Optimization of the design parameters

Operation of the Telescopic Pixel depends on several important parameters. The optimization goal is to find the conditions when the membrane deflects enough for efficient light focusing. The more the membrane is pulled towards ITO electrode, the shorter is the focal length. The maximum deflection of a thin circular membrane with fixed edges and without a hole can be described using this formula\(^{20}\):

\[
\delta_{\text{max}} = \delta_{\text{center}} = \frac{3Pr^3(1-\nu^2)}{16Et^3}, \quad (1)
\]

where \(P\) is pressure in \(N/m^2\), \(r\) is radius of the membrane, \(t\) is thickness of the membrane, \(\nu\) is Poisson ratio, \(E\) is Young’s modulus in \(N/m^2\). In particular, for aluminium Poisson ratio is 0.35 and Young’s modulus is 70GPa.

Pressure can be found as follows:

\[
P = \frac{F_{el}}{A} = \frac{\varepsilon \varepsilon_0 V^2}{2l^2}, \quad (2)
\]

Where \(F_{el}\) is the electrostatic force between two electrodes, \(A\) is the area of the electrode, \(\varepsilon_0\) permittivity of free space, \(\varepsilon\) relative permittivity of air, \(V\) is the applied voltage, and \(l\) is the gap between electrodes. In (2) we assume that the gap is constant, which is not true when the membrane deflects, but this assumption still can be used for the first order approximations.

After a closer observation of the formulas, it can be noticed that deflection can be increased by increasing the applied voltage, making larger membrane, decreasing the membrane thickness or distance between the electrodes. Usually the voltage is kept low to minimize power dissipation and simplify the device control. Making the membrane larger allows easier deflection, but also increases the pixel size. The minimum membrane thickness is limited by the fact that metal film should have
good reflective properties. Therefore, the smallest thickness is approximately 100 nm. Good optical quality film of such thickness can be easily fabricated using metal evaporation or sputtering. The smallest gap between the electrodes is limited by the fabrication procedure. Also the gap should be three times larger than the maximum deflection to avoid shorting out the device.

Furthermore, desired optical properties of the system put additional constraints on the device parameters. Focusing quality that depends on the minimum spot size can be calculated as follows:

$$\min \text{ spot size} = 2.4 \lambda \ f\#,$$

where $\lambda$ is the wavelength of light (we use 0.5 $\mu$m for our calculations), $f\# = \frac{f}{2r}$, and $f$ is the focal length of the parabolic mirror corresponding to the shape of the reflective membrane can be described by the following relation:

$$f = \frac{R}{2} = \frac{r^2}{4\delta_{\max}}.$$

Taking into account optimizations, the device parameters are: primary mirror radius $r=50 \ \mu$m, secondary mirror radius - 25 $\mu$m, radius of the hole in the membrane - 20 $\mu$m. For the gap between two electrodes $l = 6 \ \mu$m and maximum deflection $\delta_{\max} = 1.8 \mu$m, the voltage is 32 V. This will give us focal length $f=350 \ \mu$m, thus the distance between the primary and secondary mirror is 175 $\mu$m. This means that $f\#$ is 3.5 and minimum spot size is 4.2 $\mu$m that gives us a system with the desired optical quality.

In the display, pixels will be stacked one next to each other and projected onto a screen. Light diverges after leaving the pixel, thus for a screen placed at the optimal distance from the primary mirror (equal to the focal length, $f=350 \ \mu$m) light spots will be large and there will be no empty space between pixels.
Fabrication details

To fabricate the membrane, a 6 µm thick layer of polyimide HD4000 is spin-coated on top of ITO glass (Fig. 3.b). After that, it is post-baked on a hot plate. A 100 nm 99%Al+1%Si layer is sputtered on the polyimide. Positive photoresist AZ1512 is used for photolithography to define holes in the membranes (Fig. 3.c). Next, aluminium is etched in heated to 45° C aluminium etchant for 2 min. After that the sample is rinsed with water and dried with a nitrogen gun. Finally, a Benson Barrel Etcher is used to release the membranes (Fig. 3.d). By nature of isotropic etching the membrane has a perfect circular shape and is self-aligned to the hole in the centre. The residual polyimide stays as a support for the membrane.

Secondary mirrors are fabricated on a separate substrate – Micro Slides Corning glass. Metal is sputtered on the glass (Fig. 3.e) and patterned using photolithography (Fig. 3.f). After that membranes and secondary mirrors are aligned under microscope with 180 µm separation (Fig. 3.g).

All the fabrication steps – ITO and metal sputtering, plasma etching, polyimide deposition – are LCD fabrication processes compatible. The details of the LCD fabrication process can be found here: http://www.avdeals.com/classroom/fabricating_tft_lcd.htm.

Operation of the Telescopic Pixel in “reflective mode” for projection TVs

A slightly modified design of the Telescopic Pixel can be used to create a reflective display technology for projection TVs. Light will not go through the pixel, but will be reflected off, magnified and projected onto a screen located at the same side as the light source (in a fashion similar to DLP chip). A non-reflective shutter has to be used instead of the secondary mirror. The operation mode will also change in comparison with the transmissive mode. With no voltage applied the planar primary mirror will reflect light, which will be later projected onto a screen, and the pixel will be bright. When voltage is applied, the activated membrane (parabolic primary mirror) will
focus light onto the shutter, so it will not be reflected back to the observer and the pixel will appear dark.

Supplementary Figure 1. Side view of one reflective pixel in (a) on- and (b) off-states.

**Validation the pixel’s efficiency, contrast and cross-talk**

1. The light efficiency (experimental measurements).

The experiment for measurement of single pixel transmission efficiency showed that 61% of the light not blocked by the shutter could reach opening in the primary mirror. The measurements were done using two pixels, which were separated by 100 µm. One pixel has both primary and secondary mirrors, and the other one had primary mirror removed. Therefore light could freely propagate in the second pixel in the whole area where primary mirror was before, and was only partially blocked by
the secondary mirror. The amount of light from the first pixel in on-state and from the second pixel were compared, and it was found that pixel with 2 mirrors transmits 61% of available light. This can be further optimized by improving reflecting properties of the primary mirror, which was not perfectly smooth because of the non-optimized fabrication process. The result is the total experimental backlight efficiency achievable (without further optimization) for this technology is \( \pi/4 \times 0.75 \times 61\% \approx 36\% \), which is already 350-700\% of LCD backlight transmission efficiency.

2. The light efficiency (simulations).

The light efficiency, contrast and crosstalk for the transmissive Telescopic pixel were done using OptiFDTD software. It takes into consideration the diffraction effects and gives very precise simulation results. 2D profiles of the open and closed pixel used in simulations are illustrated in Supplementary Figure 2. Metal is shown in blue and air in red. Light shines from the left to the right. The device configuration is similar to that in Figure 1 of the paper.

![Supplementary Figure 2](image)

**Supplementary Figure 2.** 2D pictures of the open and close pixels. The primary mirror diameter is 100 \( \mu \)m, the secondary mirror diameter – 50 \( \mu \)m, opening in the primary mirror – 20 \( \mu \)m, distance from the primary to the secondary mirror – 80 \( \mu \)m, deflection of the center of the primary mirror in on-state – 3.9 \( \mu \)m.
Supplementary Figure 3. Simulation of the pixel in the on-state. Top left – design of the pixel (a part of the pixel was used in the simulation due to its horizontal symmetry). Top right – power distribution in the pixel. Light shines from the left, reaches the parabolic mirror, is focused on the secondary mirror and propagates in the hole in the primary mirror. Bottom – intensity profile at the output of the primary mirror.

When light propagates in the pixel, first, 25% is blocked by the secondary mirror, and the rest of it reaches the primary mirror. Simulations showed that 95% of the light reaching primary mirror goes to the pixel output. This gives single pixel transmission efficiency $0.75 \times 95\% \approx 71\%$, and maximum possible backlight transmission efficiency $\pi/4 \times 0.75 \times 95\% \approx 56\%$.

3. Experimental measurements of the display contrast (ratio of ON to OFF state light transmission)
**Supplementary Figure 4.** Experimental pictures showing light output in on- and off-configurations. The current contrast ratio is 20:1 due to the non-optimized pixel design and non-collimated backlight. However, this is a limitation of the current prototype, but not of the technology, which is supported by the simulations. The data below demonstrate that at least 800:1 is possible.

4. Simulations of the Telescopic pixel contrast.

Propagation of the light through the pixel in off-state taking into consideration diffraction is shown in Figure 5. The integrated power of the pixel output in on and off states was calculated using OptiFDTD software. The ratio of the pixel power in on and off states provides the contrast 800:1. This number can be improved even more by design optimization (smaller focusing spot will allow smaller opening in the primary mirror and less diffraction leakage).

![Supplementary Figure 5. OptiFDTD simulation of the turned off pixel. Top left - simulation domain with metal shown in blue and air shown in red. Top right - power distribution when](image-url)

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collimated light propagates from the left to the right. You can see that almost nothing propagates in the opening in the output membrane. Bottom picture - intensity profile at the output of the primary mirror.

5. Simulation of the cross-talk between pixels.

To simulate the cross-talk, one of the pixels was completely on and a pixel next to it was completely off. The results in Figure 6 demonstrate that neither transmission efficiency, nor contrast is compromised, and the pixel operation is very independent.

**Supplementary Figure 6.** OptiFDTD simulation of the cross-talk. The top left - simulation domain with a closed pixel (at the top) and opened pixel (at the bottom). Top right – power distribution
inside the pixels. Outside of the pixel light propagates only for the opened configuration. The intensity profiles at the output are shown below. The whole picture and right and left part of the picture plotted with different scale for the comparison with previous simulations shown in Figures 2 and 4.