Actuated MOEMS Micro-Mirror based on PMN-PT Piezoelectric Material

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***Abstract*—This paper investigates the use of a PMN-PT [001] piezoelectric actuator to be integrated in smart Micro-Opto-Electrical-Mechanicals Systems (MOEMS). Unlike most piezoelectric materials, PMN-PT [001] can generate large-stroke out-of-plane displacement. This is due to its very high longitudinal piezoelectric coefficient of up to 4500pm/V. After an introduction on MOEMS actuation and a short description of the Reconfigurable Free Space Micro-Optical Bench (RFS-MoB) in which the studied actuator may be included is presented, a bulk actuator is proposed. FEM simulations are then presented highlighting some tradeoffs: increased displacement with the reduction in size while decreasing the optical aberration. It was observed that for actuators with a smaller surface than 800x800µm^2 and 200µm thick, displacement larger than 325nm is largely achievable and that the size of the usable area of the actuator varies in size with the applied voltage.**

I. INTRODUCTION

In micro-optical applications there is an ever growing demand for better micro-mirror control and better actuator integration. Related applications notably count optical switches [1] [2], variable optical attenuators [3] or biomedical imaging [4] [5]. Among the challenges encountered in MOEMS when aiming for increased functionality is the local displacement. Nowadays commonly used micro-actuators are either electrostatic [6] or thermal [7]. There is, however, a growing use of piezoelectric actuators in MOEMS due to their better understanding, also to the new developments regarding hysteresis reduction and the emergence of new improved materials. Having high bandwidth [8] and sub-nanometer resolution capabilities, piezoelectric actuators show interesting features when actuating micro-mirrors in optical applications. This is key in developing better performing MOEMS applications.

Commonly, piezoelectric actuators used in MOEMS are made of PZT, a piezoceramic material with a granular structure. It does present some drawbacks, one of which is its high hysteresis [9] that has great impact on accuracy. Novel materials aim not only at reducing the hysteresis but also at increasing performance. Lead–Magnesium–Niobate—Lead–Titanate (PMN-PT) is a piezoelectric material with a mono-crystalline structure which presents high dynamic range and piezoelectric coefficients while reduced hysteretic behavior [10].

Among the advantages of using PMN-PT we note its ability of being used in bulk [11] and the ease of fabrication [12]. This paper investigates how bulk PMN-PT actuators behave when integrated in MOEMS. The objective is to further investigate the usability of a bulk piezo-actuator made of PMN-PT in a MOEMS as a micro-mirror actuator. In [13] the connection between the decrease in measured displacement and the increase of the actuator width has been shown. Here, Finite Element simulation studies on how the usable surface varies with the applied voltage is presented. This is followed by a study on how the usable surface varies with the increase of the actuator size. Working domains are then defined.

This paper is structured as follows: a brief introduction in MOEMS, the actuation principles and materials used are presented in Section I. A short description of the Reconfigurable Free Space Micro-Optical Bench (RFS-MoB) in which the studied actuator may be included is presented, along with its particularities in Section II. Section III investigates the design and simulations, while Section IV focuses on the experimental measures regarding the PMN-PT actuator. A conclusion ends the paper highlighting the results and the defined domain of actuation.

II. MOEMS APPLICATION

A. Reconfigurable Micr-Optical Bench

A Reconfigurable Free Space Micro-Optical Bench (RFS-MoB) has been designed [14] using removable and adjustable silicon holders for easy manipulation and alignment by a robotic micro-assembly station.

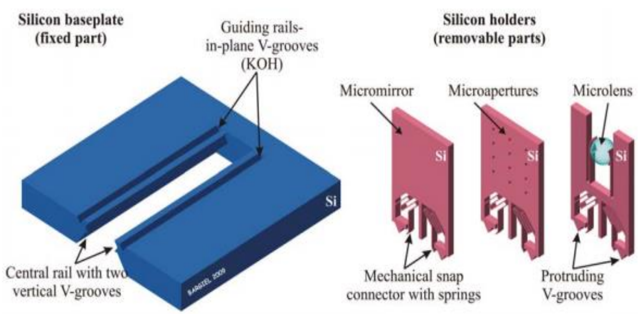

Fig. 1. Main components of the RF-MoB [14]

While already having developed different components (Fig. 1.) such as hybrid micro-lenses, beam splitters, micro-apertures and micro-mirrors, there is a need for actuated micro-mirrors for enhancing the usability of the RFS-MoB, for instance in interferometer applications. This means adapting an actuation solution.

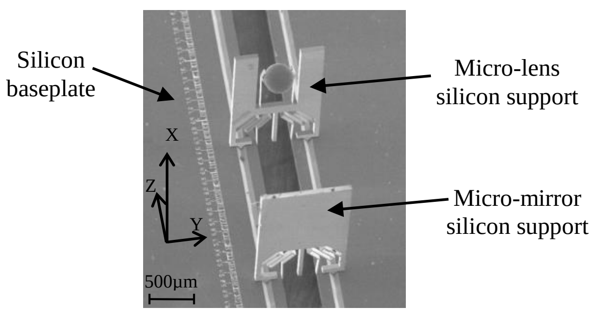

Fig. 2. Assembly proposition [14]

The designed silicon micro-mirror support measures (Fig.2.) 1.2 x 0.8 x 0.1 mm^3 (height x width x thickness) and presents an elastic structure at the base, for position holding in the RFS-MoB structure.

The objective of the actuator is to fit the micro-mirror with an out-of-plane perpendicular displacement and to be integrated on the silicon support for better dynamics and small space occupancy (Fig. 3).

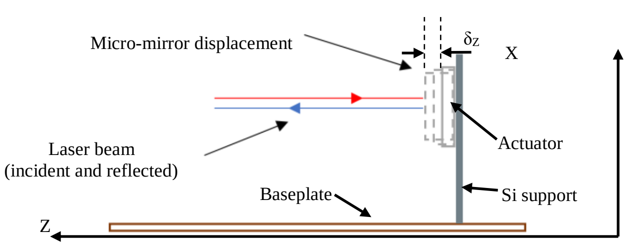

Fig. 3. Actuation in respect to the vertical support

B. *Actuation approach*

The actuator intended to achieve the out-of-plane motions falls under constraints regarding surface and thickness. Due to the design of the silicon support, the maximum usable surface measures 0.8 x 0.8 mm^2 (Figs. 1-2). The thickness of the actuator is also of importance as to not topple the holder due to its inertial mass or during actuation.

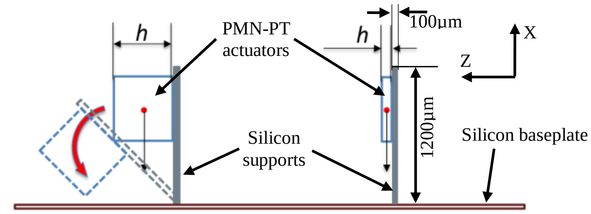

Fig. 4. Toppling of the silicon support as a result of a too thick actuator. The thickness (*h*) has been exagerated.

The displacement needed in optical applications are related to the wavelength (λ) of the light used and as such a minimum is required. In the case of spectral interferometry the required displacement is reduced to meaning that for a traditional red laser beam (λ=~650nm) the minimum displacement is half the wavelength (~325nm). To achieve this while also maintaining the thickness of the material low, materials with high and very high piezoelectric coefficients are needed. PMN-PT cut and polled along the [001] crystalline direction stands out. Recent improvements in crystal growth techniques have shown the possibility of obtaining values of over 4500pm/V [13] for its piezoelectric coefficients. Studies on the actuation potential of PMN-PT [001] have shown that for a 200µm think film actuation can exceed the 325nm limit [15].

III. Finite Elements Simulations

The goal of the Finite Elements (FEM) simulations is to provide guidelines for the expected behavior of PMN-PT micro actuators.

As the micro-actuator is intended for a micro-mirror, one more aspect in regards to the optical necessities to be met is the maximum accepted aberration for planar displacement which is 10% (or a maximum $\lambda/20$ in our case). The parameter values used in the FEM simulations are presented in Table I. The values for d_{31} and d_{33} were found experimentally by measuring multiple 200µm thick PMN-PT [001] actuators.

TABLE I. Values of PMN-PT [001] specific coefficients

Constant	Unit	Value	Source
s^E_{11}	$x\ 10^{-12}\ m^2/N$	*69.0*	[16]
s^E_{12}		*-11.1*	
s^E_{13}		*-55.7*	
s^E_{33}		*119.6*	
s^E_{44}		*14.6*	
s^E_{66}		*15.2*	
d_{15}	$x\ 10^{-12}\ C/N$	*146*	
d_{31}		*-980*	*measured*
d_{33}		*2520*	
$\varepsilon^T_{11} / \varepsilon_0$	•	*1600*	[16]
$\varepsilon^T_{33} / \varepsilon_0$		*8200*	

The actuator is simulated as being fixed on one side to represent the soldered side and free on the opposite side to simulate the mirror. The clamping has been done on the entire fixed surface, without any planar freedom. Due to this fixing, specific free-side behavior is noticed (Fig. 5). A curvature of the top surface arises, which is dependent on the bulk actuator size and also on the applied voltage.

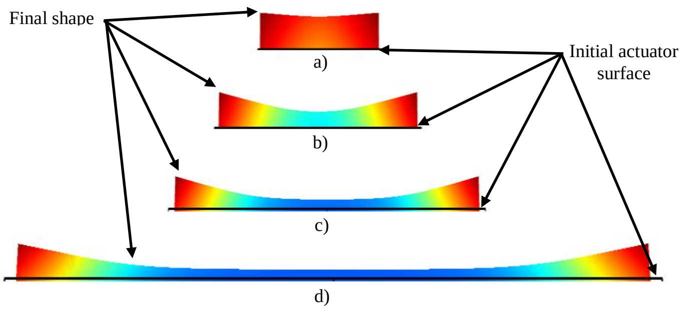

Fig. 5. Diagonal section view of free side behaviour for different actuator widths at an applied voltage of 400V: a)250x250μm²; b)300x300μm²; c)400x400μm²; d)800x800μm². PMN-PT thickness is 200μm.

The signal applied varies between 0V and 400V, a value that approaches the saturation limit of PMN-PT. As actuation is observed no matter the size of the actuator, the focus is on what the maximum diameter of a laser beam can be in order to maintain a maximum 10% aberration while still reaching the 325nm displacement threshold. Figure 6 presents a schematic view of the elements of interest: the displacement δ_Z, the aberration limit $\lambda/20$, the width of the actuator w and the maximum diameter of the usable surface Φ_{max}.

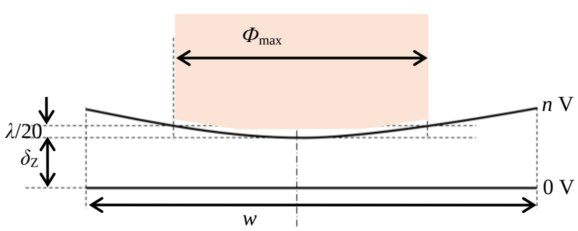

Fig. 6. Actuator free surface shape and variables of interest for an applied voltage of *n* V.

To observe the dependence of the maximum laser beam diameter that can be used without aberrations on a mirror actuated by PMN-PT four sizes were arbitrarily considered in order to 250x250μm², 300x300μm², 400x400μm² and 800x800μm². Figure 7 presents the usable surface limits in relation to the minimum displacement needed.

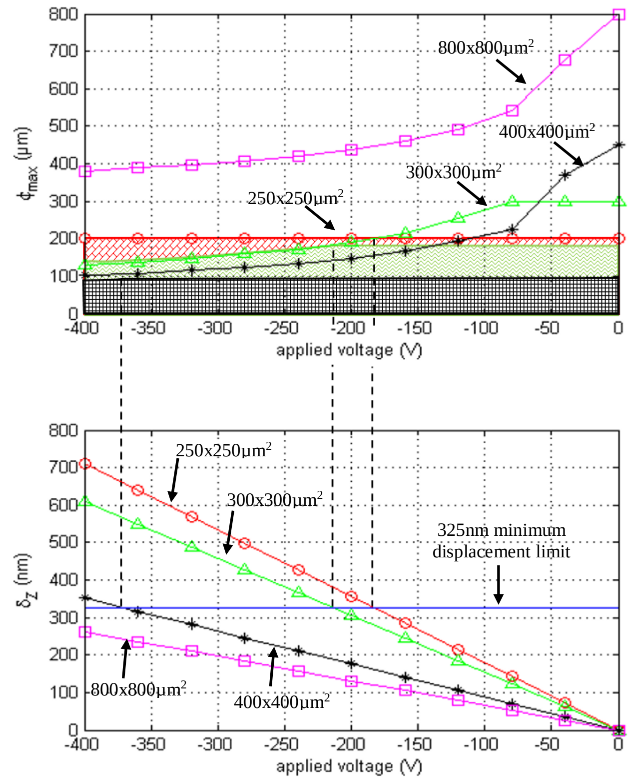

Fig. 7. Displacement curves for the selected size actuators (bottom graph) and the variation of the diameter of an usable laser beam (top graph)

The top graph from Fig. 7 represents the usable diameter corresponding to actuators of different widths, as pointed out. The bottom graph represents the evolution of the displacement at the center of each individual actuator, as predicted by the FEM simulation. The points where each displacement curve intersects the minimum needed displacement of 325nm are then transferred to the top graph as being the minimum applied voltage required for each size actuator to reach 325nm. As there is a need for planar displacement, the usable area is defined as the displacement at the center of the actuator plus the max accepted aberration (32.5nm). The points where the minimum displacement value intersects the actuator displacement curve is correlated with the maximum value of the laser beam diameter. The curves in the top graph from Fig. 7 show the variation of Φ_{max}. This means that phase-shifting interferometry is possible if the diameter value of the used laser beam is situated under and, at most, on the curve drawn for the chosen actuator size, while remaining inside the defined checkered area. It can be observed that for the 250x250μm² actuator the maximum diameter is that of the inscribed circle on the surface (79% of the available surface); for the 300x300μm² actuator the value decreases to ~180μm (29% of the available surface) while for the 400x400μm² only an area with a maximum diameter of ~110μm (6% of the available surface). Although the 800x800μm² actuator shows the largest planar surface, it does not reach the minimum displacement needs.

IV. Experimental Results

A series of experimental measurements have been done on different size PMN-PT actuators in order to quantify the displacement. To ensure the best conductivity, the 200µm thick PMN-PT plate has been cleaned and recoated with a 140nm thick gold layer. It has then been soldered to a gold coated glass support using silver based solder 30µm thick. The PMN-PT samples have been cut using a saw dicing machine. The dimensions that were cut range from 200x200µm^2 to 800x800µm^2, with 100µm increments for both the width and the length simultaneously. To ensure the separation between the actuators, the saw dicing was done 20µm from the glass baseplate. The connections of the actuators have been done using gold wire bonding, with 30µm in diameter wire. Figure 8 presents the fabrication process.

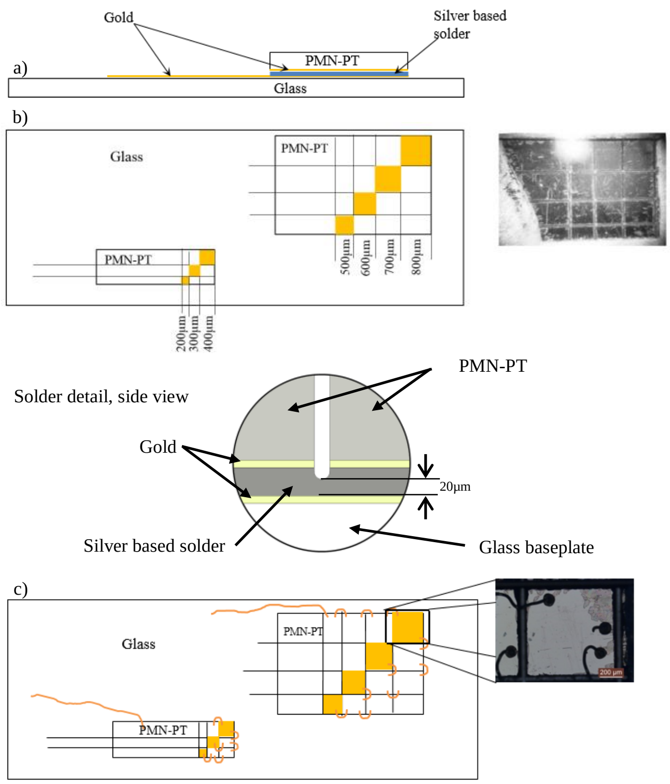

Fig. 8. Key steps in the fabrication process of PMN-PT bulk micro-actuators: a) soldering; b) saw dicing; c) wire bonding

Using an interferometer, individual measurements were done at the center of each PMN-PT actuator. The max measured displacements were then compared with the FEM simulations. Due to the wire-bonding characteristics, measurements on the smaller size actuators (200x200µm^2 to 500x500µm^2) failed directly. The interface between the gold wire and the actuator surface generated too significant noise and spurious reflections resulting in the disregard of the measurements. Fig. 9 presents the predicted maximum displacement curve of different size actuators coupled with the experimental measures of only the 600x600µm^2, 700x700µm^2 and 800x800µm^2. The measured displacement does, however prove consistent as the result for the 600x600µm^2 is very close to previously measured values [13].

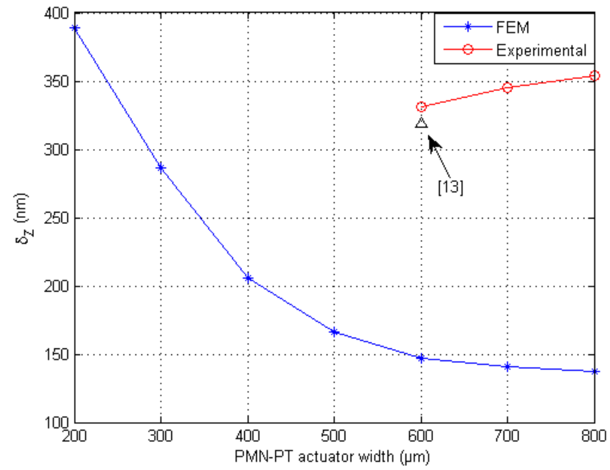

Fig. 9. Comparison between measured displacement and FEM simulation for PMN-PT actuators at 400V

The values for the measured displacement on the graph represent the average of 8 independent measures on the 600x600µm^2, 700x700µm^2 and 800x800µm^2 respectively. The measures were done after repositioning the interferometer spot on the actuator surface. The maximum displacement measured at the center of the PMN-PT actuator is larger than the FEM predictions. This is due to the inherit elasticity of the silver based solder and its thickness. A plausible explanation for the decrease in the measured displacement of the PMN-PT actuator with its width is the faster saturation of the PMN-PT actuator, having a smaller volume.

The results lead to the following conclusions: first, the minimum desired displacement can be achieved with larger size actuators, making fabrication easier and allowing for larger diameter beams to be used and second, the free face surface presents a larger curvature radius, allowing again to add to the maximum diameter of a used laser beam.

V. Conclusion

The paper has presented how a bulk 200µm thick PMN-PT poled in [001] crystalline direction can be used for a MOEMS micro-mirror actuator by capturing its behavior through FEM simulations. A contribution of the paper is the definition of laser beam maximum usable diameter in regards to the size of the actuator, while achieving a minimum 325 nm required actuation. Another contribution is showing the direct influence of the clamping interface over the displacement of large micro-actuators.

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