MEMS Piston Mirror Arrays for Computer Generated Holography

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ABSTRACT

Computer generated holography (CGH) offers the best possible solution for very interesting applications like virtual, augmented and mixed reality. To get the images from the computer into the real world, spatial light modulators (SLMs) are required that fulfil very demanding specifications. Unfortunately, none of the currently available kinds of SLMs can meet this challenge fully. Within the European Union funded Project REALHOLO we are therefore developing a novel kind of MEMS (micro electro mechanical system) SLM especially for CGH applications. The challenge is to modulate the phase of incoming coherent light with millions of individually controllable pixels. The pixels have to be only a few micrometers in size for acceptable diffraction angles and still have a stroke range of half the wavelength of visible light, about 350nm. Within this range, each pixel needs to be set very precisely to one of many deflection levels at frame rates of more than one kHz. This paper discusses the challenge and our solution: an innovative MEMS comb drive actuator array, monolithically integrated on top of a CMOS backplane. The advantages of this design are compared to other types of SLMs and its superior performance is shown by FEM simulations. We also discuss the impact of effects like charging and fabrication imperfections on the deflection precision. Our newly developed MEMS technology and SLM will also enable many other applications that may benefit from the fast and precise phase modulation by a large number of pixels, like wave front shaping or quickly re-programmable diffractive optical elements (DOEs).

Keywords: computer generated holography, mixed/augmented/virtual reality, spatial light modulator, micro mirror array, MEMS, piston mirror array, phase modulation, comb drive actuator

1. INTRODUCTION

The demand for 3D displays for virtual, augmented and mixed reality is increasing rapidly. While there are a number of such displays already available, there is still a need for improvement of the image features and quality. Regular and extended use of 3D displays demands a natural visual experience with all natural depth cues, without limitations in depth perception, and especially without physiological side effects for the user like eye fatigue, depth misjudgement, motion sickness and accommodation-vergence conflict, which are known from alternative and intermediate technologies such as stereoscopic displays. The best possible solution is the full reconstruction of a natural light field by real holography for perfectly realistic images. The term 'holography' unfortunately is widely used for all kinds of displays where the screen is not obviously visible, often even for 2D imaging. In this paper, we use this term in its original sense only for a display that realistically reconstructs the field of light in three dimensions just as if it came from a real object. A display, as opposed to a still image, moreover allows updating the image fast enough to show moving scenes.

The key component of such a real holographic 3D display is a spatial light modulator (SLM). For holography, the best choice is a modulator allowing a multi-level precise phase control of the incoming coherent light, see Figure 1. The huge amount of information in a hologram requires as many millions of individually addressable pixels as possible. To keep the effort at all manageable, our solution is to provide only a small 'viewing window' for the user's eyes with image content, see [1]. Even then, the SLM will have quite challenging specifications.

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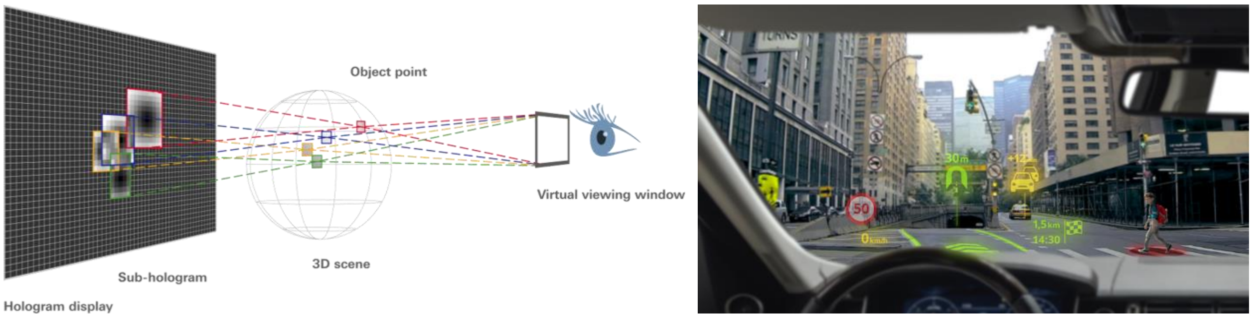
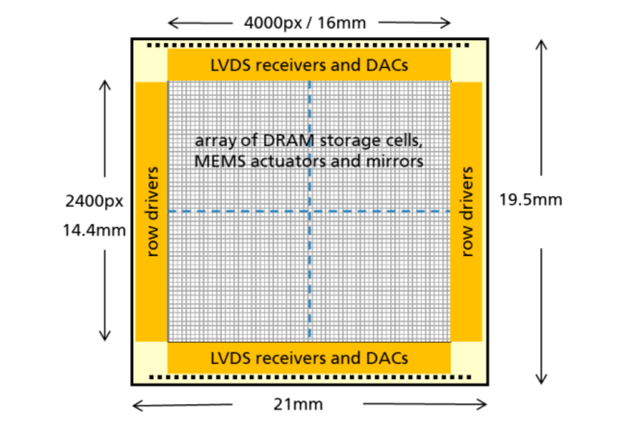


Figure 1: A piston micro mirror array can modulate coherent light to produce fully realistic 3D images correctly located in the real world

As a first application, REALHOLO is aiming at an automotive driver assistance holographic 3D display. For a good quality holographic image, the project partners anticipate that the SLM needs to fulfil the specifications in Table 1.

Table 1: key SLM specifications and chip floorplan:

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



The relatively high frame rate requirement is motivated by the plan to multiplex the images for the two eyes of the user as well as three primary colors sequentially on one SLM. We believe this will be easier to achieve than multiplying the pixel number instead, in view of the already quite large chip MMA size and yield considerations.

From a MEMS point of view, we would like to have an even higher addressing voltage to get more actuator force. However, to be able to deflect all the pixels individually they need to be integrated on top of a mixed signal CMOS driving circuit (a so-called backplane) with the same pitch. Each micro mirror pixel requires its own DRAM-like cell to store its individual analogue addressing voltage. We didn't find a commercial CMOS process allowing to fit transistors for higher voltages into the space available. At the same time, higher voltages would also increase the power dissipation, whose limit is already challenging to comply with at this voltage level considering the high data bandwidth.

The phase modulation of coherent light could in principle be achieved by existing SLMs based on LCoS (liquid crystal on silicon) technology (e.g. [2]). Compared to these, micro mirror arrays (MMAs) can have many advantages for real holography: the phase across a pixel is more uniform, there may be much less cross talk between neighbor pixels, they can be switched much faster, and are independent from polarization. Well-known MMAs are offered by Texas Instruments as Digital Light Processing technology (DLP, e.g. [3]). These, however, have been optimized for 2D-image projection and are not well suited for holography: the pixels deflect in tilt mode instead of the piston mode preferred in holography and there are only two possible addressing states for each pixel instead of the many required here. The few existing piston-mode MMAs (e.g. [4] to [7]) usually have quite large pixels (several ten micrometers and more) and therefore much too few pixels for good quality holography, sometimes combined with low bit depth.

2. PARALLEL PLATE ACTUATOR EVALUATION

The straightforward choice used in many known MMAs for phase modulating micro mirrors would be an electrostatic parallel-plate actuator. However, we found that this concept might not be feasible for this application. To avoid the well-known pull-in, the actuator gap has to be quite large: for visible light, the required stroke is about 350nm and the minimum actuator gap is about 1,8µm. A bias voltage can effectively improve the resulting very small forces, but requires an even larger gap due to the bias voltage deflection. Figure 2 shows an example with a bias voltage of 3.3V where the maximum force would still be only about 1.5nN for the parameters of Table 1. Thus, the hinges can only be quite fragile and sensitive to fabrication tolerances, and the response curve even within the working range is non-linear and rather sensitive at one end, as discussed in [9].

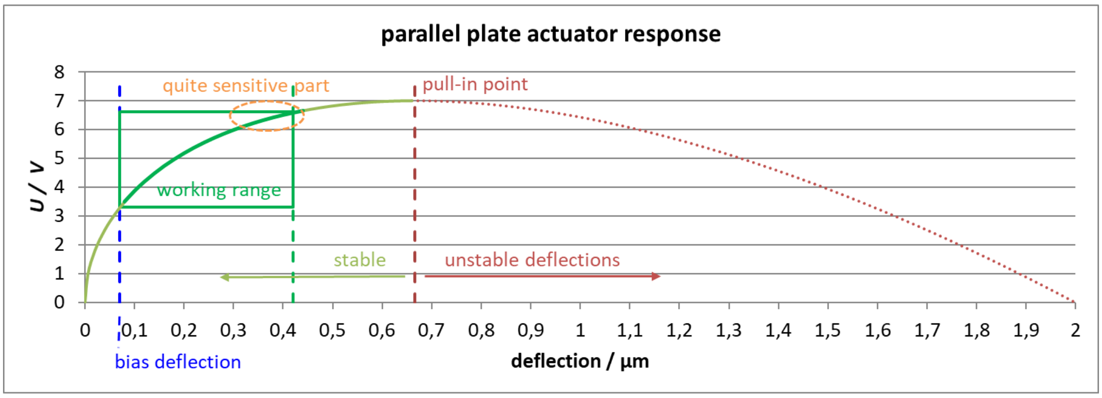


Figure 2: response curve of a parallel plate actuator with the planned parameters, including a bias voltage of 3.3V

The combination of large gaps and small lateral pixel sizes of the tightly packed actuators will also produce a severe crosstalk between neighbor pixels. As an example, Figure 3 shows 2D FEM simulations of 2 neighboring parallel-plate actuators with a 4µm pitch and 2µm actuator gap. Here the left pixel is slightly deflected by the bias voltage, while the right one is deflected a further 300nm. An extraction of the electrostatic forces from the simulation shows that the change in the force acting on the right pixel is almost 4%. If one included the neighbors on the other 3 sides in 3D, the cross-talk could reach up to 14%. With this, the required deflection precision (8bit or 0.39%) would be completely out of reach.

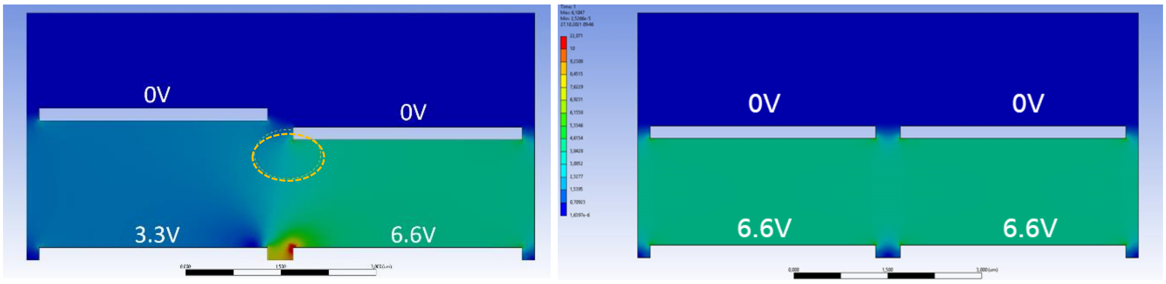


Figure 3: FEM electrical field strength simulation of two neighboring parallel-plate actuators illustrating cross-talk

In principle, one could try to reduce the cross talk by reducing the electrode size and/or by introducing shielding structures between pixels within the actuator gap. This would however further reduce the already small actuator forces and it is very questionable whether the required precision could be reached at all.

In addition, the response curve of parallel plate actuators is very non-linear (see Figure 2 and [4]), so that the precision of the addressing voltage has to be much better than the required precision of the deflection.

3. NOVEL COMB DRIVE ACTUATOR ARRAY CONCEPT

All these drawbacks can be overcome by a comb-drive actuator, see Figure 4 for the basic concept. With a comb drive actuator, there is no pull-in in the stroke direction. Therefore, the electrodes can be much closer to each other, approximately 200nm. Simulations show that more than 10 times higher actuator forces can be achieved in spite of the reduced electrode area, see Figure 7.

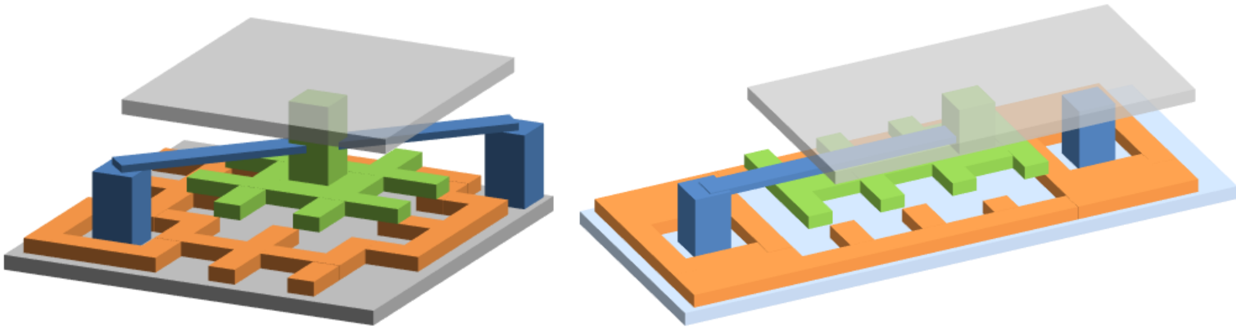


Figure 4: first concept sketches of our novel MEMS comb drive actuator for large arrays of micro mirrors at a pitch of only a few micrometers.

Figure 4 (right) shows an asymmetric actuator with only one hinge and one fixed post. This is a very favorable design for small pixel pitch and large deflections, especially with the limited voltages and corresponding actuator forces available. Properly designed, the actuator can be force-balanced and may show a pure, tilt-free piston motion, see [8].

However, the first comb drive concepts of Figure 4 still have some issues: firstly, even a small misalignment between the two combs may cause quite large torques from horizontal forces and a mismatch of the vertical forces on opposite sides, resulting in a large mirror tilt. The comb drive is much more sensitive in this respect than the parallel plate actuator.

Secondly, the single hinge is quite sensitive to stress gradients within its thickness that would cause it to bend upon the release etch. Tuning the fabrication technology to almost zero stress gradient is quite difficult.

Another concern is the isolating material below the actuator (light blue in Figure 4). From experience we know that such isolators can trap electrical charges that influence the actuator position. Unfortunately, these charges are not very stable and change quite unpredictably over time depending on the electrical fields and temperature, impeding the precision of the deflection.

A fourth point is, one would like to have a common voltage on all the mirrors, as otherwise one gets again some cross talk from the electrostatic field between neighboring mirror edges. As the slits between mirrors should be small for a good fill factor, this cross talk can again easily reach many percent of the stroke, which we cannot accept here. Therefore, in Figure 4 the orange comb would have to carry the individual pixel voltage and would have to be isolated and mechanically separated from the neighbor. In this case the circumference of the comb and thereby the actuator force can only be smaller than would be possible if the outer comb would carry the common voltage.

Finally, we also have to consider the circuit below the actuator, which can exert an additional unwanted electrostatic force. This force can be quite large due to the substantial area of the moving comb. It will also change very non-linearly with deflection similar to a parallel-plate actuator and severely impede the deflection precision.

4. IMPROVED COMB DRIVE ACTUATOR

To solve all these issues, we came up with the actuator design of Figure 5. It has two hinges in different MEMS layers acting as a parallelogram guide for the mirror. Therefore, there will be only very small unwanted mirror tilts even with some actuator torque from non-ideally aligned combs or with stress gradients within the hinges. The two hinges also can carry the two different electrical voltages needed to drive the actuator.

The lower half of the actuator is connected to the CMOS addressing circuitry below. It consists of a base plate (cyan in Figure 5), lower hinge (dark blue), and lower (moving) actuator comb (green). All these MEMS layers carry the individual pixel voltage, so there won't be any electrostatic fields between them. And there are no isolators (except for native oxide layers) that may trap electrical charges. The actuator is properly shielded from the circuit below by the base plate, and this base plate also offers a large area for the direct connection to the addressing CMOS.

The upper half of the actuator consists of the fixed comb (orange in Figure 5), the upper hinge (dark blue), and the mirror (transparent grey). This upper part is mechanically mounted on but electrically isolated from the lower actuator part and carries the common actuator voltage. The fixed comb is shared between neighbor pixels. Therefore, it does not need any isolation gaps and thus can be the largest possible size for large actuator forces. The common voltage can be fed in at the array edge and no extra wires are required for this within the array. Through the upper hinge all the mirrors are connected to the common voltage of the fixed comb, so no cross-talk can occur here. There are again no electrical fields and no isolators (except for native oxide layers) between these MEMS layers avoiding possible trapped charges.

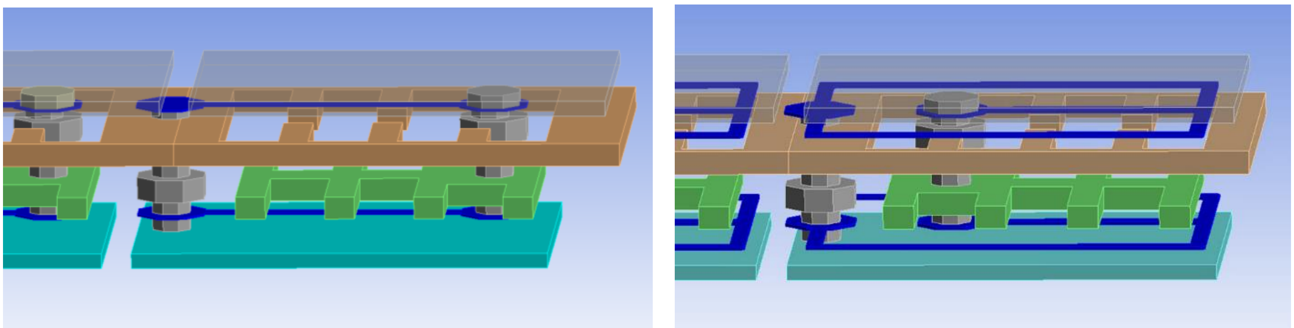


Figure 5: improved comb drive actuator with double hinge for best possible tilt-free piston movement and overall precision. left with straight hinges, right with folded hinges that may be thicker for the same spring stiffness

In this actuator design there is also very little chance for short cuts between neighbor pixels or between moving and fixed combs due to defects in fabrication, so the overall yield should be acceptable even for large arrays.

The double hinges stabilize the micro mirror very well against the unwanted tilt in the presence of stress gradients in the hinges as can be seen in Figure 6. They are on the other hand sensitive to the stress mismatch of the two hinges, but due to the large separation of the two hinges compared to the hinge thickness this leads to much smaller tilt angles that are acceptable even for the worst expected stress mismatch.

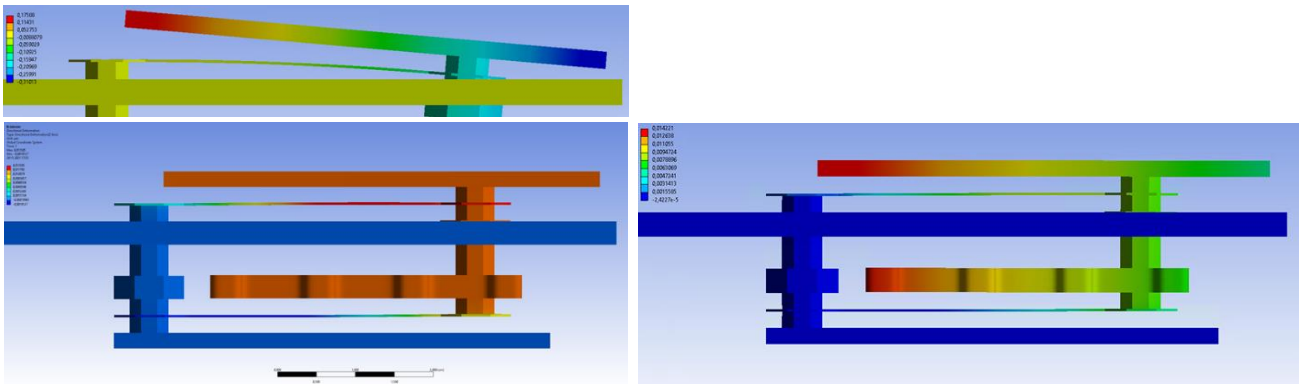


Figure 6: comparison of tilt for a single hinge with an example stress gradient of 100MPa (top, 4.8° tilt) to a double hinge actuator where both hinges have the same stress gradient (lower left, 0.00° tilt) and a double hinge actuator with stress mismatch of 100MPa in the two hinges (right, 0.06° tilt)

The spring stiffness of a thin, wide hinge is proportional to its thickness cubed, so the double hinges still have about 79% of the thickness of a single hinge for the same total spring constant.

All the advantages of this design should thus outweigh the more complicated MEMS process needed for the fabrication of more MEMS layers.

5. ACTUATOR RESPONSE AND PERFORMANCE

As the electrical field of the comb drive is truly three dimensional, a meaningful prediction of the forces generated requires an FEM simulation of the air space between the structural elements. It is computationally quite demanding to combine this with the FEM simulation of the structural deformations in a coupled simulation to get the desired response curves. It has been checked by structural deformation simulations that the hinge follows Hooke's law for the relevant range of hinge thickness and stroke. We therefore could split the simulations in two steps: first the simulation of the electrostatics for given positions of the actuator, which yielded a set of curves force vs. position for a number of voltages as shown in Figure 7 (left). We can then choose two points within the graph separated by the desired stroke and the available addressing voltage. The required spring constant k and zero-voltage vertical actuator gap can be calculated from these two points according to:

$$k = \frac{F(max.\ voltage) - F(bias\ voltage)}{stroke}, \tag{1}$$

$$zero\ voltage\ gap = gap\ at\ bias\ voltage - \frac{F(bias\ voltage)}{k} \tag{2}$$

The hinge thickness corresponding to the required spring stiffness can then be determined by the second step, a structural simulation of the design. Further we find response curves as shown in Figure 7 (right) from the intersections of the straight hinge force line and the electrostatic force curves.

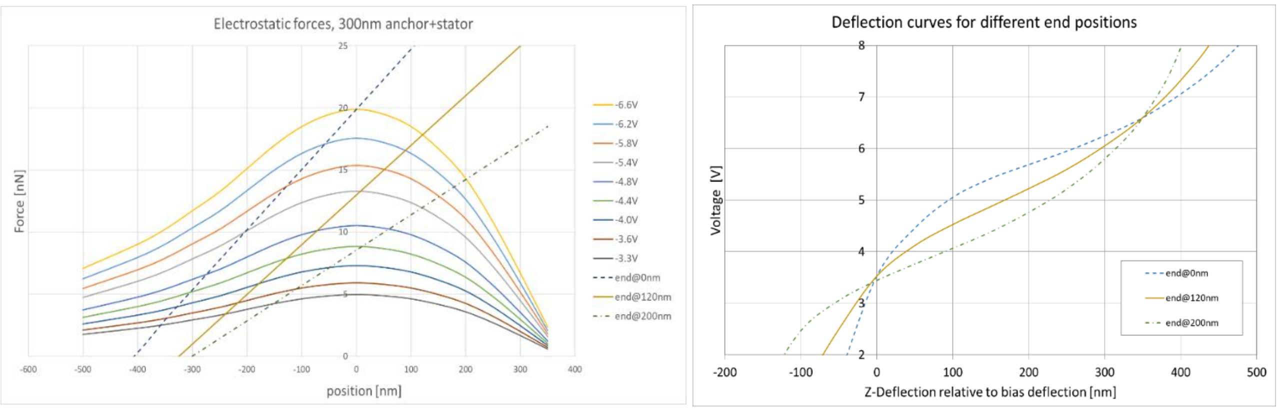


Figure 7: left: simulated electrostatic forces vs. actuator position for various voltages plus some example force lines for the hinge, right: resulting actuator response curves (required voltage vs. desired position) for the same choice of parameters;

Different choices of the two starting points result in different response curves, as shown in Figure 7. Some of these curves may contain instable regions with negative slope, which are of course not usable solutions. A low slope value at any point of the response curves means that the voltage change required to get a given change of deflection is small, or put the other way around, that a small error in voltage results in a rather large error in position. Therefore, among the monotonically rising response curves, the most attractive one is the one where the minimum slope is the greatest, and we pick this one to determine our fabrication goals for hinge thickness and vertical actuator gap.

As a figure of merit for this minimum slope value, we compare it to the average slope between the two end points of the response curve chosen above. The ratio between the two values can be considered a 'loss of resolution', which we express as a number of bits for digitizing the addressing voltage. This means that even an ideal pixel needs to be addressed with more voltage resolution than the desired deflection resolution by this number of bits (fractions are allowed here for better comparison).

$$loss\ of\ resolution = \log_2\left(\frac{average\ slope}{minimum\ slope}\right)\ [bit] \tag{3}$$

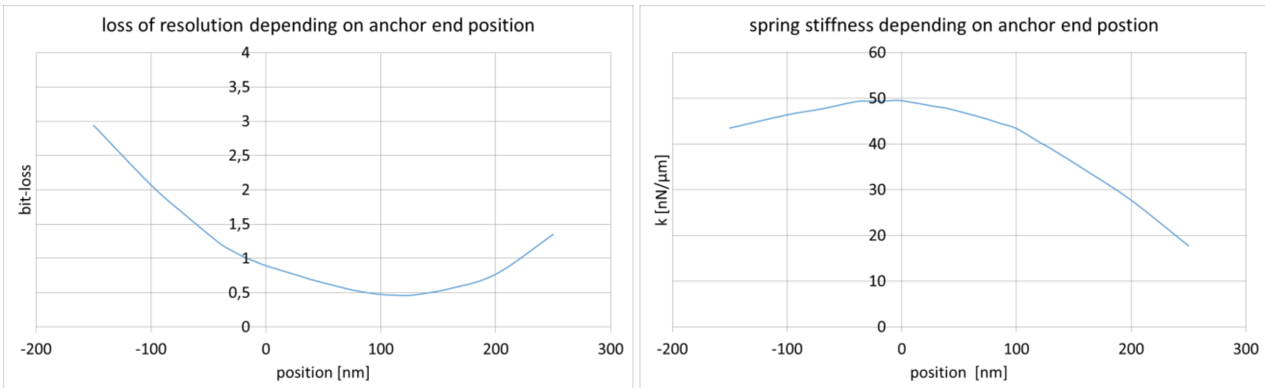


Figure 8: loss of resolution and achievable spring stiffness vs. actuator end position

For our comb drive actuators the loss of resolution can be below 0.5 bit, and it is below 1 bit for a wide range of actuator end positions, as can be seen in Figure 8. Thus, an addressing voltage resolution of 9 bit would be sufficient for the desired 8 bit resolution of the actuator position.

For a maximum hinge stiffness, the actuator end position at maximum addressing voltage is best chosen such that the moving comb is only slightly overlapping with the stator comb, see Figure 8. This overlap should definitively be less than half the comb thickness, since for deeper immersion the maximum actuator force decreases rapidly as the electrical fields approach a symmetry for full immersion and do not create any vertical force any more.

Another aspect is the horizontal force that may arise from any asymmetry of the combs in horizontal direction. This may for example be caused by lithography imperfections of the finger edges or, probably more important, by an alignment error of the two combs within manufacturing or due to stress relaxation. In any case, such horizontal forces may lead to a tilt of the micro mirror and in very severe cases even to a horizontal pull-in of the combs when they are overlapping at high addressing voltage. Figure 9 shows a cross-section of an example simulation of the electrostatic field between two (partial) stator and one movable comb finger, as well as a curve of the horizontal force due to this alignment error vs. z position. Obviously the horizontal force increases with the vertical overlap of the two combs which favors designs with less overlap. Note that the unwanted horizontal force under these circumstances is not very much smaller than the desired vertical force (Figure 7). On the other hand, the hinges are about two orders of magnitude stiffer in the horizontal direction than in the vertical one, so the horizontal movement of the actuator remains very small.

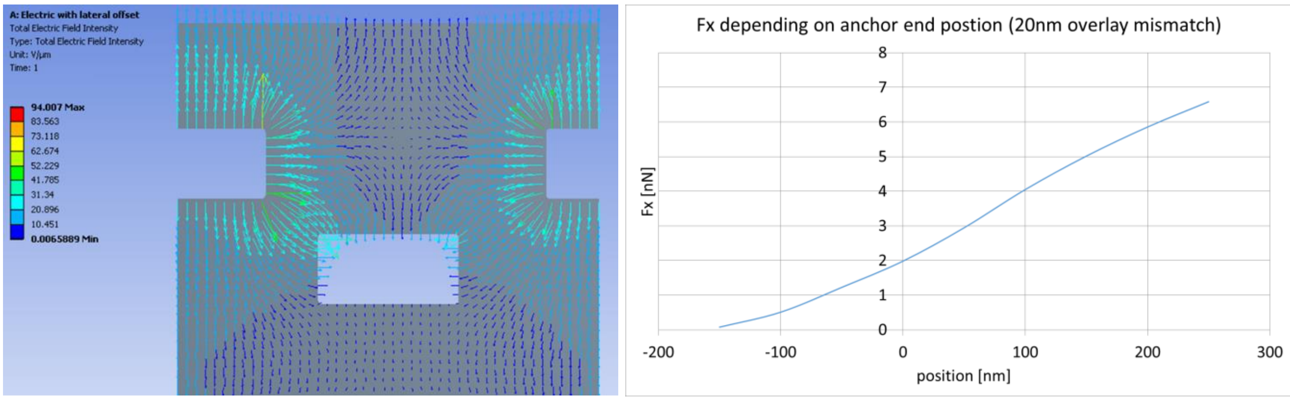


Figure 9: left: example simulated electrostatic field cross-section between two stator fingers and one yoke finger; right: horizontal force due to 20nm alignment mismatch between the combs in x direction at full addressing voltage of 6.6V

When comparing many such cases with variations in horizontal actuator gap and comb thickness, we can get better linearity of the response curve, more maximum force or less sensitivity to alignment errors of the two combs. Unfortunately, the mentioned goals partly contradict each other, but we can find a good compromise for the given application at end positions around 100nm overlap between the two combs.

Interestingly we find that it is generally best to have an actuator starting position for zero actuator voltage with a substantial vertical separation of the two actuator combs. This is very advantageous as in surface micromachining it is much easier to fabricate the two combs with a vertical separation. The sacrificial layer used for this separation can be polished by CMP (chemical-mechanical polishing) to give a flat surface to deposit and etch the second comb.

With the comb drive actuator the electrical field is mostly confined to the close vicinity of the comb fingers, see Figure 10. The first simulations of the cross talk with the above parameters yield a value of about 0.6%, which is still larger than desired 0.4% for the 8 bit precision. In spite of shielding effect of the base plate in one pixel, we still have a weak but noticeable influence of the neighbor baseplate on the field below the actuator comb. Changing the separation between the baseplates unfortunately does not change the cross talk by much. We are now working on improving the shielding between the neighboring pixels further. In the worst case, we might need to counteract the remaining level of cross talk by calculating appropriate addressing voltage values.

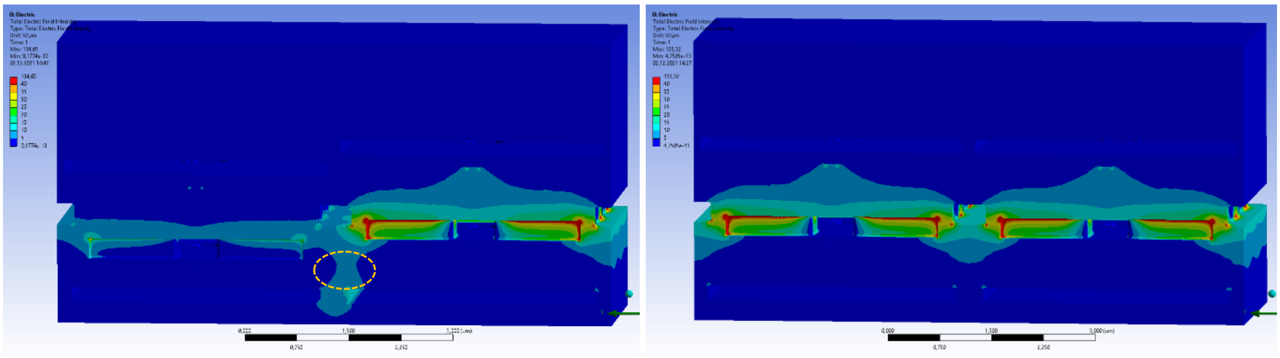


Figure 10: cross-section of 3D FEM electrical field simulations showing the electrical field strength for a low/high state (left) and for a high/high deflection state (right); one can see the difference in field strength especially at the lower side of the actuator comb

6. SUMMARY

Computer generated holography (CGH) offers the best possible solution for very interesting applications like virtual, augmented and mixed reality. To get the images from the computer into the real world spatial light modulators (SLMs) are required that fulfill very demanding specifications. In the European Union funded Project REALHOLO we are currently developing a novel kind of MEMS SLM for CGH applications, which will also be useful in other fields like wave-front shaping or re-programmable diffractive optical elements (DOEs). This paper describes the novel MEMS comb-drive actuator SLM design meeting the challenges together with simulations showing its superior performance.

7. ACKNOWLEDGEMENTS

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