Micro-Machined Three-Dimensional Micro-Optics for Integrated Free-Space Optical System

L. Y. Lin, S. S. Lee, K. S. J. Pister, *Member, IEEE,* and M. C. Wu, *Member, IEEE*

***Abstract*— Novel, integrable three-dimensional micro-optical elements have been realized by surface micromachining technology. Rotatable mirrors, lenses and beam-splitters standing perpendicular to the substrate are demonstrated. The optical elements are precisely hold at 90° angle to the substrate by side latches. The Si substrate serves as a "micro-optical bench" on which monolithic micro-optical systems consisting of movable and static micro-mirrors, lenses and other components are constructed. The optical system is pre-aligned by photolithography. This technology offers a new approach to free-space integrated optics and low-cost optical packaging.**

I. Introduction

INTEGRATED OPTICS has been an active research area since 1970's [1]. To date, most of the research efforts focus on guided-wave approach [2]. On the other hand, free-space optics offers many unique advantages that cannot be achieved in guided-wave devices. For example optical interconnect allow us to implement three-dimensional topology that could significantly improve the communication bottlenecks in VLSI systems [3]. Much higher spatial bandwidth (diffraction limit) can be achieved. It is also possible to perform sophisticated optical information processing such as Fourier transform in free space using lenses. However, most of the present free-space optical systems consist of bulk optical elements or multiple-plane microlens arrays that cannot be integrated on a single chip [4], [5].

Three-dimensional micro-optics fabricated by surface-micromachining opens a new area for integrated optics in free-space. Using this new technology, integrable micro-optical elements can be made to stand perpendicular to the substrate. Thus multiple free-space optical elements along the optical path can be made on the same substrate. This allows sophisticated optical system with a large number of optical elements to be integrated monolithically. The substrate serves as a "micro-optical bench", and lenses, mirrors and other components are pre-aligned by photolithography and then constructed by microfabrication [6]–[8]. Previously, we have successfully fabricated a micro-Fresnel lens with the Fresnel zone plate standing perpendicular to the substrate [6], [7]. Excellent optical collimating ability has been achieved. The micro-Fresnel lens was supported by micro-spring latches. Because the lens could be significantly taller than the spring latches, the angle of the lens could deviate slightly from 90°. This is undesirable for large optical systems. In this letter, we demonstrate a new side-latch that precisely fixes the angle of the lenses at 90°. It also greatly increases their mechanical strength. We further demonstrate a three-dimensional *rotatable* mirror fabricated by the same technology. This rotatable plate can be used to construct micro-spectrometers and other micro-optic systems.

Manuscript received June 13, 1994; revised August 15, 1994. This work was supported in part by ARPA NCIPT, ARPA ULTRA, and the Packard Foundation.

The authors are with the Electrical Engineering Department, University of California, Los Angeles, CA 90024 USA.

IEEE Log Number 9406200.

II. Fabrication

The three-dimensional micro-optical system is constructed on Si substrate by surface micromachining technology. Various optical elements can be made in polysilicon plates. These plates could be folded to be perpendicular to the substrate with their bottom fixed by micro-machined micro-hinges and micro-spring latches [9]. The schematic structure is shown in Fig. 1. The fabrication process is described in the following: First, a 2-μ-thick phosphosilicate glass (PSG-1) is deposited on the silicon substrate as the *sacrificial layer.* Then the first polysilicon layer (poly-1) of 2 (μm thickness is grown on PSG-1. Various optical elements such as Fresnel lenses, mirrors, beam splitters, and gratings are made on the poly-1 layer using photolithography and dry etching. The hinge pins holding the optical elements when they are lifted up are also defined on this layer. Following the deposition and patterning of poly-1, another layer of sacrificial material (PSG-2) of 0.5 μm thickness is deposited. The supporting structures such as staples and spring latches are defined on the second polysilicon (poly-2) layer. The base of the staples and torsion springs are fixed on the Si substrate by opening contact holes through both PSG-2 and PSG-1 before the deposition of poly-2 layer. The poly-2 structures can also be fixed on poly-1 by etching contact holes through PSG-2 only, as required in the rotatable mirror to be described later. The optical elements are released from substrate by selectively removing the PSG materials. After the release etching, the poly-plates with micro-optics patterns are free to rotate around the hinge pins. When the plate is lifted up, the top portion of the spring latch slides into the slot on the plate, and snaps into the narrower part of the slot, thus preventing further motion of the plates. The torsion-spring connecting the spring-latch to the substrate creates the spring force, which tends to force the spring-latch back to the substrate, therefore locks the plate in its place. The length of the spring latch defines the angle between the plate and the substrate, which is approximately 90°. After the three-dimensional micro-optics is assembled, a layer of gold is coated on the lifted poly surfaces. In binary-amplitude Fresnel

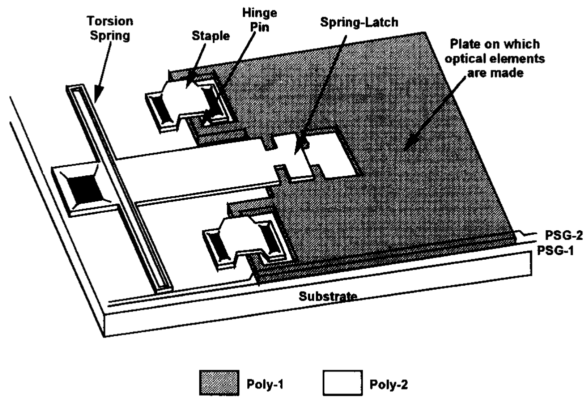


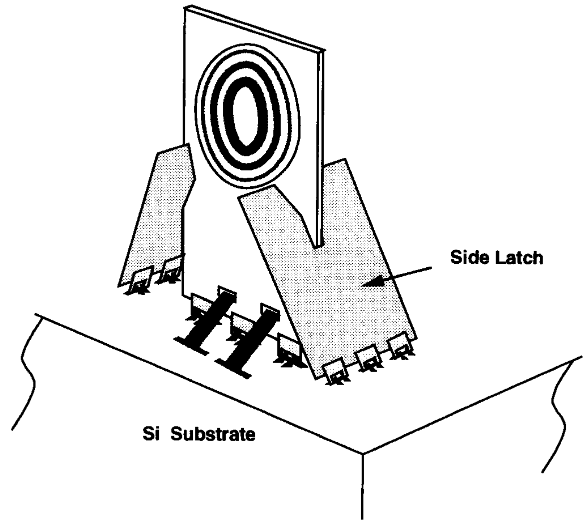
Fig. 1. Schematic structure of the three-dimensional micro-optics fabricated by surface-micromachining. After release etch, the micro-optical plate can be rotated out of the substrate plane and locked by the micro-spring latches.

zone plates or micro-mirrors, a thick layer of gold is coated to completely block the light passing through the dark zones or to make a perfectly reflecting mirror. On the other hand, thinner gold is used for partially transmitting mirrors or beam splitters.

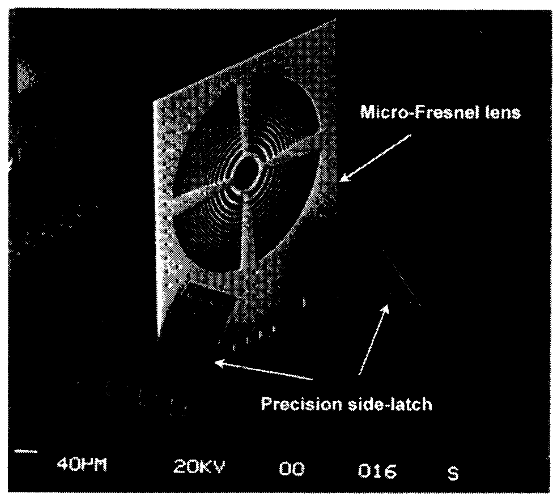
III. Results

The schematic diagram and the scanning electron micrograph (SEM) of an assembled micro-Fresnel lens is shown in Fig. 2(a) and (b), respectively. The diameter of the lens is 280 μm, and the optical axis is 254 μm above the silicon surface. Because of the height of the lens plate (430 μm), the angles between the lens plates and the substrate has some variations even though they are coarsely fixed by the spring latches. Such variations are not tolerable in large optical systems. We have designed a new "side-latch" to precisely define the angles of the three-dimensional micro-optical elements. The side latches consist of folded polysilicon plates similar to the lenses but the folding direction is orthogonal to that of the lens plate. The side latch has a V-shaped opening on the top to guide the lens plate into a 2-μm-wide groove in the center [9]. The side latches are folded from two sides of the lens plate, and can be made as tall as the lens itself. Therefore, the angle defined by the side latches are much more precise. Indeed, this has been observed experimentally. Under optical microscope, the mirror image of the lens reflected from the Si surface forms a straight extension of the lens itself. The side latches also greatly improve the mechanical strength and stability of the micro-optical elements.

One unique advantage of using surface micro-machining to implement micro-optical bench is that it is possible to fabricate movable or adjustable optical elements. Examples of that include rotating gratings, scanning mirrors, and opto-mechanical switches. Micro-machined rotation structures have been demonstrated by Fan *et al.* in their electrostatic micromotors [10]. We have successfully fabricated a rotatable mirror using the same process described earlier. In order to put the optical elements on the rotating plate made in poly-1, the optical elements are now defined on poly-2. After the release etch, the PSG materials are removed and the poly-1 layer can



(a)



(b)

Fig. 2. (a) Schematic diagram of the three-dimensional micro-optics with side latches on both sides. (b) SEM photograph of a three-dimensional micro-Fresnel lens with side latches. The lens diameter is 280 μm.

rotate freely on the substrate around the axle defined on poly-2. The fabrication process is similar to that in Fig. 1, except the spring-latches and staples are now connected to poly-1 (the rotating plate). The micro-hinges are defined on the rotating poly-1 plate, and the micro-optics patterns are defined on the poly-2 layer, with its bottom connected to the micro-hinges on poly-1. Fig. 3 shows the SEM photograph of a three-dimensional micro-mirrors fabricated integrally on a rotatable plate. The dimension of the mirror is 400 × 480 μm^2. Thirty-six ticks are made on the substrate to indicate the rotation angle of the plate (due to the contrast of the photograph, only part of the ticks are shown). The angle between adjacent ticks is 10°. The indicator on the lower part of the picture, originally pointing at the 0° tick (indicated by the white arrow), has been

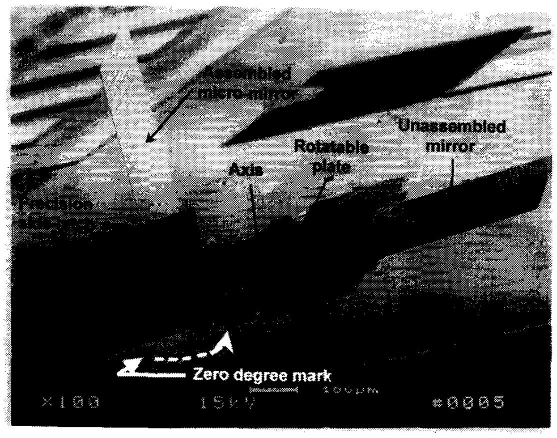


Fig. 3. SEM photograph of a rotatable micro-mirror.

rotated counterclockwise by 20° after the mirror is assembled, as shown on the picture.

The optical performance of the three-dimensional micro-Fresnel lens has been tested by collimating a divergent beam emitted from a single mode fiber at $\lambda = 1.3$ μm. This lens has a diameter of 650 μm and a focal length of 1 mm. The micro-Fresnel lens was originally designed for semiconductor lasers with numerical apertures (NA) of approximately 0.2 to 0.4 and therefore, does not match the NA of the optical fibre used in the measurement. The measurement was done using optical fibre as emitting source because of the accessibility of the microlens. Fig. 4 compares the divergence of the optical beams with and without the collimating lens. The intensity FWHM divergence angle is reduce from 5.0° to 0.33° (the corresponding 1/e angles of Gaussian beams are 8.3° and 0.56°). The collimated beam profile fits very well to the Gaussian shape (95% fit). These results are slightly improved over the previous micro-Fresnel lens at 0.98 μm wavelength [7] because of larger illumination area on the micro-lens in the present design (theoretical divergence angle is inversely proportional to the beam waist on the lens plane). A preliminary measurement has also been made with a higher NA source. A semiconductor laser with FWHM farfield angles of 18° × 40° is mounted in front of the micro-lens on the same Si chip. The collimated beam has an elliptical shape, and the intensity FWHM measured at 5 cm behind the lens are 330 μm and 788 μm, respectively. The diffraction efficiency of the micro-Fresnel lens was measured to be 8.6% using the method described by Rastani *et al.* [11]. This is in agreement with theoretical value for binary-amplitude Fresnel zone plates. Higher theoretical diffraction efficiency of 41% can be achieved by binary-phase Fresnel lens, which can be realized by an additional dry etching step.

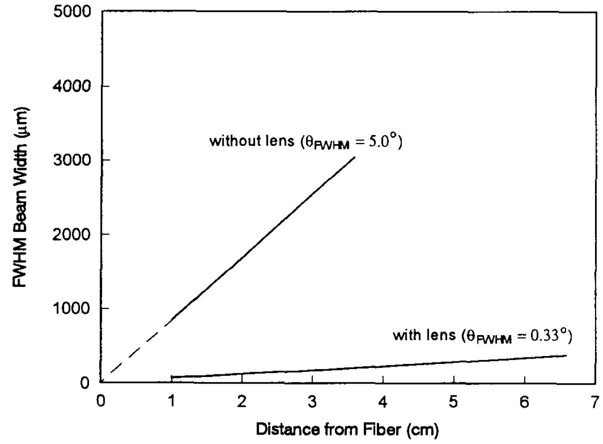


Fig. 4. Collimating performance of the three-dimensional micro-Fresnel lens at $\lambda = 1.3$ μm. The intensity FWHM divergence angle of the light emitted from a single-mode fiber is reduced from 5.0° to 0.33° by the lens.

IV. Conclusion

In summary, a new *micro-optical bench* suitable for free-space integrated optics is proposed and demonstrated. Both movable and static three-dimensional micro-optical elements such as Fresnel lenses, mirrors, beam-splitters and gratings have been realized using surface-micromachining technology. These optical elements are monolithically integrated on a small silicon chip. The optics can be pre-aligned by photolithography. The micro-lenses and rotatable mirrors reported in this letter can be used to implement free-space optical interconnects, optical switches and optical storage systems. This approach offers many new possibilities in optoelectronic packaging and micro-optical systems.

References

[1] S. E. Miller, "Integrated Optics: An Introduction," *Bell Syst. Tech. J.*, vol. 48, no. 7, pp. 2059–2068, 1969.

[2] H. Nishihara, M. Haruna, and T. Suhara, *Optical Integrated Circuits*. New York:McGraw-Hill, 1985.

[3] J. W. Goodman, F. J. Leonberger, S.-C. Kung, ,and R. A. Athale, "Optical interconnection of VLSI systems," *Proc. IEEE*, vol. 72, no. 7, pp. 850–866, 1984.

[4] F. B. McCormick and M. E. Prise, "Optical circuitry for free-space interconnections," *Applied Optics*, vol. 29, no. 14, pp. 2013–2018, 1990.

[5] S. Kawai, "Free-space multistage optical interconnection networks using micro-lens arrays," *J. Lightwave Technol.*, vol. 9, no. 12, pp. 1774–1779, 1991.

[6] L. Y. Lin, S. S. Lee, K. S. J. Pister, and M. C. Wu, "Vertical three-dimensional micro-Fresnel lenses fabricated by micromachining technique," *Optical Fiber Communication Conf.*, San Jose, CA, Feb. 20–25, 1994, postdeadline paper PD12.

[7] ——, "Three-dimensional micro-Fresnel optical elements fabricated by micromachining technique," *Electronics Letters*, vol. 30, no. 5, pp. 448–449, 1994.

[8] O. Solgaard, M. Daneman, N. C. Tien, A. Friedberger, R. S. Muller, and K. Y. Lau, "Micromachined alignment mirrors for active opto-electronic packaging," *Conf. Lasers and Electro-Optics*, Anaheim, CA, May 8–13, 1994, postdeadline paper CPD6.

[9] K. S. J. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated hinges," *Sensors and Actuators A*, vol. 33, pp. 249–256, 1992.

[10] L. S. Fan, Y. C. Tai, and R. S. Muller, "IC-processed electrostatic micromotors," *Sensors and Actuators*, vol. 20, pp. 41–47, 1989.

[11] K. Rastani, A. Marrakchi, S. F. Habiby, W. M. Hubbard, H. Gilchrist, and R. E. Nahory, "Binary phase Fresnel lenses for generation of two-dimensional beam arrays," *Applied Optics*, vol. 30, no. 11, pp. 1347–1354, 1991.