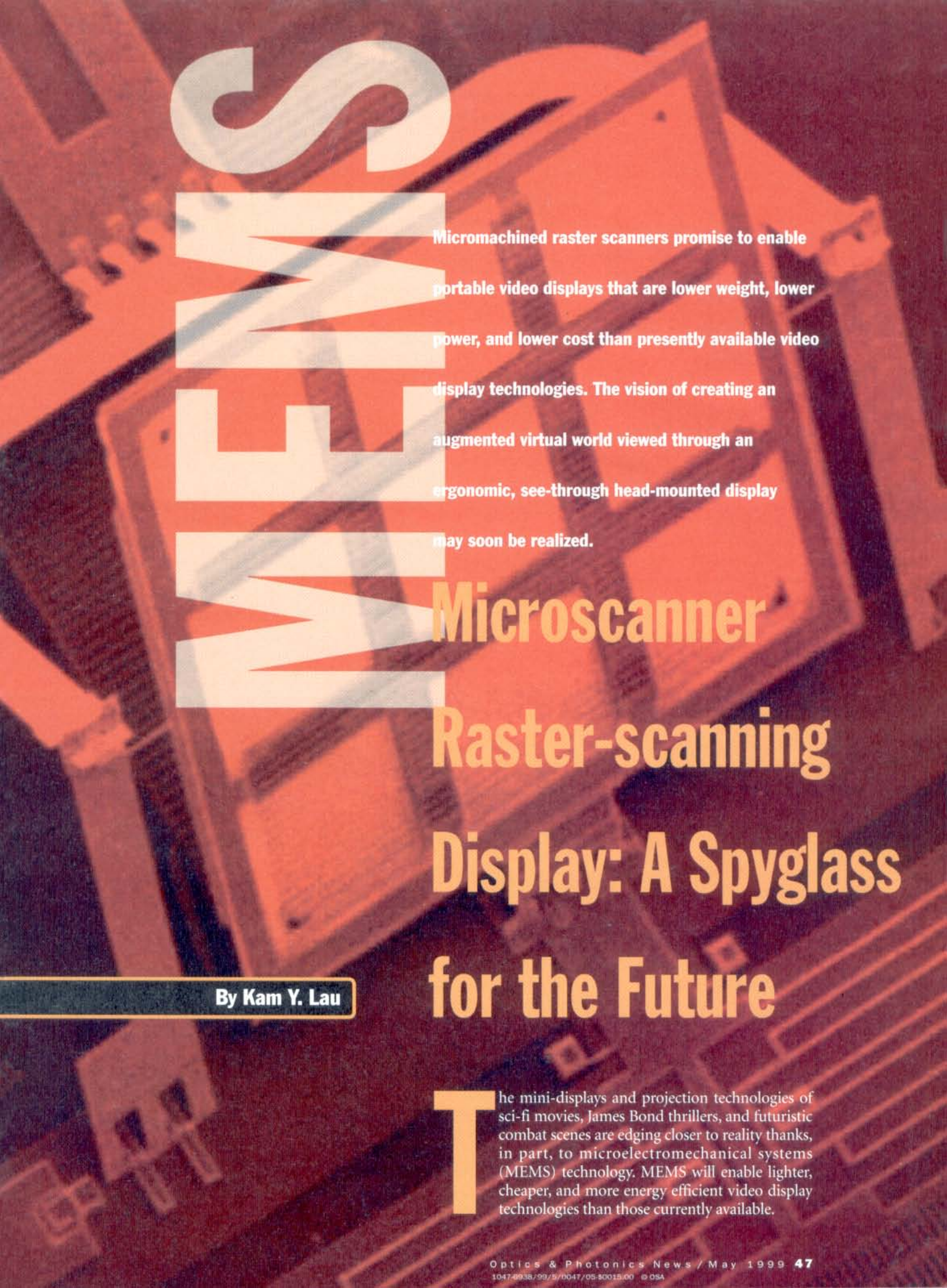

MEMS

Micromachined raster scanners promise to enable portable video displays that are lower weight, lower power, and lower cost than presently available video display technologies. The vision of creating an augmented virtual world viewed through an ergonomic, see-through head-mounted display may soon be realized.

Microscanner Raster-scanning Display: A Spyglass for the Future

By Kam Y. Lau

The mini-displays and projection technologies of sci-fi movies, James Bond thrillers, and futuristic combat scenes are edging closer to reality thanks, in part, to microelectromechanical systems (MEMS) technology. MEMS will enable lighter, cheaper, and more energy efficient video display technologies than those currently available.

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As a result of a strong push to commercialize the technology in recent years, Texas Instruments has introduced the Digital Micromirror Display (DMD™),[1] and Silicon Light Machine Inc., now markets displays that use Grating Light Valve (GLV™)[2, 3] technology. Both of these display technologies involve a planar field of movable micro-reflectors, each of which is dedicated to modulating the intensity of a pixel in the display. The micro-reflector in the DMD consists of a small (about 20-μm^2) deflectable mirror that modulates the reflected light by deflecting the beam in and out of the viewing aperture. A field of almost 1 million micromirrors is needed to produce a full SVGA quality display. At the size of about 20-μm^2 each, the display module will occupy a chip with an overall size of several centimeters. The GLV display contains an external bulk-optical scanning mirror and a 1-D array of micromachined deformable diffraction gratings that modulate pixel intensity. For SVGA quality display, the linear diffraction grating array should contain up to 1000 elements and measure several centimeters in length overall. The bulk optical scanning mirror, which is used to scan the linear array to produce the full picture frame, has similar dimensions.

Figure 1. "Wearable" raster-scanning virtual display using MEMS microscanners-on-a-chip.

Another approach to produce portable and "wearable" displays is based on raster-scanning two orthogonal mirrors to produce the image frame. A particular adaptation of this general and well-known concept of raster-scanning display involves scanning the image directly on the retina of the viewing person, a technique known as Virtual Retinal Display (VRD),[4] which has been explored at the Human Interface Technology Laboratory of the University of Washington and currently attempted to be commercialized by Microvision Inc. This approach is touted as one that has "see-through" capability, *i.e.*, the displayed image can be viewed with a bright external scene superimposed on the image—a significant advantage in cockpit displays and industrial/medical applications. It also has the potential of being "wearable" in that, since only two micromirrors are required to produce the entire image, the display hardware is truly miniaturized and fits easily onto an eyeglass frame (see Fig. 1). An excellent 1998 *OPN* article discussed the many applications and optical issues of general head-mounted display (HMD) technology.[5] The ultimate realization of this technology, of course, is contingent on the availability of micromirrors that possess superb quality and scanning performances. Such devices are still not available commercially; current VRD displays still rely on bulk-optical scanners that are not truly wearable except for those with exceptional neck muscle strength. However, the advent of MEMS-based microphotonic technologies in the past few years have made this possibility of achieving truly wearable raster-scanning displays very close at hand.

Discrete-pixel versus raster-scanning

There are fundamental differences in the requirements for micromirrors used in the DMD—which I collectively call "discrete-pixel" displays—and those used for raster-scanning for producing the full image frame. (The GLV is actually an amalgamation of the two diametric approaches—using discrete mechanical pixels in one dimension and beam-scanning in the other dimension). The main difference is in the size of the micromirrors—the discrete-pixel mirrors act primarily as a point source of on/off light scatterers and thus can be made quite small (20 μm in the case of Texas Instruments's DMD), while the dimension of the raster-scanning mirror will determine the overall resolution of the displayed image according to diffraction limit. To produce 1000 points of resolvable spots over a 30° field, for example, the diffraction limit dictates a minimum mirror size on the order of 1 mm. On the other hand, the need to scan over 1000 lines of an entire image frame at the video rate of 60 frames/s requires a scanning

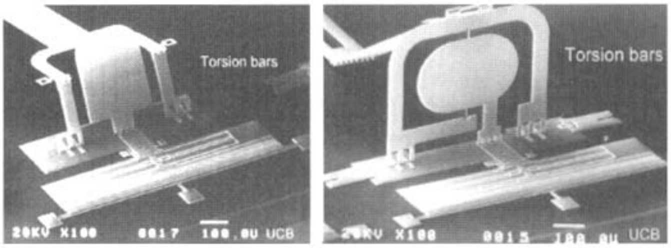


Figure 2. Vertical (left) and horizontal (right) MEMS microscanners fabricated using MUMPs polysilicon process, with torsional hinges and comb-drive actuators. The dimension of the scanners are about 500 mm in width.

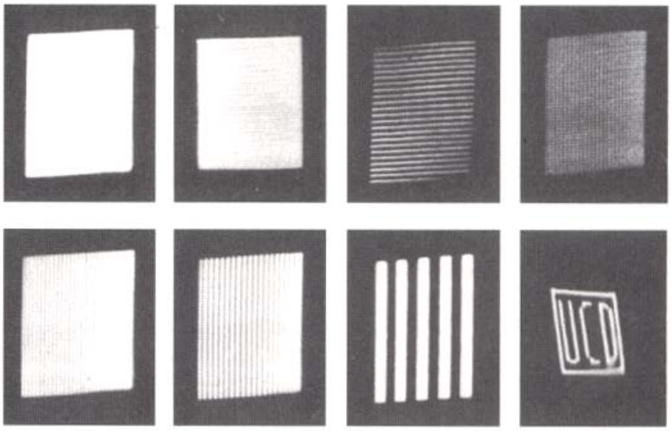


Figure 3. Simple resolution charts of MUMPs raster-scanners. The resolution is approximately 100 × 120 pixels.

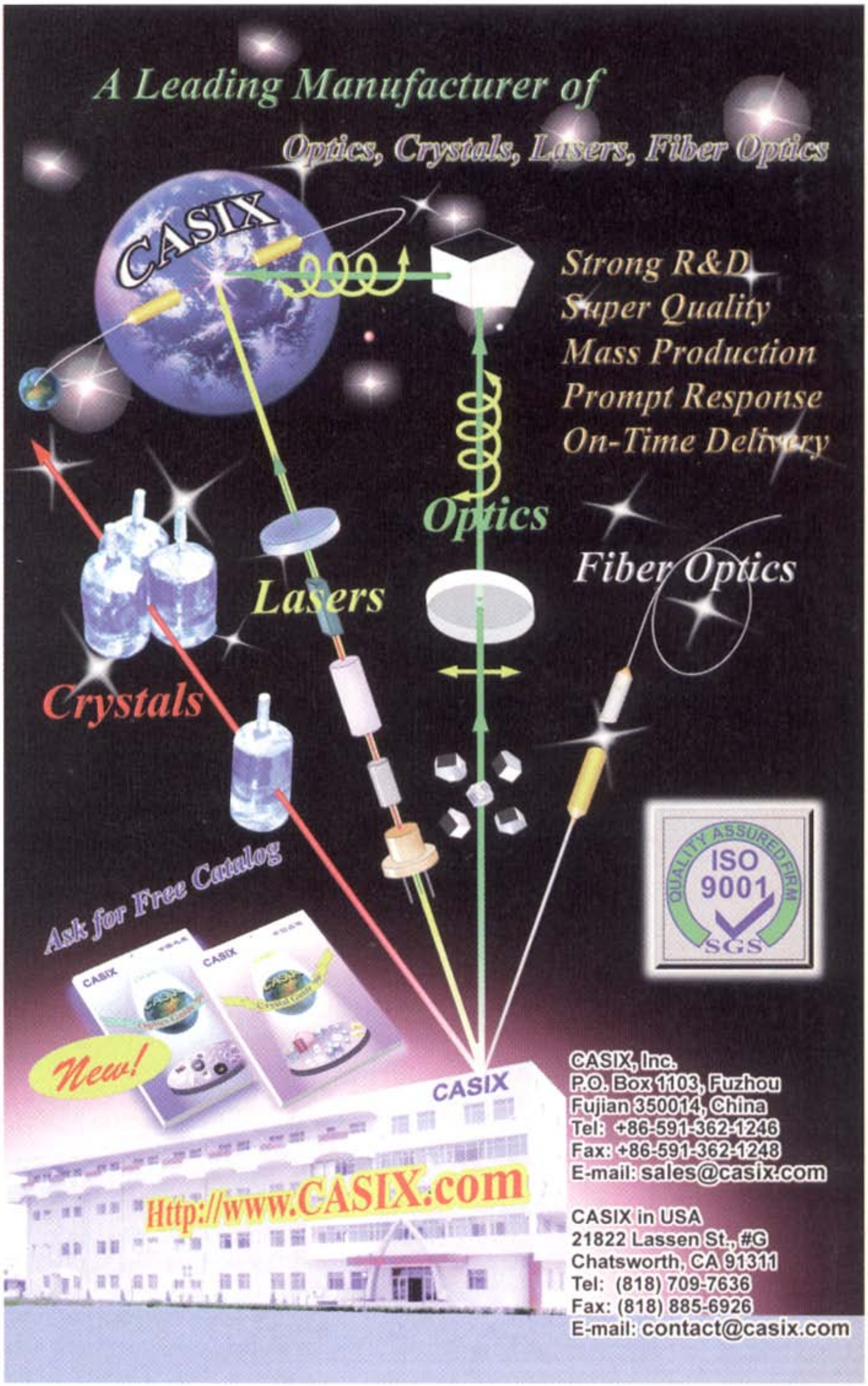
frequency of 60 kHz for the fast-mirror (the orthogonal slow-mirror scans at video frame rate). At the same time, to maintain diffraction-limited performance, the optical quality of the mirror must be maintained to a minimum *dynamic* flatness of at least λ/20, if not λ/40, over the entire mirror surface, while the mirror is undergoing scanning at high speed.

In a philosophical sense, the "discrete-pixel" and "raster-scanning" approaches are diametrically different. For the former, the demands are comparatively relaxed on the performance of each individual mirror, but requires a massive number of them to work simultaneously with exceptionally high yield. The latter demands supreme performance of the micromirror, but only needs two of them to perform the display function. The GLV display constitutes a compromise between the two extremes. It is the raster-scanning display, however, that offers the possibility of truly integrating the entire display engine on a chip, containing just two micromirrors with integrated light-sources and microlens.

MUMPS

Using silicon micromachining and silicon optical bench technologies, extremely compact optical systems incorporating low-inertia scanners can be built. As an example, the inset of Figure 1 shows a schematic of such a raster-scanner microdisplay module fabricated on a chip. The light from three semiconductor LEDs or lasers are collimated by a microlens and directed onto a pair of microscanners;[6] each consists of a micromirror and an actuator. Both mirrors stand vertically on the silicon substrate and are actuated by electrostatic combdrives. A planar-image display is achieved by raster scanning the light beam in two orthogonal directions using the two mirrors. These out-of-plane mirrors interact with optical beams that propagate in a plane parallel to the substrate onto which other micro-optical components can be integrated on the same chip. An integrated module like the one sketched in Figure 1 can be vacuum packaged or hermetically sealed to reduce air damping, mirror deformation, and particulate erosion of the mirror surface. Also, the mechanical *Q*-factors of the scanners have been found to increase significantly even under a moderate vacuum, thus reducing the drive voltage requirement. Furthermore, the positioning and alignment of the mirrors are determined during chip fabrication, and large quantities can potentially be produced inexpensively due to the batch nature of the fabrication process.

The mirrors shown in Figure 1 were fabricated at MCNC Corp. of North Carolina, using a standard polysilicon Multi-User MEMS process (MUMPs),[7] a technique commonly chosen for fabricating general purpose MEMS components. The mirrors and structures, shown in more detail in Figure 2, are made of polysilicon plates and beams that are nominally 2-mm thick.[6] Torsional hinges also 2-mm thick hold the micromirror to its frame. Mirrors typically measure 500 mm in diameter. Larger mirrors can be fabricated using this process, but severe surface warping due to residual strain in the layers presents a serious problem. The mirrors are driven by MEMS comb-drives that are linked to the bottom of the mirror through a micro-mechanical linkage. As the comb fingers shuttle back and forth under the electro-



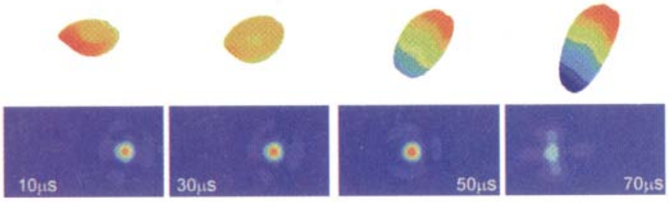
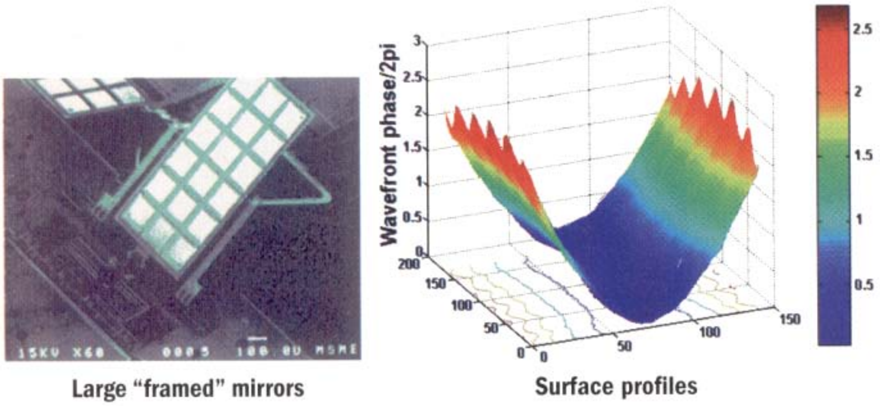


Figure 4. Dynamic deformation of the MUMPs micromirror during scanning at 6 kHz, measured by a stroboscopic interferometric system. The corresponding diffraction-limited spots of the scanned beam at four positions of the scan cycle are shown.



Large "framed" mirrors

Surface profiles

Figure 5. Static deformation of large mirrors made by MUMPs process. The mirror is 1 mm in height. Framed structures are included to increase mirror rigidity, but did not help in reducing mirror warping. The center-to-end mirror warp is more than 2 mm.

static force from an applied voltage, the mirror is scanned in the vertical or horizontal planes according to its designated design. The resonant frequency of these mirrors typically ranges between 4 and 6 kHz, and the number of resolvable spots is slightly larger than 100. A sequence of raster-scanned test patterns is shown in Figure 3 (see page 48) for a microscanner system with resolution of approximately 100 × 120 pixels.[8, 9]

Improving resolution

Improving display resolution requires increased scan range of the mirrors and elimination of surface warping of the mirrors. The typical scanning range of the mirror itself is 10–15°, the optical scanning range being double that value. At 500 mm, had the mirrors been perfect, the resolution would have been on the order of 250 × 250. Apart from the static deformation of MEMS mirrors caused by film stresses and stress gradients, dynamic mechanical effects, such as air drag and excitation of higher-order resonant modes, cause surface deformations. These static and dynamic mechanical deformations may be small from the perspective of the system's mechanical behavior, but can cause significant degradation to optical performance. We have examined in detail the high-speed dynamics of these scanning micromirrors using a time-resolved phase-shift interferomety system. An example is given in Figure 4.[10, 11] The top row shows the measured time-dependence of the optical wavefront (essentially a scaled map of mirror surface height) reflected from a comb drive-actuated polysilicon fold-up micro-mirror, scanning at 6.2 kHz. The sequence illustrates four sub-millisecond time slices, each separated by an interval of 20 ms, spanning approximately one half of the mirror period. The bottom row of Figure 4 shows the far field of a reflected beam from the mirror corresponding to each of the four time slices. In this case, a significant enlargement of the reflected beam is observed near one extreme of the scan (far right-hand image), due to the dynamic deformation of the mirror.

Based on the current design, to achieve the target of 1000 resolvable spots in a single scan, one needs to increase the size of the mirrors to > 1 mm across, and to increase the mechanical scan range to 30°, while at the same time maintaining the surface flatness of the mirror to at least $\lambda/20$ under static and dynamic conditions. Furthermore, to produce 1000 horizontal scan lines per frame, one needs to increase the resonant frequency ten-fold to 60 kHz. For the increased mirror size, it is entirely feasible to do so using the current MUMPs process, however, surface warping, which is already significant for smaller MUMPs mirrors, will be greatly exacerbated. A 1-mm MUMPs mirror with significant surface deformation due to static stress is shown in Figure 5. Attempting to solve this problem by making thicker and stiffer mirrors results in greater mirror mass. The larger mirror reduces the resonance frequency, which is contrary to the need for increased resonance frequency. By the same token, the scan angle can be increased by placing the hinge closer to the bottom of the mirror, but this will increase the effective inertial mass of the scanning mirror and drops the resonance frequency as well.

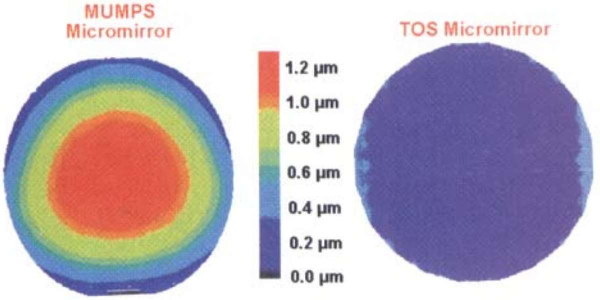


Figure 6. Comparison of static deformation of a MUMPs micromirror to that of a tensile optical surface (TOS) mirror. While the MUMPs mirror has a center-to-edge deformation of more than 1 mm, the TOS mirror has a surface deformation of less than $\lambda/20$, and is extremely light and rigid.

From these discussions it is clear that it becomes extremely hard to produce the desired results by merely extending the present design based on the MUMPs process. It should be noted that the problem involved is fundamental, and micromirrors of other geometries also come under these design and performance tolerances.

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