Improved comb drive design for MEMS piston mirror arrays

Mario Nitzsche*, Peter Duerr, Andreas Neudert
Fraunhofer Institute for Photonic Microsystems IPMS, Maria-Reiche-Str. 2, D-01109 Dresden, Germany

ABSTRACT

MEMS (micro electro mechanical system) based piston mirror arrays are key elements for real time computer generated holograms (CGH) in visualisation technologies like virtual, augmented and mixed reality (VR/AR/MR). The EU funded Project REALHOLO is developing a spatial light modulator (SLM) that is based on comb drive MEMS actuators that can fulfil the tight requirements of the optical and mechanical performance and the high level of integration. A previous design already outlined perspectives for a superior performance in comparison to other approaches for high frequency and high precision wave front modulation, but has restrictions due to the resolution and feature size of the i-line lithography system used for manufacturing. This paper discusses the optimisation of the design applying an advanced manufacturing process using DUV lithography that allows smaller features and therefore offers additional design options. By introducing an improved comb drive geometry the electrostatic force was significantly increased, which allowed the optimisation of other geometries, like horizontal and vertical gaps and additional shielding structures, for an even more linear actuator response and reduced crosstalk. The electrostatic and structural FEM simulations will show the significant improvements in overall performance, compared to the previous iteration and other types of SLMs. The improved actuator can potentially extend the field of application from the desired automotive driver assistance holographic 3D display to head mounted displays for VR, AR and MR applications as well as other technologies like material processing.

Keywords: computer generated holography, spatial light modulators, micro mirror array, MEMS, piston mirror array, phase modulation, comb drive actuator, finite element simulation

1. INTRODUCTION

Real time computer generated holograms (CGH) require a very fast and accurate modulation of light. Micro mirror arrays (MMA), MEMS (micro electro mechanical system) based spatial light modulators (SLM) are a reasonable approach to fulfill these requirements. Independent from the used principle (regular or complex) of modulation a very high degree of precision has to be achieved with high speed. Within the EU-funded project REALHOLO, Fraunhofer IPMS and its partners are developing an innovative SLM for holographic displays, see [3] and [5]. The combination of the very small pixel pitch, the high stroke, the extreme precision [2] and the high speed, results in very challenging electrical and mechanical requirements. To fulfill these requirements the design needs as much headroom as possible from any point of view. The general concept and aspects like stability were already discussed in previous papers [3] with the outcome that the countermeasures for improving the general behavior come at the cost of a reduction of the electrostatic force which is available for the modulation.

So improving the maximal achievable force within the limited pixel area and voltage budget is a key component for the final design.

While there are approaches to overcome the unwanted side effects of stereo image concepts for 3D displays, a real time generated true hologram will still be the most promising approach for achieving a display that works under any circumstances. To improve the limited image resolution, we will also increase the pixel count to several millions, even if this will cause significant computational effort.

*mario.nitzsche@ipms.fraunhofer.de, phone +49 351 8823 398, www.ipms.fraunhofer.de

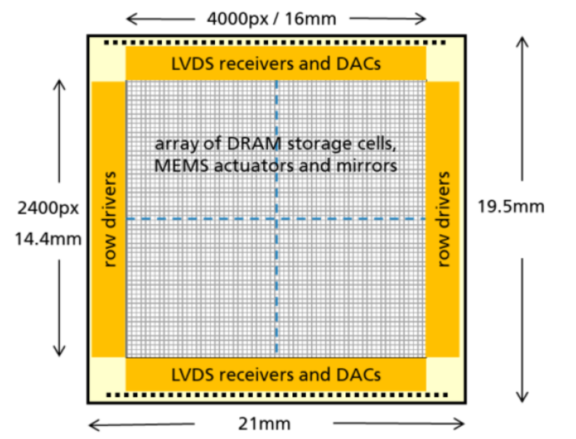
This is the ‘author’s version’ of this paper. See also:

Mario Nitzsche, Peter Duerr, Andreas Neudert, "Improved comb drive design for MEMS piston mirror arrays," Proc. SPIE 12434, MOEMS and Miniaturized Systems XXII, 124340R (15 March 2023); doi: 10.1117/12.2649743

For the generation of a real hologram the reconstruction of the field of light in three dimensions is necessary, just as if it came from a real object itself. The anticipated requirements are shown in Table 1.

Table 1: Key specification and SLM floorplan for the REALHOLO device

parameter	value
pixel count	4000 x 2400
pixel size	4µm x 6µm
frame rate	> 1kHz
vertical deflection range	0 … 350nm
deflection precision	8 bit
mirror tilt	< 0.1°
pixel addressing voltage	0 … 3.3V
power dissipation	< 2.5W



A variety of SLMs are currently available on the market, but none of them will be suitable for achieving the aimed quality. LCoS (liquid crystal on silicon) devices are able to achieve a phase modulation in an analogue way (or very many steps), but suffer from extreme nonlinearity and are unable to achieve the required framerate. There are also MMA based DLP (digital light processing) devices under development [9], which use digitally addressed piston mirrors to modulate the incoming light front in a few steps, but they are unlikely to achieve the desired phase resolution, even if pixel binning was used.

2. PREVIOUS COMB DRIVE ACTUATOR DESIGN

In our opinion, an electrostatic comb drive actuator is the best approach for reaching the challenging specifications shown above. As discussed in [3], a parallel plate actuator would not be suitable. In Figure 1 the design shows two straight hinges (blue), the fixed stator plane that is common for all pixels within the array (orange) and the movable yoke in green. The baseplate that is shown in cyan is also integrated into the simulations because it has a significant impact on electrostatic field simulations. The mirror itself sits on the post that connects the yoke with the two springs and in Figure 1 is drawn partially transparent for improved visibility of the actuator parts. The two posts will have an electrically insulating section between the yoke and stator layers so that a voltage difference between yoke and stator can be maintained.

As discussed in [3] the comb drive design has a strongly concentrated electrostatic field between the comb fingers which results in rather large forces for small pixels in combination with a potentially low crosstalk between neighbor pixels. This is essential for reaching the desired precision of deflection. As discussed in [8] even this design will not fully meet the precision goal because of the electrostatic crosstalk of about 0.5% per shared long pixel edge. To solve the crosstalk problem the design was modified by shortening the effective length of the comb drive fingers and including a screening ring in the same layer as the actuator yoke, which confines the electric fields within the pixel volume even better. By doing this the electrostatic crosstalk could effectively be reduced to 0%. While the screening ring slightly increases the available force due to the reduction of the stray fields, the shortening of the fingers decreases the force by decreasing the effective circumference of the yoke. However, a large actuator force even at the available addressing voltage limited by the CMOS backplane is important for sturdy hinges and a fast actuator response time.

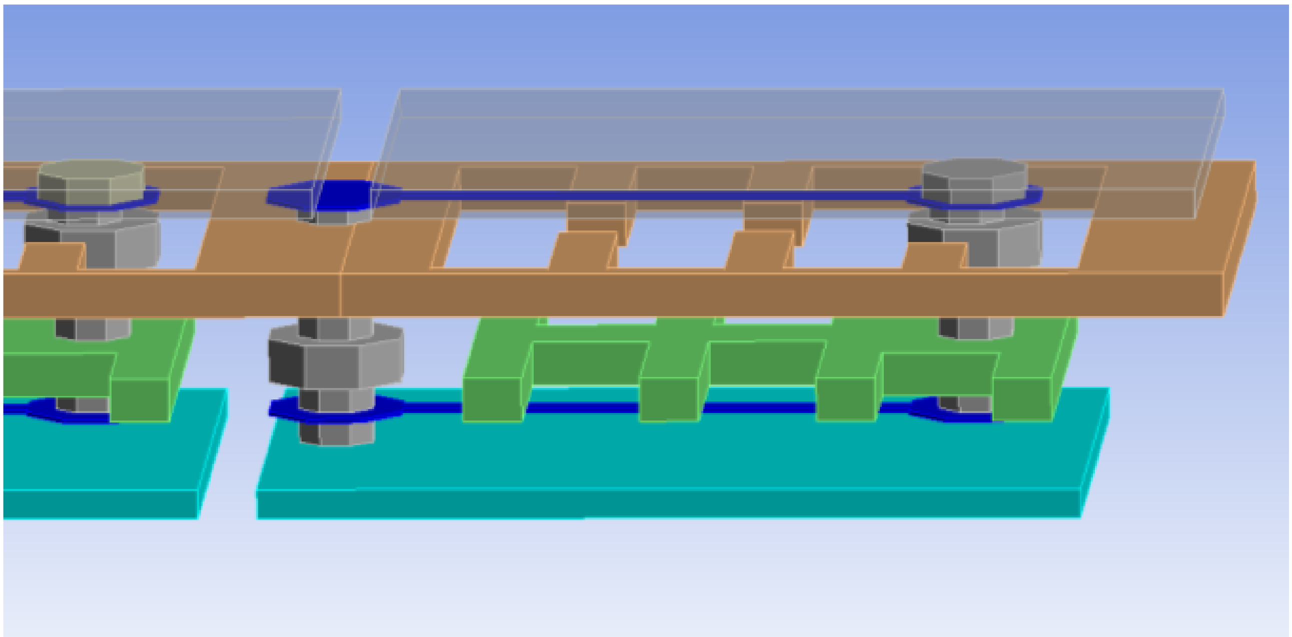


Figure 1: Original comb drive actuator design with fixed stator plate (orange), dual springs (blue) and moveable yoke (green)

The general problem of a complex design like this is that there are various restrictions. The achievable precision in manufacturing is limited, which leads to some variation in spring stiffness and actuator gaps over the active area of the device. This will cause a variation in the deflection curve and needs to be corrected which in turn requires a margin in addressing voltage, which itself is limited by the used CMOS backplane. Therefor the actuator itself needs to use the available voltage budget as efficient as possible to leave headroom for the device calibration. In other words the actuator has to generate as much force as possible from the given voltage budget.

3. FEM SIMULATION MODEL AND METHOD

Because of the complex design of the comb drive actuator, the resulting electrostatic field is truly three dimensional. For an accurate calculation of the resulting forces, a FEM simulation of the electrostatics within the actuator needs to be performed. If done in combination with the structural deformation of the hinges in a coupled simulation this would be computationally very demanding. However, as long as the electrodes (yoke and stator) do not deform due to the electric fields, the simulation can be split into electrostatic simulations with undeformed electrode surfaces and structural simulations of the deformation of the used hinge [3], which greatly reduces the effort

For the simulations of the electrostatic force, we created a cuboid and subtracted the structural model of the comb drive actuator. Only in the remaining structure (air) electric fields are present to be simulated and not in the conducting actuator structure itself. As shown in Figure 2, the top surface of the simulation cuboid and the mirror itself is set to a common (zero) potential to avoid electric fields above the mirrors. The addressing voltage of the pixel is assigned to the yoke and the base plate of the actuator, therefore no voltage difference, which would cause a downwards directed force, is created between these two parts. By applying a voltage difference between the yoke and the stator, a piston type motion of the yoke is generated.

The electrostatic force will increase with the decrease of distance between the yoke and the stator until the fingers slightly overlap. Above this relative yoke position, the vertical force will quickly decrease again, therefor this actuator design does not suffer from any pull-in in the actuator direction. On the other hand, imperfections in manufacturing may create a horizontal force that could cause a horizontal pull in, especially at high addressing voltages. The rectangular cross-section of the hinges, which is roughly ten times wider than thick, will likely prevent this kind of pull in because their horizontal stiffness is two orders of magnitudes higher than the vertical one [3].

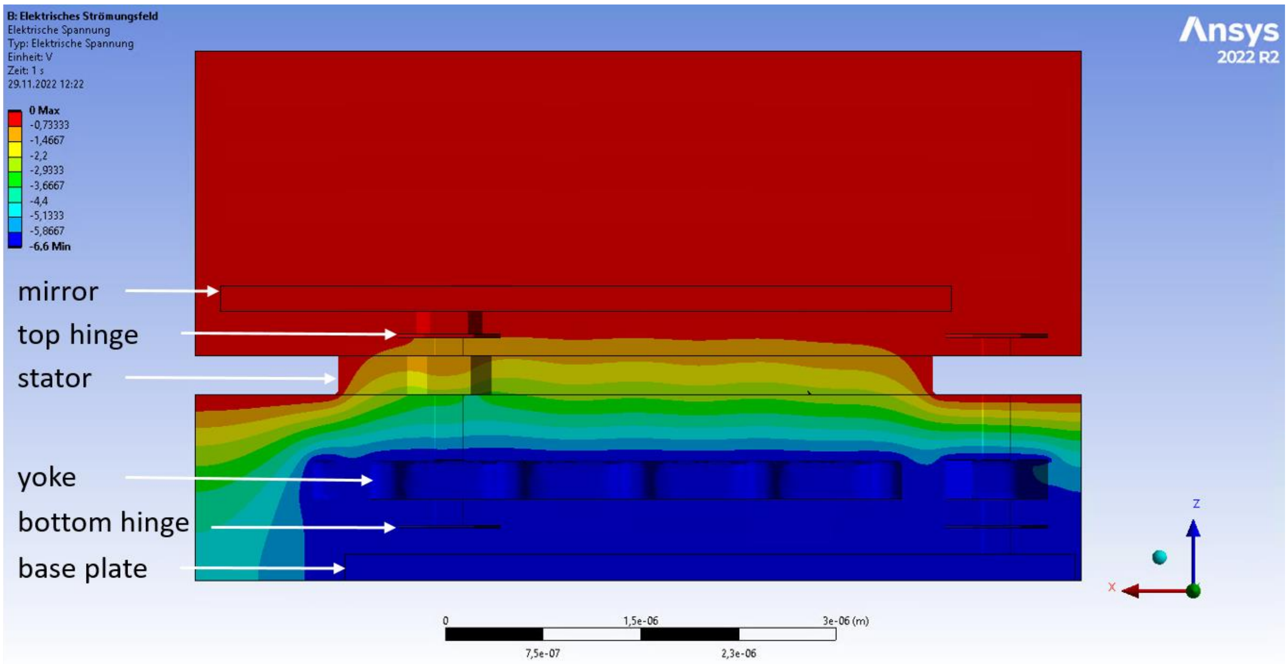


Figure 2: Simulation model of the comb drive actuator with applied voltages

4. DESIGN OPTIMIZATION OF THE ACTUATOR CONCEPT

The actuator described above had been designed within the constraints of i-line lithography in mind. With this technology the minimum feature size that can be reliably created is about 400nm. With this feature size, the design options were rather limited. By switching to an advanced Deep Ultra Violet (DUV) lithography system, we can reduce the feature size. The improved CD (critical dimension) enables a change in geometry to optimize for an increased force. The approach for reaching an increased force is the enlargement of the effective electrode circumference. This can in principle be done by creating longer comb drive fingers, creating shapes that are more complex or increasing the finger count of the current design. Increasing the finger size is hardly possible, because the current width of 3.6µm of the yoke is already extremely close to the maximum. The resulting distance between two yokes is only 400nm, so that anything less would risk the structural integrity. Also, longer fingers will increase the electrostatic stray field and therefor the crosstalk between the individual pixels, which would have negative effect on the actuator behavior.

The creation of more complex shapes would be a promising approach for increasing the effective electrode area, but due to the size of the pixels, the features would easily become smaller than even the DUV lithography can reliably produce. Especially if the shapes differ from a typical lines-and-spaces design, manufacturing would become rather difficult. Keeping the relatively simple electrode design in combination with the reduced feature size of the DUV lithography enables to fit a fifth finger within the pixel area. Figure 3 shows a comparison of the initial design (left) with this improved design (right). Because of the increased yoke cutout, the position of the post had to be shifted slightly. The shift results in a spring that is 150nm shorter than the initial one.

Beside the finger count, other parameters like the horizontal gap and the dimensions of the yoke/stator fingers could be varied. In general, a smaller horizontal gap will create higher forces but will also result in a more nonlinear reaction of the actuator. Due to the limited resolution of the available addressing voltage, the nonlinearity that can be tolerated is limited. For this reason, the horizontal actuator gap cannot be too small to achieve the desired position accuracy. The width of the fingers itself is mainly limited by the feature size of the lithography system, and should be above 200nm. With this limitation and the maximal size of the stator cutout, a horizontal gap of 240 nm is a good balance of force and linearity.

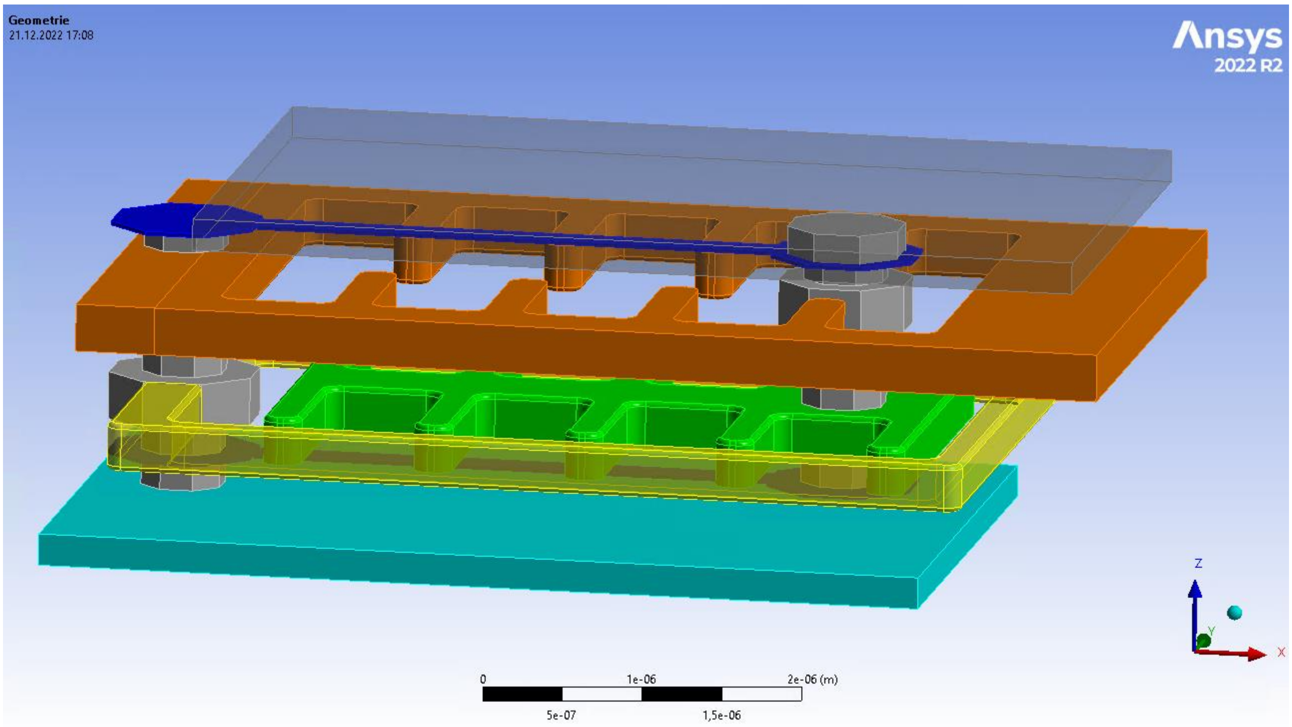


Figure 3: improved actuator design with five-finger yoke (green), and additional screening ring (transparent yellow)

5. IMPROVED ACTUATOR PERFORMANCE

As mentioned above, the simulations have been split into electrostatic and structural simulations. Figure 4 shows a comparison of the resulting electrostatic force in z direction between the previous four-finger with the improved five-finger design for a horizontal gap of 240nm. The plot shows the results of a set of electrostatic simulations of different yoke positions relative to the stator plane, at a fixed voltage of 6.6V. Note, that these are not force equilibrium states of the actuator. The graph clearly indicates the increase in resulting force for a given addressing voltage. In this example the maximal force could be increased from 14.8nN to 17.5nN which is an improvement of ~18% and goes in line with the increased circumference of the five-finger yoke. By shrinking the horizontal gap the maximal force can be increased but with suffering linearity. The modified yoke and stator geometry required a small reduction in hinge length of 150nm.

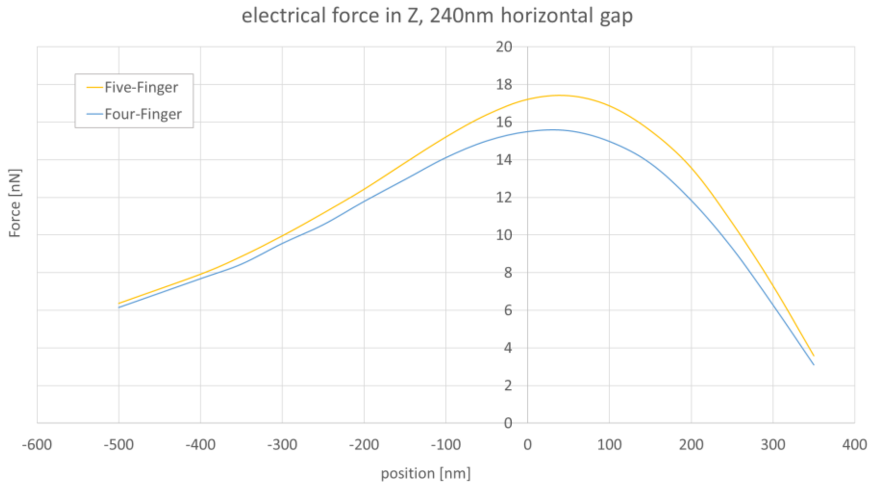


Figure 4: Comparison of the electrostatic force in z direction of the initial 4- finger with the improved 5-finger design with a 240 nm horizontal gap over the actuator position at fixed voltage of 6.6V (no force equilibrium).

The additional force budget could be invested in crosstalk countermeasures like discussed above. The shorter electrode fingers and the screening ring slightly change the behavior of the actuator. By comparing the five-finger curve in Figure 4 with the 6.6V curve in Figure 5 one can see that it creates slightly less force for small deflections but an increased force for large deflections, which is an unexpected but advantageous side effect.

Figure 5 shows the scaled curve for different voltages, with a set of three possible actuator end positions represented by the three straight lines. These lines are created by picking 2 points with the desired stroke or difference of deflection on the curves of 3.3V and 6.6V. The slope of the connecting line determines the required spring stiffness and its zero point the vertical actuator gap of the design variant. The three lines shown have different slopes and therefor correspond to different hinge stiffness. Taken alone, this aspect would strongly favor the leftmost, blue line in the graph with the largest slope and thus most robust hinges. The choice of actuator end position maximizing the hinge stiffness would be around 50nm, as can be seen in the right graph of Figure 5.

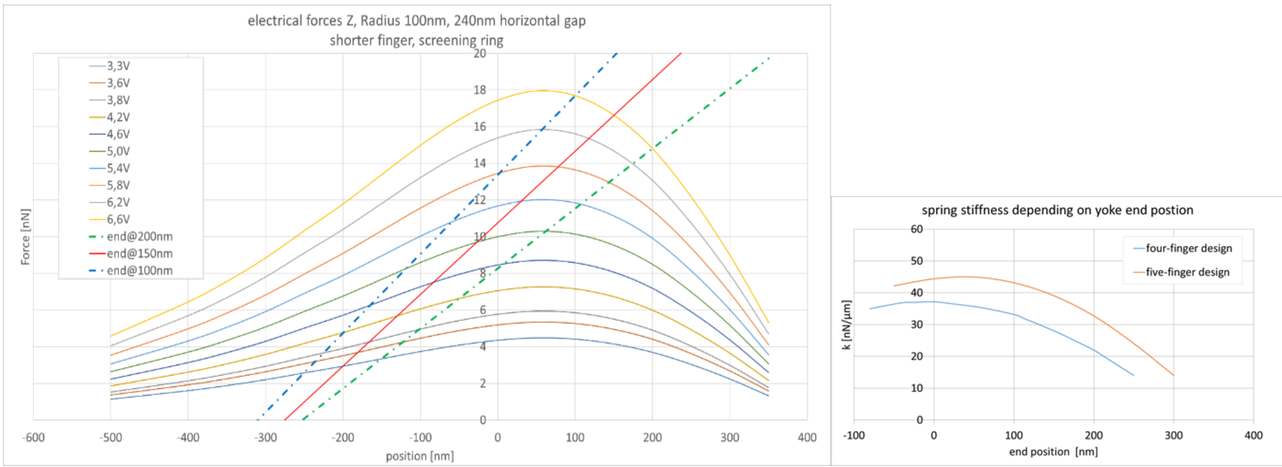


Figure 5: electrostatic force for the improved actuator for different addressing voltages and three possible working points. Right: the allowable spring stiffness is improved at any actuator end position

Figure 6 shows the response curves of these three options in comparison to the initial design. It shows that the overall behavior is at least as linear as the initial design, but with the benefit of eliminated crosstalk.

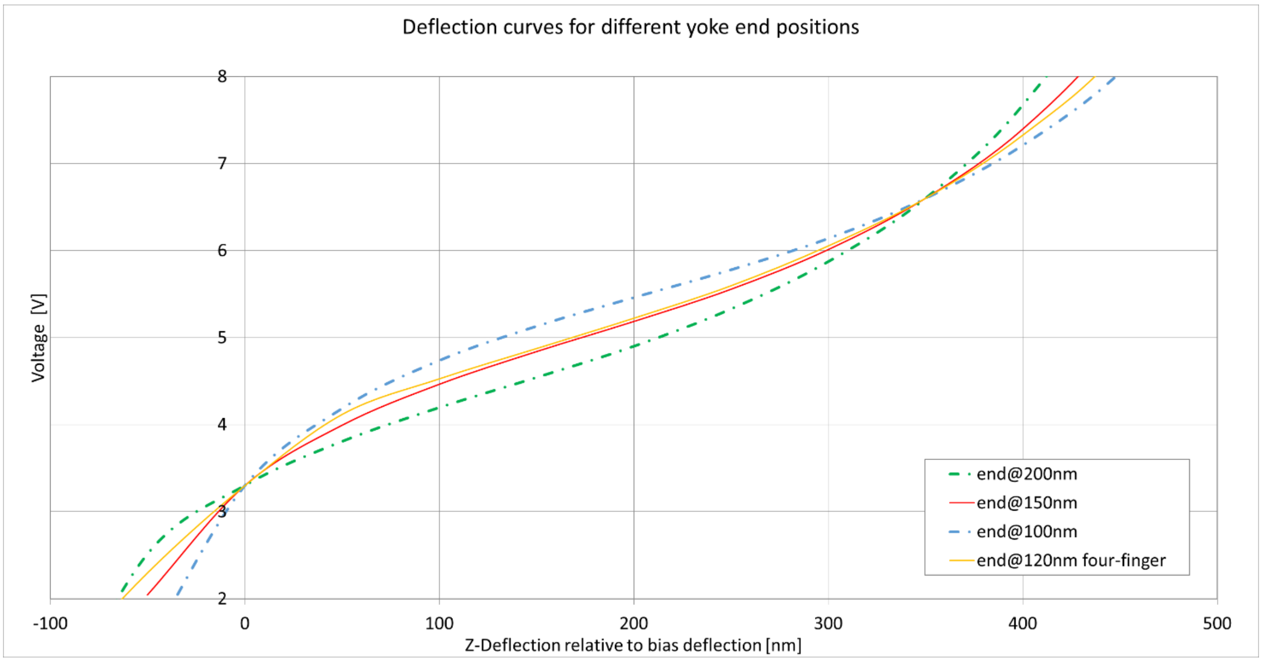


Figure 6: deflection curves of the different working points in comparison with the initial four-finger design

Ideally, the response curve of an actuator would of course be completely linear and in this case one would only need an 8-bit voltage resolution to achieve the same mechanical (and optical) resolution. As non-linearities cannot be fully avoided in electrostatic actuators, at least they should be as small as possible for the real actuator to reduce the precision requirements for the CMOS backplane. As a quantitative measure of this we use the 'loss of resolution'-value, as introduced in [3]. It is calculated as the ratio of the average slope of a response curve with its minimal slope and expressed as the number of bits (including fractions thereof) that the resolution of the addressing voltage has to be better than the required mechanical and optical resolution.

$$loss\ of\ resolution = \log_2\left(\frac{average\ slope}{minimum\ slope}\right)\ [bit] \tag{1}$$

Figure 7 shows that the new design has a significant advantage with a shifted minimum. The ideal end position of the yoke from the voltage resolution perspective lies in the range of ~180 nm.

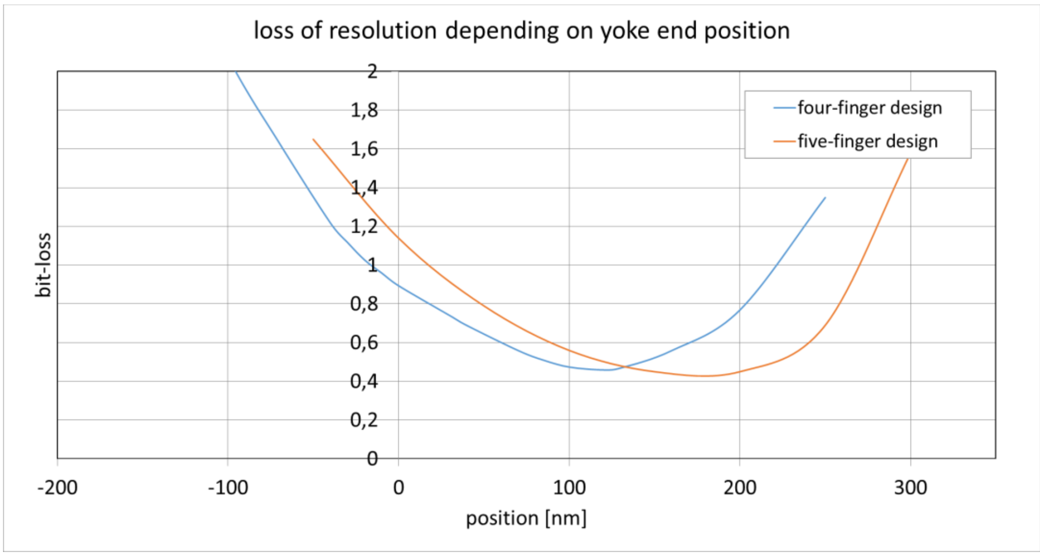


Figure 7: comparison of the actuator behavior depending on the linearity

Unfortunately this does not agree with the maximum-force criterion above, so a compromise has to be chosen. As a large end position also increases the risk of a horizontal pull-in, we tend to choose the low side at about 100nm end position where we can still get almost maximum spring stiffness (Figure 5) and do not lose too much resolution, either.

6. SUMMARY

For the realization of new visualization technologies like virtual, mixed and augmented reality, extremely advanced spatial light modulators are required. Computer generated holography (CGH) enables these kinds of 3D imaging technologies, without suffering from the distracting neurological side effects of their pseudo 3D counterparts. To fulfil the required specifications, the MEMS actuator design needs to be as advanced as possible. Within the European Union funded Project REALHOLO, Fraunhofer IPMS and its partners currently are developing a suitable MEMS based modulator. It will enable many different applications even beside visualization applications. This paper describes the improvement of the comb drive actuator, by utilization of advanced lithography processes and FEM simulations showing the improved performance compared to the initial design.

7. ACKNOWLEDGEMENTS

The project REALHOLO 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. The REALHOLO project consortium includes 6 further partners from 5 different European countries. Together we will set up a complete demonstrator 3D head-up display system. See also: https://realholo.eu/ [5]

REFERENCES

[1] R. Zabels, K. Osmanis, M. Narels, U. Gertners, A. Ozols, K. Rutenbergs, I. Osmanis, ”AR Displays: Next-Generation Technologies to Solve the Vergence-Accomodation Conflict”, Appl. Sci. 9, 3147 (2019)

[2] S. Reichelt, N. Leister, "Computational hologram synthesis and representation on spatial light modulators for real-time 3D holographic imaging", J. Phys. 415, 012038 (2013)

[3] P. Dürr, A. Neudert, M. Nitzsche, C. Hohle, H. Stolle, J. Pleikies: 'MEMS piston mirror arrays for computer generated holography', Proc. SPIE 12013, MOEMS and Miniaturized Systems XXI, (2022)

[4] A. Neudert, L. Felsberg, P. Dürr: "MEMS Aktuator-Array mit Kammantrieb und verbesserter Linearität", MikroSystemTechnik Kongress 2019, ISBN 978-3-8007-5090-0 S. 197ff

[5] REALHOLO internet site: https://realholo.eu/

[6] Wagner, Leister, Sahm, Zozgornik, Teich, Pleikies, Stolle: 'Advantages of Phase Modulating MEMS for Full 3D Hologram Scene Reconstruction', Proceedings of Optica Conference 'Digital Holography and Three-Dimensional Imaging', Cambridge, (2022)

[7] P. Dürr, A. Neudert: patent 'MEMS having a movable structural element and MEMS array', DE102018207783 and WO2019/219511

[8] Andreas Neudert, Peter Duerr, Mario Nitzsche: “Minimizing Electrostatic Cross Talk in a Comb Drive Micro Mirror Array” to be published soon

[9] Terry A. Bartlett, William C. McDonald, James N. Hall, "Adapting Texas Instruments DLP technology to demonstrate a phase spatial light modulator," Proc. SPIE 10932, Emerging Digital Micromirror Device Based Systems and Applications XI, 109320S (4 March 2019)