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THERMO-MECHANICAL BEHAVIOR OF A MICROMIRROR FOR LASER-TO-FIBER ACTIVE ALIGNMENT USING BIMORPHS WITH BREAKABLE TETHERS

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ABSTRACT

We will present a novel micromirror design in which tethered bimorph strips are used for mirror active alignment including beam steering and position fixing. A micromirror is attached to bimorphs that are pre-stressed at room temperature. A series of tethers link the bimorphs to the substrate to restrain their deformation. Breaking a tether by Joule heating allows the deformation of the bimorph to increase, changing the mirror position and orientation for precision alignment. With a large number of tethers, an optimum alignment can be achieved after breaking a selected group of tethers. We also report the experimental results of devices fabricated.

INTRODUCTION

Laser-to-fiber active alignment is commonly used in the manufacturing of optoelectronic modules. The current approach uses a precision robot to position the fiber during the alignment and welding process. Robots with a sub-μm resolution are expensive, and the precision of fixing the fiber drops significantly during welding, due to thermal shrinkage. As a result, a MEMS (Micro-Electro-Mechanical Systems)-based micromirror is a promising device; it steers a laser beam for active alignment without requiring a precision robot and fixture.

Ishikawa et al. [1] demonstrated a micromirror suspended by four thermal actuators for laser-to-fiber coupling (Figure 1).

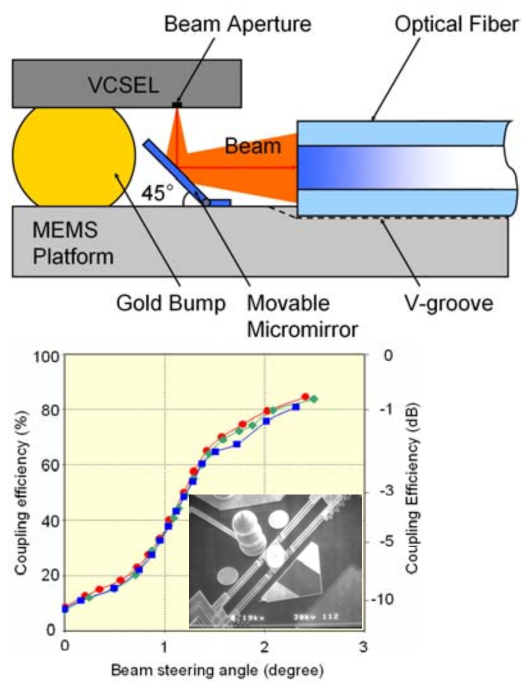

Figure 1: Schematic view of a laser-to-fiber coupling concept (upper), and a graph of coupling efficiency / beam steering angle with inset micrograph of the microstructure (lower); from Ishikawa [1].

These structures are lifted up to 45° with mechanical locking mechanisms; thereafter the micromirror can be steered two-dimensionally by the actuators. However, for fine position maintenance the thermal actuators need to be supplied with an electrical current, and no method or structures for fixing were reported in the paper. Ideally, for laser-to-fiber coupling a micromirror should remain fixed without the need for power after alignment.

Similar beam steering micromirrors have been demonstrated in many other optical MEMS papers. A couple of examples have been done on bimorph actuation of a mirror (Wang et al. [2] and Xie et al. [3]). These studies focused on scanning (i.e. unfixed) micromirrors, and again power would be required to maintain the mirrors' angle after alignment. In fact, very few previous works could be found about MEMS technologies that accomplish both alignment and fixing of microstructures.

Daneman et al. [4] has shown the use of a movable micromirror for alignment of a laser beam to a fiber and suggested that the micromirror can be carried by on-chip electrostatically-driven micro-vibromotors. Since the micromirror is held in position by frictional forces, the fixing force probably would be inadequate to hold the micromirror steady for a long period of time after adjustment.

Fedder and Howe [5] and Zhang and Lee [6] demonstrated fixing of a microstructure by resistive welding and thermal fusion, respectively. Their fixings are permanent; however, the welding and fusion process was not coupled with the beam steering required for active alignment.

Several papers showed that resistive cutting of microbridges can be accomplished by electrical means without micromanipulation (Fedder and Howe [5], Fedder et al. [7] and Miki [8] et al.). Their applications are temporal fuse-away supports that hold delicate microstructures during a wet etch of sacrificial layers and not for an angular alignment of microstructures.

Stimulated by these techniques and the aforementioned bimorph-actuated micromirrors, we have developed a new micromirror assembly for active alignment and fixing. This novel MEMS device incorporates a series of bimorphs with selectively-breakable tethers. It accomplishes both beam steering and fixing simultaneously, which is an ideal combination for applications such as laser-to-fiber coupling**.**

TETHERED BIMORPH CONCEPT

Figure 2 shows the basic concept of a tethered bimorph. A pre-stressed bimorph is linked to the substrate by multiple tethers (Figure 2, far left), so that its deformation is constrained. As individual tethers are eliminated sequentially, the strip tip deflects (Figure 2, from left to right). Selective tether elimination is accomplished by passing current through a particular tether; the resulting Joule heating melts or "burns" the tether and permits further deformation of the bimorph. This deformation could be used to control the position or angle of another microstructure connected to the bimorph tip. In this project, our objective was to position a micromirror.

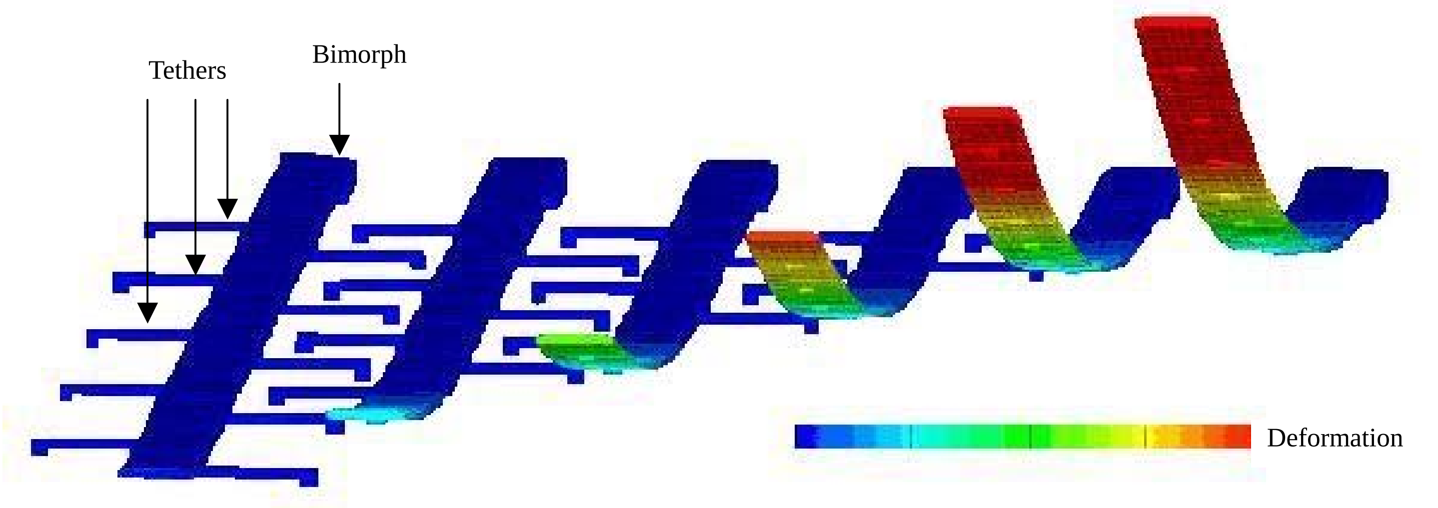

Figure 2: As tethers between the pre-stressed bimorph and the substrate (not shown) are eliminated, the bimorph deflects further incrementally (from left to right).

DESIGN

Our laser-to-fiber coupling scheme uses a combination of bimorphs and tethers to adjust and maintain the position of a micromirror. The bimorphs are annealed at elevated temperature, so that they are pre-stressed at room temperature. The tethers constrain the deformation of the bimorphs by linking them to the substrate. A series of electrical traces allows a particular tether to be burned by passing an electrical current through it. When a tether is burned, the bimorph deflects into a new equilibrium position, exerting a force on the micromirror in the process. Thus, the mirror on the chip can be aligned by electrical means alone.

To validate our concept, several designs were fabricated using the PolyMUMPs (Polysilicon Multi-User MEMS Processes)[1] foundry. The design discussed in this paper is shown in Figure 3. A single mirror is connected to two pairs of bimorph strips by means of compliant linkages. The bimorphs consist of gold-on-polysilicon layers.

To sever a tether, a voltage is applied across one of the electrodes and one of the ground pads at the fixed end of the desired bimorph. Thus, current passes along a gold-covered trace, through a specific polysilicon tether, and then along the gold-covered bimorph to the ground pad. Because the electrical resistance in the polysilicon tether is far greater than in the gold-covered components, the majority of the Joule heating is concentrated in the tether, causing it to burn. Tethers should have sufficient length that Joule heat generated in the tether will not immediately dissipate into the substrate or cause excessive heating of the bimorph.

By eliminating tethers that limit deflection of the bimorphs, the micromirror angle can be adjusted. When only two bimorph strips 1A and 1B deflect upward, the micromirror rotates about the pitch axis. Similarly, the micromirror rotates about the roll axis when, for example, strips 1A and 2A are deflected upward (Figure 4). Strips 1A and 1B have five tethers each, which are electrically connected to five nearby electrodes. Strips 2A and 2B are connected to ten electrodes by two tethers each (twenty tethers total on each bimorph).

Chu, et al. [9] derived an equation of a bimetallic cantilever bending by an analytical model:

$$r = \frac{(b_1E_1t_1^{\,2})^2 + (b_2E_2t_2^{\,2})^2 + 2b_1b_2E_1E_2t_1t_2(2t_1^{\,2} + 3t_1t_2 + 2t_2^{\,2})}{6b_1b_2E_1E_2t_1t_2(t_1 + t_2)(\alpha_2 - \alpha_1)\Delta T} \quad (1)$$

where r is the radius of curvature of the beam, E is Young's modulus, b is the width of the beam, t is the height of the beam, ΔT is the change in temperature, and α is the thermal expansion coefficient. According to the equation (1), the bimorph strips 1A, 1B, 2A and 2B are expected to bend up 91 μm at their free ends. Assuming that each compliant linkage bends only where connected to a bimorph, when the strips 1A and 1B are released completely and strips 2A and 2B are constrained, the mirror is expected to achieve a pitch of 11° (Figure 5). In reality, the linkages would be expected to bend not only where connected to the bimorphs but along their length, and so the mirror pitch would likely be larger (dashed line in Figure 5).

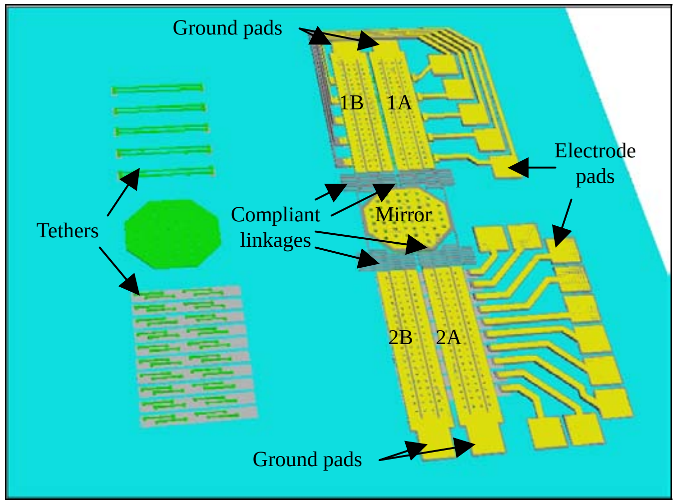

Figure 3: A design view of the device. Upper layers (Poly2 and Gold) are removed from the left half of the image to show the Poly1 tethers under the bimorphs. A pair of tethers joins each bimorph to each electrode pad.

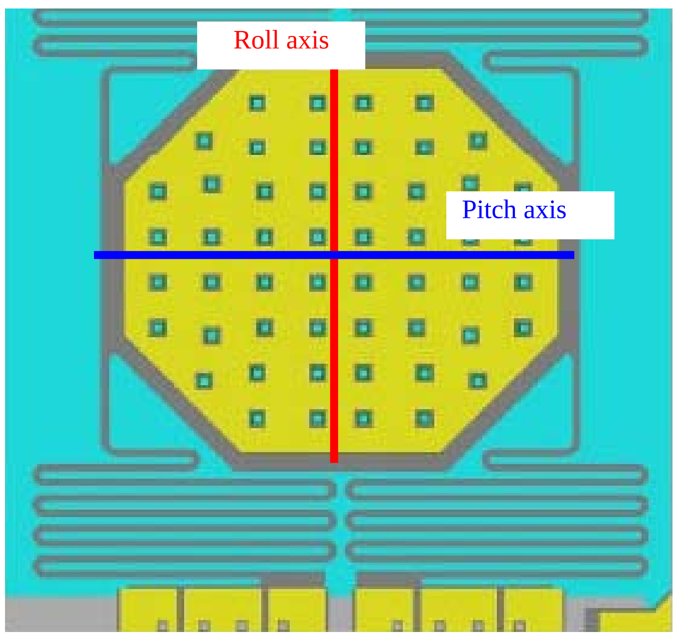

Figure 4: A close-up view of a micromirror and the four compliant linkages connecting it to the bimorphs.

[1] PolyMUMPs is a surface micromachining process consisting of three layers of polysilicon (0.5 μm Poly0, 2.0 μm Poly1 and 1.5 μm Poly2 in order from the substrate upward) and a 0.5 μm gold layer.

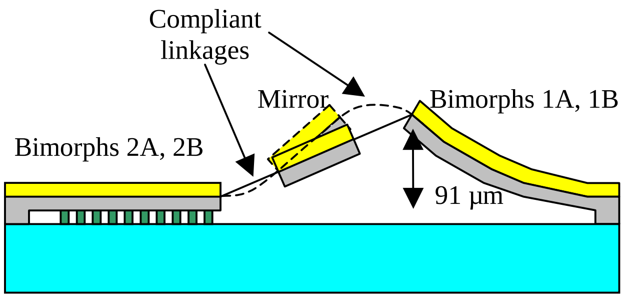

Figure 5: A schematic view showing the mirror angle when all the tethers of the bimorphs 1A and 1B are broken. Compliant linkages shown by solid lines assume bending occurs only where they connect to the bimorphs. The dashed lines assume linkages bend continuously along their length.

EXPERIMENT

Incremental changes in mirror angles in response to burned tethers were measured by means of a visible-spectrum laser reflected off the mirror surface as shown in Figure 6. Laser light reflected from the micromirror was projected onto a sheet of graph paper. Each time a tether was burned, the coordinates of the laser spot center on the graph paper were recorded. The incremental angular change of the reflected beam was determined by a simple geometric calculation based on the distance from the micromirror to the projection surface. The change of the micromirror angle was then calculated as half of the measured change in the reflected beam angle.

Before experiments, each device was annealed at 150°C for 12 hours to set the bimorphs' zero-stress temperature.

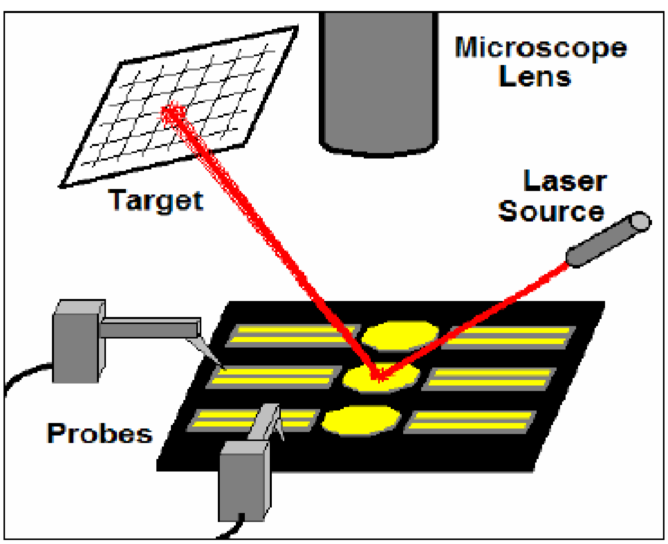

Figure 6: Experimental setup for burning tethers and measuring angular deflection of a mirror. Not to scale. Laser light reflected from the mirror strikes a simple target; the change in location of the incident light on the target can be used to calculate the angular deflection of the mirror when a tether is burned.

Before and after each series of measurements, the reflected beam angle from the chip substrate was recorded, in order to confirm that the attitude of the substrate and test equipment had not changed during the experiment.

When applying voltages to sever tethers, any voltage potential resulted in an electrostatic force that would pull the bimorph toward the substrate and temporarily affect the mirror angle. Holding the voltage of the bimorph and substrate the same reduced the movement caused by this electrostatic force, but even so some movement still remained. To assure this temporary electrostatic deflection did not influence angular measurements, the applied voltage was always set to zero before recording the mirror angle.

Figure 7 shows the trajectories of the reflected beam angles of three devices. In this test, the tethers of strip 1A and 1B were broken first, then those of strip 2A, and last those of strip 2B. The reflected beam angle from the substrate was set as the origin point of the trajectories. At first, tethers of the bimorph strips 1A and 1B were eliminated in the following order: first tether of 1A, first tether of 1B, second tether of 1A, second tether of 1B, etc. (Figure 8). The reflected beam angles from

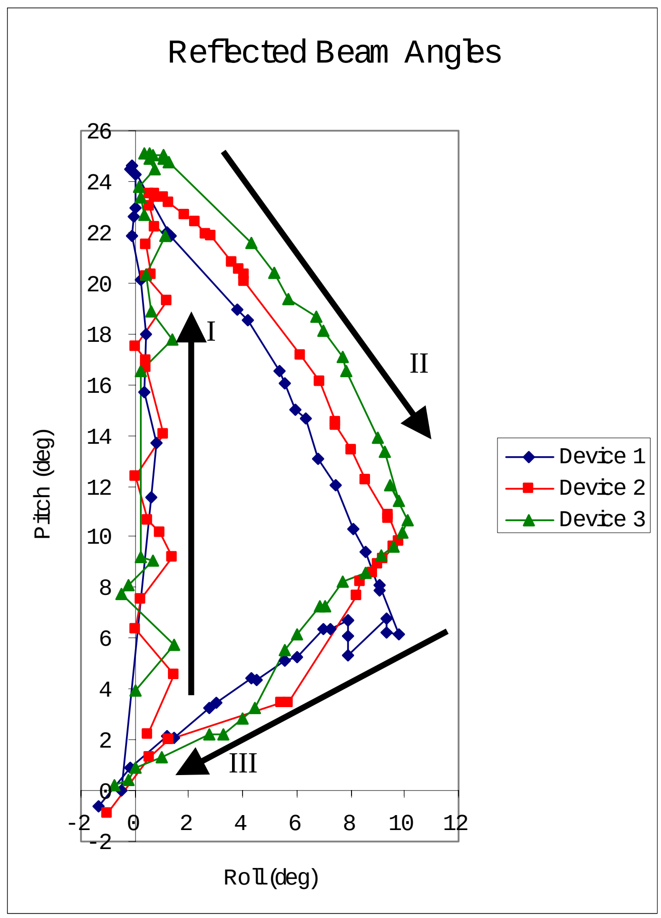

Figure 7: Trajectories of reflected beam angles. The actual mirror angles are half of these reflected beam angles.

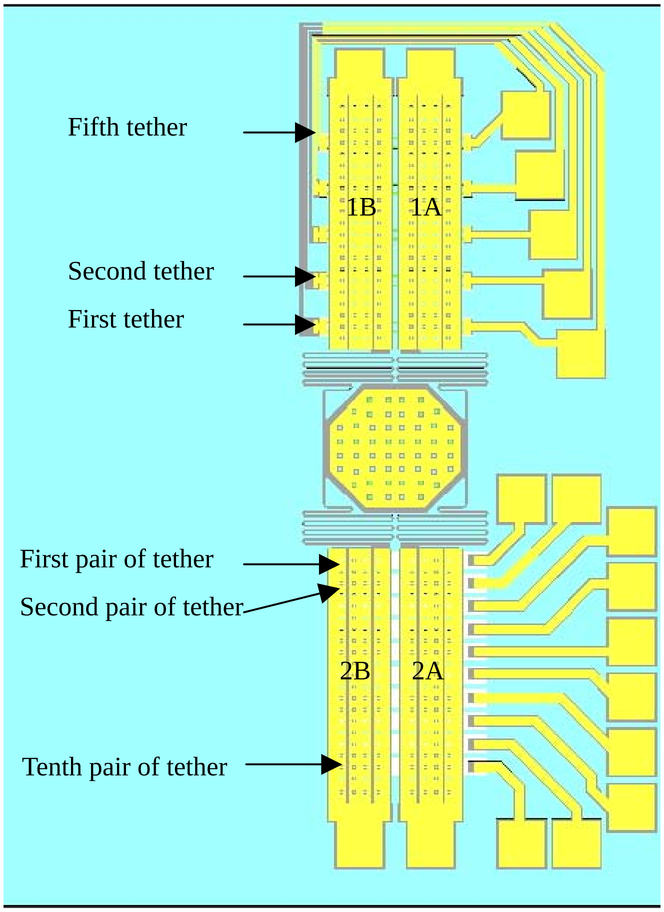

Figure 8: Overview indicating positions of tethers. The actual tethers are hidden under the bimorphs.

mirrors started at near the origin point, and pitch increased as strips 1A and 1B deflected upward (arrow I in Figure 7). After all the tethers of strips 1A and 1B had been burned, the beams reflected from the devices showed maximum pitch deflections of around 25º. Then tethers of strip 2A were broken in order from the first pair to the tenth. Since strip 2A bended upward during this procedure, roll increased and pitch decreased (arrow II in Figure 7), with maximum roll deflection angles of around 10°. Last, tethers of the strip 2B were broken. During this sequence, strip 2B bended up and roll and pitch decreased (arrow III in Figure 7).[2]

The beam angle was expected to go back to its starting point after all the tethers were broken, because the four bimorphs were of similar design and were expected to deflect to approximately the same height once all tethers had been burned; the devices generally behaved as expected. Also, as discussed above, when all the tethers of strip 1A and 1B were eliminated the mirror angle was expected to reach a pitch angle of 11° (reflected beam angle of 22°) or more. The device achieved the expected pitch when all the tethers of strip 1A and 1B were eliminated. Pairs of data points can be seen in the second and third sides of the triangle (along Arrow II and III) in Figure 7. This is because the tethers under these bimorphs broke one at a time rather than in pairs; simultaneous burning had been anticipated and would have resulted in single data points.

Figure 9 shows reflected beam angles when tethers were broken in an arbitrary order; the data points shown represent elimination of just one-third of the tethers available for the device. Figure 10, 11 and 12 present photos of the micromirrors with various tethers broken.

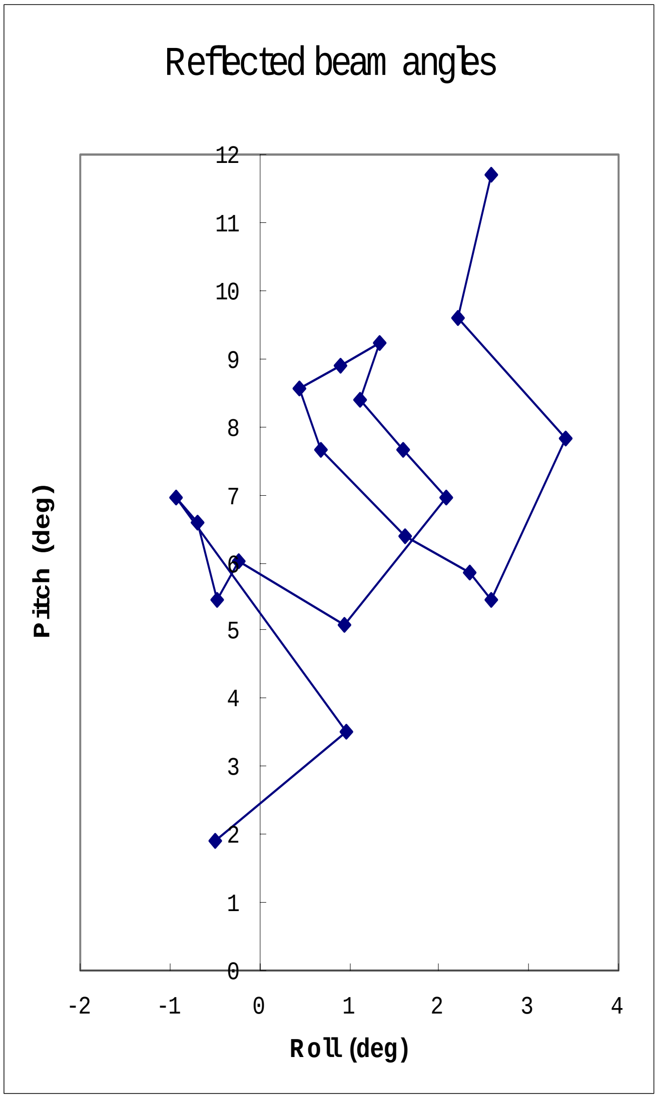

Figure 9: Reflected beam angles when tethers were broken in an arbitrary order.

[2] Certain anomalies were encountered during testing as follows. When the first tether of strip 1A of device 1 was broken, the laser spot was not recorded because the linkages between the mirror and the bimorphs was stuck to the substrate; the linkage was released by poking with a probe. When the fourth through sixth pairs of tethers of strip 2B of device 2 were broken, laser spots were not recorded because those tethers were eliminated before it was noticed that the fourth pairs of tethers had not broken. When the first through fourth pairs of tethers of strip 2A of device 3 were broken, the laser spot hardly moved, probably because of the compliant linkage sticking to the substrate.

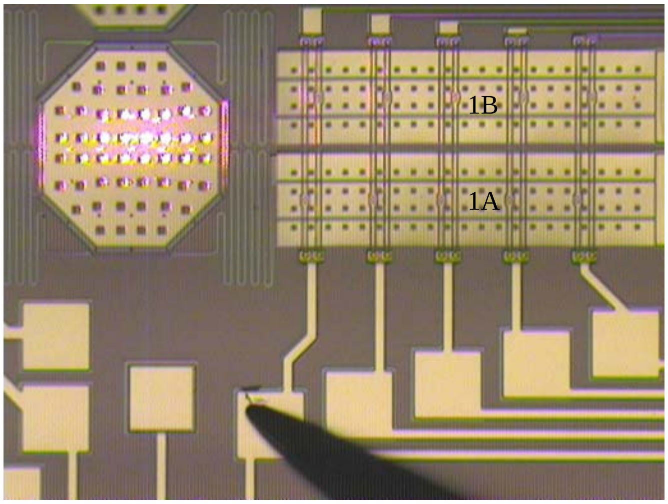

Figure 10: The mirror and bimorphs 1A and 1B of device 1 before tethers were broken. The mirror is illuminated by the laser.

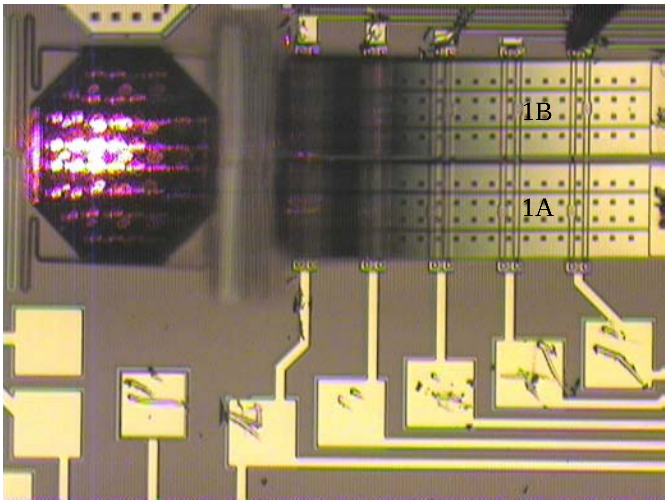

Figure 11: The mirror and the bimorphs 1A and 1B of device 1 after all the tethers of the bimorphs 1A and 1B were broken. (In figures 11-12, the mirror and the bimorph tips look dark and out-of-focus because of their large angular and vertical deflections, not because of any actual discoloration.)

Once adjusted, mirror angles were fairly stable. Table 1 shows reflected beam angle over time when the first and the second tethers of strip 1A and 1B were broken and the chip remained untouched. Though the angle changed 1°, it became stable in two days. In this prototype design, polysilicon-on-gold was the basis for all bimorphs, though this combination is known to be less than ideal for stress stability (high rate of stress relaxation). A more stable combination of materials would be desirable for any practical applications in the future.

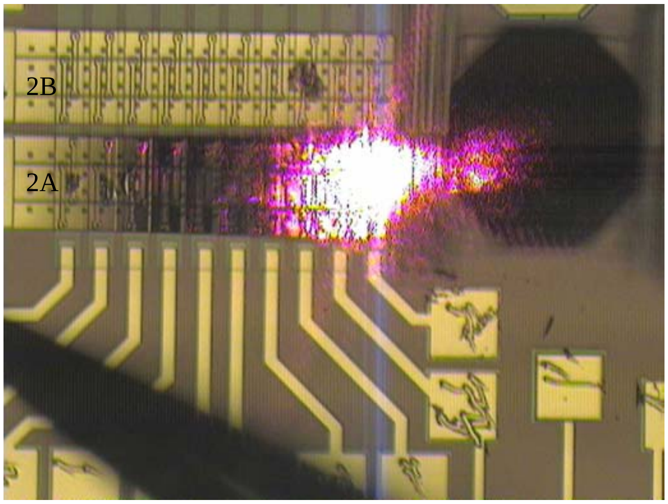

Figure 12: The mirror and bimorphs 2A and 2B of device 1 after all the tethers of bimorphs 1A, 1B and 2A were broken.

	Pitch	Roll
Initial measurement	15.6°	0.8°
After 16 hours	14.9°	0.8°
After 37 hours	14.6°	0.8°
After 47 hours	14.6°	0.8°

Table 1: Reflected beam angle change over time as the chip remained untouched.

CONCLUSIONS

A new device using a combination of bimorph strips and breakable tethers for micromirror fixing was successfully demonstrated in this research. Experiments showed that two-dimensional alignment of a reflected angle of 25° for pitch and 10° for roll was obtained with one of our designs. With laser-to-fiber coupling as a motivation, this research has demonstrated the potential of the tethered bimorph approach to be applied to the alignment and fixing of MEMS microstructures in any number of possible practical applications.

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