Surface-Micromachined Micro-XYZ Stages for Free-Space Microoptical Bench

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***Abstract*— Micro-XYZ stages have been monolithically integrated with microactuators and out-of-plane microoptical elements, all fabricated by the same surface-micromachined process, on Si free-space microoptical bench. Optical beam adjustment with three degrees of freedom has been realized without angular squinting. A positioning accuracy of 11 nm has been achieved by the integrated scratch drive actuators, with the travel distance larger than 30 μm in each direction.**

***Index Terms*— Beam steering, integrated optics, microactuators, microelectromechanical devices, optical components, optical device fabrication.**

I. Introduction

THE surface-micromachining free-space microoptical bench (FS-MOB) has been shown to be a promising technique for integrating free-space optical systems on a single chip [1], [2]. Out-of-plane three-dimensional (3-D) microoptical elements, translation and rotation stages, and microactuators can be batch-fabricated by the same surface-micromachining process and monolithically integrated on the same substrate. Various 3-D microoptical elements have been demonstrated, including diffractive and refractive microlenses, microgratings, beam-splitters, and micromirrors [1]–[4]. Microoptical systems such as single-chip free-space optical disk pickup heads [5] have also been realized. The FS-MOB can greatly reduce the size, weight, volume, and potentially the cost of the free-space optical systems. The applications of FS-MOB include optical data storage, sensing, switching, scanning, display, and printing.

Another unique advantage of FS-MOB is that the optical system can be “prealigned” during layout of the photomasks since all the microoptical elements are fabricated at the same time by photolithographic processes. This can reduce the assembly and alignment cost of bulk optical systems. The accuracy of the prealignment is, however, limited to about 1 μm due to the tolerance of the microfabrication processes. Submicron alignment accuracy can be readily achieved in conventional optical systems by micropositioners such as XYZ stages. It is therefore desirable to have integrable micro-XYZ stages on FS-MOB. In-plane micropositioners (in X- and Y-directions) have been realized by the surface-micromachined microactuators. Alignment in the out-of-plane (Z) direction, however, is more challenging since most of the vertical microactuators only have limited travel distance [6] and may not be compatible with the surface-micromachining processes. Vertical alignment has been realized by a translation/tilting micromirror [4], however, it is accompanied by angular squint. Previously, by using a novel beam steering device comprising two vertically stacked 45° mirrors, we have successfully achieved vertical adjustment of optical beams by in-plane movement only [7]. In this paper, we extend the concept into a fully integrated micro-XYZ stage with three independent degrees of freedom. Actuation with an accuracy of 11 nm has been achieved by the integrated scratch drive actuators (SDA) [8].

Manuscript received September 16, 1996. This work was supported in part by DARPA and Packard Foundation.

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Publisher Item Identifier S 1041-1135(97)01940-X.

II. Design and Fabrication

Fig. 1(a) shows the schematic drawing of a micro-Fresnel lens integrated with the micro-XYZ stage. The incoming beam (a horizontal beam from an upright-mounted semiconductor laser in this example) is reflected upward by the lower 45° mirror which is integrated with a linear translation stage. The X-adjustment (see Fig. 1(a) for definitions of X, Y, and Z) is achieved by the translation of the lower mirror. The upper 45° mirror is orthogonal to the lower mirror and is responsible for the Z-adjustment (height adjustment). The optical beam is redirected by the upper 45° mirror toward the micro-Fresnel lens. The Y-adjustment (focal length adjustment) is achieved by the translation of the micro-Fresnel lens along the optical path.

Fig. 1(b) shows the SEM micrograph of the micro-XYZ stage. Both the micro-XYZ stage and the free-space microoptical elements are fabricated using the microhinge technique [9]. The translation stages and the microoptical elements are defined on the first and the second polysilicon layers, respectively. The 3-D structures are assembled after selectively removing the PSG sacrificial material in between the polysilicon layers and the substrate. The angle of the lower 45° mirror is defined by the length of the microspring 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. The translation stages are integrated with scratch drive actuators (SDA) [8] for fine adjustment of the beam position. The SDA is particularly attractive for actuating the micro-XYZ stage because it moves in extremely fine steps (~10 nm) that can be precisely controlled by electrical pulses, occupies very small area (~100×100 μm^2), does not require standby power, and can be easily integrated with the microoptical elements on the FS-MOB through the same surface-micromachining fabrication process. The SDA is built on the second polysilicon

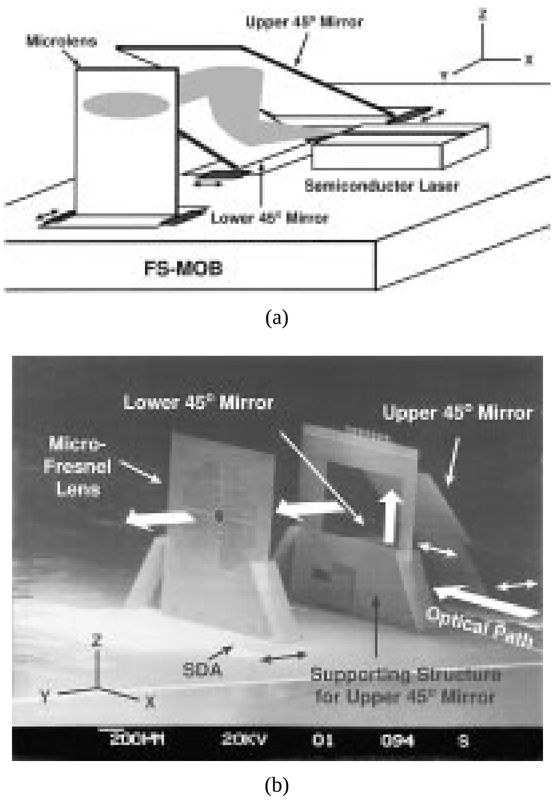

Fig. 1. (a) The schematic drawing, and (b) The SEM micrograph of the micro-XYZ stage on the FS-MOB.

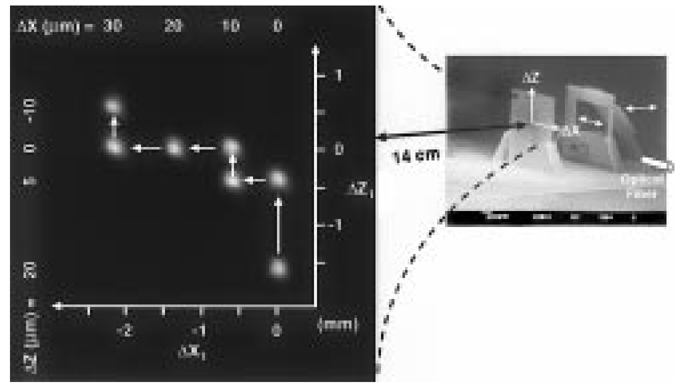

Fig. 2. Two-dimensional (X–Z plane) optical beam scanning by moving the lower and upper 45° mirrors of the micro-XYZ stage independently.

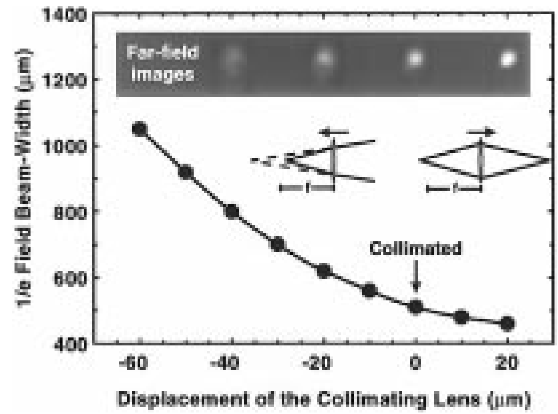

Fig. 3. Focal length adjustment by changing the position of the collimating lens along the optical path (Y-direction).

layer and connected to the moveable plate built on the first polysilicon layer through via holes. The micro-XYZ stage has the unique advantage of independent adjustment of the X, Y, and Z position without any angular beam squinting. It can be readily integrated with other surface-micromachined microoptical elements, and is very useful for high-performance single-chip microoptical systems.

III. Experimental Results

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 632.8 nm wavelength is used as the light source. Fig. 2 shows the two-dimensional (2-D) scanning 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. 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. There is no angular squinting associated with the linear adjustment. Optical beam movement over 30 μm has been demonstrated.

The focal length adjustment has also been demonstrated by moving the micro-Fresnel lens in the Y-direction. Fig. 3 shows the $1/e$ field beam-width of the far-field images on 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 is changed from 1040 μm to 460 μm when the microlens is moved from -60 μm to $+20$ μm. The far-field images at various positions of the collimating lens are shown in the inset of Fig. 3.

The micro-XYZ stage is integrated with three sets of SDA's to achieve fine optical alignment. Fig. 4 shows the top-view photograph of the micro-Fresnel lens (before assembly) integrated with eight SDA's (four on each side). The dimension of the SDA is 50 μm $\times$ 70 μm. To characterize the movement of the SDA, the velocity of the assembled micro-Fresnel lens in the Y-direction is measured under various actuating frequencies. Electrical pulses with $\pm$87 V amplitudes are applied between the actuator and the substrate. Fig. 5 shows the velocity of the assembled lens versus the actuating frequency of the SDA's. The speed increases linearly with the actuating frequency. From the slope of the fitted line, the distance of the stepwise movement is found to be 11 nm for each electric pulse actuation. Since the SDA does not need to operate under resonance condition, the microoptical elements can move at discrete steps of 11 nm, or move at any arbitrary speed (up to a few tens of μm/s) by tailoring the actuating frequency. Such precision is more than adequate for fine optical alignment. The traveling distance of the SDA is essentially unlimited as the applied bias is applied to the

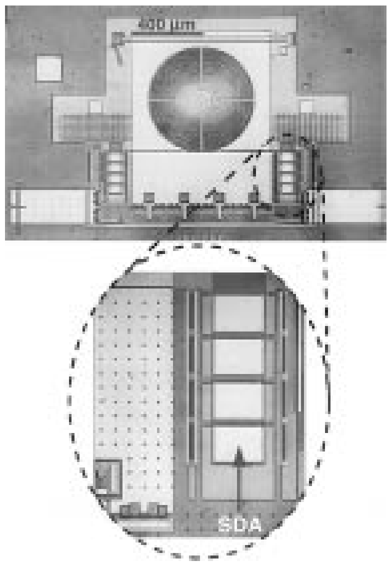

Fig. 4. The top-view photograph of the micro-Fresnel lens in the micro-XYZ stage integrated with eight scratch drive actuators (SDA) before assembly. The dimension of the lens is 800 μm $\times$ 1020 μm.

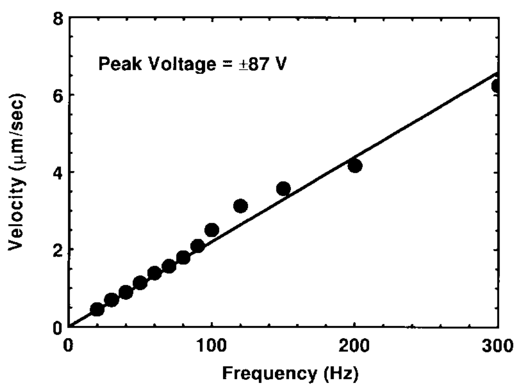

Fig. 5. The velocity of the assembled micro-Fresnel lens in the micro-XYZ stage versus the actuating frequency of the SDA.

SDA through the ground polysilicon layer and the guiding rails for the translation stages. No physical contact to the fixed electrode is required, which makes it attractive for actuating microoptical elements requiring long traveling distance. The SDA can also be combined with other high speed actuator to form a "differential drive" to actuate the micro-XYZ stage.

IV. Conclusion

A novel micro-XYZ stage with integrated scratch drive actuators has been successfully demonstrated on free-space microoptical bench (FS-MOB) using the surface-micromachining technique. The micro-XYZ stage consists of two vertically stacked 45° mirrors in orthogonal directions, each integrated with a linear translation stage, and the optical element is mounted on the third translation stage. Adjustment of the optical beam with three degrees of freedom and a positioning accuracy of 11 nm have been experimentally demonstrated. The precision XYZ stage permits high performance microoptical systems to be realized in FS-MOB.

Acknowledgment

Part of the devices were fabricated by the DARPA-sponsored MUMP's fabrication services.

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