Defence Science Journal, Vol. 59, No. 6, November 2009, pp. 616-621

Fabrication of Polymeric Microcantilevers

K.A. Thomas, Akash Singh, and V. Natarajan*

Naval Physical and Oceanographic Laboratory, Thrikkakara, Kochi–682 021
**E-mail: natarajan_vinay@yahoo.com*

ABSTRACT

Polymer cantilevers are used widely in sensing applications using different transduction methods. In this paper, a polymer microcantilever is made using microstereolithography (MSL). The MSL is the latest technology emerged from applied optical instrumentation by which the micron-size structures can be created by the photopolymersation of monomers. Cantilever length, breadth, thickness, and seismic mass attached at the free end of the cantilever decide the output voltage generated by the sensor. The effect of these design parameters on the output voltage of the sensor has been studied. The microstructure fabrication process is optimised by studying the effect of laser wavelength, laser energy, scanning speed, and photoinitiator concentration on curing width and depth, that are the critical parameters that control the resolution of the fabricated structure. A cantilever design is made of 10 x 2 x 1 mm size in CimCAD and the cantilever structure is fabricated from the CAD design using the optimised values obtained from analytical and experimental study.

Keywords: Microcantilevers, microstereolithography, MSL, polymer cantilevers, fabrication, sensors, biological sensors

1. INTRODUCTION

Cantilever structure and its array with polymer have attracted the scientific community around the world for its ease of fabrication, cost-effective process, and various types of sensors realised. Cantilever-based sensors have been used to monitor different physical and chemical processes by various means of transduction such as temperature, mass, electromagnetic field, and surface stress. The growing interest in the development of a new kind of biological sensor based on microcantilevers relies largely on the potential application for performing local, high resolution, and label free molecular recognition measurements on a portable device[1].

Possibility of polymeric cantilever as a flexible probe in numerous applications is widely explored[2-4]. Polymers offer high flexibility, and biocompatibility with reasonable mechanical properties. The low-cost and ease of processing techniques are the added advantages to the polymer. Microcantilevers fabricated by both standard silicon processing technique and SU8-based microcantilevers using two photon microstereolithography are reported in the literature and the applications are found mainly in the medical field[5-8]. Cantilever is also used for the characterisation of mechanical properties of materials by measuring the spring constants of cantilevers made by that particular material [9-10]. Fabrication of polymeric cantilever is much simpler using the microsterolithographic technique and it has not been exploited extensively. In this context, a microcantilever is fabricated using an acrylate polymer using micostrereolithography(MSL).

2. CANTILEVER DESIGN

A cantilever is a mechanical structure having a beam with its one end fixed and having a seismic mass at its free-end. The cantilever can be easily designed to respond linearly to any desired environmental changes, and hence, it is widely studied. The most important parameters in the cantilever design are its length, breadth and attached seismic mass. A sensor design can be arrived by combining the basic cantilever concept and the assumption that the strain in the beam will transfer the same (complete) strain to an attached piezosensor, which will induce a voltage.

The maximum deflection of a cantilever beam of length 'L' is given by

$$\delta = WL^3/3EI \tag{1}$$

where, E and I are the respective Young's modulus and the area moment of inertia of the beam cross-section, and W is the load acting on the cantilever. The spring constant is given by

$$k = \text{Load/deflection} \tag{2}$$

$$k = W/\delta = 3EI/L^3 \tag{3}$$

The natural frequency,

$$\omega_n = (K/M)^{1/2} = (3\,EI/ML^3)^{1/2} \tag{4}$$

where, M is the mass of the beam. The maximum bending stress can be calculated as follows:

Equivalent load, $P_{eq} = ma$,

where, m stands for mass attached to the beam, and a is the acceleration for which the beam is designed.

The equivalent load on its free-end statically loads the cantilever beam, then the maximum bending moment, $M_{\max} = P_{eq} \times L$.

Received 14 February 2009

The equivalent bending stress, $\sigma_{max} = M_{max}\ C/L$, where C is the half depth of the beam cross-section and the associated maximum bending strain will be obtained by $\epsilon_{max} = \sigma_{max}/E$.

It is assumed, that the strain in the beam will transfer complete strain to an attached piezosensor, which will induce a voltage, $V = \epsilon_{max}/d$, where d is the piezoelectric coefficient. If the actual length of the piezosensor is 1, then voltage $v = V$ x 1. This voltage generated by the cantilever is a function of the dimensional parameter of the cantilever structure and piezoelectric voltage coefficient of the sensor. The sensor can be realised taking the above design criteria.

3. ANALYTICAL RESULTS

The analytical studies for the 1, 6 hexane diol diacrylate cantilever structure was carried out using Young's modulus 1 GPa and the density 1 g/cc for the polymer[11]. Figure 1 describes the variation of the output voltage as a function of the breadth of the cantilever.

From Fig.1, it is clear that the voltage generated by piezosensor decreases steadily with the increase in breadth for decrease in cantilever length. So for achieving a better sensitivity of sensor, the breadth should be as minimum as possible.

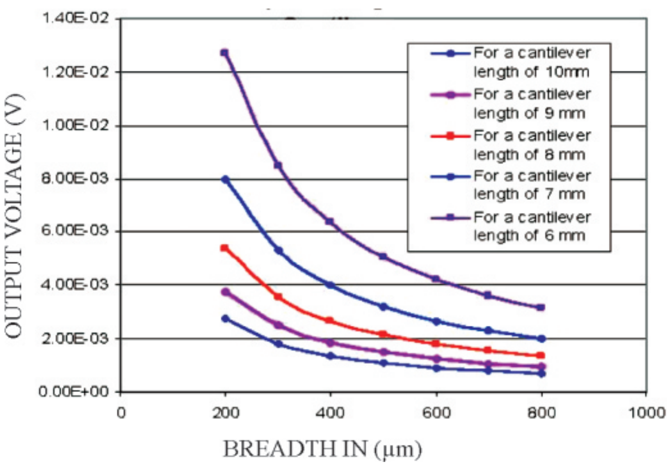

Figure 1. Variation of output voltage with breadth of beam for different cantilever lengths.

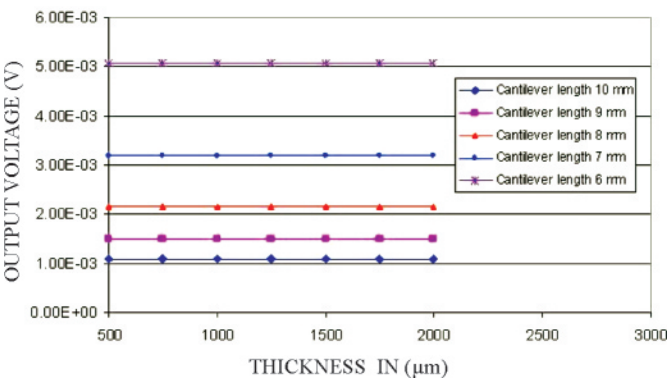

Figure 2. Variation of output voltage with thickness of beam for different cantilever lengths.

Figure 2 shows that the voltage generated by piezosensor does not change appreciably with increase in thickness of cantilever for increase in cantilever length. However, the change in thickness changes the moment of inertia of the structure, which in turn changes the natural frequency of the structure.

Similarly, Fig. 3 shows that with increase in cantilever length, the voltage generated by piezosensor decreases with increase in breadth of the cantilever. For a better sensitivity of the sensor, the cantilever length should be as minimum as possible.

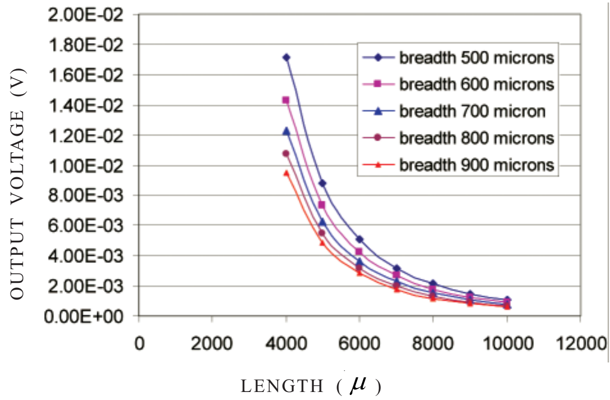

Figure 3. Variation of output voltage with cantilever length for different cantilever breadths.

It can be seen from Fig. 4, that with increase in seismic mass, the voltage generated by piezosensor increases for decrease in the length of the cantilever. For a better sensitivity of the sensor, the seismic mass should be as high as possible.

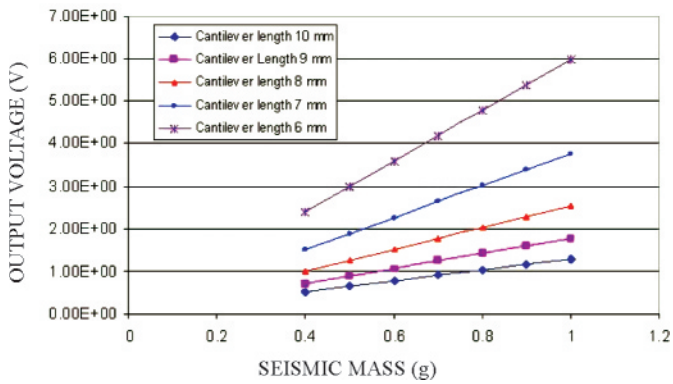

Figure 4. Variation of output voltage with seismic mass for different cantilever lengths.

4. FABRICATION OF MICROCANTILEVER

Amicrocantilever was fabricated using microstereo-lithography (MSL) technique and an acrylate polymer system. The MSL is the latest technology emerged from applied optical instrumentation by which the micron size structures can be created by the photopolymersation of monomers. It enables a constructive way of making complex 3-D and highaspect ratio structures in which there is no wastage of material (bottom-up technology). Desired polymer object was built from ultraviolet curable resin in a layer by layer additive fashion. This is a maskless fabrication process; hence, there is no need of photo mask for the fabrication of various planar designs of structures.

4.1 Microstereolithography System

Figure 5 represents an MSL system which consists of the *Ar* laser optics, XYZ positioner (aerotech make) and an UV-curable polymer. A 3-D solid model designed with CimCAD 11.0.5 software was sliced into a series of 2-D layers with uniform thickness. The NC codes generated from each sliced 2-D file were then executed to control the UV-beam scanning. The focused UV-beam scaned line-by-line over one layer and selectively cured the photopolymerisable resin.

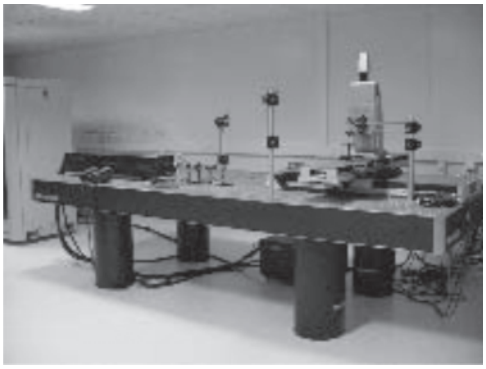

Figure 5. Microstereolithography (MSL) setup at NPOL.

The selection of spacing between the scanning lines was set according to the curing width. After the line-by-line scanning, a layer completely got cured, and after one layer was solidified, the elevator moved downward and a fresh layer of resin was filled over the already cured layer by pouring the exact amount of resin over that. The layer thickness was set according to the cured depth of the resin. The time taken for the fresh layer formation by the resin depends on its viscosity. A low-viscosity resin was recommended for a rapid formation of the fresh layer. A sufficient dwell time was given between each layer formation for the uniform spreading of the resin. The complicated 3-D microstructure was built layer-by-layer with the synchronised beam scanning (X and Y axes) and the Z axis motion (depth/height).

Curing width and depth are the most important parameters which determine the resolution of the fabricated parts and was governed by Beer-Lamberts law, according to the following equations:

$$Curing\ Width = \sqrt{2}\,W_0 \sqrt{\ln\left(\frac{E_{\max}}{E_c}\right)} \qquad (5)$$

$$Curing\ Depth = Dp\ \ln\left(\frac{E_{\max}}{E_c}\right) \qquad (6)$$

$$Penetration\ Depth,\ Dp = \frac{1}{2.303\,\varepsilon[I]} \qquad (7)$$

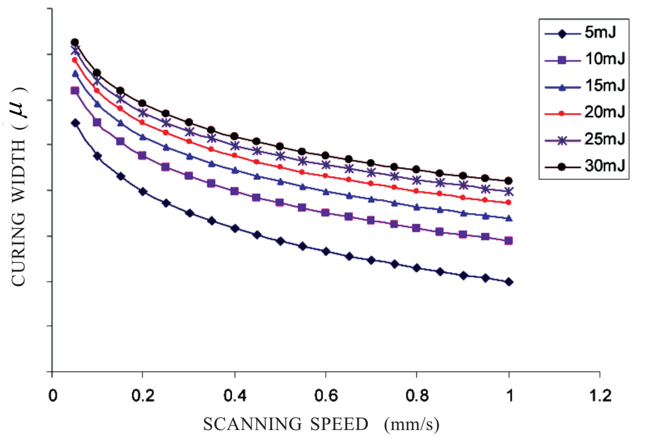

Figure 6. Variation of curing width with scanning speed for different laser energies.

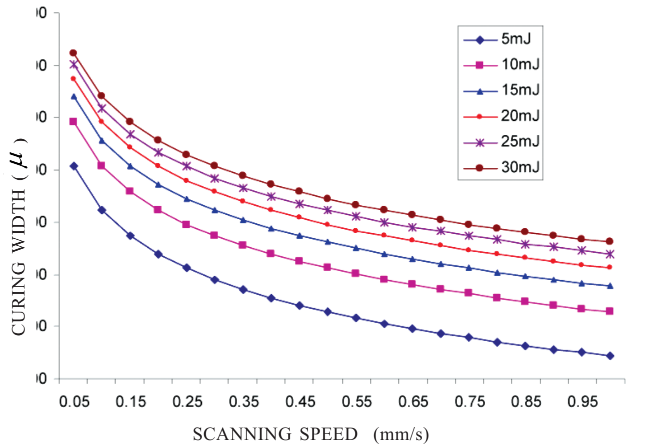

Figure 7. Variation of curing depth with scanning speed for different laser energies.

where, E_{max} is exposure energy at the resin surface; E_c is critical exposure energy; ε is molar extinction coefficient; W_o is laser spot diameter (4μm); and [I] is initiator concentration.

Based on the Beer's Lambertz law, the curing width and depth vary with both laser energy and the scanning speed and were studied analytically for 1,6 hexane diol diacrylate.

The theoretical studies reveal that the curing width and curing depth decrease with increase in scanning speed and with decrease in laser energy. The scanning speed and laser energy have greater influence on curing depth as compared to curing width.

Mesh structures of high-resolution were fabricated to get an insight on the influence of material parameters–type and concentration of photoinitiator, photoabsorption coefficient of resin, and process parameters–scanning speed, laser wavelength, diameter of beam, and energy.

4.2 Photoresin System

For the monomer, 1, 6 hexane diol diacrylate (HDDA) is selected and benzoin ethyl ether with concentration of 4 Wt per cent as the photoinitiator. As discussed earlier, the wavelength, curing depth, and curing width have to be optimised for the high-resolution of the structure and laser energy and scanning speed for good mechanical properties. The following material properties are characterised to find the optimum parameters for the fabrication of a cantilever.

4.2.1 Selection of Suitable Wavelength

The UV absorption spectra of the benzoil ethyl ether with a varying concentration of 1-4 Wt per cent is measured for the wavelength of 200-450 nm using UV-visible spectrophotometer. The selection of the wavelength is very critical as it severely affects: (a) the curing characteristics, and hence, the mechanical properties of the structure, and (b) the resolution of the structure, especially the curing depth. The UV absorption spectra of benzoin ethyl ether for different molar concentrations is given in Fig. 8 which shows that the absorption coefficient varies as the wavelength changes.

The high absorption value regions are not advisable for curing thick structures as these result in a non-uniform distribution of photoenergy throughout the thickness. This results in variation in crosslinking density across the thickness and may result in poor mechanical strength and differential shrinkage.

Selection of a proper wavelength also affects the resolution of the structure. According to the molar absorption coefficient of the resin system, the penetration depth varies which in turn affects the curing depth. The layer thickness is set according to the curing depth, as microstructure is fabricated layer-by-layer, hence this technique is called bottomup technology.

A 364 nm wavelength ws chosen based on the UV absorption spectra (Fig. 8) to have least absorption by the material to enable fabrication of high-resolution structures.

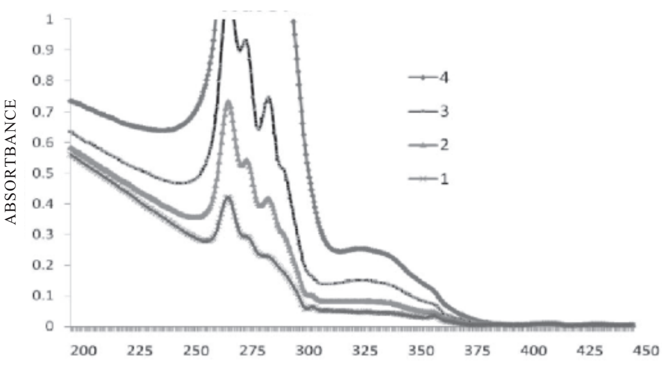

Figure 8. UV absorption spectra of benzoin ethyl ether from 1-4 Wt per cent concentrations.

UV spectra of different levels of PI concentrations were investigated to optimise the required absorption for the chosen resin.

4.2.2 Curing Width Measurement

A 2-D mesh structure was fabricated using laser scanning with different levels of optical energy and scanning speeds

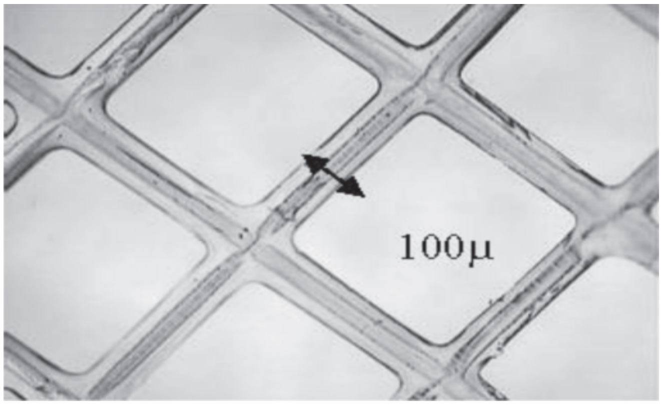

Figure 9. HDDA mesh structure (50 x).

to find out the optimum parameters to fabricate structures of high resolution. The mesh structure is observed through an optical microscope after washing with deionized water. For calculation, critical energy for curing was taken[11] as 111 mJ/cm^2. The mesh structure and its width are shown in Fig. 9.

Figure 10 shows the variation of curing width as a function of scanning speed at different energy levels. It was observed, that curing width decreases with increase scanning speed while curing width increases with increase in laser energy.

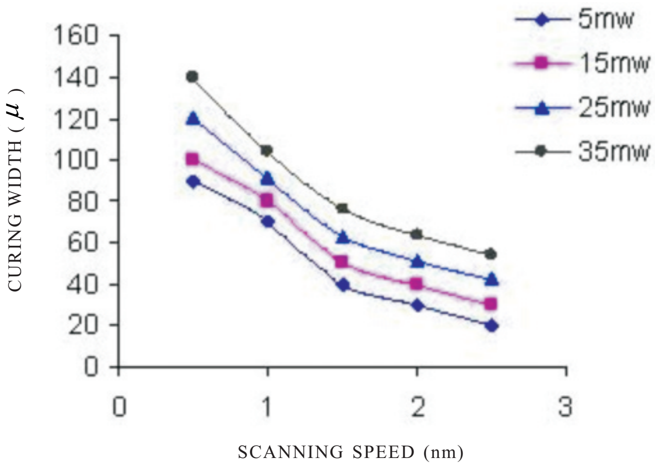

Figure 10. Variation of curing width with scanning speed for different laser energy.

4.2.3 Curing Depth Measurement

The focused Laser was scanned over the resin surface and in a line-by-line fashion with different speeds and different energies. The cured structure was carefully taken out and washed with deionized water and analysed through an optical microscope, as shown in Fig. 11.

The variation of curing depth with scanning speed at different energy levels is shown in Fig. 13. It was observed that curing depth decreases with increasing scanning speed and laser energy.

4.3 Fabrication of Microcantilever

Figure 13 shows the micrograph of the fabricated polymer-based cantilever. The cantilever is designed based

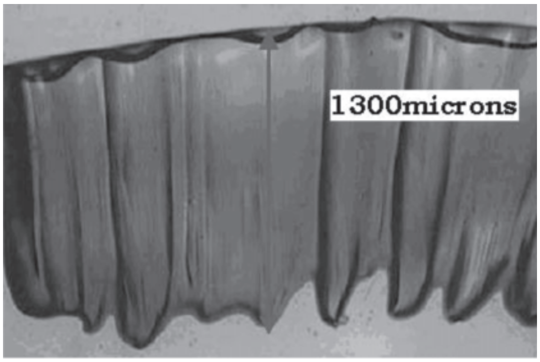

Figure 11. Cured depth portion (50x).

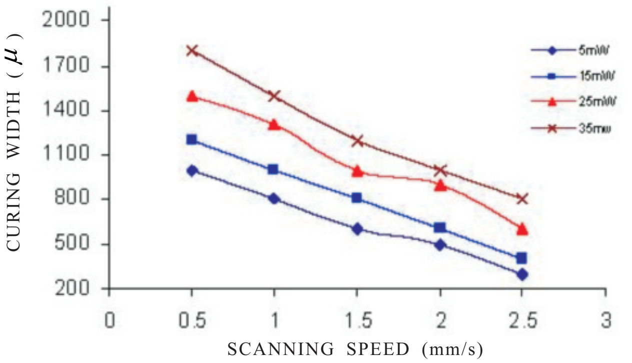

Figure 12. Variation of curing depth with scanning speed for different laser energy.

on the analytical results with a dimension 10 x 2 x 1 mm and the seismic mass to be 0.8 g. The cantilever was designed in Cim CAD and translated to numerical control (NC) code. The generated NC code is modified according to the material and process parameters and fed to XYZ position controller through Nview (interface software for MSL). After the completion of each layer, calculated amount of resin is poured over the cured part and a dwell time of 10 s was given between each layer to give sufficient time for the resin having viscosity of 150 Cp to spread. A scanning speed of 2 mm/s and laser energy 15 mw of wavelength 364 nm were used. The microstructure was taken out after the completion of laser scanning and washed with deionised water and dried in compresses dry air.

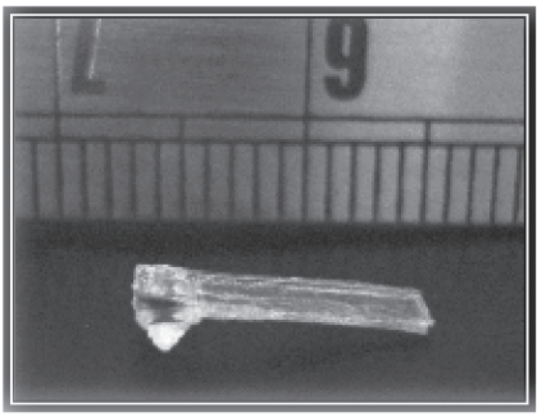

Figure 13. Photograph of fabricated cantilever.

5. CONCLUSIONS

Based on the optimisation study of material and system parameters, a programme for the fabrication of the cantilever was written in G-code using Cim CAD. The physical parameters such as laser intensity, scanning speed, laser wavelength, and material parameters such as viscosity, photoinitiator concentration were used in realising a cantilever of dimension 10 x 2 x 1 mm with a seismic mass of 0.8 g. Analytical results show that to improve the sensitivity of the sensor, trade-off between the output voltage and dimensions of the cantilever needs to be adjusted.

ACKNOWLEDGEMENTS

The authors thank Director, NPOL for permission to publish this work and Mr R.M.R. Vishnubhatla, Associate Director, NPOL for the encouragement to carry out the study.

REFERENCES

1. Calleja, M.; *et al*. Polymeric cantilever arrays for biosensing applications. *Sensors Letters*, 2003, **1**, 1–5.
2. Bayindir, Z.; *et al.* Polymer microcantilevers fabricated via multi-photon absorption polymerization. *In* American Physical Society Meeting, March 2004.
3. Watanabe, Toshiyuki.; *et al*. Photoresponsive hydrogel microstructure fabricated by two photon initiated polymerization. *Adv. Funct. Mater*., 2002, **9**.
4. Tai, Yu-chang; *et al*. Free standing polymer MEMS structures with antistiction. US Patent No. 6787968.
5. Johansson, A.; *et al.* Fast packaging of polymeric cantilever chip by micro milling. *Appl. Phy. Lett.*, 2006, **89**, 173505.
6. Bayindir, Z.; *et al*. Physical characterization of two-photon-fabricated polymer cantilevers. *In* Proceedings of Materials Research Society Symposium, 2004, EXS2.
7. Xu, Tao; Mark, Bachmana; *et al*. Polymeric microcantilever array for auditory frontend processing. *Sensors and Actuators A*. 2004, **114**, 176-82.
8. Vaziri, A.; *et al*. Flexible probes for characterizing surface topology: From biology to technology. *Experimental Mechanics*. (DOI 10.1007/s1134000790468.8)
9. Varadan,Vijay K.; *et al*. Microstereolithography and other fabrication techniques for 3-D MEMS. John Wiley & Sons Ltd, UK. 2001.
10. Gardner, Julian W.; Varadan, Vijay K. & Awaldikarim, O. Micro sensors, MEMS and smart devices. John Wiley & Sons Ltd, UK. 2001.
11. Chang, X. ; *et al*. Microstereolithography of polymeric and ceramic microstructures. *Sensors and Actuators*, 1999, **77**, 149-56.

Contributors

Mr K.A. Thomas obtained his BTech (Polymer Science & Rubber Technology), Cochin University of Science and Technology, Kochi, and MTech (Fibre Science & Technology), Indian Institute of Technology, Delhi. Currently he is working as Scientist at Naval Physical & Oceanographic Laboratory, Kochi. His areas of research are: Polymers MEMS sensors for underwater acoustic applications and microfabrication of MEMS sensors using microstereolithography.

Mr V. Natarajan, obtained his Post Graduation degree from College of Engineering and PhD from Crystal Growth Centre, Anna University. Currently he is working as a Scientist at Naval Physical & Oceanographic Laboratory, Kochi, in the area of MEMS-based sensors for underwater applications. He has vast experience in single crystal growth and acoustic measurements of sensors.