ACTIVE WINDOWS WITH MICRO MIRROR ARRAYS FOR IMPROVED UTILIZATION OF DAYLIGHT IN BUILDINGS

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1. Introduction

Using daylight is a gratuitous and maybe the most beneficial and highly valuable way of indoor lighting: it provides the highest spectral quality and high comfort at the lowest level of energy consumption at the same time, since it derives from pure renewable energy. Nevertheless, direct collecting of solar energy through windows is still inadequately applied and keeps huge idle potentials.

The photomontage (Fig. 1) shows the vision: living and working rooms can be equipped with intelligent systems based on tens of millions of micro mirrors, implemented between the panes of conventional window glazing. Groups of mirrors can be switched from an open to a closed state, so that segments of the window can either guide daylight into the room or keep it outside.

Fig 1: A room equipped with an active window system (photomontage)

The person inside the room has a shaded working place, while the window on the left, where no person is present, guides the light into the room. However, a segment on the right is opened to illuminate the plant.

Any window can be divided into segments of arbitrary size. For this application a typical segment could have a size of some square decimeters. In addition, for special applications also smaller segments can possibly be used to implement a simple black and white display or segments forming the shape of a logo etc. These features can be achieved best with some kind of micro technology – with very small blinding elements, micro mirrors, offering an (nearly) undisturbed view outside. Besides, the height of the elements is low, so the system easily fits between the panes of a normal double-glazed window (Viereck et al., 2007, 2009).

2. Principals of miniaturization

MEMS (Micro Electro Mechanical System) technology is a special kind of micro system technology. In this section we want to motivate the use of this optical MEMS technology for daylighting systems both from a fundamental and from an application point of view:

An obvious reason for the classical implementation of micro system technology is the need for really small solutions, like small grabbers or small pumps. However, it makes sense to miniaturize not only when it is useful or necessary for size reasons, but also when beneficial properties of miniaturized systems can be exploited. These can be their considerably enhanced mechanical stability, increased resonance frequencies, increased lifetime and increased efficiency of actuating forces in direct comparison to those forces causing material fatigue.

Normally a macroscopic movable mirror needs a complex drive mechanism, like an electric motor to be moved. Such a system is subject to material fatigue. Its movement speed is limited to small frequencies. Micro mirrors, however, can be resonantly driven in the kilohertz range with very high mechanical stability, because the inertia force, which is mainly responsible for material fatigue, scales in the order of a power of four when miniaturizing a system. In contrast, the electrostatic force scales much weaker with size. In case of an ideal plate capacitor with fixed voltage the electrostatic force is independent of its size. As a result, electrostatic forces can be used very efficiently for actuating microstructures. For these reasons we decided to use electrostatically actuable micromirror arrays for light steering applications. The diagram in Fig. 2 shows the change of significance and scaling behavior of fundamental forces when going from macroscopic to microscopic domains. Especially inertial forces lose their impact in microscopic dimensions.

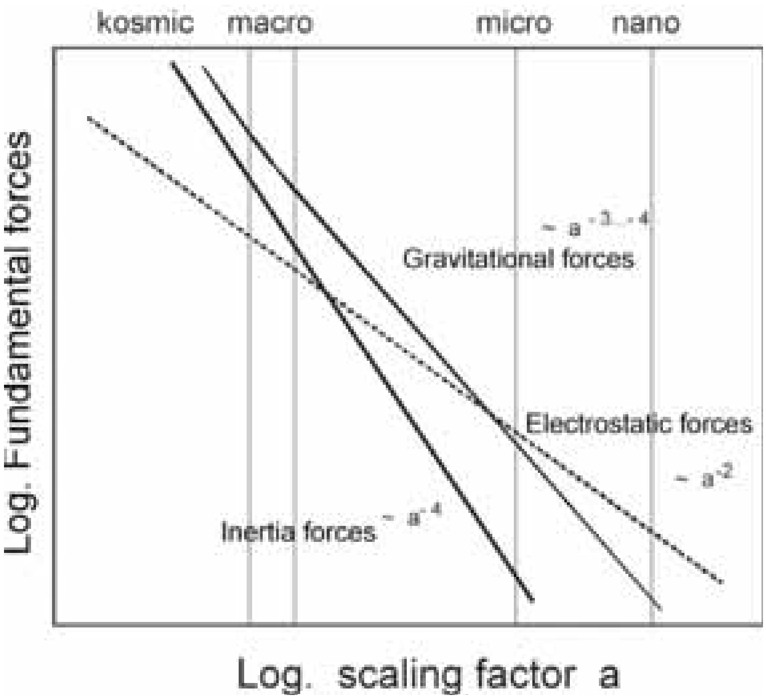

Fig. 2: relative significance of some fundamental forces in the macro- and in the micro-world.

From an application point of view these fundamentals mean that such daylighting systems based on MEMS technology have much smaller material fatigue and an enhanced mechanical stability compared to macroscopic solutions (Hillmer et al., 2003). Due to their size, the mirrors are maintenance free for their whole lifetime. They can be opened and closed within milliseconds, compared to some ten seconds in the case of conventional blinds. The mirrors can be moved by applying a voltage from an opened to a closed state. Their power consumption is extremely low: in an ideal case, the mirrors just need some power when they are actuated and no power in their static position. In reality, there are small leakage currents.

3. Working principle

The technological implementation uses common methods of microsystem technologies. In principle, there are three basic fabrication steps (see Fig. 3): a) thin film deposition of the layer system, b) micro-structuring of the layers, forming the mirror shapes and the grid by means of photolithography, c) a release of the mirrors using a self assembling step, making the mirrors upstanding without any voltage applied. This is possible by a special kind of thin film stress engineering in combination with a so called sacrificial layer technology.

Fig 3: Basic fabrication steps of the micro mirror arrays

All fabrication steps have been chosen very carefully with special respect to i) being low cost and ii) to enable scaling onto large areas. Thus, especially thin single metal layers and dielectrics have been chosen instead of expensive semiconductor materials. Using just a simple grid instead of implementing thin film transistor technologies and separating the control unit from the array enables later upscaling at reasonable cost.

Fig. 4 shows two micro mirror elements on a substrate with their vital components. The basic substrate material is a standard float glass pane. It is covered in total both with a transparent electrode layer and an insulating layer. Each single mirror element consists of an anchor area. With this anchors the mirrors are fixed to the substrate material. The mirrors themselves are flat and free standing. A hinge area between the mirrors and the anchors makes every mirror movable. The position shown in Fig. 4 is the open position without any electric voltage applied. By applying a voltage between the transparent electrode layer and the metal layer, forming the mirrors and the grid, the mirrors can all be moved simultaneously (or optionally in groups of mirrors) to an aligned in-plane position (q.v. Fig. 5, right image).

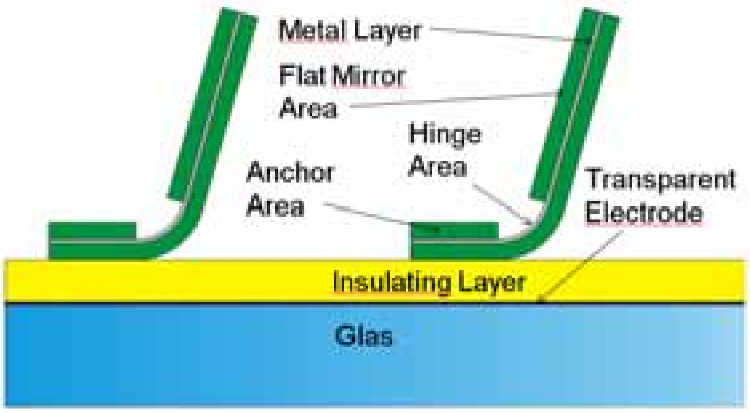

Fig 4: Cross Section of a micro mirror element with its vital components

Theoretical model calculations result in a usable angular range from nearly 90° out of plane up to about 45°. In this range the mirrors can be set to any angle by varying the applied voltage. Below this angle of 45° there is no stable equilibrium state between the electrostatic actuation force and the mirrors restoring force. Fig. 5 shows the visualization of an FEM simulation. The mirror on the left picture is at the critical angle (left). The mirror on the right, actuated with a slightly higher voltage, is lying down on the substrate.

However, it is obvious that for the daylight guiding functionalities the angular range between 90° and 45° is sufficient. For the blinding functionality the 0° position is necessary. The angular range between 0° and 45° is not important from an application point of view.

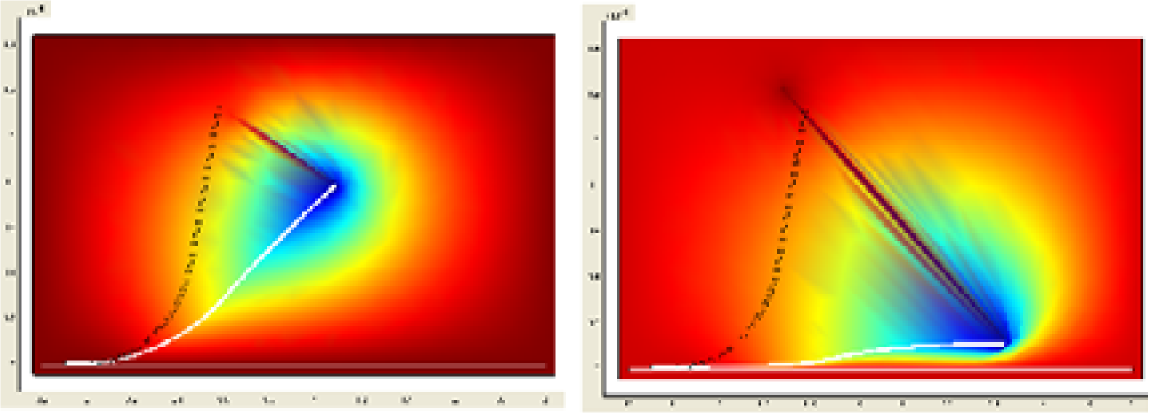

Fig 5: Theoretical model calculations by FEM showing the instable situation at the critical angle

4. Life Cycle Assessment

In a life cycle assessment (LCA) the micro mirror system is compared with an optimized conventional slat blind system. Both sunblind systems are integrated in a frameless window, covering the width of an office room (3,50 m * depth 5,00 m). The slat blind ("Genius"-profile, designed at Fraunhofer ISE, manufactured by Warema, Marktheidenfeld) is placed between a conventional double glazing and an additional uncoated outer pane as a weather shield. The LCA focuses on primary energy input (PEI) and greenhouse warming potential (GWP). Toxicity is considered qualitatively.

Processing and manufacturing

Environmental impacts, associated with processing and manufacturing of the shading systems are assessed with the help of LCA software tools (Frischknecht et al., 2004; Fritsche et al., 2007). Regarding primary energy input as well as greenhouse gases, the micro mirror system shows significant advantages, compared to the slat blind system (see Fig. 6). The main impacts are based on electric power requirements, materials are secondary due to the small quantities used. Solely chemicals like photoresists and acids for immersion bathes are causing noteworthy amounts of primary energy or greenhouse gases. No toxic substances were identified.

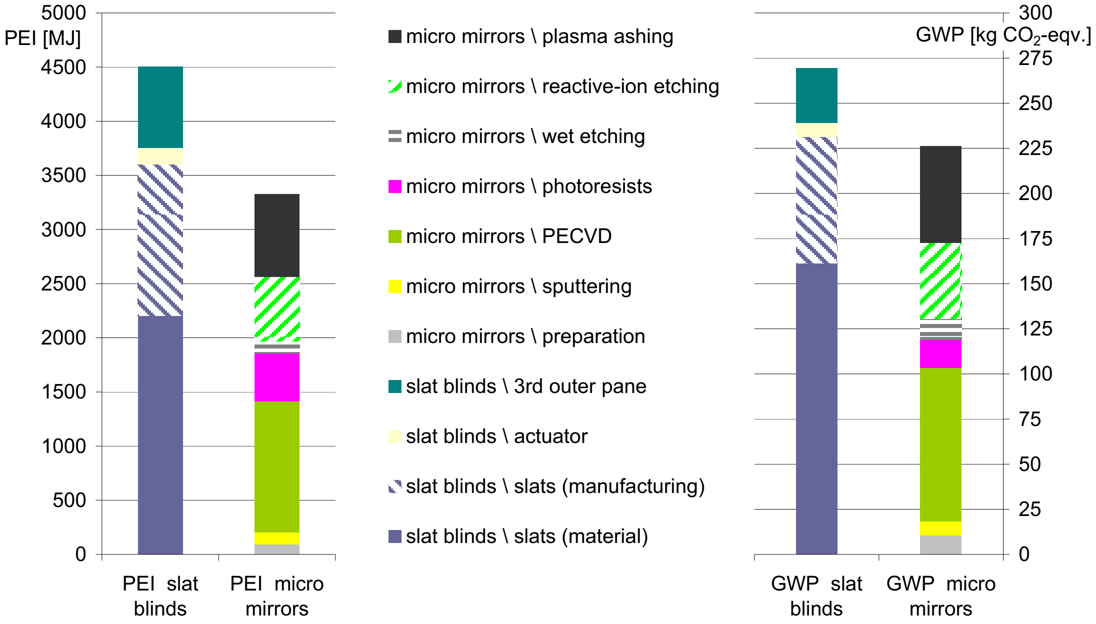

Fig 6: Environmental impacts (PEI, GWP) of processing and manufacturing

Utilization phase

For the utilization phase the two systems are examined considering their main operation purposes:

- Shading / heat protection (and with it the reduction of cooling load)
- Daylight guidance (and with it the reduced need of artificial light).

The period under consideration is the summer time from June, 21 to September, 21 over an assumed life time of 25 years.

Analysis of heat introduction

In a first step the quantity of introduced heat, transmitted through the window as solar radiation energy and due to secondary heat introduction is analysed. This amount is completely assumed as cooling load, thus as demand of electricity for air conditioning.

The HDKR model is taken for modelling solar radiation on tilted areas (Duffie, Beckman, 2006). Hourly data for global horizontal and diffuse radiation in Kassel are extracted with Meteonorm software (Meteonorm, 1997). Fractions of radiation transmittance through the window are determined with Fresnel's and Bouguer's equations (Duffie, Beckman, 2006), the secondary heat introduction q_i with a safe estimation of the Stefan-Boltzmann equation (Schmid, 1995).

Systems configurations are chosen as follows: in the lower third of the micro mirror system the mirrors are opened at 80° out of plane, the rest is closed (0°) for heat protection. The slats of the (electromotive adjustable) macrosystem are tilted 30° to the horizontal.

The whole solar irradiation on the outer window surface over the summer period is 1,417 kWh. The heat introduced through the window with the Genius slat blinds is reduced to 167 kWh – about half of that of the micro mirror system with 300 kWh. One reason is the third pane as a weather shield, reducing not only the heat but also the illumination level.

Analysis of illumination

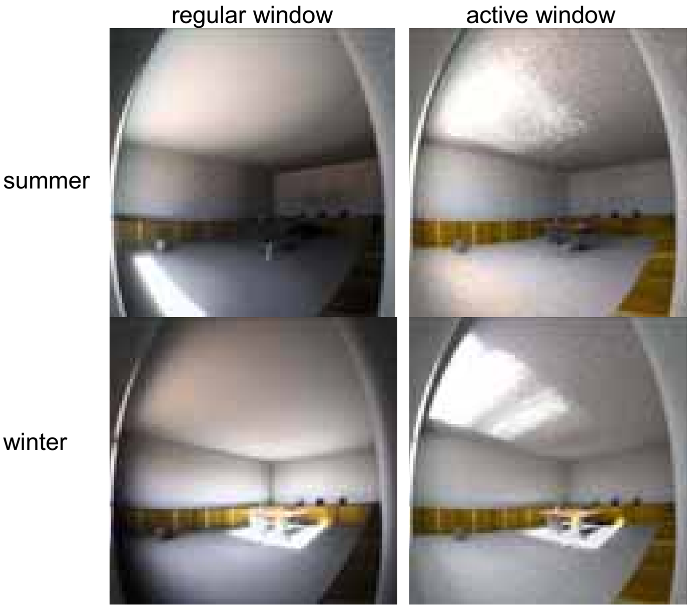

Fig. 7 Simulation of rooms equipped with regular windows, compared to rooms equipped with active windows (S. V. Araujo)

Illumination is simulated with Radiance (Lawrence Berkeley National Laboratory, 2008). For the calculation of incoming daylight, gensky is taken, which produces a Radiance scene description for the CIE Standard Sky distribution. In these simulations the micro mirrors are assumed as continuous segments over the entire width of the window, the flexible part is implemented as an ideal joint. Apart from that, dimensions and gaps conform to the real mirrors. In Fig.7, the daylight distribution with both systems in summer and winter is visualized.

The following figure exemplarily shows the illumination level from the incoming daylight for both systems on September, 21 at three room areas. When the incoming daylight falls short of a luminance of 500 lux, the corresponding room area is complementary illuminated with dimmable artificial light.

With the chosen configurations the advantages of daylight illumination with the micro mirror system are quite evident: only 132 kWh electricity is required for additional lighting over the entire summer period, compared to 255 kWh with the Genius slat blind system. Additional savings could be realised with an adapted control for the setting angle of the micro mirrors, since for long periods the simulated illumination of the back area is much higher than the set-point value. This would mean lower heat introduction.

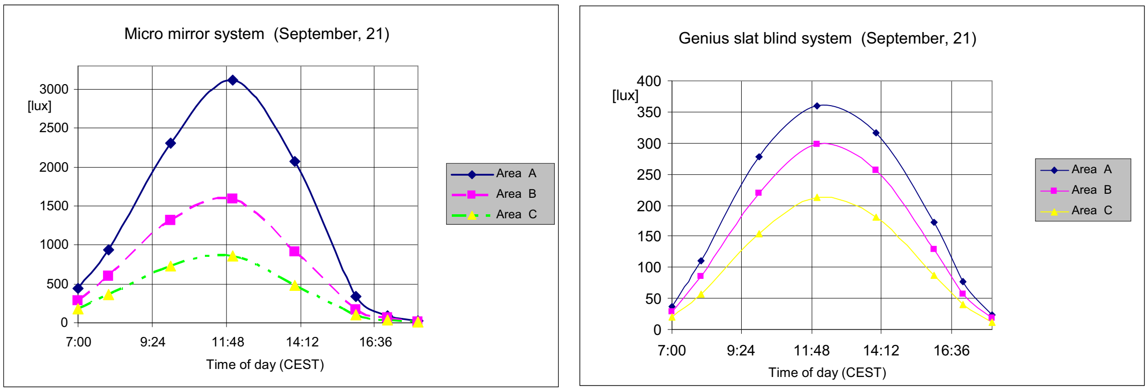

Fig. 8: Illuminance with micro mirror- and slat blind system at three room areas on September, 21

End of life, recycling

Recycling the thin-layer materials does not seem reasonable from today's view due to the small quantities used, but for the future, active windows could be de-coated in special facilities, similarly projected for thin-film PV modules. For the slat blind system, metals are considered as scrap metal fraction in the processing phase. For both systems, credits for the recycled window panes and plastics are allocated with the energy required during the recycling process.

Results in impact categories

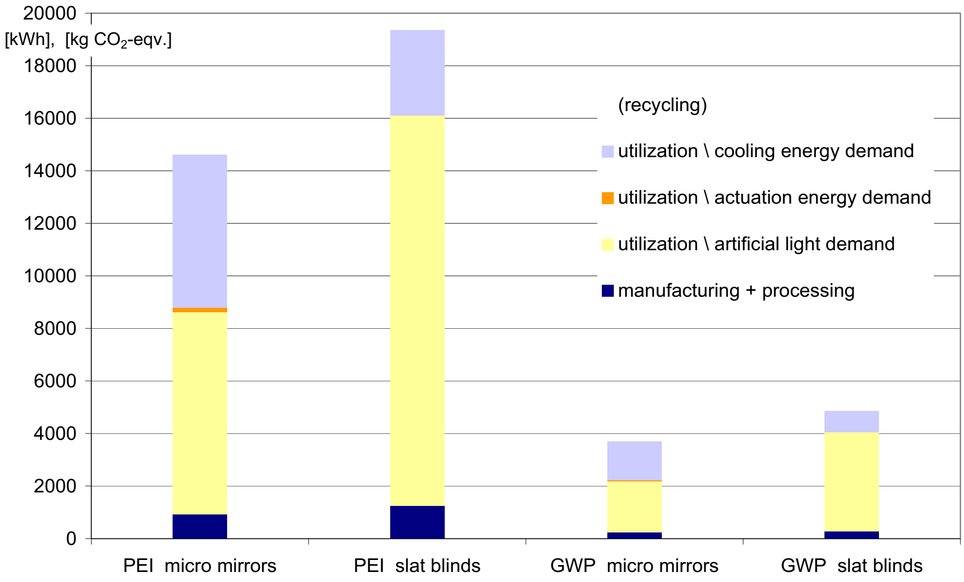

Fig. 9: Environmental impacts (PEI, GWP) of both shading systems over processing and manufacturing and a useful life of 25 years (summer periods)

In total, the micro mirror system requires approx. 4,700 kWh less primary energy, compared to the slat blind system. Indeed, the cooling energy demand in this constellation is 80 percent higher, but this is more than compensated by the lower energy demand for the lighting. Besides, nearly 1,200 kg CO_2-equivalent emissions are avoided (see Fig. 9).

5. Laboratory scale demonstration

Currently the active windows exist as a laboratory demonstrator with a size of 10 cm x 10 cm. However, that means about 100,000 micro mirrors upon this area. In the following section such arrays are illustrated. Fig. 10 shows a module with the opened micro mirrors, offering a view through the array on an illuminated logo in some distance behind the module. It can be seen that the vision through the module is nearly undisturbed, even though more than a third of the module is not transparent in the open state (q.v. Fig. 11). In the closed state the module becomes totally reflecting (q.v. right image of Fig 13). Fig.11 is a microscope image of opened mirrors from a top view. The bright stripes are the mirror anchors, the dark stripes are the opened mirror plates, which can be seen almost directly from above. The grey area in between is the transparent area, the glass itself. Fig. 12 is a SEM micrograph of opened mirrors, providing a side view on the mirrors edges.

Fig. 10: Micro mirror array – module with a size of 10cm x 10cm

Fig. 11: microscope image of opened mirrors from a top view

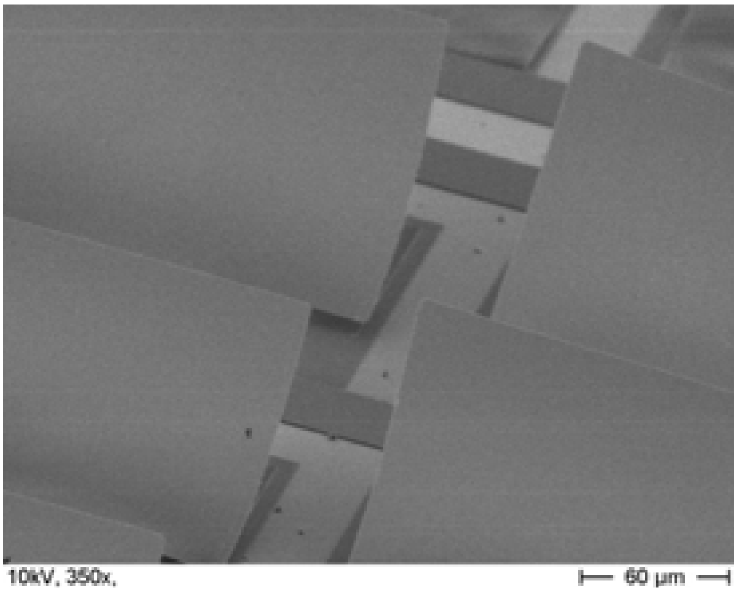

Fig. 12: SEM micrograph of opened mirrors

5. Actuation

The mirrors change their state from transparent to reflective when an electric voltage is applied. Typical values for the voltage are 80 V, best values are below 40 V, depending on the mirror's design. In Fig. 13 (left) a module in its transparent state is shown, with a logo placed directly behind the module. For the module is illuminated with very bright light from the front, the optical impression is worse than in Fig. 10 and some artefacts can be seen.

The right image of Fig. 13 shows the module with a voltage of 80 V applied. It can be seen that the module's borders do not work properly. This is caused by the laboratory fabrication technology and no basic technological problem. However, the reflection of the center area can be seen by a part of the photographer's hand being reflected in the right part of the module. The mirrors are covering more than 95 % of the substrate area, so a high reflectance and low transmission in the closed state provide not only daylighting but also suitable glare protection.

Fig. 13: Electrostatic actuation of the micro mirrors: a module with micro mirrors in their open state, without any voltage applied (left) and in their closed state with a voltage of 80 V applied (right)

6. Conclusion

Micro mirror arrays for future daylighting applications have been developed on laboratory scales, based on MEMS technologies with a size of 10 cm x 10 cm. The developed fabrication process is designed to be scalable upon large areas, even though the upscaling is still the most challenging task to be done.

The modules consist of about 100,000 individual micro mirrors, which can be moved in groups from an open out-of-plane position to a reflective in-plane position by applying a voltage of some tens of volts. Fabrication and actuation have been successfully demonstrated.

A life cycle assessment, comparing “active windows”, based on such micro mirror arrays, with a conventional slat blind system, showed significant advantages due to lower environmental impacts during processing and manufacturing and a higher energy saving potential in their utilization phase..

7. References

Duffie, J., Beckman, W., 2006. Solar Engineering of Thermal Processes; John Wiley & Sons, 3rd ed., pp. 204-213

Frischknecht R, Jungbluth N, et al., 2004. ecoinvent Data v1.1, Schweizer Zentrum für Ökoinventare, CH-Dübendorf

Fritsche et al., 2007. *Gemis 4.42*, Öko-Institut Darmstadt

Hillmer, H., Daleiden, J., Irmer, S., Römer, F., Prott, C., Tarraf, A., Strassner, M., Ataro, E., Scholz, T, 2003. Potential of micromachined photonics: miniaturization, scaling and applications in continuously tunable vertical air-cavity filters, (invited) SPIE Proc. Series Vol. 4947, 196-211 (2003)

Lawrence Berkeley National Laboratory, 2008. Radiance. Version 3.9

Meteonorm, 1997. Version 3.0, Meteotest

Schmid, J., 1995. Transparente Wärmedämmung in der Architektur, C.F. Müller Verlag, Heidelberg, pp. 56ff

Viereck, V., Li, Q., Ackermann, J., Schwank, A., Araújo, S., Jäkel, A., Werner, S., Dharmrasu, N., Schmid, J., Hillmer, H, 2007. Novel Large Area Applications Using Optical MEMS, IEEE/LEOS International Conference on Optical MEMS and Nanophotonics, pp. 55-56.

Viereck, V., Schwank, A., Neumann, U., 2009. Verbesserte Tageslichtnutzung in Gebäuden durch großflächige Anordnungen von mikro- und nanoskaligen Spiegeln in Fensterflächen (aktive Fenster). DBU Abschlussbericht, AZ 23717, Kassel.