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Micro-Positioning Stages for Adaptive Optics Based on Piezoelectric Thick Film Actuators

S. Gebhardt*, D. Ernst, B. Bramlage, O. Pabst, A. Oberdörster

Fraunhofer Institute for Ceramic Technologies and
Systems (IKTS), Winterbergstr. 28, D-01277 Dresden, Germany

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Abstract

Piezoceramic actuators based on thick film technology offer the opportunity of integrated solutions for smart microsystems. Especially in adaptive micro-optics, where the height of devices is limited, outgassing has to be inhibited and complex actuator structures are required, screen-printed actuators are of great interest. The paper highlights our recent research on micro-positioning stages for integration into a plenoptic camera. The first concept is based on through-thickness polarized lead zirconate titanate (PZT) thick films printed on a 45 mm x 44 mm x 0.17 mm LTCC (Low-Temperature Cofired Ceramics) frame with 4-mm-wide legs. Driving with an electrical field of 2 kV/mm resulted in an upright stroke of 115 µm. The second concept combines through-thickness and in-plane polarized thick films on four cantilever beams of an Al_2O_3-based micro-positioning stage. Because of the combination of d_{31}- and d_{33}-mode of excitation, each cantilever beam will provide an s-shaped bending profile allowing for a planar and tilt-free lift of 130 µm at an electrical field of 1.66 kV/mm. Both actuator concepts were utilized to adjust position of a micro-lens array between main lens and image sensor in a plenoptic camera setup. With that, the working range of the plenoptic camera could be extended.

Keywords: PZT, thick film, screen printing, actuator, adaptive optics

I. Introduction

Piezoelectric actuators are well suited for integration into optical systems, because of their high-precision positioning capability (µm-nm) and their short response time (ms-µs). Particularly in cases in which miniaturization, complex actuator structures or a high degree of integration are required, conventional piezoelectric devices have limitations. A technology is required that performs well in a minimal space and, with minimum efforts, allows for integration with surrounding electronic components and other functional elements.

Piezoceramic thick films with typical thickness of 10 – 200 µm offer the opportunity of integrated solutions for smart microsystems. Using screen-printing technology net-shaped structures can be easily fabricated on standard electronic substrates like LTCC (Low-Temperature Cofired Ceramics), Al_2O_3, ZrO_2 and silicon. The typical actuator setup consists of individual layers of piezoelectric, conductive, and insulating thick films. The pure inorganic assembly promises a wide temperature range of operation as well as chemical robustness. This is especially of great interest when high power exposure or outgassing under vacuum play a role. As a result, compact devices, which allow for a combination of piezoelectric function and electronics packaging, can be manufactured. They fulfil market requirements for miniaturization, robustness and increased functionality.

In the present paper, we investigate the development of micro-positioning stages for adaptive optics. Two concepts of low-profile actuator systems to lift a micro-lens array within a plenoptic camera are discussed in detail. The principle of the plenoptic camera has been introduced elsewhere [1–4]. In general, a micro-lens array is placed into the focal plane of a main lens allowing the capture of the 4D light information of a scene. The principle of the plenoptic camera offers the possibility to refocus through a scene after capture of an image and to generate depth maps. However, the camera's depth of field limits the refocusing range. In order to increase the depth of field, it is advantageous to adjust the position of the micro-lens array between the intermediate image plane and image sensor, as can be seen from Fig. 1. Therefore, low-profile actuators, which provide an overall stroke of 100 µm in a stepped motion of several micrometres within a few milliseconds, are required.

II. Design and Preparation

In setups where the height of the device is limited, yet high strokes in the range of 100 µm are required, beam-bending actuators offer a low-profile alternative to a levered transmission.

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* Corresponding author: sylvia.gebhardt@ikts.fraunhofer.de

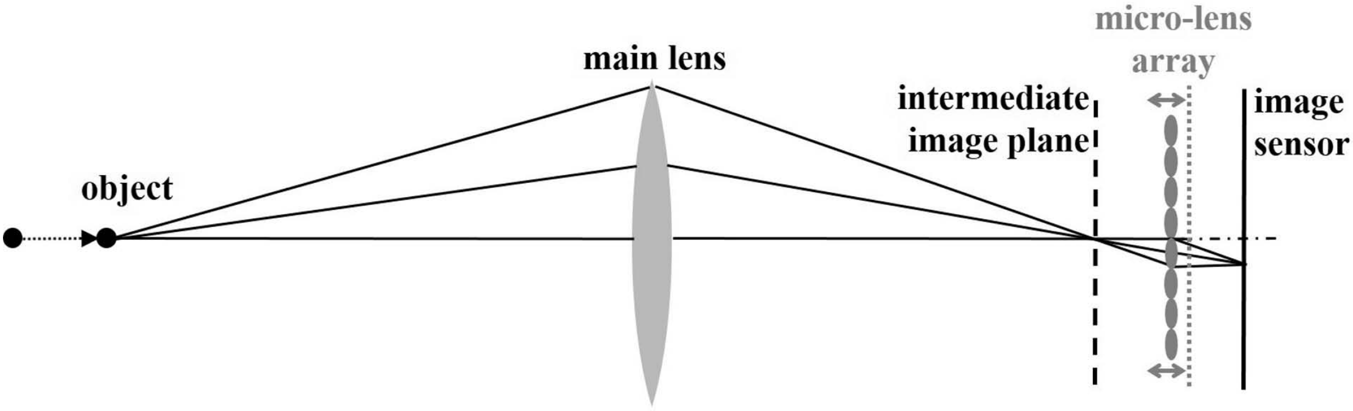

Fig. 1: Schematic representation of a plenoptic camera with adaptive micro-lens array (principle).

The typical layer setup of a beam-bending actuator consists of planar top and bottom electrodes with an intermediate piezoceramic thick film screen-printed onto a microelectronic substrate. The thick film will be poled and driven across its thickness. The so-called through-thickness polarized thick films use the d_{31}-effect, which leads into a contraction of the piezoceramic film along its lateral dimensions and to an upwards bending of the cantilever beam. Assuming a piezoceramic thickness of up to 150 µm driving voltages up to 300 V are necessary if an electrical field of 2 kV/mm is applied.

To increase working capacity of thick-film-based cantilevers, we recently introduced in-plane polarized piezoceramic thick films, which employ the higher d_{33}-effect [5]. Therefore, interdigitated electrodes (IDE) are printed on bottom and top of the piezoceramic thick film to polarize and drive the film along its lateral dimension. Depending on electrode distance, higher driving voltages in the order of 600 – 1000 V are needed to provide an electrical field of 2 kV/mm. The piezoceramic film will elongate along its length leading into a downwards bending of the cantilever beam.

We applied both principles to manufacture micro-positioning stages for integration into a plenoptic camera. The first concept is based on a LTCC frame with an overall size of 45 mm x 44 mm x 0.17 mm. Piezoceramic thick film actuators measuring 25 mm in length, 3.2 mm in width and 100 µm in thickness have been printed on two wings of the LTCC frame. Electrical connections to the actuator structure have been integrated into the LTCC multilayer. Therefore, two LTCC green sheets (GT 951, DuPont) with 165 µm and 51 µm green thickness were laminated on top of each other. Inner Au-electrodes were screen-printed between the multilayer setup on top of the 165-µm green sheet. Electrode-filled vias provided contact to the overlaying actuator structure. The LTCC multilayer was sintered in advance of applying actuator structures. For these, lead zirconate titanate (PZT) paste IKTS-PZ 5100, which has been developed for actuator applications, was chosen [6]. Four actuator frames could be manufactured out of one 100 mm x 100 mm LTCC substrate. The frames were cut out of the substrate by means of laser machining leaving two central lugs on two opposing wings for mounting the micro-lens array as shown in Fig. 2. The free length of the active wings was 37 mm and the width 4.0 mm.

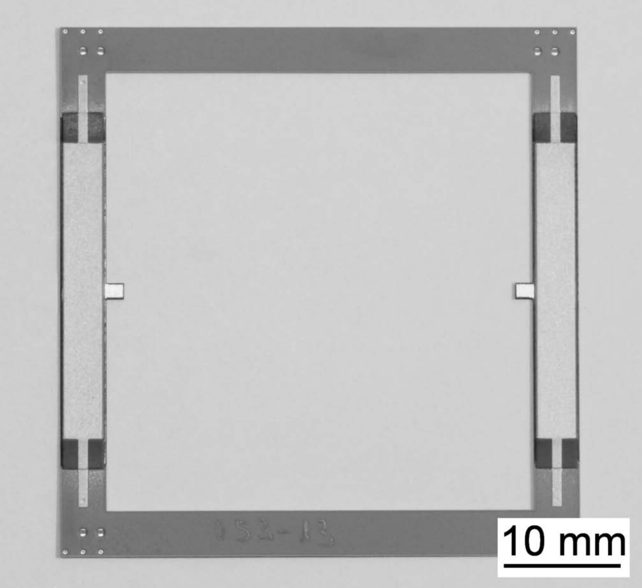

Fig. 2: LTCC-based actuator frame.

For integration into the plenoptic camera, the actuator frame was mounted face-down onto a printed circuit board (PCB) to enable a stroke in z-direction. Electrically conductive epoxy adhesive applied at the frame corners provided mechanical fixation and electrical connection to the printed circuit board (PCB). A micro-lens array measuring 5.7 mm x 4.3 mm in size attached to a glass beam was glued onto the two lugs as shown in Fig. 3.

In structures with multiple bending actuators in different orientations, actuators will work against each other, limiting stroke and warping the object. A second concept allows for a planar lift of an optical platform based on four s-bending cantilevers. Therefore, piezoceramic thick film actuators combining d_{33}- and d_{31}-mode of excitation were printed on four legs of an Al_2O_3 platform. For the latter, a pure Al_2O_3 substrate (99.6 %, Rubalit 710, CeramTec) with a thickness of 250 µm has been chosen. The PZT layer of each actuator structure had a length of 43 mm, a width of 3.8 mm and a thickness of 115 µm. Again, IKTS-PZ 5100 paste was used for PZT thick film preparation.

Each actuator structure comprised two areas: a through-thickness polarized PZT thick film segment with 21 mm active length and an in-plane polarized PZT thick film segment with 21 mm active length separated by a 1 mm inactive zone. For the in-plane polarized PZT thick film segment IDEs with 150 µm electrode width and 600 µm electrode distance have been applied.

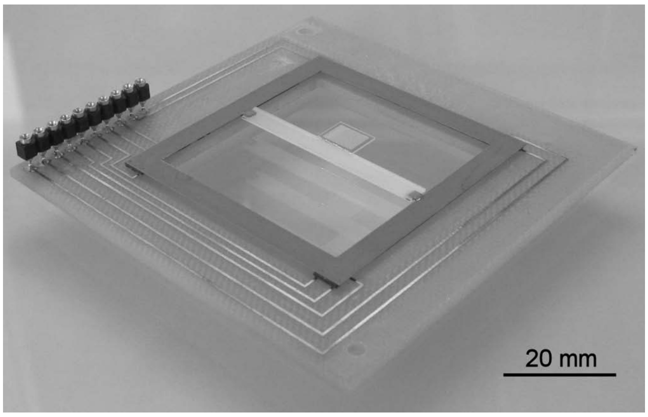

Fig. 3: LTCC-based actuator frame with centrally held micro-lens array measuring 5.7 mm x 4.3 mm in size mounted onto a printed circuit board.

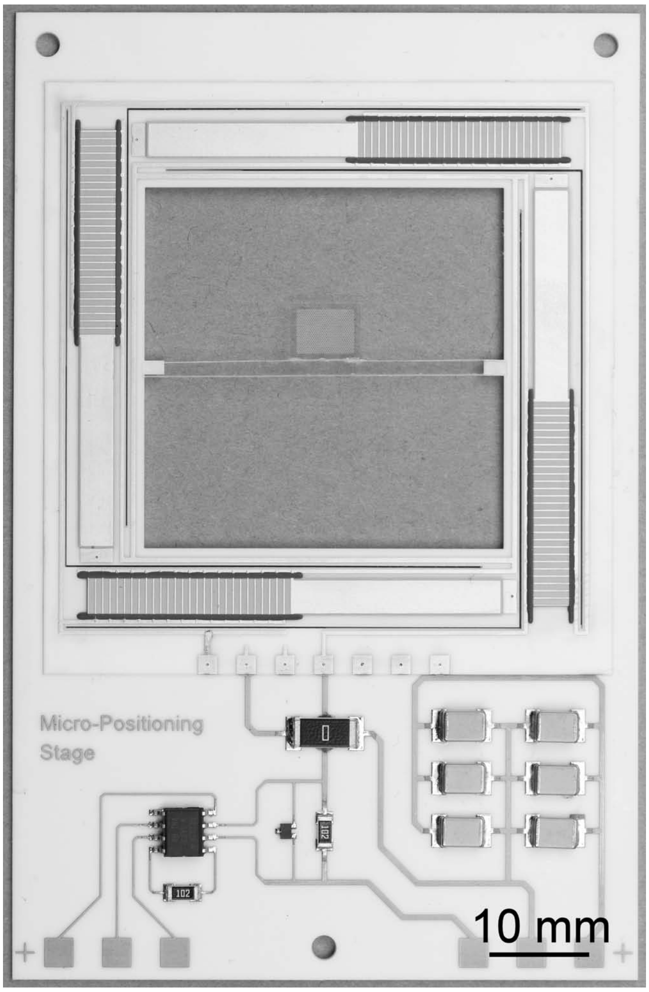

Fig. 4: Al_2O_3-based micro-positioning stage with four actuator structures combining through-thickness and in-plane polarized segments and with integrated SMD components for voltage division and monitoring. At two central lugs, a micro-lens array of 5.7 mm x 4.3 mm in size has been attached.

Four beams measuring 47 mm in length and 6 mm in width were cut out of the alumina substrate, providing 4 mm wide hinges to a central platform. The platform measured 41 mm x 41 mm. For assembly with the micro-lens array, a small frame of 2 mm width was cut out of the platform by means of laser machining, leaving two lugs for mounting as shown in Fig. 4.

The combination of through-thickness and in-plane polarized piezoceramic thick films requires excitation with two driving voltages to receive s-bending motion of the cantilever beam. In our case, the surface near both ends of each beam remains parallel, when an equal electrical field is applied to both segments. This means that for an electrical field of 1.66 kV/mm supply voltages of 1000 V (in-plane) and 190 V (through-thickness) would be necessary. This can be achieved by driving with two separate electrical sources, which would be inadequate in manufacturing compact devices.

However, since the design allows for a fixed ratio of 5 : 1 between the two supply voltages, surface-mounted devices (SMD) can be integrated providing a voltage divider. Using hybrid technology, capacitors, bridge and measuring resistors were integrated as SMDs onto the Al_2O_3 substrate to allow for voltage division and monitoring purposes. Thus, only the supply voltage for the IDE electrodes is applied to the system and the required portion provided for the through-thickness polarized segments.

Fig. 4 illustrates the final Al_2O_3-based micro-positioning stage with integrated SMD components and mounted micro-lens array.

III. Characterization

All PZT thick films were poled at room temperature with an electrical field of 2 kV/mm applied for 2 min. Capacity and dielectric loss were measured 24 h after polarization (1 V, 1 kHz) using an impedance analyzer (HP 4191A, Hewlett Packard). Relative permittivity after polarisation $\varepsilon_{33}{}^T/\varepsilon_0$ results from:

$$\frac{\varepsilon_{33}^T}{\varepsilon_0} = \frac{C\, t_{pZT}}{\varepsilon_0 A}$$

where A denotes the active area, C the capacity and t_{PZT} the PZT thickness.

Displacement of the Al_2O_3-based micro-positioning stage was measured using laser triangulation sensors (ILD 1700 – 2 and 2300 – 2, Micro-Epsilon). To obtain surface scans another laser triangulation unit (ILD 2000 – 5, Micro-Epsilon) was mounted on a motorized XY-stage and the position measured over the whole sample before and during excitation. They were recorded using custom-built software. The stroke of the actuator stage resulted from differential values.

Blocking force measurement was conducted by loading incremental weights to the active wings of the LTCC-based actuator frame until deflection was blocked to zero. The electrical field was kept to 2 kV/mm.

IV. Results and Discussion

PZT thick films possessed a dielectric constant $\varepsilon_{33}{}^T/\varepsilon_0 = 2170$ and a dielectric loss factor tan $\delta = 0.05$ after poling.

Driving both actuators of the LTCC-based actuator frame generated a bridge-shaped deformation as plotted in Fig. 5. A stroke of 115 µm at the micro-lens array mounted on two lugs in the middle of the LTCC frame was measured by applying an electrical field of 2 kV/mm (200 V). The difference in deflection was less than 1.5 µm measured at the micro-lens array along its diagonal. This value is within the allowed range for application in a plenoptic camera. A blocking force of 110 mN under an electrical field of 2 kV/mm was determined. Total stroke, accuracy under load and response time fulfil the positioning requirements within a plenoptic camera.

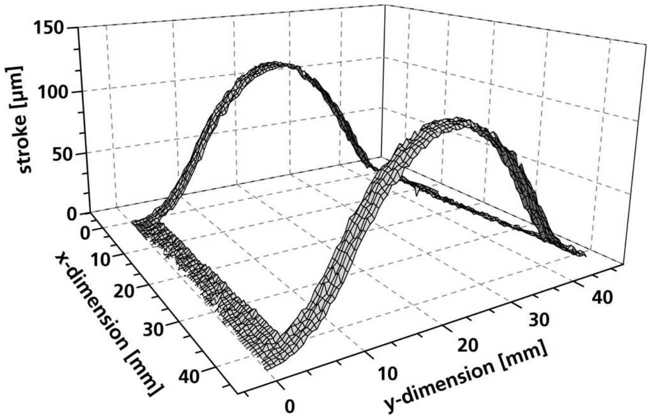

Fig. 5: 2D-scan of stroke of LTCC-based actuator frame driven with an electrical field of 2 kV/mm.

Excitation of the actuator frame not only yields into a movement in z-direction but also into a contraction in y-direction. Mounting of the developed LTCC-based actuator frame by conductive epoxy adhesive provided for a relatively flexible clamping and thus high attainable deflections. In systems with rigid clamping, deflection will be significantly reduced.

The Al_2O_3-based micro-positioning stage with four cantilever beams combining through-thickness and in-plane polarized areas overcomes the contraction problem. Because of the combination of d_{31}- and d_{33}-mode of excitation in one monolithic setup, each cantilever will exhibit upwards and downwards bending along its length leading into an s-shaped bending profile. The platform fixed to the actuator beams by 4-mm-wide hinges will only lift in z-direction without clamping in x- and y-direction.

Fig. 6 shows the 2D-scan of deflection of the Al_2O_3-based micro-positioning stage by operating with an electrical field of 1.66 kV/mm (1000 V). A total stroke of 130 µm could be demonstrated. Rotation of the platform was measured with 0.14 µrad, which is very low in respect of application needs. The elevated platform shows a planar lift with minimal deviations of ± 2 µm over the range of 40 mm. Line scans of the cantilever beams demonstrated that the slope of the s-bend at its end is zero.

Configuration of d_{31}- and d_{33}-mode segments of the actuator structures had been designed to allow for an equal electrical field with a fixed voltage ratio of 5 : 1. With that, only minimal torque has been introduced into the platform. If the d_{31}-elements are driven with a lower, insufficient electrical field compared to the d_{33}-elements, tilted contour lines indicating torque were measured.

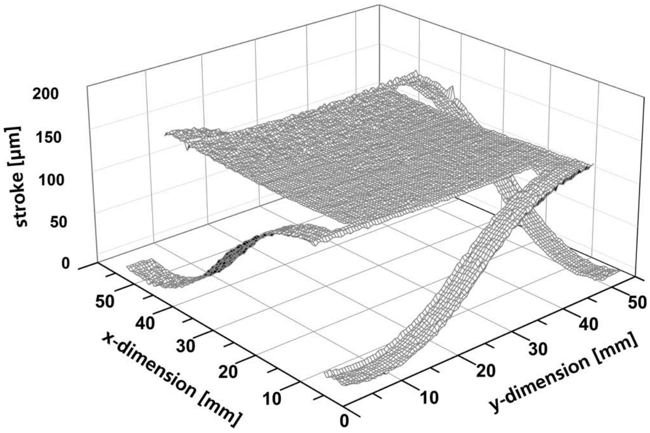

Fig. 6: 2D-scan of stroke of Al_2O_3-based micro-positioning stage driven with an electrical field of 1.66 kV/mm.

To extend the working range of a plenoptic camera, several exposures of the same subject with different focus settings have to be taken. Therefore, position of the micro-lens array has to be moved stepwise and held at a certain position for a few milliseconds. Optical demands on the actuation of the micro-positioning stage were specified according to obtain a displacement step size of 20 µm, a rise time of 20 ms and a dwell time of 200 ms.

In a first experiment, the micro-positioning stage was gradually actuated to reach 20-µm displacement steps. Therefore, a certain voltage according to the stroke needed was applied to the actuators and held for 200 ms. Deflection was measured at the two lugs, where the micro-lens array was mounted (point 1 and 2).

The recorded displacement by stepwise excitation of the micro-positioning stage showed a highly resonant behaviour as can be seen from Fig. 7. The desired position was stable only after extensive oscillations longer than 200 ms.

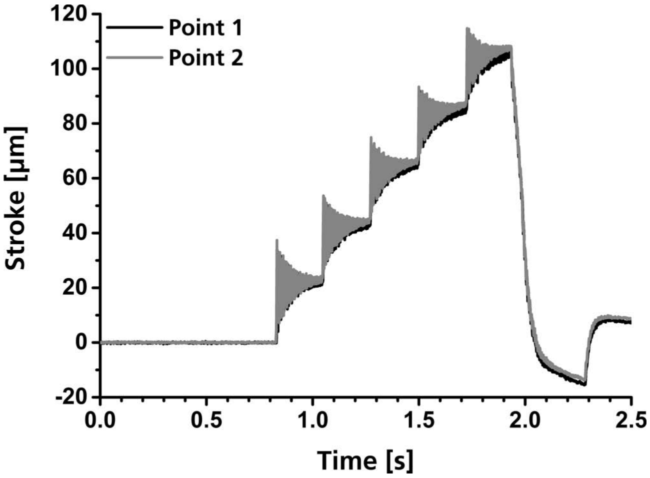

Fig. 7: Deflection of Al_2O_3-based micro-positioning stage measured at two central lugs (point 1 and 2) – stepwise excitation without compensation.

In a second experiment, a low pass filter was applied in order to reduce oscillations. Exponential drift compensation was used to adjust creeping of the signal. An incremental change in the supply voltage in 100 V steps thus modified resulted in displacement steps of 20 µm as depicted in Fig. 8.

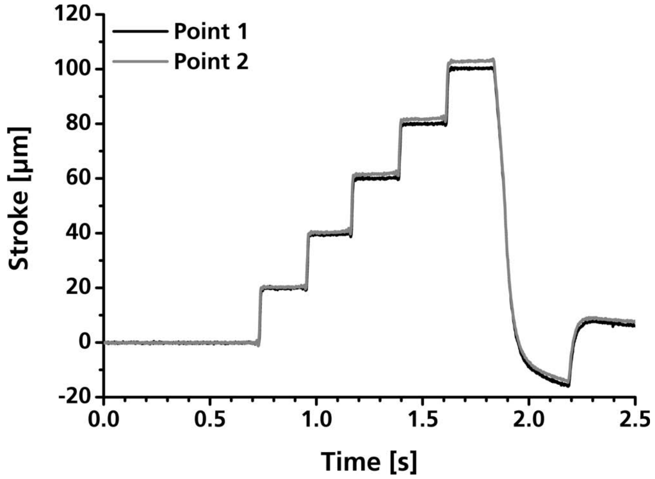

Fig. 8: Deflection of Al_2O_3-based micro-positioning stage measured at two central lugs (point 1 and 2) – stepwise excitation with compensation.

The desired positions were reached within the required time of 20 ms and no shift of deflection was observed during dwell time of 200 ms. The excitation curve is shown in detail in Fig. 9.

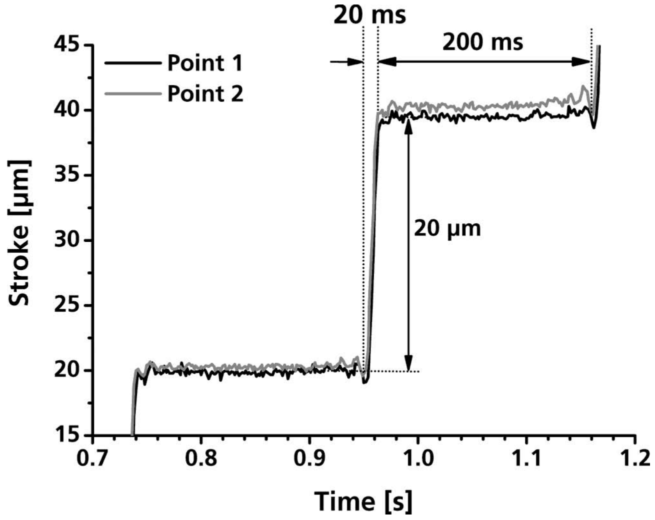

Fig. 9: Detail of deflection of Al_2O_3-based micro-positioning stage measured at two central lugs (point 1 and 2) – stepwise excitation with compensation.

To confirm that the performance of the two positioning stages was sufficient for extending the depth of field of a plenoptic camera, we integrated one specimen of each stage concept into an experimental setup of a plenoptic camera. The test system consisted of a 16-mm C-mount lens, a commercial CMOS sensor, and the micro-lens array mounted onto the micro-positioning stage as can be seen in Fig. 10. In plenoptic cameras, the imaging process takes place twice: first, the C-mount lens creates an aerial image inside the camera, and second the micro-lens array creates multiple images on the sensor. In the latter case, the focal length is very short. Even small shifts of the micro-lens array have a large effect on the focused distance. In the test system, the displacement of the micro-lens array was altered between 0 and 100 µm.

Measurement of the through-focus modulation transfer function (MTF) of the micro-images confirmed that this shift was sufficient to move the MTF to shorter distances. Without movement of the micro-lens array, the smallest object distance possible was about 800 mm. When the position of the micro-lens array was shifted from 0 to 100 µm, object distance could be significantly lowered from 800 mm down to 350 mm. Thus, the working range of the plenoptic camera could be successfully extended.

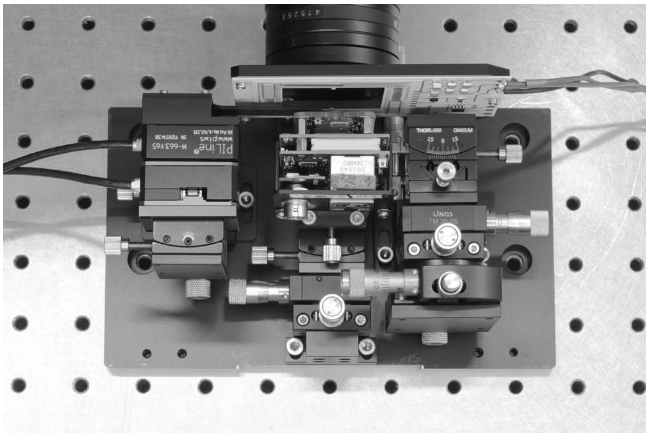

Fig. 10: Experimental set-up of a plenoptic camera consisting of C-mount lens, Al_2O_3-based micro-positioning stage with micro-lens array and CMOS sensor.

V. Conclusions

For adaptive micro-optics, actuator structures are needed which allow for high strokes while maintaining low-profile design. Two concepts of micro-positioning stages based on PZT thick film actuators have been proposed and demonstrated.

The first concept uses 100-µm-thick through-thickness polarized PZT films printed on a 170-µm-thick LTCC frame. Driving actuators with an electrical field of 2 kV/mm resulted in an upright stroke of 115 µm. In a second concept, segments with 115-µm-thick through-thickness and in-plane polarized PZT thick films were applied along four cantilever beams of a 250-µm-thick Al_2O_3-based micro-positioning stage. The combination of d_{31}- and d_{33}-effect in one monolithic setup enabled for an s-shaped bending profile and thus for a planar and tilt-free lift of 130 µm at 1.66 kV/mm.

Both micro-positioning stages have been used to adjust position of a micro-lens array within a plenoptic camera. Step size of displacement, rise time, and dwell time fulfil the optical requirements. The working range of the camera could be significantly improved.

Acknowledgement

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