Integrated 2-axis MEMS Scanners for Optical Applications

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Abstract

Two types of integrated MEMS scanner have been developed using a commercial multi-user MEMS foundry process. One type provides a wide field of view (up to 50^0 degrees at fixed scanning frequencies) while the other permits arbitrary pointing of the scanner over a narrower field of view. The scanners have been deployed in demonstrations of laser confocal microscopy, intra- cavity laser control, and in a single detector imaging system.

Introduction

Reduced size, weight, cost and power consumption together with high reliability and technical performance are the key factors taken into consideration when designing compact and portable military hardware. MEMS (micro-electro-mechanical systems) technology provides a means of attaining most of these factors, as evidenced (in the non-military sector) by the successful incorporation of MEMS into consumer and automotive products e.g. safety systems in cars, image stabilisation systems in digital cameras, microphones in mobile telephones and digital light projection systems in projectors.

Whilst the incorporation of MEMS technology into military ordnance is known, the use of MEMS in military remote sensing applications, such as active imaging, laser radar, remote velocimetry and vibrometry, is much less advanced. One of the essential components of such sensing applications is a means of scanning a laser beam across a field of view, or alternatively, scanning the field of view across a single point detector. Conventionally, this function is performed by bulky opto-mechanical devices with high power consumption such as rotating mirrors or galvo scanners.

An alternative, MEMS–based scanning approach has been investigated over the last three years supported by EMRS DTC. Two families of MEMS scanners have been developed that have much smaller electrical power requirements. A further advantage of the MEMS scanners is that their mirrors tilt in two-axes so that a single MEMS device may replace two conventional single-axis scanners and the associated relay optics, significantly reducing system volume and mass.

Other MEMS-based scanners have been reported in the literature and some are commercially available. All these require either complex custom fabrication processes or some post fabrication alignment and assembly of components. The designs reported in this paper use a simple commercial multi-user fabrication process.

Initial efforts concentrated on scanners with small mirrors for use with Er fibre sources, and with special dielectric coatings that could handle up to 4 W over a circular spot 100 µm diameter. Recent work has focused on increasing the size of the mirrors so that they might be used with non-fibre laser sources, and to offer greater compatibility with existing optical systems. In addition computer-controlled driving systems have been assembled and several bench top applications established.

The design process for the micro-scanners began with finite element modelling in order to evaluate the likely performance of various candidate devices. Once the optimum device geometries had been identified, mask layouts were then prepared for the fabrication of the scanners, which was carried out by a commercial MEMS silicon foundry using a well-established multi-user SOI bulk micromachining process, SOIMUMPs [1]. The devices are defined in a 10 µm-thick layer of mono-crystalline silicon that is attached to a thicker wafer for ease of handling and greater rigidity. The handle wafer is etched away in the vicinity of the devices to allow the components to move freely.

Two families of MEMS scanners have been developed with differing actuating mechanisms and characteristics.

Electrostatically actuated scanners.

Scanners with electrostatic actuation require very low electrical power for their operation. Large tilt angles can be achieved with field of view up to 50^0, but only over a limited range of frequencies that correspond to mechanical resonant modes of the structure (1-10s kHz). Operation of this type of scanner has been discussed in detail in papers presented at previous DTC Technical conferences. [2, 3]

The scanner mirror has two resonant oscillation modes relevant to operation as a scanner that involve tilting about two orthogonal axis intersecting at the centre of the mirror (Figure 1). The first mode is an oscillation about the suspension beam that supports the mirror, and the second is an oscillation about an axis in the plane, perpendicular to the suspension beam, and passing through the mid point of the mirror.

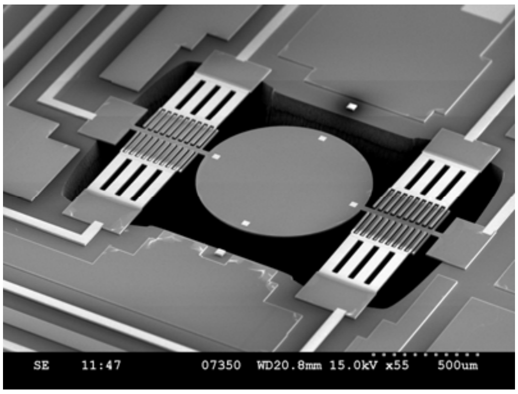

Figure 1 Electrostatic 2-axis scanner (SEM image).

Electrostatic MEMS scanners with mirrors up to 2 mm in diameter have been successfully fabricated and tested. Devices with 2.5 mm diameter mirrors have also been fabricated but not yet fully characterised. The radius of curvature of the micro-mirrors has been found to be independent of mirror size, with a value of 0.08 m. While this degree of curvature is greater than that of bulk optics scanners, it could be compensated for by appropriate optical elements within a system.

Electrothermally actuated scanners.

A schematic diagram of an electrothermally actuated scanner is shown in Figure 2. Four actuators, each comprising three arms each 2 mm long, are attached to the mirror by means of a linking rod and spring and anchored to the substrate at the other end. There is some process-induced strain within the SOI layer in which the scanner is formed that causes the actuators to curve upwards by a few microns from the plane of the device. When current is passed through the outer arms of an actuator those arms are heated and undergo expansion. No current flows through the central arm and it acts as a pivot for the force generated by the heated arms. Because of the initial upward curvature of the structure, the thermally induced force causes the end of the actuator near the mirror to rise out of the plane. As a result the mirror tilts, as shown in Figure 3, an FEA simulation of a device. By adjusting the currents flowing through any two adjacent actuators the mirror can be made to tilt separately in two axes.

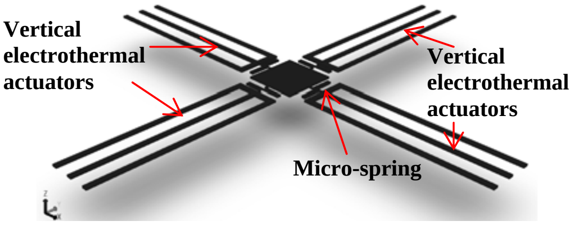

Figure 2. Schematic view of electrothermal MEMS scanner.

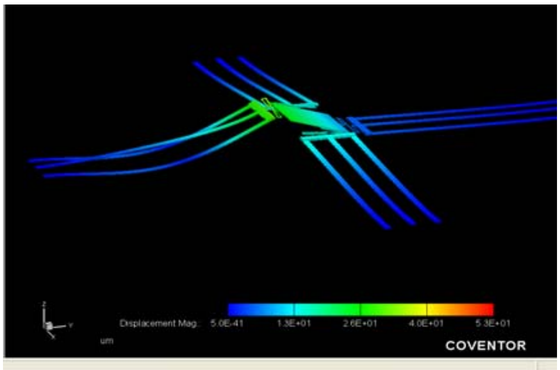

Figure 3. FEA simulation of operation of electrothermal MEMS scanner.

Typically, the actuator arms are 2 mm long and 50 µm wide. In contrast with the electrostatic devices described above, electrothermal devices can achieve significant amounts of tilt at low drive voltages (2 degrees for 15 V) and the scanners can be maintained at an arbitrary angle. The electrical power required for each axis when operated at its maximum tilt angle is 0.3 W, much less than the 10s W required for conventional galvo scanners.

A scanner was linked via a DAC to a computer running a LabVIEW program to generate scan patterns. It was observed that the actuators have a non-linear response to drive voltage, exhibiting threshold behaviour. The position of a laser spot reflected off the mirror and incident on a screen was monitored by a camera also controlled by the LabVIEW program. By driving each actuator separately, a look-up table was generated to allow the laser beam to be directed at any part of the field of view.

Examples of experimental scan patterns of a reflected laser beam observed on a screen are shown in Figure 4, illustrating that arbitrary and non-raster patterns can be achieved.

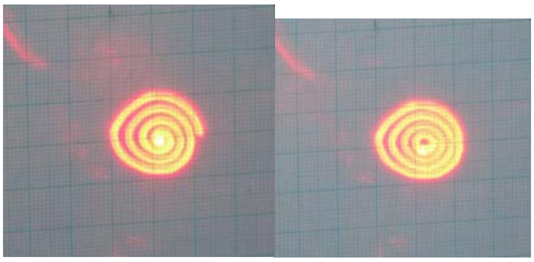

Figure 4. Experimental scan patterns from computer–controlled electrothermal scanner.

The frequency response of a scanner with a 500 x 500 µm mirror was determined (see Figure 5). The roll-off in tilt angle around 50 Hz is a limitation of the thermal time constants of the actuation process. This restricts the framing rate that can be achieved by the scanner when used for live imaging. It may be possible to increase the frequency range of the scanners by changing the geometry of the actuators.

The peaks in response at higher frequencies correspond to mechanical resonances excited by the small thermally induced motion of the actuators. This high frequency regime has been exploited in order to generate a type of raster scan capable of scanning the field of view at up to 15 Hz (consistent with live imaging). The horizontal scanning axis was driven at its resonant frequency while a ramp or staircase voltage was applied to the vertical scanning axis in order to sweep the scanned line down the field of view. The two drive waveforms were synchronised so that the mirror completed a certain number of complete cycles at its resonant frequency between before being stepped down to the next scan line.

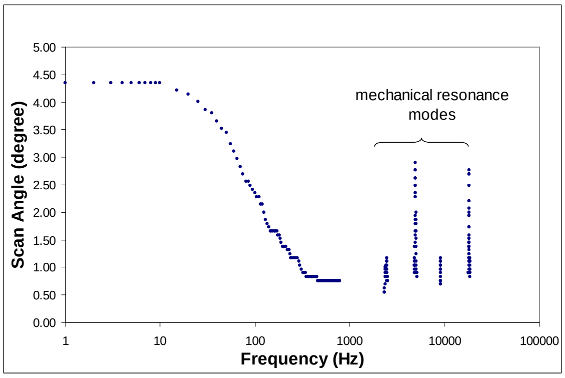

Figure 5. Frequency response of an electrothermal scanner.

A series of electrothermally actuated scanners has been successfully fabricated and tested, with mirrors up to 3 x 3 mm in area. The dimensions of the actuators in each of the scanners were identical. It was found that the maximum tilt angle of the larger scanners reduced from the 4^0 of the smallest device to 2^0.

Applications

The micro-scanners developed through DTC-funded research have been used in several internally-funded projects at the University of Strathclyde. In the course of developing these applications limitations of the scanners were identified and addressed. As a result, the improved scanners and driving systems should be more readily incorporated into other optical systems. Confidential discussions are taking place with three industrial companies with a view to exploring the use of MEMS scanners in their systems.

Laser control

Electrothermally actuated MEMS micro-scanners have been utilised as one of the cavity mirrors within doped glass lasers, with the aim of allowing modulation control or Q-switching of the laser output. The MEMS components have the potential of being cheaper and more robust than alternative devices, such as Pockels cells, that are used to perform these functions.

The doped glass lasers operate at wavelengths in the 1 µm band where silicon is partially transmitting. To increase the reflectivity of the mirrors a series of dielectric coatings was applied to them. In an earlier stage of the project, a multi-layer coating scheme, provided by an external contractor, had been identified, that consisted of 8 pairs of SiO_2/Nb_2O_5 and was capable of withstanding high power fluxes. This coating has also been found to have low residual stress, important in ensuring the flatness of the micro-mirror [3]. It was found that flatness of the micro-scanner mirrors was improved by applying the coating, with radius of curvature increased from 0.08 m to 1.0 m. The coating was designed to have a reflectivity of 99 % at a wavelength of 1064 nm, and measurements confirmed that the coating met the specification.

Initial testing of scanners in the laser cavity indicated that, even with this high reflectivity, enough energy was being absorbed in the mirror to cause sufficient distortion of mirror so that lasing stopped. Changes were made to the cavity configuration to reduce sensitivity to thermally-induced mirror curvature. Stable laser operation has been achieved with 20 – 40 mW CW output at 1060 nm. Under these conditions there is 2 W circulating power within the laser focused on the micro-mirror to a circular area 60 µm in diameter. Despite the high flux of 70 kW cm^{-2}, no mechanical or optical damage was evident on the micro-mirrors [4].

The electrothermally actuated scanners used in this application provide relatively slow switching of the laser at < 100 Hz or more rapid pulsing at about 1 kHz. Higher rates of switching, up to 40 kHz, can be achieved using electrostatically actuated scanners.

Single detector imaging system

In another application, the scanners are being utilised in an imaging system where the field of view is scanned over a single point detector. Currently, for ease of development, visible laser light is being used, but the system could find application in regions of the spectra such as terahertz where arrays of detectors are not available. The project is carried out in collaboration with an image processing group.

The experimental setup is shown in Figure 6. The test object is a sheet of paper with the letter “Z” printed on it. M_2 is an electrothermally actuated MEMS scanner whose scan pattern is controlled by a computer which also records the output from the photodiode, D, as the image is scanned across the pinhole, P.

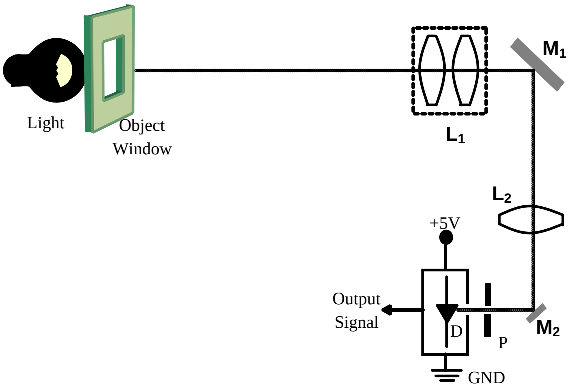

Figure 6. Schematic of single detector imaging system.

The MEMS micro-mirror, with a diameter of 2.5 mm, deflects the image in the x,y-plane and can be tilted by ±3^0 when a full-scale voltage of 15V is applied to horizontal or vertical actuator of the scanner. In the present optical setup, this angle corresponds to the maximum scan field of roughly 2.5mm x 2.5mm at the plane of the pinhole. The current pinhole is relatively large, with an area of 0.09 mm^2, limiting the resolution of the system to 7 x 7 pixels with no overlap between pixels. The effective resolution was increased to 16 x 16 pixels by allowing overlap between pixels and applying image processing techniques to the data [5].

Examples of raw and processed images from the system are shown in Figure 7. As expected, by straightforwardly arranging the measurements in the 16 x 16 matrix, a severely blurred image is obtained due to the fact that neighbouring scanned areas were overlapped. One can also notice a very low resolution of the resulting image due to a large pixel size and substantial measurement noise due to low-complexity optics. The images in the second and third rows show the results of applying various algorithms: wavelet denoising with soft thresholding only (middle left); bilinear interpolation only (middle right); bilinear interpolation after denoising (lower left); and the result of two further bilinear interpolation steps and another denoising step (lower right). It can be seen that processing steps removed blocking effects and much of the “measurement noise” [5].

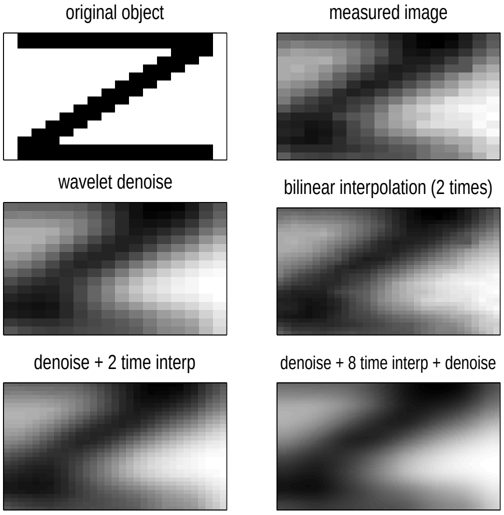

Figure 7. Images from single pixel camera: target (top left), raw captured image (top right), and the results of various image processing algorithms.

More advanced image processing techniques are currently being considered for further improvements. Refinements will also be made to the optical system, such as decreasing the pinhole size so that resolution can be increased.

Confocal laser microscope

In collaboration with the Institute of Photonics at the University of Strathclyde, a scanning laser confocal microscope has been set up that includes a MEMS device to perform the scanning function (see Figure 8). A system based on this approach has the potential of forming a compact system that could be used in an endoscope for medical examinations.

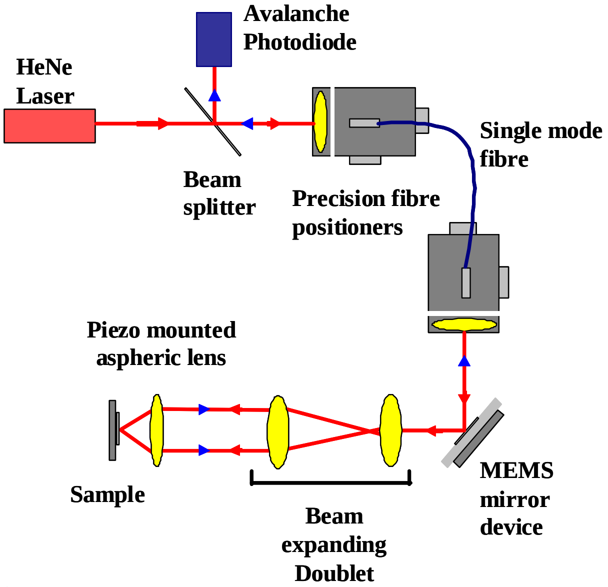

Figure 8. Layout of laser confocal microscope with MEMS scanner.

The electrothermally actuated micro-mirror, under computer control, scans the laser over the sample. Light reflected from the area illuminated by the laser is directed onto a photodetector. The end of the single mode optical fibre acts as the aperture in this arrangement. Scanning in the “depth” axis is achieved by moving one of the lenses by means of a piezo- actuator.

The mirror is scanned in a raster pattern, covering one frame per second. With a field of view 28 x 28 μm in extent, the resolution of the systems was found to be 1.7 ± 0.1μm and 2.6 ± 0.5μm for the x- and y-axis respectively [6].

The field of view of the current system could be extended by a factor of three in both x- and y-axis by adding amplifiers to the drive circuits of each axis. The mirrors used in this application have had no special coating applied so their reflectivity is limited to about 30 %. Scanners have been subsequently prepared with gold coatings that have reflectivities > 90 %. Their use in the system would reduce the noise present in the images.

Conclusions

Two families of scanners have been developed and demonstrated in a range of applications. A variety of scanning patterns has been generated through a computer controlled driving system. MEMS scanners have several advantages over conventional bulk scanners but may require some adaptation of existing optical systems. For example, a non-raster based scanning scheme may have to be accepted.

Acknowledgements

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