Micromachined Mirrors in a Raster Scanning Display System

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This paper describes a 2-D raster scanning system incorporating two surface-micromachined mirrors fabricated on separate chips: a fast mirror for horizontal and a slow mirror for vertical scanning (Figure 1). The mirrors are tilted out-of-plane on polysilicon hinges and are connected to their supporting frames with torsional polysilicon beams (Figure 3). The tilt-up mirror design accommodates large mirror areas and allows integration of optical components on the same chip. Prior work on tilt-up micromirrors by Kiang et. al. [1-2] has demonstrated the feasibility of resonant mirrors for 1-D barcode scanning. The raster scanning mirrors are nearly circular, measuring 565 µm along the scan axis and 500 µm along the perpendicular axis. The mirror surfaces are linked to comb drive actuators, and both have a resonant frequency of 4.54 kHz (Figure 2). The measured optical scan angle of the fast mirror is 5.3 degrees when operated at resonance, driven with a 116 Vpp sine wave and zero DC offset. The scan axis of the fast mirror is oriented perpendicular to the slow mirror. The slow mirror is identical to the fast mirror, except bi-directional comb drives allow it to be driven in opposing directions. Triangular voltage waveforms at 167 Vpp rotate the mirror, deflecting the optical beam through 5.7 degrees. The slow mirror governs the image refresh rate.

The mirrors in this scanning system exhibit convex curvature, resulting from stress gradients in the polysilicon film. Differences in curvature were found between identical devices on separate chips. Such anomalies are likely due to variations in the fabrication process. The horizontal and vertical axes of the mirrors also exhibit slightly different curvature. The fast and slow mirrors have focal lengths of -1.2 cm and -1.9 cm respectively.

A 5 mW HeNe laser operating in the red (633 nm) is the light source for the raster scanner. The light first passes through an acousto-optic (AO) modulator followed by a spatial filter and a mechanical shutter. A 50.2 mm and a 100 mm focal-length lens correct for curvature in both mirrors. The optics form a virtual 6.02-micron waist 7.5 mm behind the fast mirror, with a $1/e^2$ beam radius of 250 µm at the mirror. Two 62.9 mm focal-length lenses between the mirrors image the fast mirror onto the slow mirror. These lenses could also be used to correct for mirror curvature. In the Fourier plane of the 30cm output lens, the $1/e^2$ optical beam radius is 360 µm on the vertical axis and 410 µm on the horizontal axis. Without optical curvature compensation, the spot would have been 1,716 times greater in area. Preliminary data suggests that the spot size does not change appreciably as the mirror rotates.

Several raster patterns were photographed to demonstrate the 2-D scanning ability of the system (Figure 4). Speckle is observed when the raster-scanned image is projected onto a screen. The speckle in the figures was eliminated by projecting the light directly onto film in the camera. Raster images are made by modulating the light with the AO crystal. A 3 cm horizontal by 2.8 cm vertical raster scan is present in the Fourier plane of the 30 cm output lens. By rule of thumb [3], spacing between scan lines is the full-width-half-maximum of the intensity of the optical field. In accordance with this principle, the 2-D scanning resolution is 62x66 pixels, which is supported by experimental evidence. Figure 4b shows 88 light and dark horizontal lines, and Figure 4f shows 60 light and dark vertical lines. Vertical line contrast is limited by the performance of the AO modulator. Horizontal resolution is determined by the number of lines that the fast mirror can scan during the refresh period of the slow mirror. An image containing the characters “UCD” (Figure 4e) was generated by driving the fast mirror at 4.6 kHz and the slow mirror at 11.5 Hz. Mechanical instability of the fast mirror causes overlap of scan lines, distorting the image and requiring a 2X reduction in slow mirror frequency. The slow mirror also exhibits mechanical instability. The effect of mechanical inaccuracies are avoided by selectively switching the light off. The light was switched off by the AO modulator during the right-to-left half-cycle of the fast mirror scan and the bottom-to-top half-cycle of the slow mirror scan. Optical scan angles of up to 11 degrees have been demonstrated on both mirrors, with a corresponding decrease in scan repeatability.

This experiment has demonstrated raster-scanned images generated by a surface-micromachined mirror system. The mechanical stability of the optical scan limits the refresh rate and resolution in the current design. Continuing research is aimed at extending the resolution to VGA quality by further refining the mechanical design and increasing the scan angle.

References

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3. J. Hagerman. “Optimum spot size for raster-scanned monochrome CRT displays”, Journal of the SID, vol. 1, no. 3, 1993. pp. 367-369.

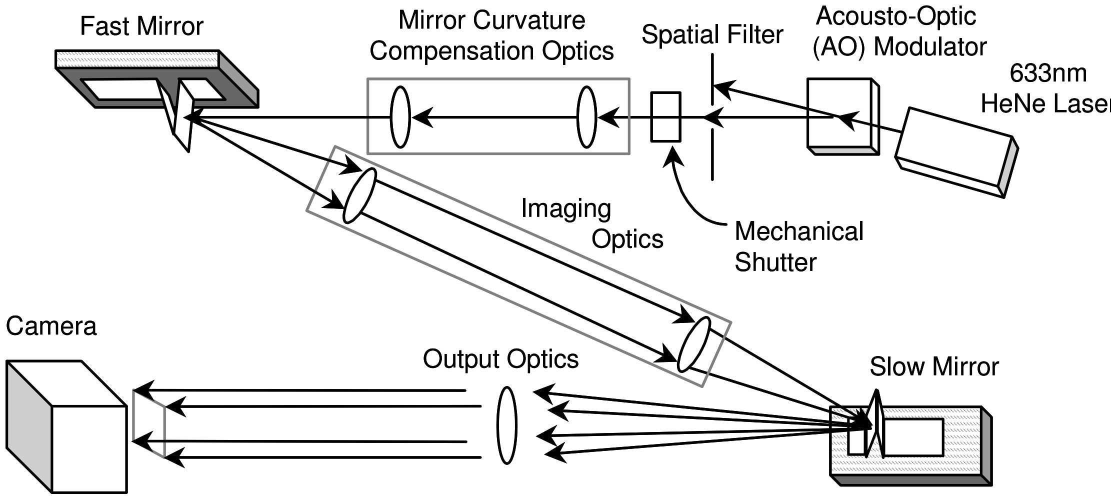

Figure 1. Experimental setup for orthogonal raster scanner

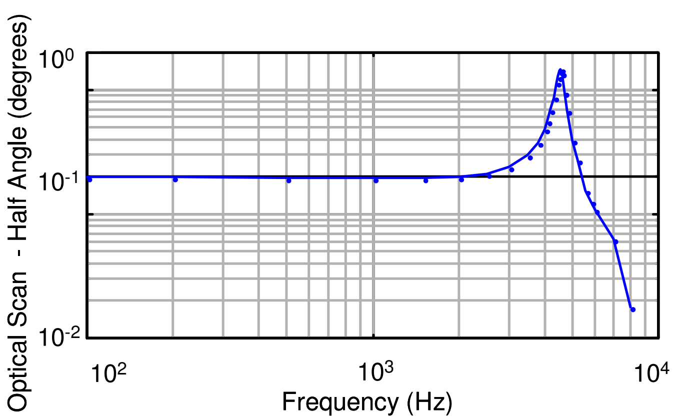

Figure 2. Small-signal freq. response of slow mirror

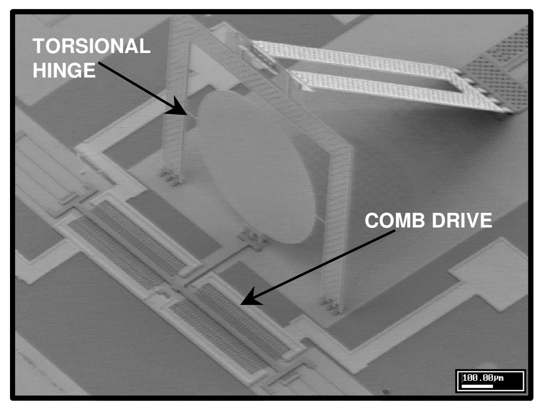

Figure 3. SEM image of slow mirror - vertical scan

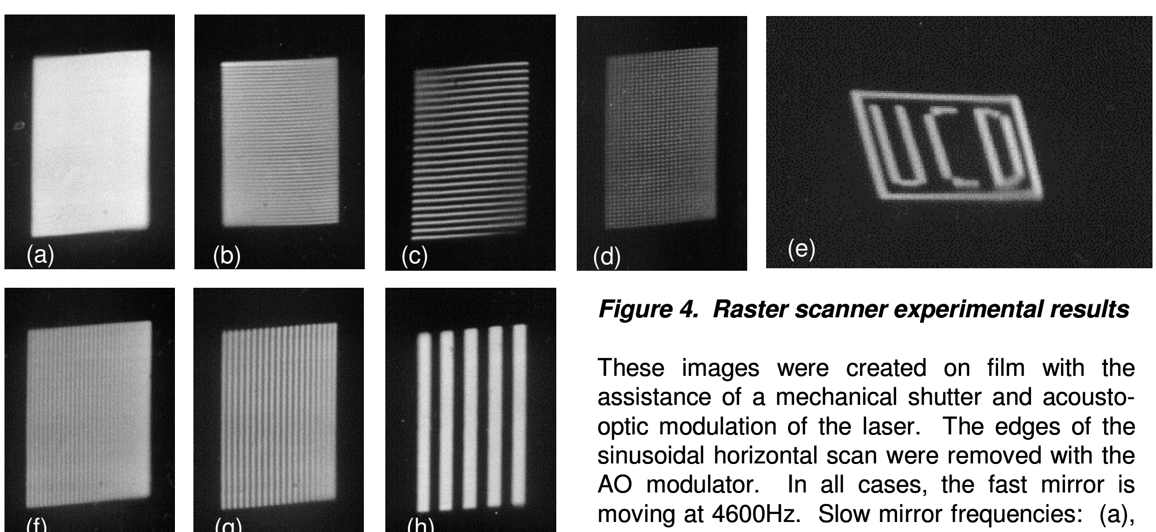

Figure 4. Raster scanner experimental results

These images were created on film with the assistance of a mechanical shutter and acousto-optic modulation of the laser. The edges of the sinusoidal horizontal scan were removed with the AO modulator. In all cases, the fast mirror is moving at 4600Hz. Slow mirror frequencies: (a), (e)-(h) 11.5Hz, (b) and (d) 23Hz, (c) 46Hz.