MICROACTUATED MICRO-XYZ STAGES FOR FREE-SPACE MICRO-OPTICAL BENCH

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ABSTRACT

A novel microactuated micro-XYZ stage with large travel distance and fine positioning capability has been demonstrated using the surface-micromachining technology. The micro-XYZ stage consists of three in-plane translation stages driven by integrated scratch drive actuators. Two vertically stacked 45° micromirrors in orthogonal directions are employed to achieve vertical beam adjustment without using vertical actuators. Large travel distance (> 30 μm) and fine moving steps (11 nm) have been achieved experimentally in all three directions. The micro-XYZ stage can be monolithically integrated with the surface-micromachined microlenses, or other out-of-plane micro-optical elements, for optical alignment or reconfiguration in free-space micro-optical benches (FS-MOB).

INTRODUCTION

Precision micropositioning stages with three degrees of freedom (XYZ stages) and submicron resolution are the key components for optical alignment in bulk optical systems. Recently, there has been a growing interest in applying the micro-electro-mechanical-system (MEMS) technology to realize part or all of the optical systems. Previously, we have shown that the complete optical systems can be monolithically integrated onto a single chip of substrate using the free-space micro-optical bench (FS-MOB) technology [1,2]. The FS-MOB, which combines the surface-micromachining technology with the micro-optics fabrication techniques, can monolithically integrate micro-optical elements, micropositioners, and microactuators on the same substrate using batch fabrication processes. The FS-MOB can significantly reduce the size, weight, and cost of free-space optical systems, and has applications in optical data storage, switching, scanning, display, and printing.

Various three-dimensional micro-optical elements such as diffractive and refractive microlenses, micro-gratings, beam-splitters, and micromirrors, have been demonstrated [1-5]. Monolithic micro-optical systems such as free-space optical disk pickup heads [6] have also been realized. However, micro-XYZ stages with large travel distance and submicron positioning accuracy have not been realized. Though integrated XY comb drive with torsional Z actuator has been demonstrated for micro-scanning tunneling microscope application, it is not suitable for optical application because of the limited travel range (< 1 μm) [7]. One of the main challenges for surface-micromachined micro-XYZ stage is the lack of vertical actuators with large enough travel distances. Most of the conventional surface-micromachined microactuators move in the plane of substrate. A vertical comb drive actuator has been demonstrated, however, it has limited travel distance (~ 8 μm), and may be difficult to integrate with other components [8]. Though large out-of-plane displacement has been demonstrated by in-plane actuators using buckling mechanism [9], the vertical motion is coupled with in-plane displacement. Using a combined translation and tilting mechanism, two-dimensional alignment has been realized by a microactuated micromirror [4] using the surface-micromachining fabrication process. However, the vertical beam adjustment is accompanied by angular squinting because of the tilting mechanism.

In this paper, we report on the first demonstration of microactuated micro-XYZ stages fabricated by the surface-micromachining technology. The micro-XYZ stage has travel distances over 30 μm and resolution of 11 nm in all X-, Y-, and Z-directions. Integration of the micro-XYZ with microlenses has also been demonstrated on FS-MOB. The micro-XYZ stage is very important for high performance integrated micro-optical systems.

DESIGN AND FABRICATION

Z-stage

Our objective here is to achieve vertical adjustment of optical beams (Z-stage) using only in-plane microactuators. A novel beam-steering device consisting

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of two 45° mirrors is utilized to transform the in-plane motion of the mirror to out-of-plane (vertical) displacement of the optical beam [10]. The schematic structure of the micro-beam steering device, together with a semiconductor laser source, is illustrated in Fig. 1. The fixed, lower 45° mirror reflects the optical beam upwards. The moveable upper 45° mirror redirects the light back into in-plane direction. This design effectively transforms the in-plane motion of the upper mirror into out-of-plane adjustment of the optical beams. In addition to optical alignment, this device can also be used to match the optical axes of different micro-optical components.

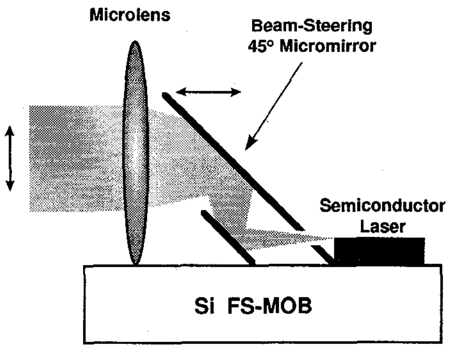

Figure 1 The schematic drawing of a monolithic Z-stage using only in-plane microactuators.

Figure 2 shows the far-field patterns of the optical beams imaged through the integrated microlens as the upper 45° mirror moves towards the microlens. The patterns are measured by a CCD camera positioned at 8.5 cm from the microlens. Very good beam profiles have been obtained, as shown in Fig. 2. Large vertical displacement of 140 μm has been achieved by the current device. It is only limited by the size of the upper 45° mirror, and can be further increased if necessary.

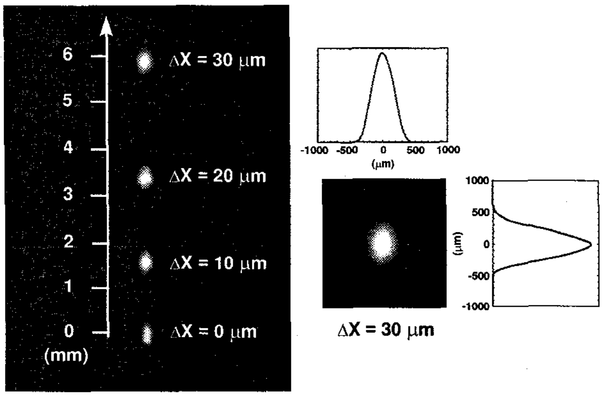

Figure 2 The far-field patterns of the optical beams imaged through the microlens as the upper 45° mirror is moved towards the lens.

The vertical displacement of the optical beam before the microlens is equal to the in-plane displacement of the upper 45° mirror. This is confirmed in Fig. 3, which shows the measured position of the imaged beams versus the displacement of the upper 45° mirror. The vertical displacement before microlens can be deduced using paraxial approximation at small displacement. Good agreement with theoretical prediction has been obtained.

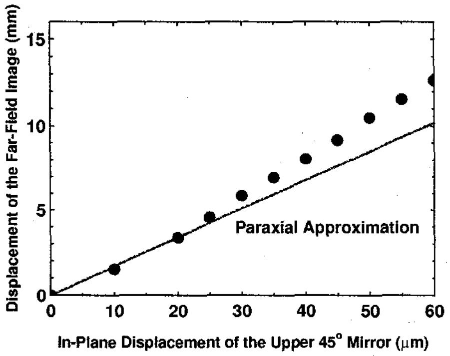

Figure 3 Position of the imaged optical beams versus the displacement of the upper 45° mirror.

Micro-XYZ stage

The Z-stage is modified to form an XYZ stage by turning the lower 45° mirror by 90°, and integrating translation stages to both the lower mirror and the microlens plate. Figure 4 shows the schematic drawing of the micro-XYZ stage.

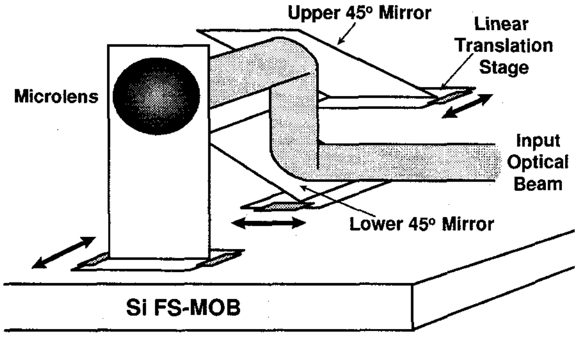

Figure 4 Schematic drawing of the microactuated XYZ stage.

Lateral adjustment of the optical beam is achieved by moving the lower 45° mirror, while vertical (height) adjustment is accomplished by moving the upper 45° mirror. Longitudinal (focal length) adjustment is attained by moving the micro-Fresnel lens along the optical path. *This unique micro-XYZ stage design allows adjustment of optical beams in the out-of-plane direction without requiring any out-of-plane actuators. Independent adjustment of X, Y, and Z positions without* *angular beam squinting can be achieved using only in-plane microactuators.*

The scanning electron micrographs (SEM) of the micro-XYZ stage are shown in Fig. 5. Both the micro-XYZ stage and the microlens on the FS-MOB are fabricated by the surface-micromachining technology with two structural polysilicon layers. The three-dimensional plates are supported by the micro-hinges [11]. The translation stages and the micro-optical elements are defined on the first (poly-1) and the second (poly-2) polysilicon layers, respectively. The moveable plates are confined by the guiding rails defined on poly-2. The details of the fabrication process is described in Ref. [2]. The three-dimensional structures are assembled after release etching, which selectively removes the phosphosilicate glass (PSG) sacrificial materials. The angle of the lower 45° mirror is defined by the length of the micro-spring latches. The upper 45° mirror is flipped from the other side and locked to the supporting structure, whose height defines the angle of the mirror.

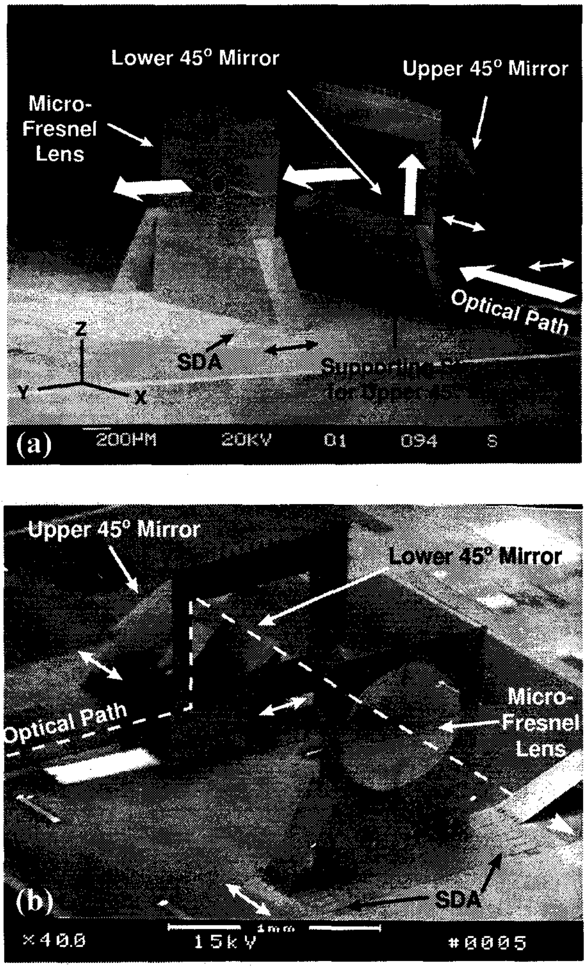

Figure 5 The SEM micrographs of the micro-XYZ stage from two perspectives.

Integration with microactuators

To achieve on-chip optical alignment in FS-MOB, integrable microactuators with fine motion control (sub-0.1 μm step size) are needed. The scratch drive actuator (SDA) [9] is particularly attractive for actuating the micro-XYZ stage because it has reasonably large force and long travel distance, and yet occupies a very small area (~ 100 × 100 μm^2 for each SDA). It is a stepping microactuators with extremely fine step-sizes (~ 10 nm) that can be precisely controlled by electrical pulses without requiring resonance operation, does not require standby power, and can be easily integrated with the micro-optical elements on the FS-MOB through the same surface-micromachining fabrication process.

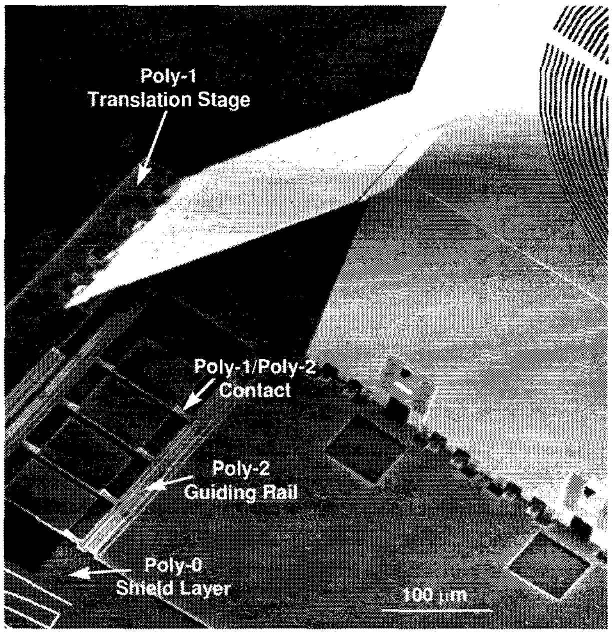

Figure 6 The close-up SEM micrograph illustrating the integration of the SDAs and the three-dimensional micro-optical elements sitting on translation stages.

Figure 6 shows the SEM micrograph illustrating the integration of the SDAs and the three-dimensional micro-optical elements sitting on translation stages. The SDA is built on the second polysilicon layer and connected to the moveable plate built on the first polysilicon layer through via holes. The fabrication process of the SDA is shown in Fig. 7. A layer of Si_3N_4 is first deposited on the conductive silicon substrate for electrical insulation. The bushing part of the SDA is formed by etching a via hole through the first PSG layer (PSG-1) and depositing the PSG-2 and poly-2 layers. As the SDA is attracted to the substrate by applying pulse bias between the poly-2 plate and the substrate, the bushing is pushed forward because of the bending of the SDA plate. When the bias returns to zero, the poly-2 plate is released from the substrate and the SDA is pulled forward by the bushing due to the friction between the bushing and the substrate. The motion of the SDA can therefore be controlled very precisely by the electric pulse bias. The details of the working principles of the SDA can be found in Ref. [9]. A polysilicon layer (poly-0) is deposited between the Si_3N_4 layer and the translation stage for electric shielding. The bias for the SDA can be applied through the poly-0 layer and the poly-2 guiding rails for the translation stages which are connected to the poly-0 layer.

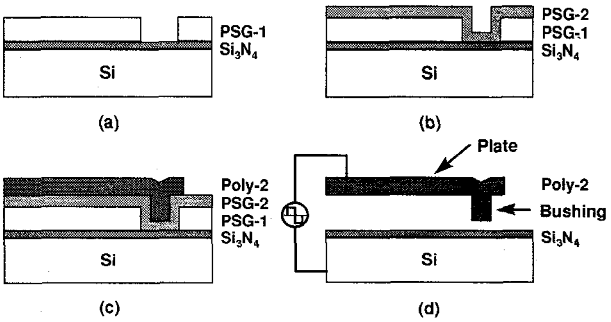

Figure 7 The surface-micromachining fabrication process of the scratch drive actuators (SDA).

EXPERIMENTAL RESULTS

Two-dimensional scanning (in X-Z plane)

To characterize the performance of the micro-XYZ stage, a CCD camera is employed to measure the scanned far-field patterns of the optical beams after passing through the integrated micro-Fresnel lens. The focal length of the micro-Fresnel lens is designed to be 2.3 mm, and the distance between the CCD camera and the device is 14 cm. Light emitted from a single mode fiber at a wavelength 632.8 nm is used as the light source. The fiber is placed at the focal point of the Fresnel lens. Figure 8 shows the two-dimensionally scanned images of the optical beam in the X-Z plane. The ΔX and ΔZ are the displacement of the optical beam on the micro-Fresnel lens with respect to the center of the lens, while ΔX_1 and ΔZ_1 are the corresponding far-field displacement on the CCD camera after imaged by the Fresnel lens. The ΔX and ΔZ directly correspond to the translations of the lower 45° mirror in X-direction and the upper 45° mirror in Y-direction, respectively. The displacements of the far-field patterns are amplified by the Fresnel-lens. The ΔX_1 (ΔZ_1) is related to ΔX.(ΔZ) by

$$\Delta X_1, \Delta Z_1 = \Delta X, \Delta Z \cdot \frac{D-f}{f} \approx \Delta X, \Delta Z \cdot \frac{D}{f} \qquad (1)$$

under paraxial approximation, where *D* is the distance between the CCD camera and the Fresnel lens, and *f* is the focal length of the Fresnel lens. The optical beam can be independently moved in the X- and Z-directions, to any desired position in the X-Z plane, by moving the lower and upper 45° mirrors, respectively. The adjustment range corresponds to the linear translation of the mirrors directly, and there is no angular squint associated with the linear adjustment. Optical beam movement over 30 μm in both X- and Z-directions has been achieved. The corresponding far-field displacement is 2.3 mm, as shown in Fig. 8.

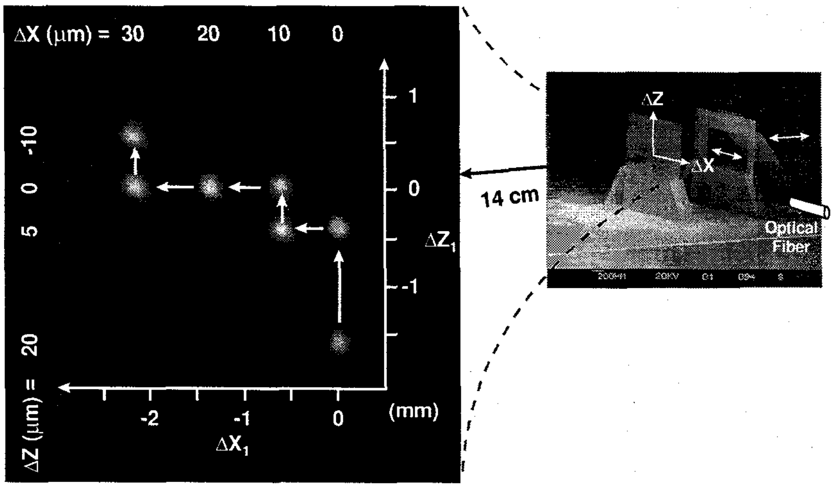

Figure 8 Two-dimensional (X-Z plane) optical beam scanning by moving the lower and upper 45° mirrors of the micro-XYZ stage independently.

Focal length adjustment (Y-direction)

The focal length adjustment in the micro-XYZ stage was also demonstrated by moving the micro-Fresnel lens along the optical path (Y-direction). The positions of the lower and upper 45° mirrors are fixed such that the optical beam is aligned with the center of the micro-Fresnel lens in this experiment. Figure 9 shows the 1/e field beam-width of the far-field images measured by the CCD camera versus the displacement of the collimating lens. The origin of the lens position is defined to be the collimation point. The optical beam diameter changes from 1040 μm to 460 μm when the microlens is moved from -60 μm (towards the light source so that the optical beam is divergent) to +20 μm (away from the light source so that the optical beam is focused). The far-field images for various positions of the collimating lens are shown in the inset of Fig. 9. The effect of adjusting the position of the collimating lens can be easily seen from these far-filed images.

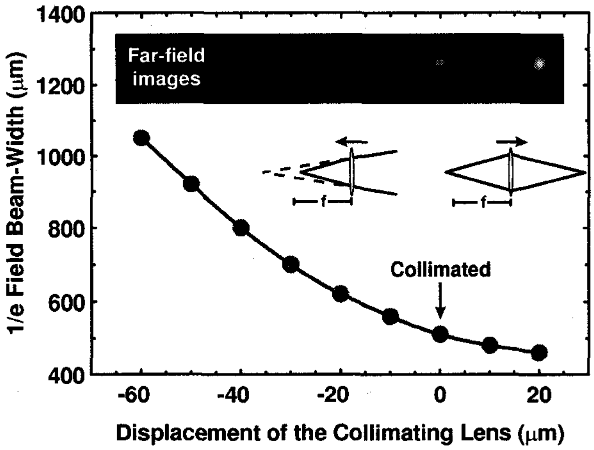

Figure 9 Focal length adjustment by moving collimating lens along the optical path

Microactuation

The three linear translation stages in the micro-XYZ stage have been integrated with the SDA's to achieve fine optical alignment. Figure 10 shows the SEM micrograph of the micro-Fresnel lens integrated with eight SDA's (four on each side). The dimension of the SDA is 50 μm × 70 μm and the dimension of the Fresnel lens is 800 μm × 1020 μm. To characterize the resolution of the SDA, the velocity of the micro-Fresnel lens in the Y-direction is measured under various driving frequencies. Electrical pulses with ±87 V amplitudes are applied between the actuators and the substrate. The velocity of the micro-Fresnel lens versus the actuating frequency of the SDA's is shown in Fig. 11. The speed of the micro-Fresnel lens increases linearly with the actuating frequency. From the slope of the fitted line, the average step-size of the SDA is found to be 11 nm for each electric pulse actuation. The standard deviation of the step-size for different frequencies is 0.76 nm. Since the SDA does not need to be operated under resonance condition, the micro-optical elements can move at discrete steps of 11 nm, or move at any arbitrary speed (up to a few tens of μm/sec) by tailoring the actuating frequency. Such precision is more than enough to achieve fine optical alignment. The travel distance of the SDA is essentially unlimited as the electrical bias is applied to the SDA through the poly-0 shield layer and the poly-2 guiding rails for the translation stages. No physical contact to the fixed electrode is required for the SDA, which makes it attractive for actuating micro-optical elements requiring long travel distance. The SDA can also be combined with other high speed actuator to form a "differential drive" to actuate the micro-XYZ stage.

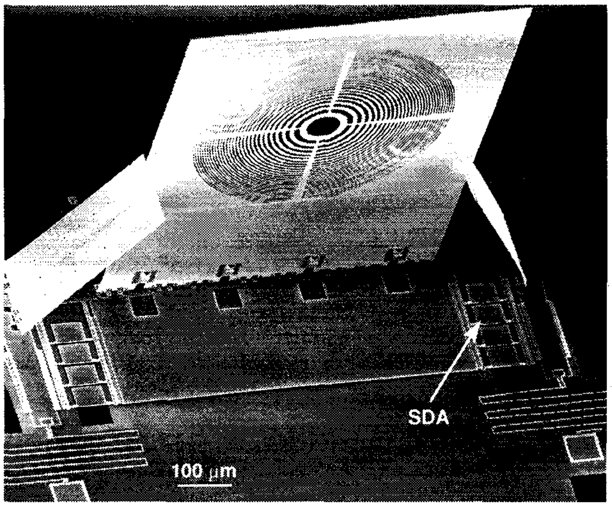

Figure 10 The SEM micrograph of the micro-Fresnel lens in the micro-XYZ stage integrated with eight scratch drive actuators (SDA).

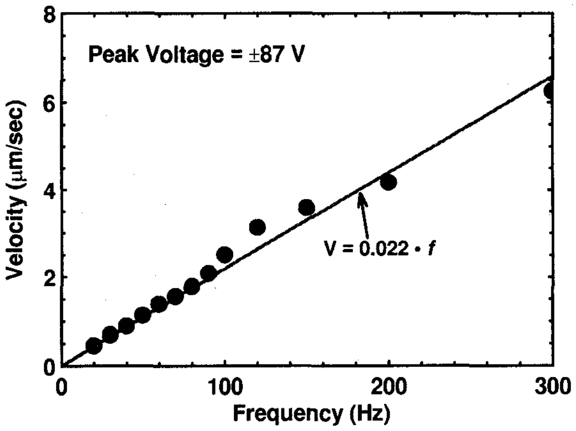

Figure 11 The velocity of the micro-Fresnel lens in the micro-XYZ stage versus the actuating frequency of the SDA's.

CONCLUSION

A novel micro-XYZ stage with integrated scratch drive actuators has been successfully demonstrated on the free-space micro-optical bench (FS-MOB) using surface-micromachining fabrication technique. High positioning accuracy (11 nm) and large travel distance (> 30 μm) have been demonstrated in all three directions. The micro-XYZ stage with submicron resolution greatly enhance the capabilities of the FS-MOB technology, and is very useful for high performance micro-optical systems.

ACKNOWLEDGMENTS

The authors would like to thank Professor K. S. J. Pister for helpful discussions, and Li Fan for technical assistance. This research is supported by DARPA and the Packard Foundation. Part of the micromachined devices were fabricated by the DARPA supported MUMPs fabrication services at MCNC.

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