Frequency Tuning of Silicon Micromechanical Cantilevers by Laser Ablation

B. J. Gallacher*, J. Hedley*, J. S. Burdess* and A. J. Harris*

*Institute for Nanoscale Science & Technology,
Newcastle University, Newcastle-upon-Tyne NE1 7RU, England, John.Hedley@ncl.ac.uk

ABSTRACT

A theoretical model for frequency tuning of a cantilever is presented, both stiffness and mass effects have been considered. A cantilever was ablated at its fixed and free end using a Nd:YAG laser, a tuning resolution of 1 Hz was obtained. There was some disagreement between the theoretical values of -29 Hz (fixed end), 10 Hz (free end) and an actual experimental tuning of -19 Hz (fixed end), 3.5 Hz (free end). This has been attributed to the debris present around the ablation site. Consideration of this debris shows that there is a reduction in tuning of around 30% (fixed end) and 50% (free end) in the theoretical values.

Keywords: resonators, frequency tuning, laser ablation.

1 INTRODUCTION

The high Q-factor and stability of micromechanical resonators makes them attractive for a range of applications such as R.F. filters [1] and resonant sensors [2]. In many cases, a specific resonant frequency is necessary for optimum performance [3,4], however this cannot be guaranteed as fabrication tolerances, defects and stresses will shift the natural frequencies of the resonator. A tuning method must be employed to re-align the centre frequency of the resonator with the specified band [5]. Either a laser or a FIB [6] could be used for such tuning, FIB has the advantage of a more precise cut as compared to laser ablation. However laser ablation offers the possiblilty of removing mass quickly and can be incorporated into an optical measurement system where the resonant frequency can be monitored. Permanent tuning using a Nd:YAG laser is examined in this paper.

2 THEORY

By applying the elementary theory of bending of beams [7], it can be shown that the fundamental natural frequency of a cantilever of length L, width b, thickness d and density ρ vibrating laterally is given by:

$$\omega = \beta^2 \sqrt{\frac{EI_{xx}}{A\rho}} \quad \text{where } \beta = \frac{1.875}{\mathrm{L}},\ A = bd \text{ and } I_{xx} = \frac{1}{12} bd^3.$$

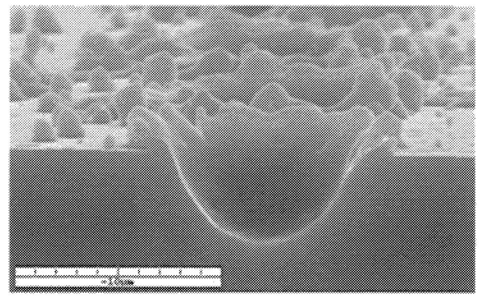

Figure 1: A single laser shot produces a hemispherical cavity.

The mode shape associated with the fundamental natural frequency of the cantilever may be written in the form:

$$X(y) = C[\cos \beta y - \cosh \beta y] + \sin \beta y - \sinh \beta y$$

where C = -1.36.

A series of ablation holes were cut into a piece of silicon. These were then cleaved and the resulting SEM images (figure 1) showed the ablation profile to approximate to a hemisphere with radius 4 μm.

Figure (2) shows an ablated cross-section. The X and Z axes are centroidal principal axes and it is assumed that the ablated hemisphere is positioned symmetrcally about the Z axis. For ablation performed at a distance y from the root of the cantilever, both the mass and stiffness of the cantilever will be reduced in general. The resulting change in frequency may be calculated by considering the change in the generalised mass and stiffness of the cantilever. As the root and free end of the cantilever correspond to extreme values of the generalised stiffness and mass, these two cases are considered.

The change in generalised stiffness due to ablation of hemispherical volume of radius R_o at the root and free end of the cantilever is given by:

$$k_{root} = -E \int_0^{2R_O} [I_{xx} - I'_{xx}(y - R_o)] \left[\frac{d^2}{dy^2} X(y)\right]^2 dy,$$

$$k_{free} = -E \int_{L-2R_O}^{L} [I_{xx} - I'_{xx}(y - [L - R_o])] \left[\frac{d^2}{dy^2} X(y)\right]^2 dy.$$

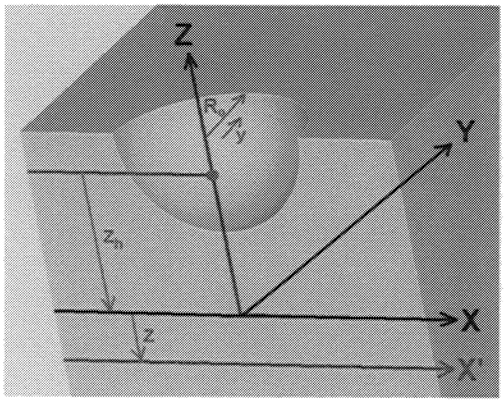

Figure 2: The geometry of the modelled ablation.

Note that I'_{xx} refers to the second moment of area of the ablated cross-section. As the ablation profile is hemispherical, the position of the neutral plane (zero axial stress as indicated by X' in figure 2) will vary between adjacent cross-sections over the ablated region. The displacement of the neutral plane of the ablated region with respect to the neutral plane of the unablated regions (X in figure 2) is given by:

$$z(y) = \frac{\frac{1}{2}\pi R(y)^2\left[\frac{1}{2}d - 0.4234R(y)\right]}{A - \frac{1}{2}\pi.R(y)^2}$$

where $R(y) = \sqrt{R_O{}^2 - y^2}$.

The distance between the centroid of the removed semicircular section and that of the unmodified cross-section is given by:

$$z_h(y) = \frac{1}{2}d - 0.4234R(y).$$

Thus the distance between the centroid of the ablated cross-section and that of the removed semicircular section is given by:

$$\bar{z}_h(y) = z_h(y) + z(y).$$

Therefore:

$$I'_{xx}(y) = I_w(y) - I'_h(y)$$

where:

$$I_w(y) = I_{xx} + A.z(y)^2,$$
$$I'_h(y) = I_h(y) + A_h(y).\bar{z}_h(y)^2.$$

The terms A_h and I_h represents the area and the second moment of area of the removed semicircle about its centroid position respectively and is given by:

$$I_h(y) = 0.1098.R(y)^4,$$
$$A_h(y) = \frac{1}{2}\pi.R(y)^2.$$

By approximating the mass removed to be a point mass m_p, the change in the generalised mass due to ablation at the root and free end of the cantilever are given by:

$$M_{root} = 0,$$
$$M_{free} = -m_p X(L)^2,$$
where $m_p = \frac{2}{3}\pi R_o{}^3\rho$.

The frequency of the fundamental mode after ablation at the free end and root of the cantilevers is given by:

$$\Omega_{free} = \sqrt{\left[\frac{\omega^2 + \frac{k_{free}}{M_c}}{1 + \frac{M_{free}}{M_c}}\right]}, \quad \Omega_{root} = \sqrt{\left[\frac{\omega^2 + \frac{k_{root}}{M_c}}{1 + \frac{M_{root}}{M_c}}\right]}$$

where $M_c = A.\rho.\int_0^L X(y)^2 dy$ and represents the generalised mass of the cantilever. The frequency shift resulting from ablation at either the free end or root of the cantilever is given by:

$$\Delta f_{free} = \frac{1}{2\pi}\left[\Omega_{free} - \omega\right], \quad \Delta f_{root} = \frac{1}{2\pi}\left[\Omega_{root} - \omega\right]$$

The predicted frequency shift of the fundamental flexural mode of vibration due to a single laser shot is shown in figure (3) for ablation performed at the fixed and free ends of the cantilever.

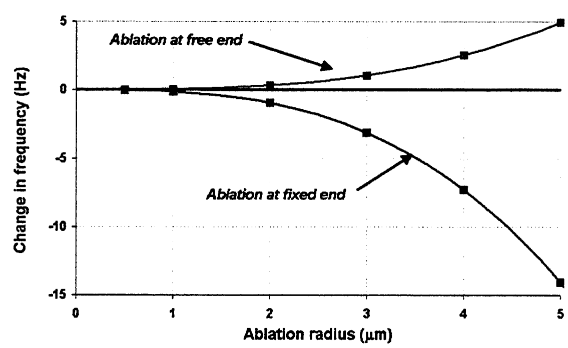

Figure 3: The theoretical frequency tuning of a cantilever for an ablation radius of 4 µm.

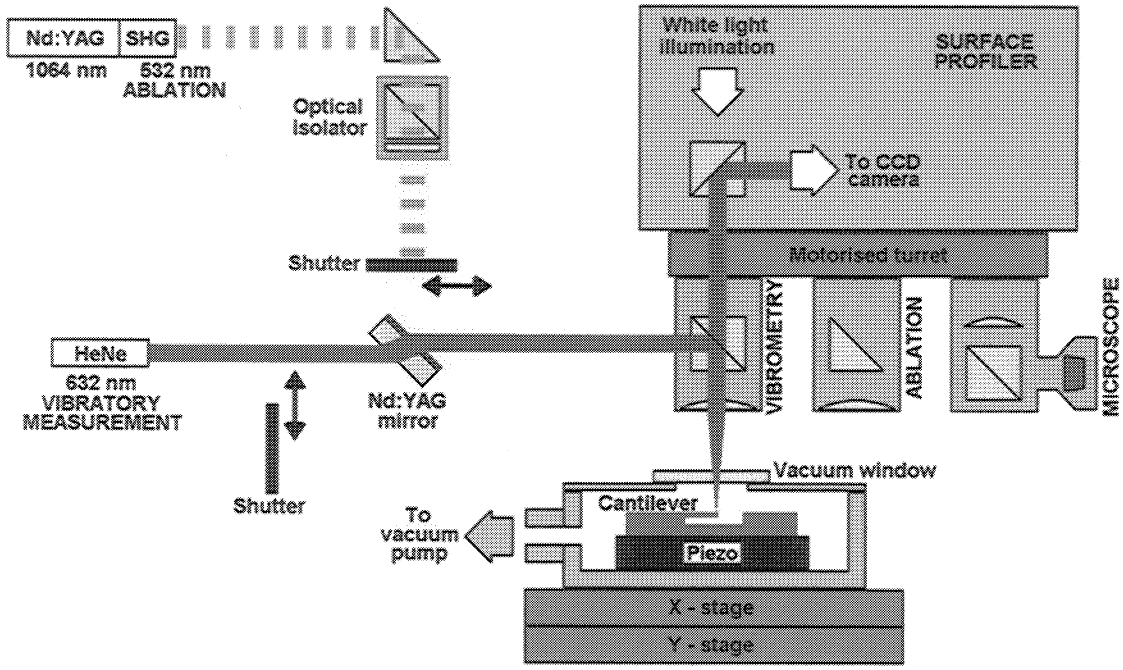

Figure 4: Optical arrangement of the tuning / measuring process.

3 EXPERIMENTAL DETAILS

An optical workstation [8] incorporating a frequency doubled Nd:YAG laser, a laser vibrometer and a surface profiler were employed to perform the tuning, measure the frequency shift and characterise the ablation sites, respectively. A schematic of the apparatus is shown in figure 4. A SOI cantilever was used for the experiment, this was mounted onto a piezo disk for actuation. To prevent squeeze film damping, resonant measurements were performed at a pressure of 20 μbar. This partial vacuum also prevented oxidation around the ablation site and assisted in dispersal of the ablated material. Although chemical wet etching can be used to remove ablation debris [9], problems with stiction would render this approach impractical for resonating devices.

To prevent the pulsed Nd:YAG light from entering the CCD camera, a prism within the ablation objective was used to direct the beam towards the sample. Since this prevented viewing of the ablation site, a calibration shot was taken and its position noted using one of the microscope objectives on the turret, these calibration shots can be seen next to the cantilever structure in figures 5a and 5b. This calibration technique slowed the tuning process and limited the accuracy of the ablation positioning to around 10 μm due to slack in the motorised turret.

The Nd:YAG power was set to 2 mJ, this being close to the lasing threshold, the beam was then passed through a 10% transmission filter. This 5 mm diameter beam was focused using a 2 cm focal length lens onto the sample giving a spot size of 10 μm. The tuning process consisted of a single laser shot at the root of the cantilever and then an additional three shots. This process was repeated for the end of the cantilever. The resonant frequency of the cantilever was measured several times between ablations so that changes in the frequency caused by room temperature variations could be accounted for.

4 RESULTS AND DISCUSSION

The measured tuning is shown in figures 5a and 5b, the dotted lines (translations of the data points) show the estimated frequency drift due only to environmental temperature variations. This can be accounted for by the variation in cantilever length due to temperature which produces a frequency shift of -0.2 Hz / K.

For the single and subsequent three laser shots, the model predicts a shift in resonant frequency of -7.3 Hz, -29 Hz (fixed end) and 2.5 Hz, 10 Hz (free end) compared with the measured values of -1.1 Hz, -19 Hz (fixed end), 1.0 Hz, 3.5 Hz (free end). Although the model predicts the direction of the shift, there is a large discrepancy in the magnitude; this has been attributed to the redistributed material around the ablation site.

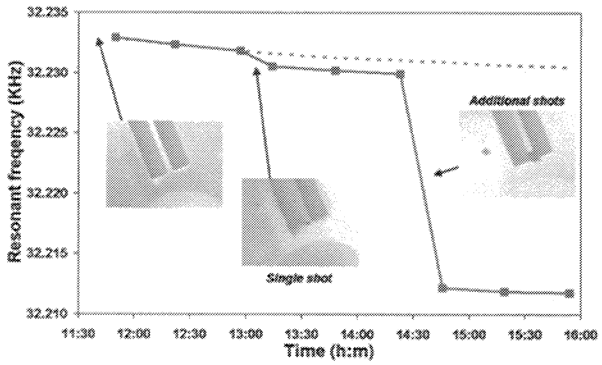

Figure 5a: The measured change in resonant frequency of a cantilever ablated at the fixed end.

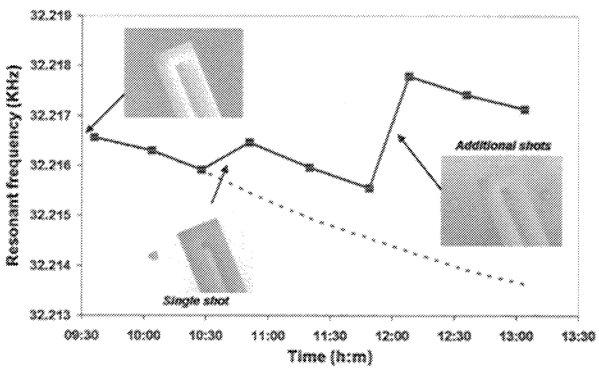

Figure 5b: The measured change in resonant frequency of a cantilever ablated at the free end.

To give an indication of the error in the original model, the ablation profile was remodelled to incorporate a lip of debris, see figure 6. From the SEM image of the ablation profile this was estimated to be a ring of cross-sectional area 1.5 μm × 1.5 μm. This modified ablation cross-section gave a reduction of 30% in tuning at the fixed end of the cantilever and 50% for the free end which is in closer agreement with the observed values.

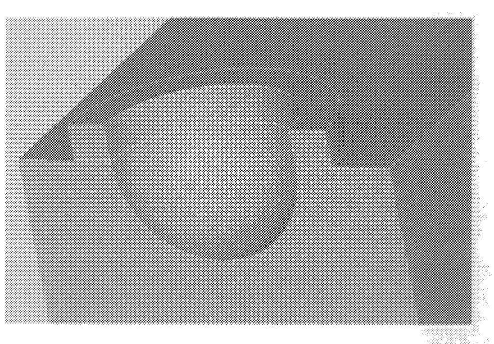

Figure 6: A refined model of the ablation process incorporated a ring of debris around the ablation site.

5 CONCLUSIONS

Further modelling to incorporate this debris does lead to better agreement however accurately predicting the resulting frequency from tuning by laser ablation remains problematic due to the non-predictable dispersal of the debris. Post-processing to remove this debris is not an option for resonating devices. Therefore for laser tuning, modelling can only act as a rough guide, it is necessary to monitor the resonant frequency of the device during the tuning process. A microscope objective is currently under development to simultaneously measure and ablate devices.

ACKNOWLEDGEMENTS

The authors would like to acknowledge EPSRC for the research grants GR/M31026 and GM/M13756.

REFERENCES

1. J. J. Yao, "RF MEMS from a Device Perspective," *Journal of Micromechanics and Microengineering* **10**, R9-R38, 2000.

2. J. S. Burdess et al., "A Review of Vibratory Gyroscopes," *Engineering Science and Education Journal*, 249-254, 1994.

3. K. Maenaka et al., "Analysis of a Highly Sensitive Silicon Gyroscope with Electrostatic Actuation and Sensing," *Sensors and Actuators A* **54**, 568-573, 1996.

4. B. J. Gallacher et al., "The Principles of a Three Axis Vibrating Gyroscope," *IEEE Transactions On Aerospace and Electronic Systems* **37**, 1333-1343, 2001.

5. C. P. Fell, "Method for Matching Vibration Mode Frequencies on a Vibrating Structure", *UK Patent GB 2 292 609 A*, 1996.

6. D. F. Moore and R.R.A. Syms, "Tuning of Vibrating Micromechanical Resonators Using A Focused Ion Beam," *Demonstrated Micromachining Technologies for Industry* Birmingham, England, IEE, 2000.

7. W. Weaver, S. P. Timoshenko and D. H. Young, "Vibration Problems in Engineering", Wiley, 416-428, 1990.

8. J. Hedley et al., "The Development of a Workstation for Optical Testing and Modification of IMEMS on a Wafer", *SPIE Proceedings Design, Test and Packaging of MEMS/MOEMS 2001* Cannes, France, SPIE **4408**, 402-408, 2001.

9. S. Dauer, A. Ehlert and S. Büttgenbach, "Rapid Prototyping of Micromechanical Devices using a Q-Switched Nd:YAG Laser with Optional Frequency Doubling", *Sensors and Actuators A* **76**, 381-385, 1999.