Optical Scanners Realized by Surface-Micromachined Vertical Torsion Mirror

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Abstract— **We report on a novel vertical torsion mirror fabricated by surface-micromachining for optical scanner applications. Driven by an electrostatic actuator, the scanning mirror has a resonant frequency of 0.5 kHz and an optical scan range of 26°. The maximum achievable number of resolvable spots for this 300 μm × 250 μm scanner is 238.**

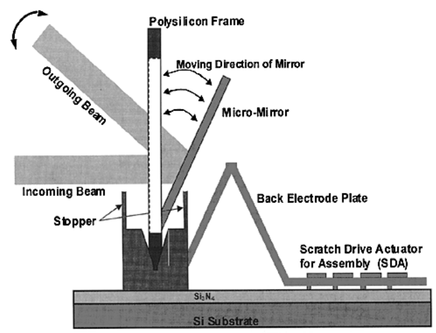
Index Terms— **Electrostatic actuator, microelectromechanical systems, microoptoelectromechanical systems, optical scanner.**

I. Introduction

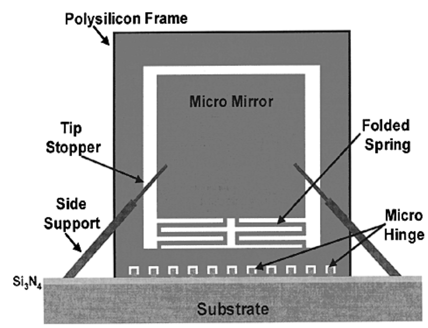
OPTICAL scanners are widely used in scientific and industrial applications ranging from laser imaging to printers and scanning displays. Present optical scanners are generally based on rotary or galvanometric systems. They are usually heavy, expensive, and have poor reliability. The micromachining technology is very attractive to reduce the size, weight, and cost of the scanners. Previously, optical scanners have been realized by both bulk and surface micromachining technologies [1]–[5]. Surface-micromachined optical scanners with out-of-plane mirrors are particularly interesting because they can be integrated with other micromechanical and/or optoelectronic devices. Surface-micromachined scanners with microhinge (staple-and-pin hinge) [1] and torsion bar hinge [5] supports have been reported. The angular position accuracy of the torsion mirror scanner was shown to be five times better than the scanner with staple-and-pin hinge [5]. However, the loose staple-and-pin joints used to connect the out-of-plane mirrors and in-plane comb drive actuators can still cause angular inaccuracy and constant wear and tear. In this letter, we report on the performance of an out-of-plane vertical torsion mirror scanner. We employ an angular gap-closing actuator, thus avoiding the use of any loose hinges in the scanner. An optical scan range of 26° and a resonant frequency of 0.5 kHz have been experimentally demonstrated. This device is compact, lightweight, and can be mass-produced at potentially low cost.

II. Design and Fabrication

The scanner is realized by the surface-micromachined micro-optical bench technology (FS-MOB) [6]. Fig. 1 shows the schematic diagram of the vertical torsion mirror scanner. The scanner consists of two main components—a vertical torsion mirror and a fixed back electrode; both are fabricated by the three-layer surface micromachining technology. The micromirror is attached to a polysilicon frame by a pair of folded torsion springs using the same layer of polysilicon, and is designed to rotate up to 20° mechanically toward the back electrode. The polysilicon frame is folded up from the substrate and fixed vertically by the side latch. The tips extruded from the side latch (see Fig. 1) serve as mechanical stoppers to prevent the torsion mirror from contacting the back electrode. The back electrode plate is integrated with a scratch drive actuator array for self-assembly [7]. The self-assembly process is completely controlled by electrical bias, and no manual freeing or intervention is necessary. When voltage is applied between the micromirror and back electrode, the micromirror is attracted toward the back electrode plate by electrostatic force, as shown in Fig. 1. Since no loose hinge



(a)



(b)

Fig. 1. Schematic diagram illustrating the operation of the vertical torsion mirror.

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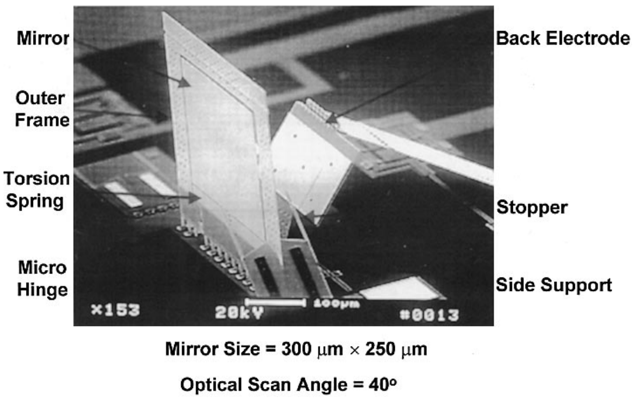


Fig. 2. The scanning electron micrograph of the vertical torsion mirror.

joints are used to connect the micromirror or the actuator, this scanner is expected to have better pointing accuracy. Because there is no constant wear and tear, this scanner is also expected to be more reliable. The actuation mechanism is similar to Texas Instruments' Digital Micromirror Device operating in the analog regime, which has been shown to be very reliable [8].

The scanning electron micrograph (SEM) of the vertical torsion mirror is shown in Fig. 2. The microstopper integrated on the side support plate is clearly visible. This device is fabricated at the MEMS Technology Application Center at North Carolina (MCNC) [9]. All structures are made of polysilicon deposited by low-pressure chemical vapor deposition (LPCVD). The mirror is 300 μm wide, 250 μm tall, and 1.5 μm thick. The folded torsion beam is 912 μm long, 2 μm wide, and 1.5 μm thick.

III. Measurements and Discussions

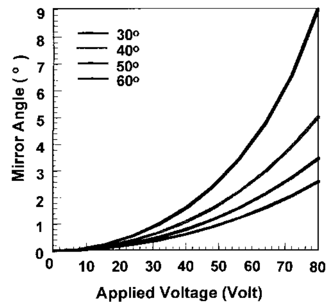
The vertical torsion mirror scanner employs an angular gap closing actuator. Electrostatic force is generated when voltage is applied between the micromirror and back electrode. The torque exerted on the mirror is calculated by integrating the product of electrostatic force and the distance to the pivotal point over the entire mirror area. It is given by

$$T_e = \frac{1}{2}\xi w V^2 \times \int_0^h \frac{x}{(x\tan(\theta)+d_o)^2}\,dx \quad (N-m) \tag{1}$$

where w and h are the width and the height of the mirror, and d_o and θ are the spacing and the angle between the mirror and the back electrode, respectively. The electrostatic force is balanced by the restoring force of the torsion spring attached to the micromirror. The torsion force is given by [10]

$$T_m = 2\times\frac{Gwt^3}{3l}\theta\left(1-\frac{192}{\pi^5}\times\frac{t}{w}\tanh\left(\frac{\pi w}{2t}\right)\right) \qquad (N-m) \tag{2}$$

where G is the shear modulus, and w, l, and t are the width, the length and the thickness of the torsion spring, respectively. The deflection angle of the mirror at a given voltage can be calculated by setting $T_e = T_m$. The calculated mirror angles versus applied voltage for various angles and spacings between the mirror and back electrode are plotted in Fig. 3(a) and (b), respectively. One can see that the driving voltage can be decreased by reducing the angle and spacing between the mirror and the back electrode.



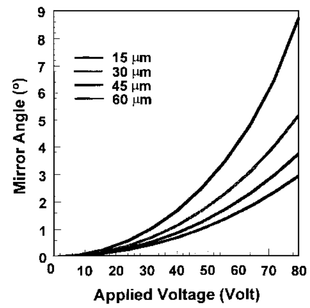


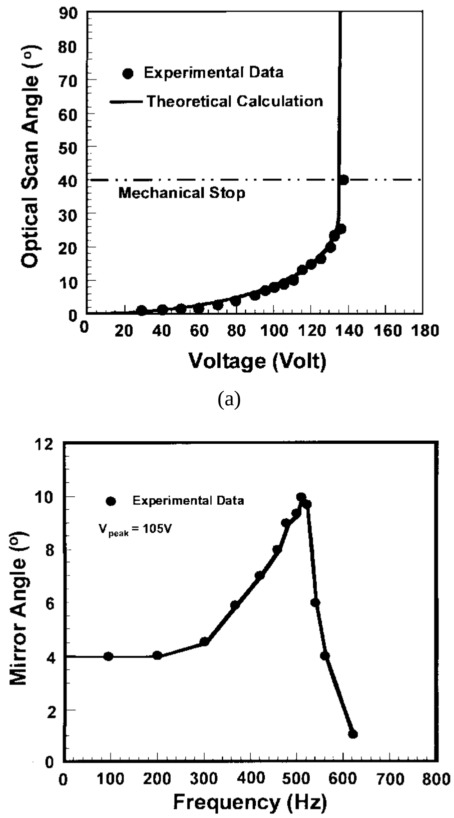
Fig. 3. Scan angle versus applied dc-bias voltage for different (a) angle and (b) spacing between the mirror and back electrode plate.

In our experimental device, the angle and spacing between the micromirror and back electrode plate are 45° and 30 μm, respectively. The measured optical scan angle versus the dc-bias voltage and its frequency response are plotted in Fig. 4(a) and (b), respectively. The torsion mirror has a pull-in voltage of 136.5 V and a release voltage of 115 V. The operating voltage can be reduced by decreasing the spacing between the micromirror and the back electrode, as shown in Fig. 3. The pull-in voltage can be reduced to 110 V when the spacing decreases from 30 to 5 μm. The optical scan angle is 40° before the micromirror hits the stopper. The stable optical scan range is 26°. The resonant frequency is measured to be 0.5 kHz. The experimental data agrees very well with the theory.

Even though the bias voltage is high (>100 V), the power consumption is very low because it is basically a capacitive load and does not consume dc current. For example, the scanner consumes about 600 μW when it operates at 300 Hz. Therefore, the scanner can be operated by battery and the high voltage can be generated by a dc voltage converter.[1]

The torsion mirror can operate in either small-signal or large-signal regime. In small-signal operation mode, the mirror scans up to 26° optically and can be used as scanners. For a one-dimensional (1-D) scanner application, the maximum number of resolvable spots [11] for the scanning mirror with an area of 300 μm × 250 μm is 238 for the HeNe laser

[1] For example, see the PICO Electronics Inc., Mt. Vernon, NY, Catalog 2025, p. 68.



(b)

Fig. 4. (a) Scan angle versus applied dc-bias voltage. (b) Frequency response of the vertical torsion mirrors.

wavelength of 633 nm. In practical operations, the number of resolvable spots could be reduced by mirror warping and wobbling of the frame [12], [13]. This is currently under investigation. For a two-dimensional (2-D) scanning system, this 1-D scanner can be integrated with another orthogonal 1-D scanner [14] to form a monolithic 2-D raster scanner.

When the peak bias voltage exceeds 136.5 V, the mirror operates in bistable mode and can be used as an optical switch or chopper. As a switch, the switching time is measured to be less than 1 ms. It can also be used as a chopper if the deflected light is made to miss the aperture of the next optical element (e.g., a lens aperture of a pinhole) which has the same effect as blocking the light.

IV. CONCLUSION

A novel surface-micromachined optical scanner has been successfully demonstrated using an out-of-plane vertical torsion mirror. An optical scan angle of 26°, and a resonant frequency of 0.5 kHz have been achieved. Its applications include optical scanners, displays, switches, and on-chip optical choppers for monolithic microoptical instruments. The device consumes very low power (about 600 μW) and can be operated by battery.

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