Self-Assembled Microactuated XYZ stages for Optical Scanning and Alignment

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ABSTRACT

A novel self-assembled, surface-micromachined micro-XYZ stage with large displacements and fine positioning accuracy has been demonstrated on Si micro-optical bench for optical scanning/alignment applications. Continuous lateral scanning up to 120 μm and vertical scanning up to 250 μm have been achieved with integrated scratch drive actuators (SDA), which have step resolutions of 27 nm. The XYZ stage can be fully assembled by applying electric bias only. Focus adjustment of the micro-Fresnel lens integrated on the micro-XYZ stage has also been successfully demonstrated. They are useful for two-dimensional scanning, dynamic focusing/tracking, and fine optical alignment.

Keywords: self-assembly, surface-micromachining, microactuators, out-of-plane displacement.

INTRODUCTION

Surface-micromachined free-space micro-optical bench (FSMOB) has been shown to be a promising technique for implementing free-space optical systems [1]. It combines surface-micromachining techniques with conventional micro-optics fabrication technology. Out-of-plane three-dimensional (3D) diffractive microlenses, refractive microlenses, microgratings, micromirrors, etalons, and other elements have been demonstrated. Single-chip optical systems can be constructed by monolithically integrating these optical components on a Si substrate. In FSMOB, micropositioners and microactuators can be monolithically integrated with the 3D micro-optical elements using the same surface-micromachining process. This allows one to perform on-chip fine optical alignment, optical scanning or switching on FSMOB. The applications of FSMOB include optical switching, optical sensing, optical data storage, and optical interconnect.

One of the main challenges in FSMOB is the lack of vertical actuators with large travel distance. Vertical actuators have been realized by high aspect ratio structures such as vertical spring [2], multi-level LIGA-like process [3], or vertical comb actuators with trench refill technology [4]. However, their travel distances are limited and the integration with micro-optical components is difficult. Vertical actuation has also been achieved in surface-micromachined structures by converting in-plane motion to out-of-plane displacement [5, 6]. However, the vertical displacement is usually coupled with horizontal displacement.

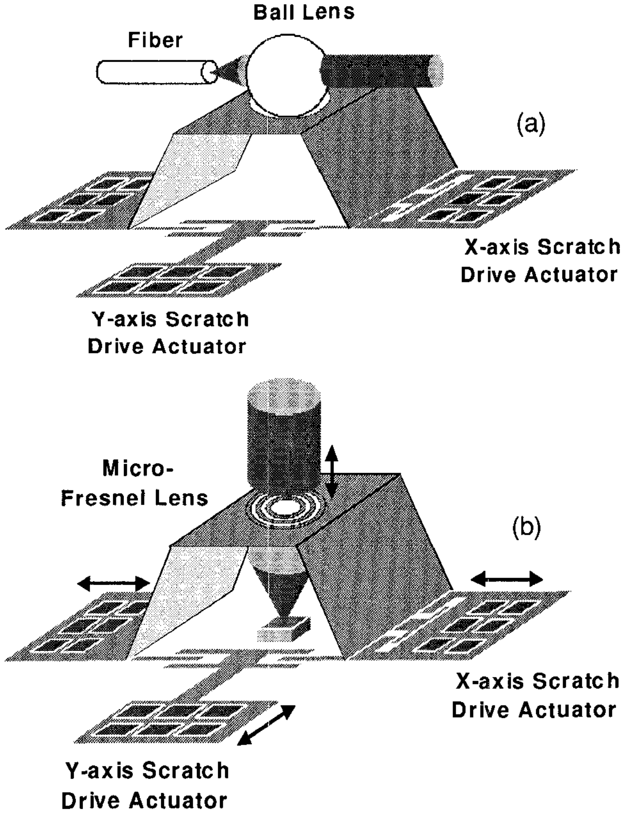

Figure 1: Schematic diagram of self-assembled micro-XYZ stage with (a) external optical elements and (b) integrated optical elements.

Another challenge of surface-micromachined 3D structures is that substantial manual assembly is required. This could significantly increase the system cost. There have been growing interests in the 3D microstructures that can be self-assembled. Surface tension force of molten solder has been used to rotate hinged joint for non-reconfigurable structure [7]; active polymers have been used for self-assembly in electrolyte liquid solution [8]. Recently, reshaping technology has been shown to be very promising for assembling 3D surface-micromachined microstructures [9], however, the positioning accuracy required by optical systems is still beyond that of the current reshaping technology.

In this paper, we report on a novel self-assembled micro-XYZ stage monolithically fabricated by the surface-micromachining technology. It has three independent axes of motion, large out-of-plane (250 μm) and in-plane displacement (120 μm), and very fine step resolution (27 nm). Monolithic integration of such XYZ-stage with micro-Fresnel lens has also been demonstrated. Focus adjustment using the actuated micro-XYZ stage will be reported.

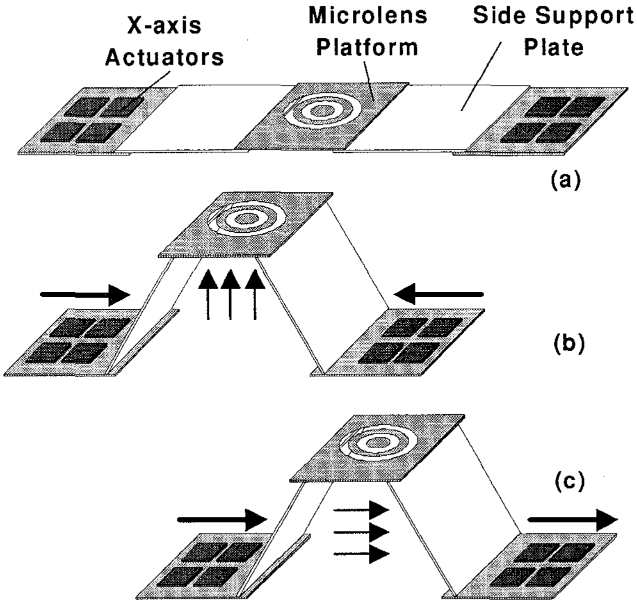

Figure 2: Schematic diagrams illustrating the principle of the self-assembled micro-XYZ stage (a) before assembly, (b) vertical displacement, and (c) lateral displacement.

PRINCIPLE AND DESIGN

The schematic structure of the micro-XYZ stage is shown in Fig. 1. It consists of a platform with side-supporting plates. The platform can be raised from the substrate (Z direction) by the in-plane actuators connected to the side-supporting plates. Independent movement in the substrate (XY) plane is accomplished by using sliding joints to connect actuators in the X and Y directions. This micro-XYZ stage can be used to position external macro optical elements such as the ball lens shown in Fig. 1(a). Alternatively, it can be monolithically integrated with surface-micromachined micro-optical elements, as shown in Fig. 1(b). Since the micro-XYZ stage can physically move in three axes, it can be used for in-plane optical systems (Fig. 1(a)) as well as systems with surface-normal optical access (Fig. 1(b)).

The principle of the self-assembled XYZ stage is illustrated in Fig. 2. The basic structure consists of three parts: the microlens platform, the side supporting plates, and the microactuator plates. The plates are joined together by *polarity hinges* and *slide joints*. The polarity hinges allow the two joined plates to bend only in one direction, while the slide joints permit simultaneous X and Y movements. The detailed design of the polarity hinges and the slide joints will be discussed later. This unique design allows the platform to move in all three directions. To raise the platform, the two actuators in the X direction are biased to move in the opposite directions with the same speed. The side supporting plates with polarity hinges effectively translate the in-plane motion into out-of-plane motion, which in turn raise the platform, as shown in Fig. 2(b). To move the stage in the X direction, the two actuators now move in the same direction at the same speed. The platform will maintain the same height and move along the X-axis, as shown in Fig. 2(c). The platform can also move in the Y direction by activating the actuator in the Y direction. Independent movement in the XY direction is accomplished by the use of sliding joints, as shown in Fig. 1. Therefore, independent movement in all three axes can be achieved. This design also allows large travel distances in all X, Y, and Z directions, which are highly desirable for optical applications.

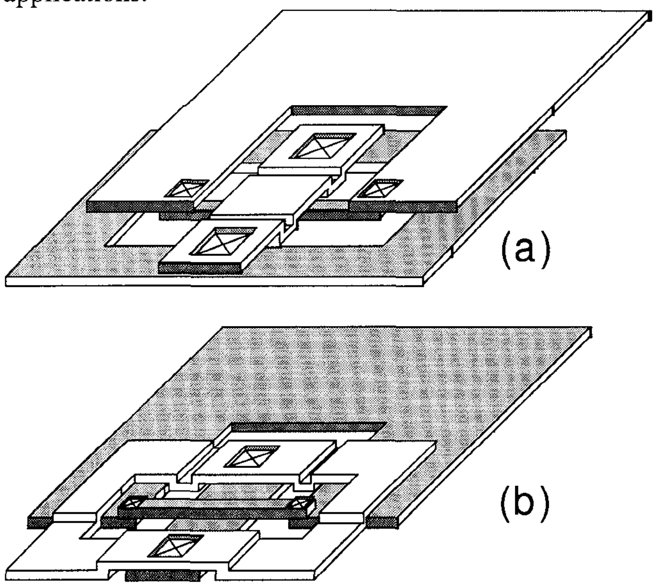

Figure 3: Schematic diagram of (a) the normal polarity hinge (b) the reverse polarity hinge.

One of the key elements in the micro-XYZ stage is the *polarity hinge*. The polarity hinges join two polysilicon plates together and allow them to bend only in one direction (either upwards or downwards). The main difference between the polarity hinges and the conventional scissors hinges [10] is that the polarity hinges can achieve more precise control of the relative plate positions. In conventional scissors hinges, the large gap spacing between the plates result in positioning inaccuracy in access of 10 μm. This variation has been reduced to 2 μm in both vertical and lateral directions by using polarity hinges. The schematic drawing of the polarity hinges are shown in Fig. 3. Figure 3 (a) shows the schematic structure of the *normal polarity hinge*, which allows the plates to bend upwards. The plate is defined on the second polysilicon layer (poly-2) and the hinge pin is defined on the first polysilicon layer (poly-1). This normal polarity hinge is used to join the actuator plates and the side supporting plates. Figure 3 (b) shows the schematic structure of the *reverse polarity hinge*, which allows the plates to bend downwards. The plate is made of ploy-1 and the hinge pin is made of poly-2. The reverse polarity hinge is used to join the microlens platform and the side supporting plates. Since accuracy of the angle and position of the platform in the XYZ stage is directly related to the gap variation, more precise control of the hinge gap will improve the precision of the XYZ stage.

Another important element is the *sliding joints,* which enables simultaneous movement of the stage in X and Y directions. If the actuator plates are directly connected to supporting plates, they cannot move in both X and Y directions. In order to have independent movement along these two axes, a sliding joint is introduced between the X-axis and Y-axis. Figure 4 shows the schematic diagram of the sliding joint, which consists of a sliding pin and a U-shaped confinement slot. The pin can slide freely along the Y direction, at the same time, it will move together with the confinement slot in the X direction. When the actuators in both X and Y directions are connected by such sliding joints, independent XY movement can be achieved.

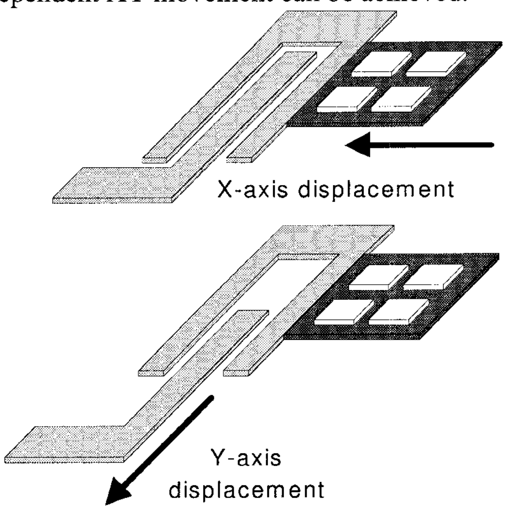

Figure 4: Schematic diagram of the sliding joint.

Compared with self-assembled structure with buckling beams, this micro-XYZ stage has the following advantages: (1) the height and position of the raised platform is more predictable. The shape of the XYZ stage is precisely defined by the rigid plates and the polarity hinges. There is no plastic deformation on the polysilicon plates. (2) The raised platform is more stable and does not suffer from tilting or deformation because of the large supporting plates and the large contact areas.

EXPERIMENTS AND RESULTS

The self-assembled micro-XYZ stage is fabricated using the three-layer polysilicon surface-micromachining technology offered by MEMS Technology Application Center at North Carolina (MCNC) under Defense Advanced Research Projects Agency (DARPA)-supported Multi-User MEMS Processes (MUMPs). Figure 5 shows the scanning electron micrograph (SEM) of the assembled vertical actuator. Similar structures with integrated sliding joints have been realized for XYZ stages. Four Fresnel microlens have been directly integrated on the polysilicon platform. The dimension of the platform is 250 μm x 250 μm, and those of the side supporting plates are 200 μm x 350 μm. A group of nine scratch drive actuators (SDA) [6] have been integrated with each actuator plate. The SDA's are employed here for their long travel distance, fine step sizes, large force, and compact area. Other actuators with large travel distance could also be used with this micro-XYZ concept. To assemble the stage, the two actuators along the X-axis move in from both sides, and the side supporting plates transform the lateral displacement into vertical displacement and raise the microlens platform. The micro-XYZ stage can be reproducibly assembled by the integrated SDA's. By moving X-axis actuators by 110 μm, the vertical displacement is measured to be 250 μm.

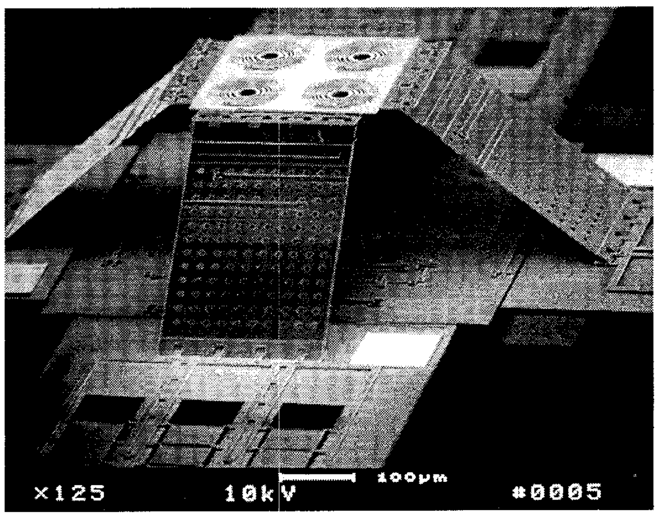

Figure 5: The scanning electron micrograph (SEM) of assembled micro-XYZ stage. Four micro-Fresnel lens have been integrated with the XYZ stage.

To characterize the performance of the integrated microlens, the microlens is illuminated by a collimated laser beam. The focal length of the microlens is designed to be 300 μm, and the reflected light beam should focus at 300 μm above the plate. Figure 6 shows the measured far field patterns and the corresponding optical beam spot size versus the height of the microlens. The far field patterns show that the beam spot is precisely focus at 300 μm above the platform. The focus can be varied continuously when the SDAs are biased with electrical pulses with ± 90V peak amplitudes. For each electric pulse actuation, the SDA moves by a step size of 27 nm. Since the SDA does not need to operate at resonance, the vertical actuator can move at steps of 27 nm when the side support plate is assembled at the angle of 45°. In our current structure, the SDAs connected to the same polysilicon plate can only move in one direction because substrate is used as the bottom electrode. In order to have bi-directional scanning, a hardened-photoresist bridge has been used to connect the forward-moving and the backward-moving SDAs.

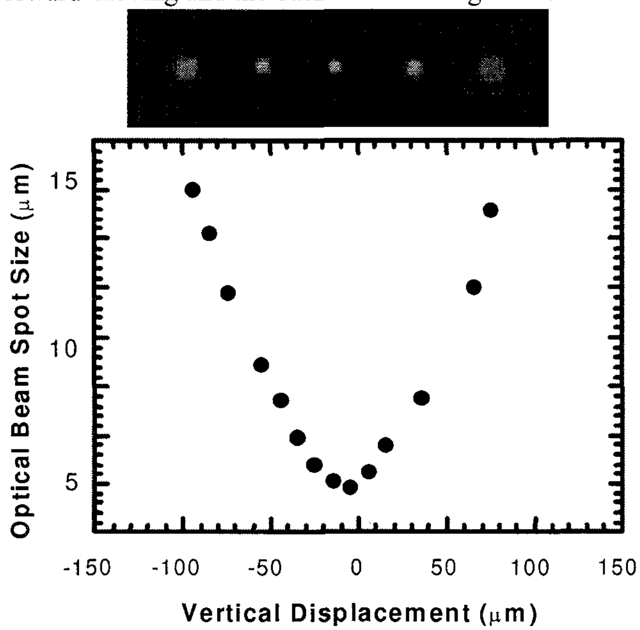

Figure 6 : Focus adjustment by raising the height of the microlens with microactuators.

The micro-XYZ stage can be easily integrated with most of the surface-micromechanical optical elements, such as micro-gratings, micro-mirrors, and refractive microlens. A hole can also be patterned on the platform to hold a ball lens or other external macro optical elements. The micro XYZ stages can also be integrated with two-dimensional arrays of active optoelectronic devices such as vertical cavity surface-emitting lasers (VCSEL) [11]. The XYZ stage and the VCSELs can be integrated by flip-chip mounting, epitaxial liftoff, or wafer bonding techniques. Two-dimensional optical scanning, dynamic optical focusing/tracking, and fine optical alignment can be achieved.

CONCLUSION

A novel self-assembled micro-XYZ stage with three axes of motion has been demonstrated. The XYZ stage is actuated by scratch drive actuators, and has fine step size (27 nm) as well as large travel distance in all three directions (250 μm in vertical direction, and 120 μm in lateral directions). This micro-XYZ does not need any manual assembly, can be readily integrated with surface-micromachined micro-optical elements on FSMOB or hold external macro-optical elements, and can be mass-produced by batch fabrication process.

ACKNOWLEDGMENTS

This project is supported in part by DARPA and the Packard Foundation.

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