TWO-AXIS MICROMACHINED STEEL SCANNERS

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Abstract — *This paper presents the fabrication and test results of two-axis micromachined micro-mirror steel scanners developed for display and imaging applications. The novel fabrication method uses the conventional lithography and electrochemical metal etching. Only one photomask is used to define the whole structure, resulting in a simple and inexpensive fabrication process. The device employs the magnetostatic actuation to generate excitation force/torque. The produced and characterized gimballed cantilever device is capable of scanning angles of* 31.7° *and* 30° *in slow and fast scan directions, consuming 25 mW and 8.5 mW, respectively.*

Keywords: Scanning mirror, Micromachining, Steel.

I INTRODUCTION

Micromechanical mirror scanners (i.e. micro-scanners) are mainly used in the display/imaging applications where a light beam is scanned in two dimension to create a raster image. There are a number of actuation techniques and mechanical design strategies to implement a micro scanner aiming to obtain wide optical scan angles for both axes and a high fast scan frequency to slow scan frequency ratio. Various materials have been tried, specifically silicon based scanners [1, 2], polymers [3] and metals [4].

In this paper, we present a novel two-dimensional mirror scanner which uses steel as the structural material. Distinctive to the present device, the scanner is fabricated by using conventional lithography and electrochemical metal etching, which makes it different than the previously reported steel scanners along with its novel architecture giving better total optical scan angles [4]. Steel is an alternative structural material to traditionally used Silicon: it offers a higher Young's modulus (E), a higher torsional modulus (G), a comparable flexural mode frequency coefficient (defined as the ratio between the Young' modulus and the material density: $\sqrt{E/\rho}$), and a comparable torsion mode frequency coefficient (defined as the ratio between the torsional modulus and the material density: $\sqrt{G/\rho}$) [4]. Additionally, since steel is a soft-magnetic material, electromagnetic actuation can inherently be utilized to generate excitation force/torque. As a result, similar performances in terms of total optical scan angle, mechanical quality factors and mode frequencies can be obtained by using steel.

II DEVICE OPERATION

Schematic of the proposed device is sketched in Fig.1, where a slow-scan axis which is orthogonal to the fast scan axis can be identified. A frame is suspended to the anchor through the springs with the length of L_S and the width of W_S, similar to a cantilever design. A mirror is gimballed to that frame by the suspension with the length of L_F and the width of W_F. The device is actuated by magneto-static drive method; alternative current passing through the windings of an electro-coil produces a magnetic flux and the flux interacts with the suspended magnetic (i.e. steel) sections thereby generating forces and displacements [5]. When the frequency of the a.c. flux is around the resonance peaks of the vibration modes, the displacements are enhanced by the mechanical quality factors of the respective motion.

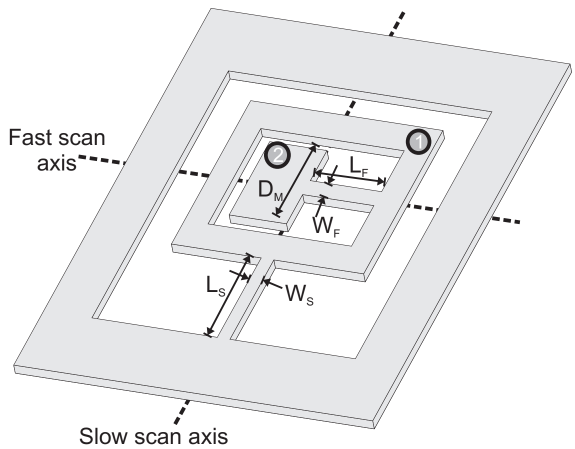


Figure 1: Schematic of the 2D scanner device. A gimballed mirror with electromagnetic actuation is prefered for mechanical excitation.

Table 1: Dimensions of the gimballed cantilever scanner.

Geometry	W_S	L_S	W_F	L_F	D_M	t
Value [mm]	1	7	3	1	3.5	0.1

Fig.2 shows the finite-element analysis result of the device. According to this analysis, outer cantilever frame can be used in its fundamental mode (i.e. out of plane bending mode) to generate angular displacements about the slow scan axis, as shown in Fig.2(a). This mode is designed to have a low resonance frequency since it will correspond to the refresh rate of the 2D display [4]. The fast scan mode has to generate a scan line that is orthogonal to the slow-scan mode, and a suitable candidate is the out-of plane motion of the inner cantilever as depicted in Fig.2(b). The slow scan mode and the fast scan mode are excited by supplying a.c. signal components at the center frequencies of the corresponding resonance peaks.

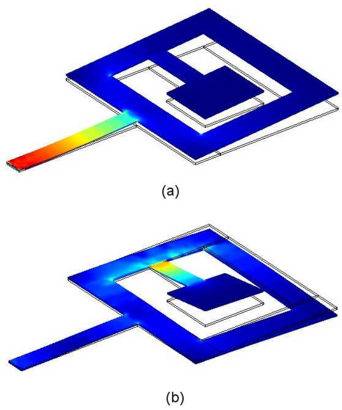


Figure 2: FEA results of the scanning mirror (a) Outer frame bending mode (b) Mirror bending mode corresponding to the slow and fast scan motions, respectively.

III FABRICATION

The proposed bulk fabrication method uses a 100 μm thick, stainless steel 301 (SS301) substrate. The substrate is spin coated with a 6 μm thick Shipley 1828 photoresist (PR) which is baked at 90 °C for 60 seconds. The resist is then exposed to UV light where a nominal exposure time of 6 minutes is used. After the development of the PR, the substrate is baked at 110 °C for 30 minutes in order to make it more durable against the subsequent electrochemical etch process. The substrate is then attached onto an insulator plate holder in order to protect the back side of the material from etching. Following, the steel substrate is immersed into an electrochemical cell which is full of 1:7 HCl:DIwater solution and connected to a current source as it is depicted in Fig.3(b). The parts to be etched forms the anode part of the electrochemical cell and the counter plate that collects the etched away particles, forms the cathode electrode. These electrodes are both connected to a DC power supply which provides current to the cell.

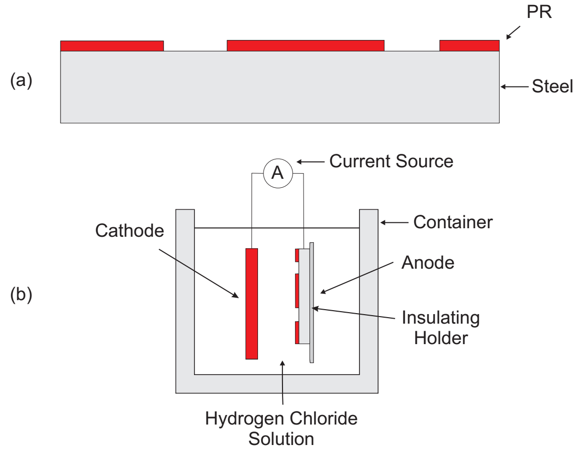
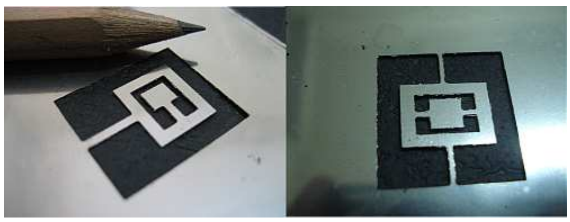


Figure 3: (a) 100 μm thick SS301, spin coated and patterned with 6 μm PR mould (b) Schematics of the used electrochemical cell.

Anisotropy of the etch process profile can be controlled by the etch rate through the current-density. However, the masking resist in electrochemical etch solution can be eroded during the process. this, in turn, causes variations in the etch profile. The prefered masking scheme enables the etching of 100 μm thick stainless steel in about 5 minutes, using a current density of approximately 9 A/cm^2. The proposed devices are etched in just, 4 to 5 minutes with a rate of approximately 25 μm/min depending on the structure. Finally, after electrochemical etch, the PR mould is stripped off. Produced devices are shown in Fig.4.



Type-A Type-B

Figure 4: Pictures of the two different designs. Type-A, gimballed cantilever type scanner. Type-B, gimballed torsional scanner.

IV TEST RESULTS

Fig. 3 shows the mechanical transfer characteristics of the device as a function of the operation frequency. This plot is obtained by driving the electro-coil with a constant magnitude current, varying the frequency and collecting the vibration displacement by a Laser Doppler Vibrometer (LDV, Polytec OFV 2500). As can be seen from this figure, there are two points of interest on the device, namely point-1 and point-2 (refer to Fig.1 for the locations of these points), which indicate the slow-scan and the fast-scan operations respectively. Mode-1 corresponds to the out of plane displacement of the outer frame at point-1, generating a scan line at 112 Hz. This resonance peak, given in Fig.6(a) with detail, results in a quality factor of 170 in air. Mode-2 corresponds to the torsional movement of the outer frame which has a resonance frequency of 371 Hz. Subsequently, point-2 is used in the following measurements to define the characteristics of the fast-scan operation. The inner cantilever produces the maximum scan line by making an out of plane displacement at 882 Hz which is defined as Mode-3 in Fig.6(b). This resonance peak generates a scan line that is orthogonal to the scan line produced by the Mode-2, thus can be chosen as the fast scan operation mode. Mechanical quality factor for this mode is measured to be approximately 100 in air. Mode-4 in Fig.5(b), depicts the torsional movement of the inner mirror at a resonance frequency of 998 Hz. This mode is depicted with a better frequency resolution in Fig.6(b). In this case, fast scan frequency (mode-3) to slow scan frequency (mode-1) ratio is 7.87 for resonant-resonant actuation of both modes. If non-resonant actuation is used for the slow scan, e.g. 60 Hz refresh rate, the ratio between the fast scan frequency and the slow-scan frequency becomes 14.7. this implies that one can write 15 lines in the vertical direction using the proposed device.

Fig.7 shows the laser scanning experiments of the proposed device. The laser beam is positioned on the inner mirror and the device is actuated in the slow-scan and the fast scan resonances respectively. A white, scaled metric screen is placed 22 cm away from the 2D scanner, where reflected laser beam generates one-dimensional scan line for each axis. As can be seen from Fig.7(a), the slow-scan motion produces a scan line of 12.5 cm, corresponding to a total optical scan angle of 31.7° at the drive power of 25 mW. Similarly, the fast scan operation at the drive level of 8.5 mW results in a scan line of 11.8 cm, yielding a total optical scan angle of 30°. The dependency between drive current and displacement is linear due to the direct relation between the magnetic flux and the exerted force.

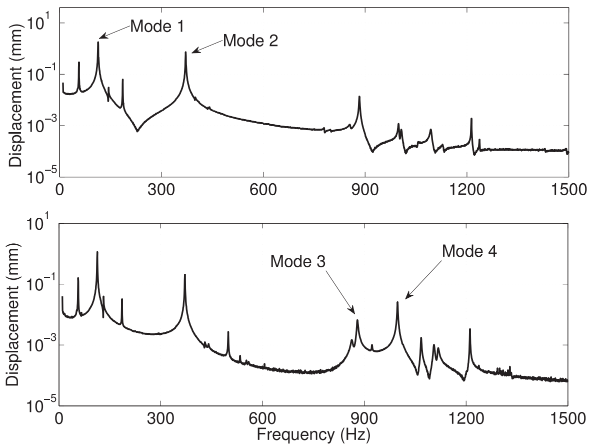


Figure 5: Vibration displacement of (a) the outer frame (point-1) (b) inner mirror (point-2) of the scanner as a function of frequency.

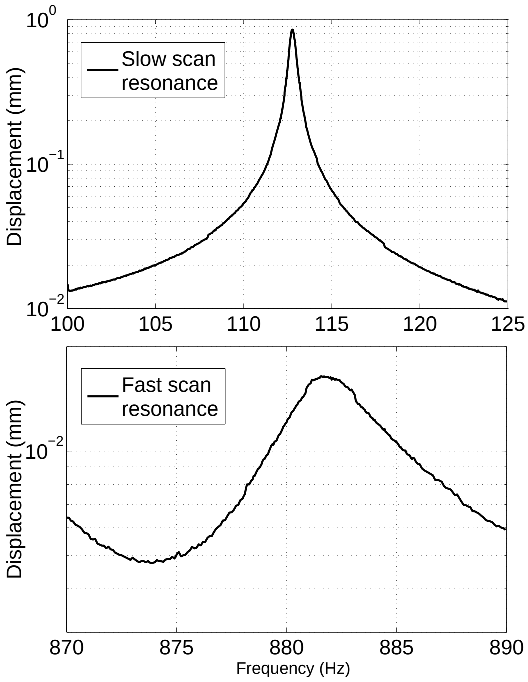
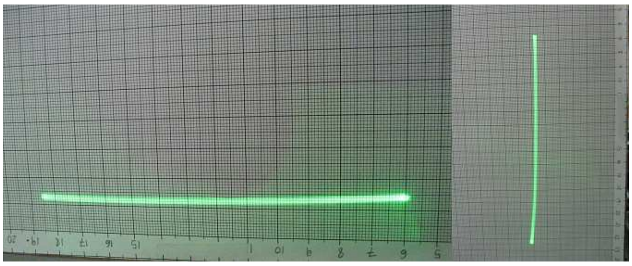


Figure 6: (a) Out of plane displacement resonant peak of outer frame (b) Out of plane displacement resonant peak of inner mirror



(a) (b)

Figure 7: (a) 12.5 cm horizontal scan line is observed at a distance of 22 cm from the steel mirror using a drive power of 25 mW producing a 31.7 ° total optical scan angle (b) 11.8 cm vertical scan line using a drive power of 8.5 mW, producing a 30 ° total optical scan angle.

V CONCLUSION

A novel steel fabrication method is presented along with new architectures of gimballed MEMS scanners. The proposed fabrication method, uses only one photomask and a single lithography step at the same time ensuring an etching uniformity with an etching rate of 25 μm/min. Using this method, a family of scanners are fabricated and two of these scanners are presented and shown that they are capable of being used in the display applications. The first device, tagged as Type-A, is a gimballed, cantilever-cantilever structure which gives wide total optical scan angles, exceeding 30°, in both the slow-scan axis and the fast scan axis. Power consumption of the device is quite low (25 mW and 8.5 mW for slow and fast axis, respectively), thanks to the moderate quality factors (above 100 in ambient air) of the resonance peaks.

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