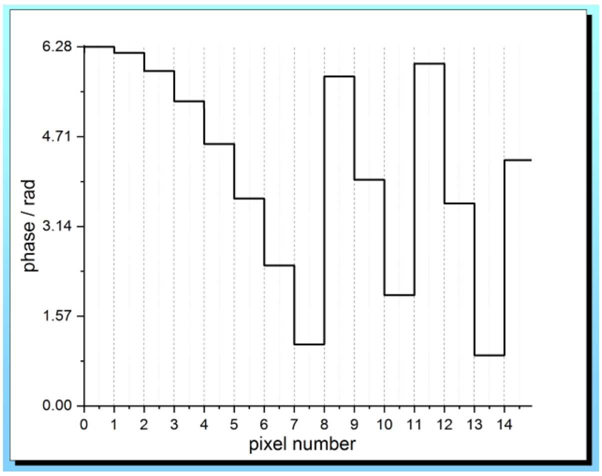


Figure 6. Right half of a Sub-hologram lens function – similar to a Fresnel lens.

LCoS displays have been established as the most common type of phase modulating device[9] but also do have some limitations. One of these limitations is pixel crosstalk, the impact of which is explained here by means of simulations. The following figures illustrate for a cross section through a sub-hologram, how the lens function of the sub-hologram is affected by the LC modulation in the LCoS. Figure 6 shows half of the lens function of a sub-hologram. In this example the full lens function extends over 31 SLM pixels half of which are used for simulation as the lens function is symmetrical to its center. Ideally the lens function is step-like with one dedicated phase value per pixel. Due to the modulation range of 0 to 2π the phase function includes 2π steps and is relatively flat at the center of the sub-hologram (on the left side of the figure) but becomes steeper with more 2π steps towards the edge.

For LCoS pixels the LC layer is continuous. That means, individual pixels are not strictly separated from each other. Fringe fields as well as the mechanical interaction of the LC molecules lead to a smoothing of phase steps. In Figure 7 an LC simulation and the resulting retardation (phase) from the liquid crystal response is displayed. The pixel electrodes are located on the lower substrate, the common electrode on the upper substrate. The black lines indicate the orientation of the liquid crystal director.

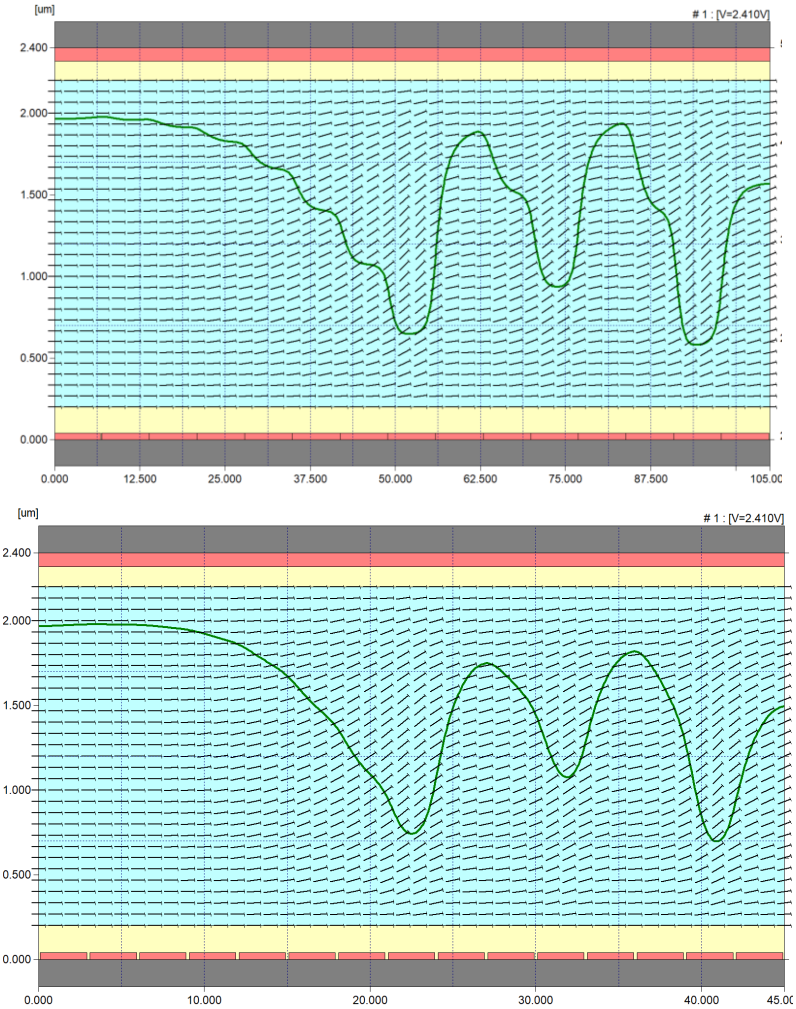


Figure 7. Liquid crystal simulation for an LCOS with a pixel pitch of 7 µm (upper part of the figure) or with a pitch of 3 µm (lower part of the figure) respectively, showing half of a sub-hologram and the smoothing of the sub-hologram phase function due to fringe fields and LC response. The impact of smoothing is more pronounced for the smaller pitch.

For comparison the LC simulation is done for 2 different pixel pitch values of the LCoS, namely for 7 µm and for 3 µm. Clearly the smoothing gets worse for smaller pixels. While the steps are rounded but still noticeable in case of the 7 µm pitch, the phase profile almost looks like a continuous phase function for the 3 µm pitch.

The actual pixel-crosstalk in an LCoS may depend on several parameters like rubbing direction, pre-tilt, anchoring strength cell-gap the latter related to the birefringence of the LC material[10]. Therefore, the actual crosstalk of a device may be subject to optimization by the LCoS supplier[11], but it will never be possible to totally eliminate pixel-crosstalk in an LC based device and for the same measures applied to reduce crosstalk it`s impact will always be worse for smaller pixels than for larger ones.

The following data visualize how such a smoothing in the LCoS affects the parameters of the hologram reconstruction in the HUD. Figure 8 shows a simulation of efficiency and contrast from a HUD scene assuming a typical amount of pixel crosstalk in the LCoS. In this example typical HUD symbols are used – all symbols are placed in the same 2d plane as this is more straightforward for data analysis.

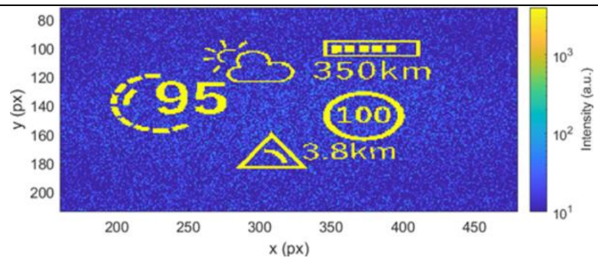
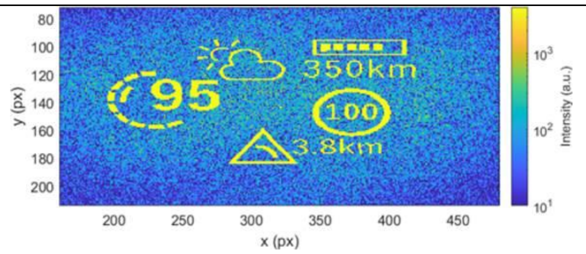
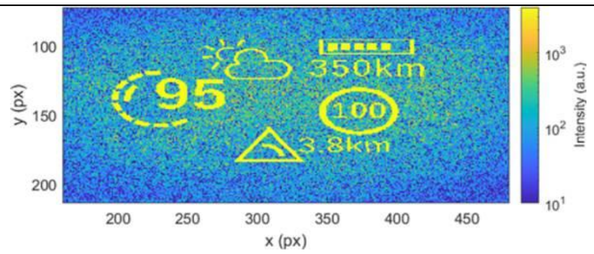
Pixel crosstalk	**Simulation result**	**Relative efficiency**	**Normalized contrast**
Ideal pixel		Reference 100 %	Reference 1.0
7 µm pixel With crosstalk		82.5 %	0.32
3 µm pixel with same crosstalk level		80 %	0.19

Figure 8. Simulations for a HUD using a phase LCoS – impact of pixel crosstalk on achieved contrast and efficiency in a HUD scene – logarithmic scale.

The data in the figure are displayed on a logarithmic scale to enhance visibility of the noise in the background. For a hologram with ideal rectangular phase steps (upper part of the figure) a very high contrast can be achieved although the background intensity is still different from zero. The calculation of the phase-only hologram is based on a Gerchberg-Saxton algorithm. If taking in the simulation the smoothing for a larger 7 µm LCoS pixel into account for the same parameters of the Gerchberg-Saxton hologram calculation, this leads to an increase of average background intensity by a factor of 3.1. This means the contrast is reduced by that factor. In case of the smaller 3 µm pixel with the same level of pixel crosstalk the contrast reduction would be a factor of 5.3. Whereas the smoothing by pixel-crosstalk has a large impact on contrast, the effect on efficiency of the hologram reconstruction is much smaller. Even for the 3 µm pitch the efficiency is only reduced by 20% compared to the ideal rectangular phase profile.

A phase modulating LCoS can be suitable for a first 3d holographic HUD product but the simulations illustrate that it has some severe drawbacks and limitations. In principle LCoS devices with a pixel pitch in the range of 7 µm or larger would be preferred to get better modulation and better reconstruction features like higher contrast. On the other hand, this also means a trade-off with cost. Larger pixels for devices with the same resolution mean that the number of devices that can be fabricated on a single wafer becomes smaller leading to higher cost per device. In general, this motivates LCoS suppliers to develop devices with small pitch in the range of 4 to 5 µm or even down to 2.6 µm in case of high resolution devices[11]. For 3d holography, if using LCoS, however it may be useful to go to slightly larger pitch as a compromise between cost and performance.

Ideally instead of an LCoS some kind of device with high pixel count, small pixel pitch but nevertheless clean modulation would be required.

2.5 Trade-off for using LCOS in HUD, parameter: frame rate

Another potential limitation of LCoS is frame rate. As micro-displays typically do not use color filters, a sequential operation of RGB is required for applications like a HUD, that require full color. In addition, in the 3d holographic system the two viewing windows for left and right eye need to be generated time-sequentially. This means, the micro-display SLM needs to operate at 360 Hz in case of 60 Hz content frame rate. Even faster operation (540 Hz or more) would be preferred to eliminate artifacts from color break-up that can be an issue in color sequential systems. Although some phase LCoS are capable of achieving a 360 Hz frame rate, it is nevertheless challenging for a liquid-crystal based device to get optimum modulation quality at high speed. Some other HUD systems that make use of LCoS, therefore operate with a set-up of 3 devices, one for each color, which then needs to achieve 120 Hz. Content for 3 colors is then generated at the same time and superimposed from 3 separate LCoS by a combiner set-up for example a X-Cube. This however has also impact on total cost of the system as well as on the system volume. Some special type of LCoS based on ferroelectric LC can achieve frames rates of up to 4.5 kHz but this device is capable of binary modulation only[13]. For 3d holography a binary device is not sufficient.

So, in addition to high pixel count, small pitch and clean modulation, a device with a sufficient grey level resolution which is also capable of kHz frame rates would be desired.

3. MMA DEVELOPMENT

Micro mirror arrays (MMA) based on tilt mirrors are common for amplitude modulation in projection displays (DMD). An MMA based on so-called piston mirrors can be used for phase modulation. In principle an independent deflection of individual mirrors without interaction (crosstalk) between individual pixels will lead to large improvement of phase modulation compared to use of an LCoS. MMA devices also are capable of higher frame rates compared to LCoS, as the single mirrors are small and lightweight and the required range of mechanical movement is small (approx. 350 nm).

Bartlett et al. presented an MMA device with high frame rate and very good phase stability of only 2nm[13]. This device clearly demonstrates the potential of MMA for phase modulation but still has a relatively large pixel 10.8 µm, limited pixel resolution, limited bit depth and a non-linear phase curve. In the EU funded project Realholo a MMA device with 8 bit phase modulation with 4k x 2k pixel resolution and with 4x6 micron pixel pitch is developed [14, 15, 16].
Allowing for a small pixel pitch and therefore a large pixel count on a compact device this MMA fulfills the requirements for holographic HUD application. The practical implementation of such an MMA is of course non-ideal and includes several types of potential errors but nevertheless promises to be superior compared to LCoS.
Figure 9 shows the sophisticated mechanical design to get precise phase modulation with small mirror elements. For details see[16].
Two main aspects of advancing and refining MMA technology are numerical simulations to predict performance parameters and rigorous characterization of prototypes. This process ensures that each iteration of novel devices not only meets theoretical expectations but also stands up to the practical demands of real-world application.

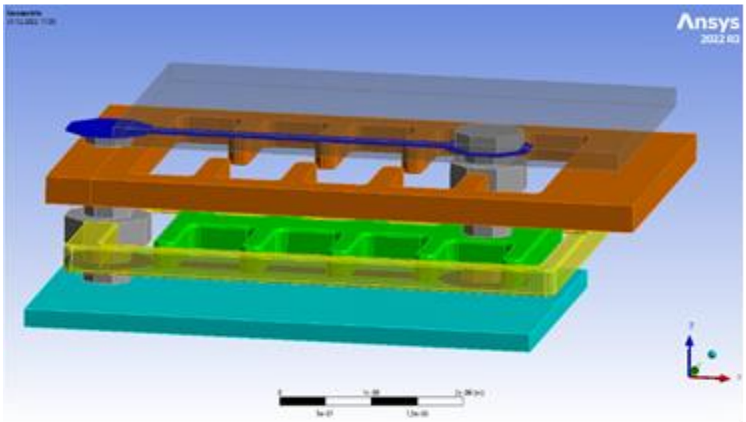


Figure 9. Mechanical design of single mirror with 4x6 micron pitch with fixed stator plate (orange), dual springs (blue) and moveable yoke (green).

Figure 10 consists of six contour plots, all demonstrating the simulated reconstruction quality of phase-only holograms based on different mirror errors being potentially present in MMA devices used for digital phase-only holography. The key parameter across all plots (as in the LCoS simulations in the previous section) is again the normalized contrast, which represents the visibility of objects against a dark background, normalized to an optimal case with perfect SLM pixels. This parameter is essential for HUD applications where contrast determines the readability and visibility of the display against the ambient background.

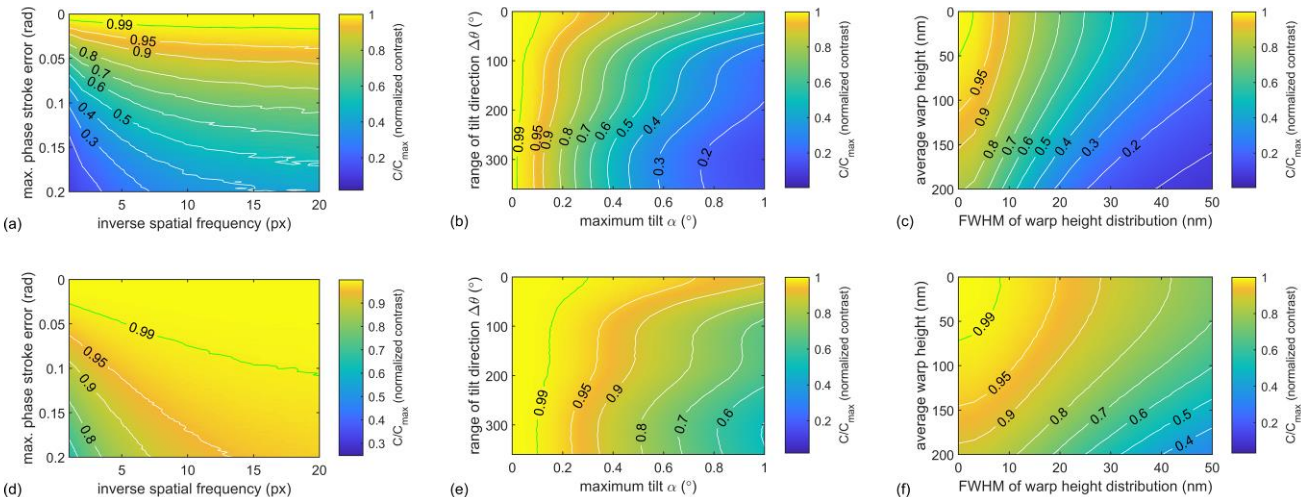


Figure 10. Comparative analysis of simulated reconstruction quality represented by the dependency of the normalized background contrast on various potential mirror errors (phase stroke, tilt, and warp) for both Fresnel (top) and Fourier (bottom) holograms.

The top three diagrams (a), (b), and (c) depict the scenario for Fresnel holograms, while the bottom three (d), (e), and (f) are for Fourier holograms. Fourier and Fresnel refer to different types of holographic reconstruction methods, which can affect the quality of the resulting image.

The results on the left (a, d) show the impact of vertical mirror offsets on the normalized contrast. Higher spatial frequencies (lower values on the x-axis) and larger maximum values of the random distribution (higher values on the y-axis) tend to degrade the contrast more significantly. This suggests that fine details (high spatial frequencies) are more susceptible to mirror misalignment. The contrast is better maintained across a wider range of spatial frequencies in the case of Fourier holograms than in Fresnel holograms.

The diagrams (b) and (e) assess how the maximum mirror tilt and its orientation range affect the contrast. A lower maximum tilt and a narrower orientation range are associated with higher contrast, indicating a more faithful reconstruction. Fourier holograms again demonstrate a higher tolerance to these errors compared to Fresnel holograms, as evidenced by the broader areas of high contrast.

On the right, the results (c) and (f) demonstrate the effect of parabolic mirror deformation. The dependence of image quality on the average warp height and the Full Width at Half Maximum (FWHM) of the warp height distribution suggests that lower warp heights and narrower distributions (lower x and y values) are optimal for maintaining high contrast. The warp height represents physical deformations in the mirror surface, which can distort the holographic image. The patterns are similar for both Fourier and Fresnel holograms, but Fourier holograms maintain higher contrast across a larger parameter space.

The data indicates that Fourier holograms generally offer better robustness against these types of mirror errors, maintaining higher contrast across a broader range of error magnitudes. For both hologram types, minimizing mirror tilt, warp, and offsets is critical for maintaining high contrast and thus better image quality. The performance of the display in terms reconstruction quality is more sensitive to errors at higher spatial frequencies and larger deformations.

Based on these investigations, target parameters for mirror properties are defined and used for the development of novel devices allowing for high-quality holographic image reconstruction. Figure 11e presents a comprehensive view of the mirror-surface characterization and functional performance of a MEMS test chip in the current stage of development.

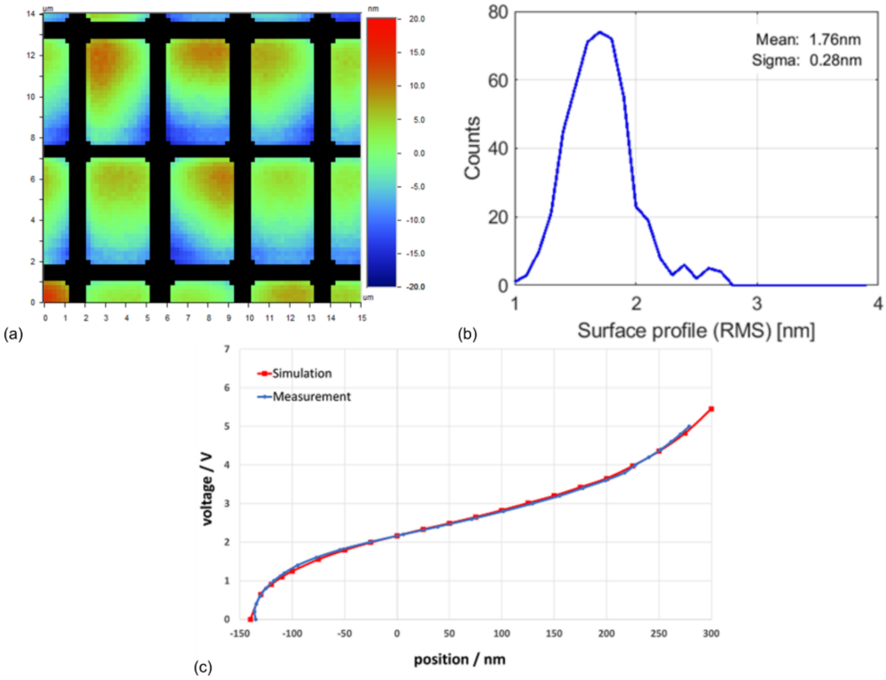


Figure 11. Optical assessment of mirror surfaces of a MEMS prototype. (a) Spatially resolved height profiles. (b) RMS histogram after numerical subtraction of plane tilt. (c) Voltage-Offset characteristic.

The image on the top left shows the surface profiles of several individual display mirrors, where the colour variations indicate height differences, revealing any systematic deformations such as warping or tilting. As can be observed by the data, the predominating misalignment is constituted by a tilt out of the horizontal orientation. However, since there is a pronounced preferential direction and the individual tilt angles are below 0.3°, the impact on the reconstruction quality is in the optimal regime in the case of Fourier holography (see Figure 10e). Even in the case of Fresnel holograms, the impact of deviations from the ideal situation observed here is significantly less detrimental than typical crosstalk effects induced by fringe fields in an LCoS devices with comparable sizes, as can be seen in comparison to the simulation results from Section 2.4.

The graph on the top right shows the Root Mean Square (RMS) deviation from the mean height of the mirror surfaces after a corrective plane fit for tilt has been applied. The bell-shaped distribution peaks around a mean value of 1.76 nm with a standard deviation of 0.28 nm, suggesting a good degree of surface flatness and consistency across the micro-display. In addition, misalignments constituted by warping effects do not play a decisive role in these devices.

On the bottom, a comparison between the simulated and actual measured characteristics of mirror position, as influenced by applied voltage, shows a tight correlation. This congruence affirms the simulation model's accuracy, which is vital for anticipating the phase errors in holographic reconstruction that affect image quality.

This empirical data complements the simulations from above by demonstrating actual device performance, underscoring the precision of the micro-display mirrors in maintaining the high-quality holographic reconstructions that the simulations predict. The minimal surface deviations and the accurate voltage-offset response are integral to achieving the high normalized contrast levels depicted in the simulations.

The experimental results are still based on investigation of first test samples. Some parameters are expected to be subject of further improvement in the next iterations. The comparison between simulation and experiments and also the comparison to LCoS simulations give strong evidence for the superior performance of the new MMA devices.

4. SUMMARY

MMAs have huge advantages for many applications. In this paper the application in a 3d holographic HUD is described.

By simulations the impact of MMA parameters like mirror tilt and mirror curvature on hologram reconstruction was shown and compared to an LCoS device. The latter shows a worse loss of contrast due to imperfect modulation.

Measurements on mirror performance made at first test MMA devices and comparing these to simulations confirmed that the MMA design can achieve a performance that is required for a good holographic reconstruction.

While a first generation of a holographic HUD product would still use LCOS, the results for the MMA measurements show the path to superior performance of a future second generation 3d holographic HUD.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101014977. It is an initiative of the Photonics Public Private Partnership.

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