Integrated 2-axis MEMS scanners for high power fibre lasers

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Abstract

Compact, low operating power optical scanners using MEMS technology have been practically demonstrated. The scanners, driven at their mechanical resonant frequencies (~10 kHz), are capable of deflecting 1W IR laser radiation generated from erbium fibre lasers in two axes, with mirror tilt angles of up to ±13^{0}.

Keywords: micro-scanner, MEMS, fibre laser, dielectric coatings

Introduction

High-power fibre lasers have a number of merits as regards military applications: a) the ability to produce high power without the need for water-cooling; b) high overall efficiency; c) unsurpassed, near diffraction limited beam quality (M^2 ≈1); and d) operation at eye-safe wavelengths. These features will drive the development of fibre lasers for military remote sensing applications by providing, from non-water-cooled systems, higher optical intensity at longer distances compared to existing commercial sources. Typical applications of CW high-power fibre lasers in the remote sensing arena include remote vibrometry and velocimetry, active imaging, target illumination, wind shear sensing and the interrogation of remote sensing devices, such as those falling under the concept of "smart dust".

These applications require beam steering/scanning of the high-power fibre laser beams. However, at present, commercially available fibre laser systems do not offer an integrated, compact, high-power beam steering capability. The available option for beam scanning is to use off-the-shelf electro-mechanical scanning platforms (the actuators) to which are fixed high-power handling reflective optics, such as dielectric coated mirrors. This existing hybrid arrangement has the disadvantages of high weight, large volume and high operating power requirements. MEMS technology can produce miniature optical scanners where both the actuators and the reflectors are integrated into a single, compact, low-electrical-power unit dimensionally compatible with the beam diameter from a fibre laser.

However, before MEMS scanners can be used with any high-power lasers, they must be designed to withstand any potential damage which could arise from the incidence of the high-power beams on the relatively thin (< 25 μm) reflecting mirrors of the scanners. The development of MEMS scanners for high-power laser sources, with a view to practical demonstration of such devices with a high-power (up to 5 W CW) erbium doped fibre laser at the eye-safe wavelength of 1550 nm, is the principal aim of our research. The benefits are the implementation of high-power beam-scanned laser systems of reduced size and weight using scanners of ultra-low power consumption – these are the desirable features of portable military equipment. The utilization of MEMS scanners also has an economic advantage since they can be produced at a significantly lower manufacturing cost compared to conventional bulk scanners.

A precursor DTC project, undertaken by Strathclyde University in 2005, established that static MEMS mirrors fabricated by a silicon-on-insulator (SOI) foundry process (SOIMUMPS) from MEMSCAP [1] and coated with gold or a custom dielectric multilayer stack were capable of withstanding high levels of laser irradiation [2]. The mirrors were subject to 1 W CW at 1550 nm wavelength incident on a circular area with radius 100 μm for several hours with no apparent damage. In the first year of DTC-supported research, single-axis MEMS scanners capable of handling similar laser power levels at 1550 nm were demonstrated [3]. This paper describes the work undertaken in selecting an improved dielectric coating and in developing 2-dimensional scanners.

Modelling and Design

An example of the design of single-axis scanner that was developed in the first year of the project is shown in Fig 1. The circular area in the middle of the device acts as the scanner mirror and is located in the middle of a torsion beam. The device is actuated electrostatically by the comb drives located on either side of the torsion beam. One set of teeth in each comb drive has a vertical offset induced by applying a layer of gold during fabrication. The vertical offset of the comb drive ensures that the applied force of the drives has a vertical component and can initiate a rocking motion of the mirror about the torsion beam.

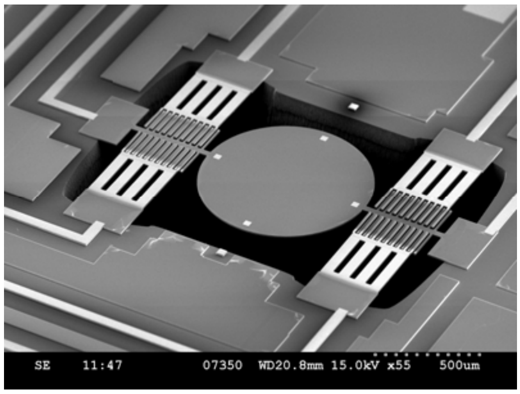

Figure 1 *SEM image of single axis SOI MEMS scanner.*

Material properties of the silicon device layer used in the fabrication process were determined from load versus deflection measurements made on cantilevers fabricated by the same foundry process. From the device designs prepared using the MEMSPRO L-Edit layout editor, a 3d model of the device was generated and finite element analysis (FEA) carried out using the Coventorware software package. Modal analysis of the devices indicated that in addition to the principal scanning mode there was a further mode, consisting of an oscillation about an axis orthogonal to the first (Fig 2). Hence, the design of Fig 1 can be driven to generate beam scanning in two orthogonal directions. This observation was subsequently confirmed during laboratory testing.

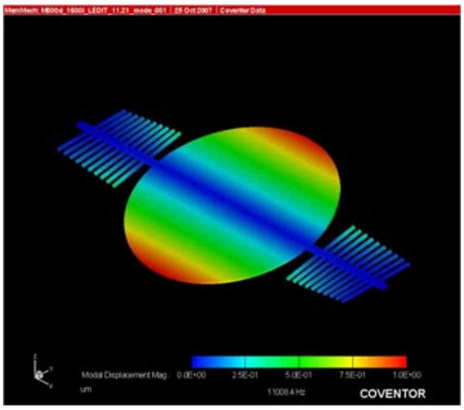

Figure 2(a) *FEA modelled mode shape: first scanner mode.*

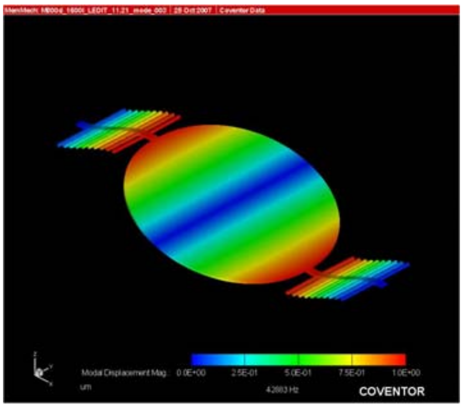

Figure 2(b) *FEA modelled mode shape: second scanner mode.*

A series of scanners was designed with circular mirrors, 800 µm in diameter, and with torsion beams ranging in length from 1600 to 2200 µm. The device layer was 10 µm thick and the torsion beams were 30 µm wide.

Initial static and dynamic testing

Following fabrication at the silicon MEMS foundry, static testing of the scanners was undertaken. The flatness of the mirror components was assessed by carrying out surface profilometry using white light interferometry. Due to stress induced during fabrication, the mirrors are found to be concave up, with the centre of the mirror 0.9 µm lower than the edge.

Dynamic testing of the scanners was also carried out. The devices were examined under a microscope-based laser vibrometer whilst they were driven by a time-varying voltage (a unipolar signal consisting of a sine wave plus a DC offset up to 200 V peak to peak.). It should be noted that the current required to operate the devices is very small. There is no conduction path through the device, and the only current flow is required to charge and discharge the capacitance of the device. As the drive frequency was increased from 100 Hz, the mode frequencies and types could be measured and identified. The mode frequencies calculated from FEA were found to agree within 10% of the measured values. For example, one device had calculated scanning mode frequencies of 11.0 and 42.9 kHz, compared with measured values of 10.2 and 41.7 kHz. This level of agreement was typical of the other devices.

The laser vibrometer is restricted by its method of operation to measuring the vibration of surfaces that have a maximum tilt angle of ~3^0. This angle could be readily exceeded with the MEMS scanners, and so another method was required to determine the maximum operating tilt angles of the scanners. A visible laser beam was directed onto the scanner mirror at an angle of incidence of ~45^0 and the length of the reflected scan line measured on a screen at a known distance from the mirror. By simple trigonometry, the angle subtended at the mirror by the scanned line could be calculated. The angle swept out by the mirror is half the subtended angle value. It was assumed that the mirror oscillated symmetrically about its rest position, so the range of tilt angle achieved by the mirror from rest is ± (half the angle swept out by the mirror). Note that all reported measurements were made in an ambient atmosphere, i.e. the scanners were not vacuum packaged.

Scanner type	Maximum tilt angles	
	1st mode	2nd mode
Small mirror	$\pm 14^0$	$\pm 2.2^0$
Large mirror	$\pm 5.1^0$	$\pm 3.1^0$
Large mirror with frame	$\pm 7.9^0$	$\pm 12.9^0$

Figure 3 *Table listing maximum tilt angles achieved by various iterations of scanner design.*

The tilt angles for the two scanning modes are shown in Fig 3 for various iterations of design all with the same dimensions of torsion beam. The devices with small mirrors (circular with diameter 400 µm) are early versions described in [3]. While this device has a wide operating range in the first scanning mode, its performance in the second mode is much smaller. The "large mirror" type is that discussed above (with mirrors of 800 µm diameter). It has a reduced performance in the first mode, since the mirror occupies a larger part of the torsion beam, increasing the stiffness of the device. An SEM of the third type, "large mirror with frame" is shown in Fig 4. The mirror is attached to the suspension beam by means of a frame that is intended to isolate the mirror from distortions due to flexing in the second mode.

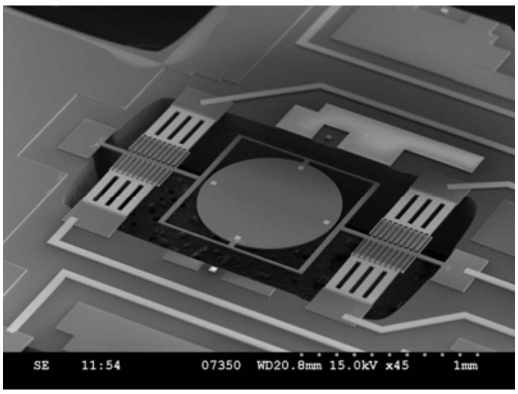

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Figure 4 *SEM image of MEMS scanner with mirror attached within frame.*

A further advantage of the inclusion of the frame is that the performance in the second mode has been enhanced. It is desirable that the scanner describe a square area, i.e. that the scan angles in each direction should be similar, and the mirror with frame most closely approaches this behaviour. The attachment arms connecting the mirror to the frame provide another degree of freedom in tuning the relative scan angles. By selecting the appropriate width and length of attachment arms it is predicted that equal scan angles could be achieved.

The two scanning modes of the devices can be excited simultaneously by supplying two separate drive voltages of the appropriate frequencies to two of the comb drives. The resultant scan patterns of two devices in the far field from a visible laser are shown in Fig. 5. The device in Fig 5a has a large circular mirror and was designed to have scanning modes whose frequencies have an integral ratio, in this case 1:4. The mode frequencies were measured to conform to that ratio, being 10.25 kHz for the horizontal scanning direction and 41 kHz in the orthogonal direction. That the ratio is indeed 1:4 is evident from the 4 closed loops visible along the horizontal direction and the single loop in the vertical direction. The tilt angles of the mirror in this case are $\pm 1.6^0$ in the horizontal direction and $\pm 1.2^0$ in the vertical direction. If one drive frequency is altered by a few Hertz, the pattern can be made to "rotate", and thus the whole of the field of view can be illuminated by the scanned laser beam acting in a flying spot mode.

In the second case (Fig 5b), there is a non-integer relationship between the two scanning mode frequencies and so the Lissajous pattern formed is dense. By adjusting one drive frequency a stable Lissajous pattern can be observed, albeit a more complex pattern with approximately 10 loops in each dimension. The whole filed is illuminated at a faster rate with the second device. The scan patterns shown in the images are not rectangular only because the screen was not positioned perpendicular to the laser beam.

Figure 5(a) *Far field scan pattern of MEMS scanner with scanner mode frequencies in ratio 1:4.*

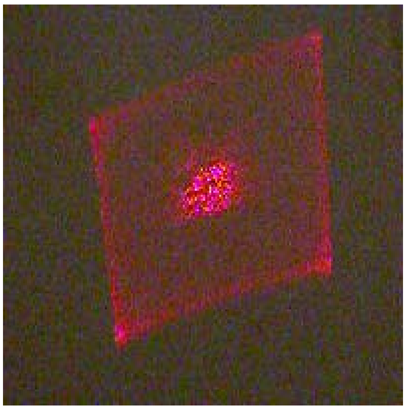

Figure 5(b) *Far field scan pattern of MEMS scanners with non-integer ratio of scanner mode frequencies.*

Optical coating and post-coat testing

Silicon has low reflectance at IR wavelengths so the scanners must have a multi-layer dielectric coating applied if they are to be utilised with fibre lasers. Such a coating was designed and supplied by a commercial optical coating provider. The coating was specified to have >99% reflectivity at 45^0 incidence for both s and p polarisations at a centre wavelength of 1550 nm. An issue in earlier work [3] was that the film used then (8 pairs of SiO_2/Nb_2O_5 deposited by magnetron sputtering), while possessing satisfactory optical properties, had a high residual stress that caused marked curvature of the thin MEMS mirrors.

A series of alternative coatings was investigated and an SiO_2/Nb_2O_5 coating, deposited by cold cathode ion-assisted deposition was found to have the lowest stress of those examined. Relative stress of the coatings could be determined by comparing the curvature of MEMS mirrors coated with the various dielectric coatings. Values for the stress were obtained by applying the Stoney formula [4] to measurements of the curvature of silicon strips before and after coating. Similar values of stresses were also determined by applying the Atkinson approximation [5] to measurements of the curvature of MEMS test structures before and after coating. The stress in the SiO_2/Nb_2O_5 coating, deposited by cold cathode ion-assisted deposition was found to range from -50 to +20 MPa. The curvature of devices coated with the revised SiO_2/Nb_2O_5 multilayer was found to have a similar magnitude but opposite sign to that of the structures as delivered form the foundry, before coating.

High power optical testing of the coated devices was carried out by directing the output of an erbium fibre laser on to a micromirror via a cleaved monomode fibre positioned < 1mm above the mirror. The energy reflected from the mirror was measured and the reflectance of the film was found to be 98 ± 1 % for the p mode, within the specification of the coating design.

1 W of CW laser radiation at 1550 nm was directed on to coated devices in the manner described above for 1 hour. No change in reflectivity was observed and no damage to the coating was visible. It is expected that any deterioration of film would occur on a time scale much shorter than 1 hour, either due to breakdown due to the intense electric

field of the laser radiation, or by thermal runaway arising from absorption by imperfections or inclusions in the coating.

A scanner was operated while 500 mW laser irradiation was incident at 1550 nm. An image of the scanned pattern formed on IR sensitive card is shown in Fig 6. This power level is lower than the intended operating range of the device but was chosen in order to prevent damage to the IR sensitive card that was required in order to render visible the locus of the scanned beam.

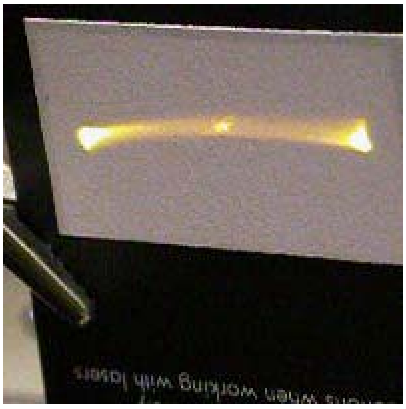

Figure 6 *Far field scan pattern of MEMS scanner obtained with infrared laser..*

Conclusions

MEMS scanners operating in two dimensions have been fabricated in 10 μm thick SOI. They have successfully been demonstrated achieving mirror tilt angles of up to 13^0. Scanners were demonstrated operating with CW laser irradiation at levels of 18 MW m^{-2} with no damage sustained. The scanners may be used in applications requiring rapid scanning of wide fields of view and offer advantages of compact volume and low electrical power requirements.

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