An Optical Wireless Bistable Micro-actuator

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***Abstract* - An optical wireless bistable micro-actuator is presented in this paper. The bistable mechanism is based on antagonistic pre-shaped double beams, which have the merits of simple pre-load operation and symmetrical output force. The bistable micro-actuator was fabricated with deep reactive ion etching (DRIE) technique using silicon on insulator (SOI) wafer. The bistable beam has a thickness of 25 µm and a depth of 400 µm. The stroke of the bistable micro-actuator is 300 µm. An 8 µm thick compressive SiO_2 layer is deposited on one side of the strip shaped (0.1×1×3 mm) shape memory alloy (SMA) active element, acting as the biasing spring. The SiO_2 layer created a two way memory effect and eliminated the load effect of SMA element. Stroke of SMA element is tested. The wireless actuation was realized by laser heated SMA active element.**

Index Terms - Bistable micro-actuator, shape memory alloy, Micro-fabrication, Wireless actuation.

I. INTRODUCTION

Micro-actuators, as actuators, have the ability to transform a certain amount of energy from other form to mechanical energy. At the same time, they have small size and precise output. However, with the developing of micro-systems, micro-actuators with smaller dimensions are required. The size reduction has increased the complexity of integrating sensors and power supply unit. Thus, bistable micro-actuators have attracted the researchers' attention by their merits, such as, simple mechanism, open-loop controllability and low power consumption, etc. Moreover, the low power consumption characteristic has led to the possibility of being actuated through wireless approach, which could solve the problem of power unit's integration.

Bistable buckled beam is one of the most commonly used bistable mechanisms because of its simple design and relative big output force. According to the methods of buckling the beam, there are three groups of bistable buckled beams: pre-compressed, pre-stressed and pre-shaped beam. Pre-compressed beam is fabricated in straight form and buckled through longitudinal compressing under external force. It has the advantage of symmetrical force output. However, the pre-compress operation is difficult to control. Reference [1] presented a bistable actuator based on pre-compressed bistable beam, which was fabricated by 3D printing using ABS+ plastic material. The straight plastic beam was buckled to the designed shaped under the help of two precise linear stages. In [2], the pre-compressed bistable beam was used in vibration energy harvesting application. In the aim of avoiding pre-compress operation but conserving the advantage of symmetrical output force, Pane et al. developed a pre-stressed beam based bistable mechanism [3]. It is realized on silicon wafer by micro-fabrication technique. Instead of buckling the beam by compression from external force, residual stress was used to curve the straight beam. The residual stress was introduced by the different thermal expansion ratios between silicon and silicon dioxide material. Buckling happened during the fabrication process, but controlling the thickness of oxidized layer is complex. Pre-shaped beam is the approach, which has completely no need of compression neither during nor after fabrication. Beams are fabricated with buckled shape without residual stress. In [4], a pre-shaped beam based bistable mechanism was reported. The beam was fabricated with a designed cosine shape by deep reactive ion etching (DRIE) technique with silicon on insulator (SOI) wafer. According to [4], a single pre-shaped beam could not be bistable, thus, double parallel pre-shaped beams were centrally clamped to constrain the rotation of midpoints and achieving the bistability. However, there is a geometrical limit for parallel pre-shaped bistable double beams. The original rise of midpoint (this value is about the half of the distance between the two stable positions) should be more than 2.31 times of the beam's thickness in order to be bistable. Because of this limit, the stroke of parallel pre-shaped double beams based bistable mechanism is bigger than that of pre-compressed bistable mechanism, which has similar dimensions. Furthermore, the output force is asymmetrical which is not good for applications that require same output behavior in both actuation ways.

For the wireless actuation methods, contactless energy transformation should be employed. Electromagnetic field coupling was a commonly used approach, however, the power source should be close to the power receiver otherwise the energy transformation efficiency will be very low. Radio frequency electromagnetic waves could be a solution for longer distance transformation, but additional circuits are necessary on receiver [5]. In [1], a contactless energy transformation via laser heated shape memory alloy (SMA) active element was demonstrated. The power was emitted by laser diode, guided by reflectors and focused using a lens on SMA element. The shape memory effect was exploited to realize the transformation from thermal energy due to the illumination to mechanical energy, which was used to drive the bistable actuator.

In this paper, a bistable micro-actuator will be presented. Bistable mechanism based on antagonistic pre-shaped double beams will be discussed. Then, a wireless actuation method through laser heated SMA active element will be described. A two way memory effect using deposited SiO_2 layer on SMA will be introduced and tested. At last, the wireless actuation experiment will be presented and some first results will be given.

II. Bistable Micro-actuator Design

A. Bistable Mechanism

In the aim of simplifying the pre-load operation for pre-compressed beam, a bistable mechanism based on antagonistic pre-shaped double beams is developed (Fig. 1(a)). It is composed of two pre-shaped beams, which are antagonistically curved to each other. The midpoints of two beams were linked together to constraint the rotation, in order to make the micro-actuator bistable. A gap is designed between the support parts of two beams. The pre-load operation could be completed by compressing the support parts until the gap disappears. Then, these two parts are fixed together and the antagonistic pre-shaped double beams, as a whole, become bistable and can be switched from one stable position to the other one.

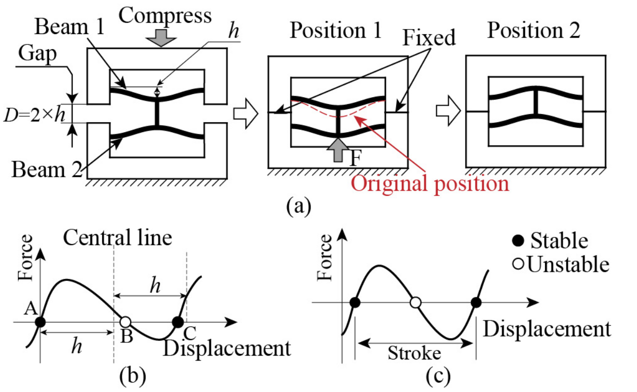

Fig. 1. (a) Bistable mechanism based on antagonistic pre-shaped double beams; (b) Force-displacement chart of parallel pre-shaped double beams; (c) Force-displacement chart of antagonistic pre-shaped double beams.

In the introduction part, it was mentioned that the parallel pre-shaped double beams has asymmetrical output force like it is shown in Fig. 1(b). Because of the fabricated shape, the beam always tends to recover to the original form, thus the output force towards original position is bigger than the force in the opposite direction. In the antagonistic configuration, two pre-shaped beams are against each other. So, despite the asymmetry of a single beam, the output force is symmetrical when two antagonistic beams are considered as a whole (Fig. 1(c)). The detail of this mechanism could be found in an article which will be soon published.

A model of single pre-shaped beam with midpoint's rotation constrained is shown in Fig. 2. According to [6, 7], normalized force of single pre-shaped beam could be calculated by equation (1).

$$F_N(\Delta)=\begin{cases}\frac{3\pi^4Q^2}{2}\Delta\left(\left(\Delta-\frac{3}{2}\right)^2-\left(\frac{1}{4}-\frac{4}{3Q^2}\right)\right) & p_1\le p<p_2\\ 4.18\pi^4-2.18\pi^4\Delta & p_2\le p<p_3\\ 8\pi^4-6\pi^4\Delta & p\ge p_3\end{cases} \quad (1)$$

Where $F_N=Fl^3/EIh$ is the normalized force. Parameters E, l and h are Young's modulus, length and original rise of midpoint, respectively. The inertial moment of beam's cross section with respect to the deflection axis can be expressed as $I=bt^3/12$. Parameters b and t represent the depth and the thickness, respectively. The normalized displacement is given by $\Delta=d/h$, where d is the displacement of midpoint. $Q=h/t$ is the geometrical factor. Finally, p is the axial load, p_1, p_2 and p_3 are the critical axial loads for the first three buckling modes.

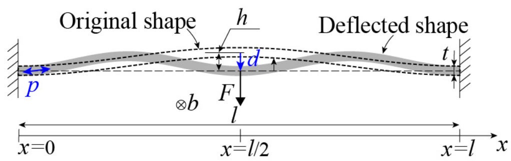

Fig. 2. Model of a single pre-shaped beam with midpoint's rotation constrained.

For the antagonistic pre-shaped double beams, the normalized total force F_{NA} for two beams could be obtained by equation (2).

$$F_{NA}(\Delta)=F_N(\Delta)-F_N(2-\Delta) \quad (2)$$

Where $F_{NA}=F_Al^3/EIh$ with F_A is the total force for two antagonistic pre-shaped beams. According to equations (1) and (2), the normalized force-displacement curves are calculated in Matlab and shown in Fig. 3. As we see, parallel pre-shaped double beams started being bistable when $Q\ge 2.31$, while the antagonistic pre-shaped double beams are already well bistable. Furthermore, the critical geometrical limit for antagonistic pre-shaped double beams is $Q\ge 1.16$.

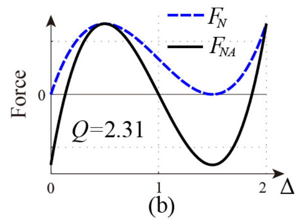

Fig. 3. Normalized force-Displacement curves for parallel pre-shaped double beams (F_N) and antagonistic pre-shaped double beams (F_{NA}).

B. Wireless Actuation

In [1], the bistable mechanism was wirelessly actuated by laser heated SMA element. However, because the SMA elements used have only one way memory effect, it remains its memorized shape (flat) after being heated. As a consequence, when bistable beams come back, they would be blocked by SMA element. Hence, due to the load added by SMA element, the bistable stroke will be reduced. Inspired by the work presented in [5], a two way memory approach for SMA element can be used to wirelessly actuate the bistable mechanism without introducing additional load on bistable beams. The working principle is shown in Fig. 4.

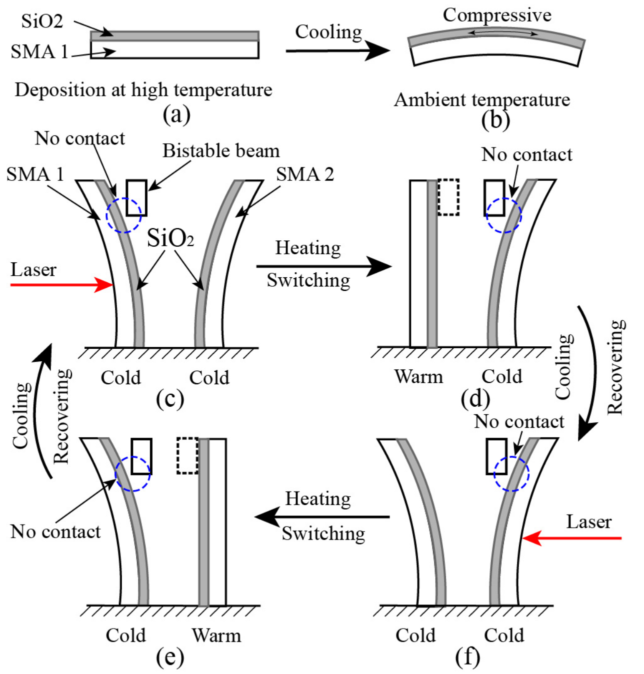

Fig. 4. Two way memory principle of SMA element with deposited SiO_2 layer.

As shown in Fig. 4 (a) and (b), the basic principle is to use deposited SiO_2 layer as biasing spring for SMA element. Because the thermal expansion ratio of SMA material (Nitinol: 55% Ni - 45% Ti) is bigger than SiO_2, SMA material will shrink more than SiO_2 layer when it is cooled from the deposition temperature to room temperature. As a consequence, compressive stress is created in SiO_2 and due to this stress, SMA will be bent together with SiO_2 layer (Fig. 4 (b)). Using the SMA element with SiO_2 layer, which can be regarded with two way memory effect, bistable beams can be actuated without load effect (Fig. 4 (c)-(f)). Firstly, the bent SMA (SMA 1 in Fig. 4(c)) in cold state is located at the position where there is no contact with bistable beam. Then, SMA is heated up to the austenitic final temperature. The martensite phase in SMA 1 is converted into austenite phase, which has higher elastic modulus. Due to the shape memory effect, SMA tends to recover the flat form, which is the memorized shape. This recovery action converted light energy to mechanical energy, which could be used to switch bistable beam from the left stable position to the right stable position (Fig. 4 (d)). Then, laser is turned off, SMA 1 is cooled down, SMA retransforms to martensite phase, SiO_2 layer becomes stronger and bends SMA to the original shape in cold state (Fig. 4 (f)). Therefore, when bistable beam is switched back to the left stable position, SMA 1 will not block it in its path. As a consequence, bistable mechanism conserves its original designed stroke.

III. Fabrication of Micro-actuator

A. Micro-fabrication of Bistable Micro-actuator

The minimal stroke of the bistable micro-actuator depends on the thicknesses of the beams: the thinner the beams are, the smaller the stroke could be. Furthermore, the symmetrical output force of antagonistic pre-shaped double beams is based on the condition that two beams have precisely the same shape. Thus, micro-fabrication technique DRIE was adopted. The fabrication work flow is explained in Fig. 5.

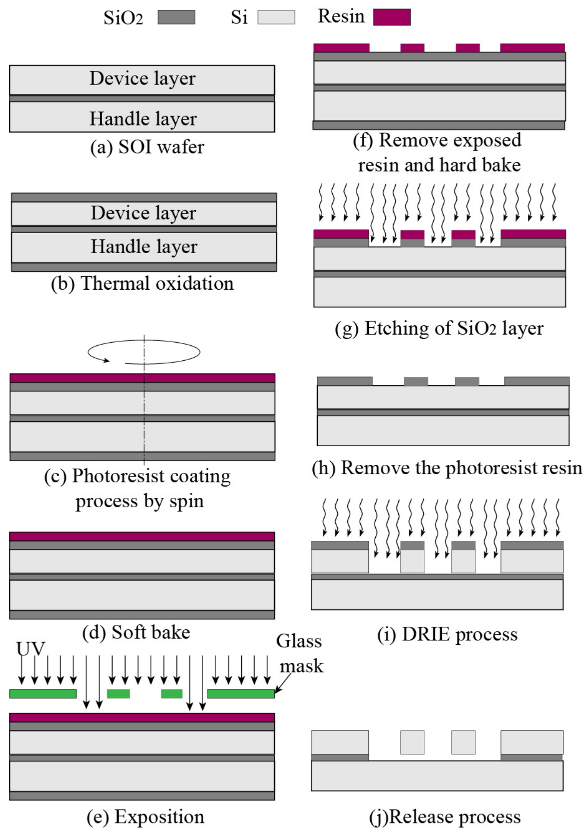

Fig. 5. Micro-fabrication work flow.

The bistable micro-actuator was fabricated with the SOI wafer, which has a device layer of 400 µm. The insulation and handle layer's thickness is 3.5 µm and 500 µm, respectively. In the first step, the SOI wafer is oxidized in oven at a temperature of 1100 ^{o}C to grow a 4.5 µm thick SiO_2 layer on both top and bottom surface. This SiO_2 layer will be developed as the mask for DRIE process. Then, photoresist resin was spin coated (3500 rpm for 30 s) and soft baked in oven (110 ^{o}C for 15 minutes). After UV light exposition, the exposed resin was removed and hard bake was completed in oven. CHF3 gas was used to remove the unprotected SiO_2 layer and develop the mask for etching process. After mask development, photoresist resin was removed by acetone. Then, the etching process was carried out with mixed gases of

SF6 and C4F8 at the temperature of 20 °C. Finally, the micro-actuator was released from SOI wafer with 50% HF acid. The fabricated bistable micro-actuator is shown in Fig. 6.

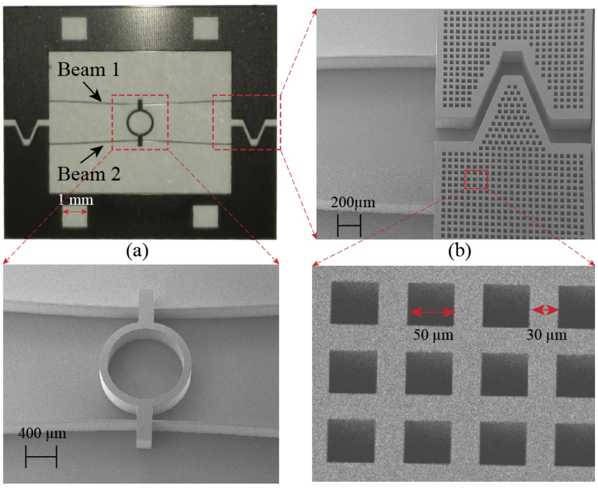

Fig. 6. (a) Fabricated bistable micro-actuator; (b) SEM photo of gap part; (c) SEM photo of central link; (d) SEM photo of release holes.

The length of the fabricated bistable beam is 8 mm, the thickness is 25 μm and the original rise of the midpoint is 150 μm. As we see in Fig. 6 (a) and (c), the central link part was a circular structure whose inner diameter is 1 mm. This circular part will be used for the integration of output end effector. In order to accelerate the release process, square holes were designed. The size of holes is 50 μm and a distance of 30 μm separates them.

B. *Cutting and deposition of SMA element*

Nitinol (alloy of Nickel and Titanium) was chosen as the SMA active elements due to its better thermo-mechanical properties as compared to the other commercially available shape memory alloys [8]. The Nitinol sheet (100 μm thick) was purchased in annealed state with the chemical composition of 55% Ni–45% Ti from Johnson Matthey company. The austenitic warm form of this SMA element is flat. Nitinol SMA active element was cut to the dimensions of 3×1×0.1 mm by a laser cutting process as discussed in [1]. According to [1], the heat affected zone was less than 10 μm, which is small as compared to the dimensions of SMA element. Thus, the shape memory effect was mainly conserved. The SiO_2 layer is deposited by magnetron sputtering of a silica target with an argon plasma (pressure 1 Pa; RF power 300 W; growth speed around 2 μm per hour). Before deposition, the SMA element was pickled in HF acid to improve the surface condition. The deposited thickness of the SiO_2 layer is 8 μm.

IV. Experimental Test

A. *Stroke Measurement for SMA Element*

The stroke of SMA element with deposited SiO_2 layer was measured using the setup shown in Fig. 7. A force sensor with a measurement range of 0-1000 mN was used in the setup. The sensor outputs a voltage signal and the sensitivity is 2.4mV/mN. As we see, the sensor was fixed on two linear stages in orthogonal configuration. Firstly, the force centering ball was adjusted to the same height with the SMA element's top end. Then, centering ball was moved slowly towards SMA element until there was a change from the force sensor's output voltage, which means the centering ball starts contacting the SMA element. Then, a red laser (λ = 660 nm, P = 100 mW) was turned on in order to heat the SMA. When the temperature rise up to the austenitic final temperature, SMA tends to recover the memorized shape, i.e., flat. However, the SMA already has a contact with centering ball. As a consequence, the recovery action exerted a force on the sensor. Keeping the laser on, the force sensor was moved away while the output voltage of force sensor was recorded. This was done until the contact between SMA and centering ball disappeared. The total movement of force sensor is considered as the stroke of SMA element.

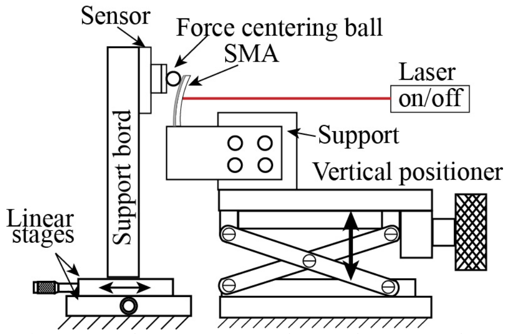

Fig. 7. Setup for measurement of SMA elements' strokes.

The measured results for an SMA element with 8 μm thick SiO_2 layer are shown in Fig. 8. As we see, there is output force until the sensor is moved about 300 μm away, which means the stroke is about 300 μm. However, the fabricated bistable micro-actuator has a stroke of 300 μm. Theoretically, after bistable beam is switched to the middle position (150 μm), it could automatically snap to the other stable position. Considering the fabrication defects, there could be a small drift for snap position. Furthermore, to avoid the load effect, 20 μm distance will be preserved between SMA element and bistable beam. Therefore, the stroke of SMA element is enough to switch the bistable beam from one stable position to the other one.

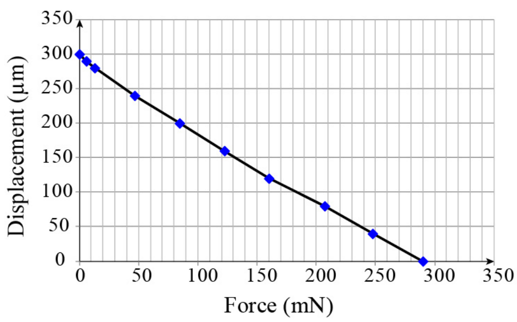

Fig. 8. SMA stroke measurement results.

B. *Wireless Actuation*

The wireless actuation was carried out by the experimental setup shown in Fig. 9. The energy was provided by a 100 mW power laser diode (λ = 660 nm). Firstly, laser beam was focused by lens 1 onto an optical beam steering micro-mirror (S1492, from Mirrorcle Technology). The steering micro-mirror's diameter is 2 mm. It can rotate in the range of ± 5° with respect to two axes under a numerical control using PC. After the reflection of the micro-mirror, the laser is focused again onto bistable micro-actuator.

As shown in Fig. 9, two SMA elements are integrated in the micro-actuator in order to switch the bistable beams in two opposite directions. The rotation ability of micro-mirror gives the possibility of heating two SMA elements with a single laser. As we see in Fig. 9, SMA 1 can be heated directly. SMA 2 can switch the bistable beams from the left stable position to the right stable position, when the micro-mirror is oriented with a pre-calculated angle. In that case, the laser beam can illuminates SMA 2 with reflections of two fixed mirrors.

A cross section view of the micro-actuator part is shown in Fig. 9, where, SMA active elements are fixed on two precise linear stages which are used to adjust SMA's original position relative to bistable beams. To avoid the load effect, SMA elements are positioned close to the beam but without contact.

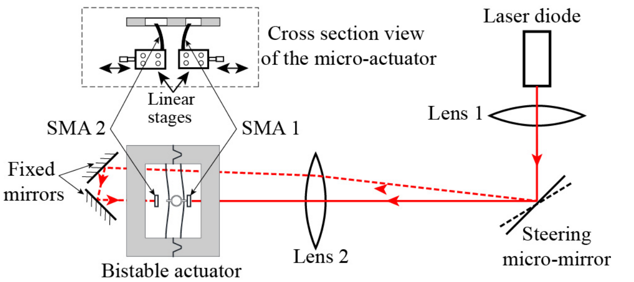

Fig. 9. Experimental setup for wireless actuation of bistable micro-actuator.

The wireless actuation of the fabricated bistable micro-actuator was realized successfully. A photo of the setup's top view is shown in Fig. 10 (a). The silicon micro-actuator is fixed in a plastic (PMMA) support structure. Two small fixed mirrors are located under the support behind SMA 2. The side views of micro-actuator when the bistable beams are at the right and left stable position are shown in Fig. 10 (b) and (c), respectively. Furthermore, in the zoomed view, we can see that there is a small gap between SMA and bistable beams at both stable positions, i.e., there is no load effect from SMA elements.

As mentioned in former part, the laser needs to be reflected two times to heat SMA 2 and because of the energy loss during reflections, the laser power irradiated on SMA 2 is less than the power on SMA 1. As a consequence, SMA 2 needs to be heated for a longer duration (about 2 s) than SMA 1 (about 1.5 s) to switch the beams.

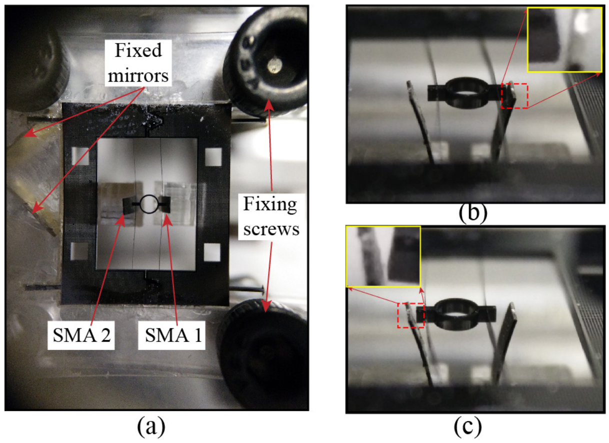

Fig. 10. (a) Top view of real setup; (b) Side view when bistable beam was at the right stable position; (c) Side view when bistable beam was at the left stable position.

IV. Conclusion

An optical wireless bistable micro-actuator was designed, fabricated and experimentally tested. The bistable mechanism was realized through antagonistic pre-shaped double beams. The micro-actuator was fabricated by micro-fabrication technique DRIE on SOI wafer. SMA active element was used to wirelessly actuate the bistable micro-actuator. Deposited SiO_2 layer was acting as a biasing spring and created a two way memory effect. The bistable micro-actuator was actuated in two directions by a single laser diode with the help of an optical beam steering micro-mirror.

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