ENABLING TECHNOLOGY FOR ULTRALOW-COST RF MEMS SWITCHES ON LTCC

Mario D'Auria[1], Ayodeji Sunday[2], Jonathan Hazell[1], Ian D. Robertson[2] and Stepan Lucyszyn[1]

[1] *Imperial College London*
[2] *University of Leeds*

Abstract

In this work we propose a novel idea, which allows the integration of Radio Frequency Microelectromechanical Systems (RF MEMS) switches on Low Temperature Co-fired Ceramic (LTCC) using low cost materials and assembly techniques. Shunt switches and varactors can be realized using aluminium foil cantilevers, which can be actuated under electrostatic control.

Basic prototype components have been manufactured and preliminary measurements suggest good mechanical behaviour. It is believed that this enabling technology can be applied to realize ultralow-cost RF MEMS switches and varactors.

Introduction

LTCC is an attractive substrate for microwave circuits, as it offers high performance (i.e. low loss and high Q-factor components) and a relatively cheap manufacturing process. The conventional techniques for defining metallisation on LTCC are screen printing and laser machining. Surface micromachined structures, in the form of self-assembled microwave inductors, have been previously demonstrated at Imperial College London, using thick-film processing on ceramic substrates [1]. In this paper, we propose the use of thick-film processing on LTCC to create mechanical switches and varactors.

Building mechanical switches and varactors in this way offers an extremely low cost method of integrating reconfigureability into a design, as it requires no additional tooling. This offers a significant cost advantage over previously reported techniques (e.g. additional thin-film processing [2]).

Here, the implementation of such devices can only be achieved with designs that incorporate small feature sizes. Previous work in this area has shown that very fine features can be obtained by screen printing conductive pastes on LTCC, followed by laser patterning. This allows both precision and flexibility in the manufacturing process [3]. The same laser can be used to introduce a stressed layer in a region near the anchor and then cut thin metal foil cantilevers, which releases the cantilever into a knee-shaped beam [4-6]. In this paper it is shown, for the first time, that these manufacturing techniques can be combined to produce RF MEMS switches directly on LTCC substrates.

Design and Fabrication Process

A key parameter in the design of MEMS cantilevers is the size of the gap between the beam and the actuation pad. This is because the actuation voltage V_{ACT} is strongly dependent on the size of the gap spacing:

$$V_{ACT} = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^3} \tag{1}$$

where, k is the spring constant; ε_0 is the permittivity of free space; A is the actuation pads area; and g_0 is the gap spacing.

For planar circuits, screen printing has acceptable tolerances. However, the thickness of the deposited layer has insufficient accuracy to be used as a spacer layer, shown green in Fig. 1(a). In order to avoid this issue, the proposed alternative is to introduce a well-controlled laser-induced stress layer region, as indicated in Fig. 1(b), which will cause the thin foil cantilever to bend upwards, creating the required gap separation distance, as illustrated in Fig. 1(c). The aluminium foil was measured to be 13 ± 1μm thick, cut and bent using a LPKF ProtoLaser 200 Nd:YAG infrared laser (1064 nm).

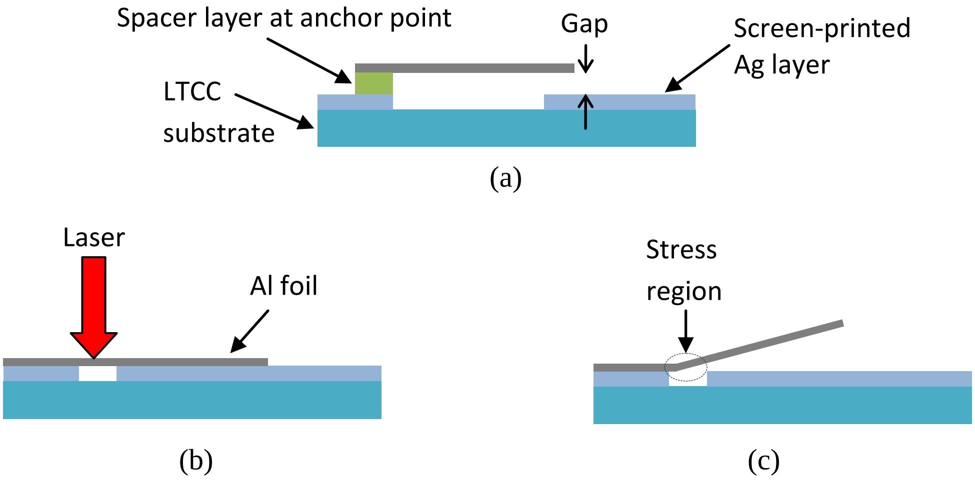
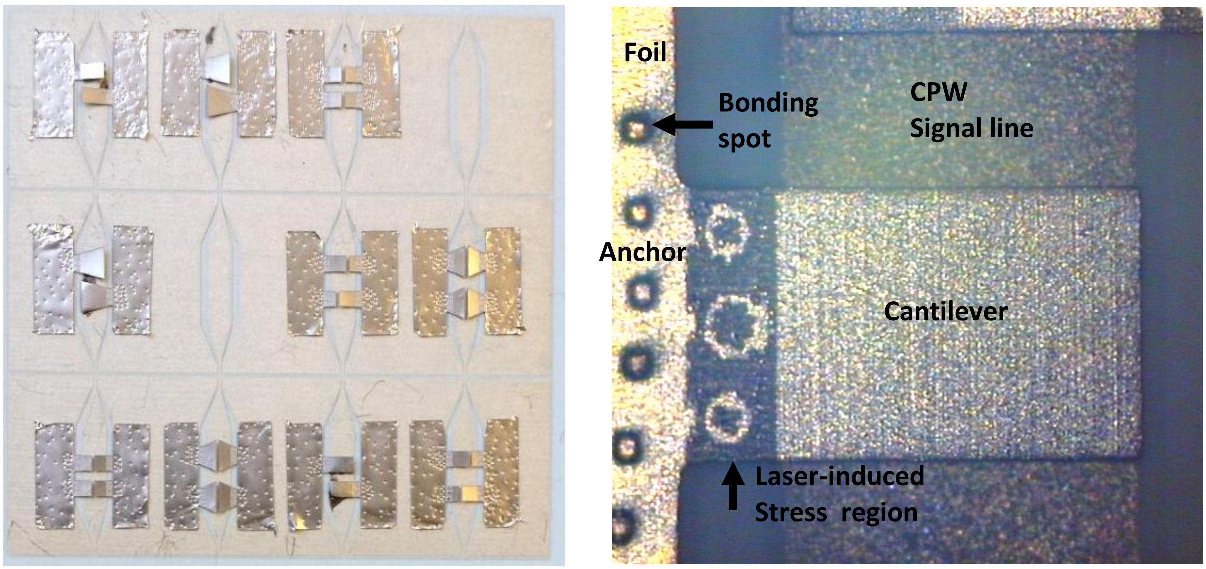


Fig. 1. (a) generic MEMS cantilever structure; (b) aluminium foil beam laser bending region; and (c) cantilever beam after laser bending and releasing

The preliminary proof-of-concept design considered the use of a cantilever to implement a shunt RF MEMS switch on a coplanar waveguide (CPW) transmission line. A variety of different cantilever structures were designed and manufactured with laser machining. The foil cantilevers were then attached to the CPW ground plane using an ultrasonic wedge bonder, with the results shown in Fig. 2.



(a) (b)

Fig. 2. Photographs of: (a) array of laser-bent Al foil cantilevers on CPW lines; and (b) close-up view of a single rectangular cantilever, having dimensions of 2 x 1 mm^2

Mechanical and Electrostatic Actuation Measurements Results

Each cantilever has been mechanically tested, in order to derive practical design parameters (e.g. spring constant and Young's modulus). These measurements were performed using a Veeco Dektak3ST contact profiler. The probe tip was swept from the end of the stress region to the free end of the cantilever, using different forces, and the deflections were then measured. The actuation voltage of the devices was also measured. The longer cantilevers were tested by applying a potential difference between the ground-plane (where the cantilever is anchored) and the signal line (which was used as an actuation electrode). As the voltage was increased, physical displacement was observed, until 'snap down' occurred.

Based on previous experience, measurements focused on 2 x 1 mm^2 cantilevers. The mechanical tests provided information on the displacement and spring constant of the cantilevers. Results for one of these devices are shown in Figs. 3 and 4.

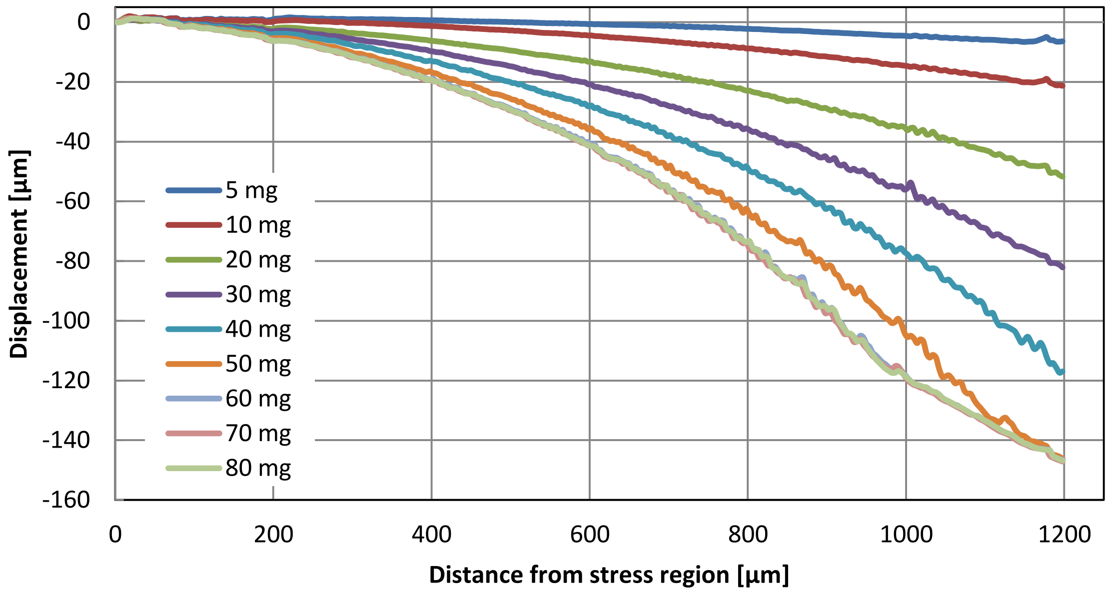


Fig. 3. Measured displacement along the beam for different applied forces

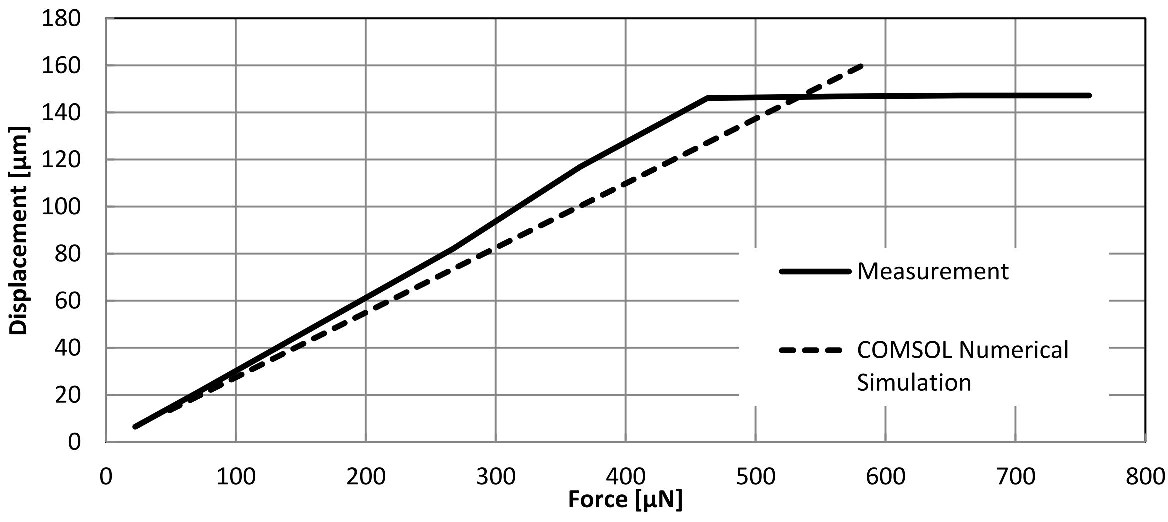


Fig. 4. Maximum displacement at the tip against applied force. (Beyond 463 µN, no further displacement is observed, because the cantilever hits the substrate)

As can be seen in Fig. 4, the cantilever exhibits linear behaviour, which indicates a constant spring constant, according to equation (2):

$$F = kx \tag{2}$$

where F is the applied force and x is the measured displacement at the free end of the cantilever. Due to the relatively small curvature of the beam, it can be approximated to a straight cantilever, where standard textbook equations apply. Under this assumption, the equivalent Young's modulus E was extracted using (3):

$$E = \frac{4kl^3}{wt^3} \tag{3}$$

where l, w and t are the beam length, width and thickness, respectively. Fig. 5 shows various extracted Young's moduli for different experimental cantilevers.

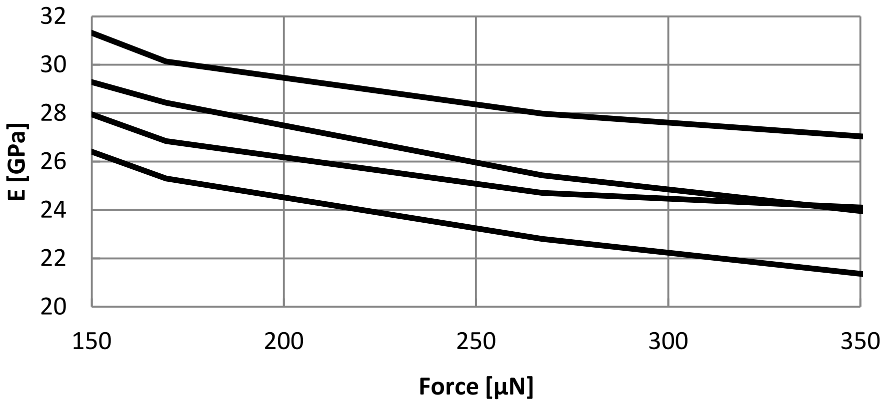
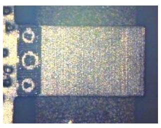
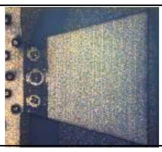


Fig. 5. Extracted Young's moduli for four different experimental cantilevers

The measured results for electrostatic actuation showed a large spread for the two different cantilever shapes (rectangular and flared); values ranged from 255 to 505 V, as shown in Table 1. The spread for each shape can be attributed to irregularities in the bond locations within the anchor pads, which causes an inconstant gap distance. It is anticipated that this could easily be corrected for with a more controlled application of the ultrasonic bonding. Nevertheless, all switches actuated and showed good contact resistance (i.e. below 1 Ω), which indicates that the design is insensitive to manufacturing tolerances.

Table 1. Actuation voltages for 2 mm length laser-bent aluminium foil cantilevers

Cantilever Shape		Actuation Voltage [V]
Rectangular		430
		515
		405
		505
Flared		330
		255
		415

Proposed RF Design Example

One obvious design configuration, as illustrated in Fig. 6, is a series microstrip switch. The width of the beam has been reduced to 300 µm. The justification for this is that by reducing the height of the microstrip, down to a single sheet of LTCC (e.g. 250 or 125 µm), then the off capacitance C_{OFF} is minimised; thus, improving the OFF-state isolation. Fig. 7 shows the simplified electromagnetic simulated performance of the switch in Fig. 6; for convenience, only lossless materials were considered. As can be seen in Fig. 7(a), isolation is acceptable up to and beyond 10 GHz. It should be noted that, detailed modelling of the ohmic contact resistance R_{ON} is currently being studied.

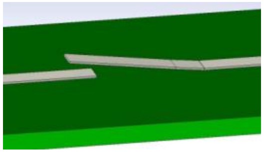


Fig. 6. Proposed design of an in-line microstrip cantilever switch

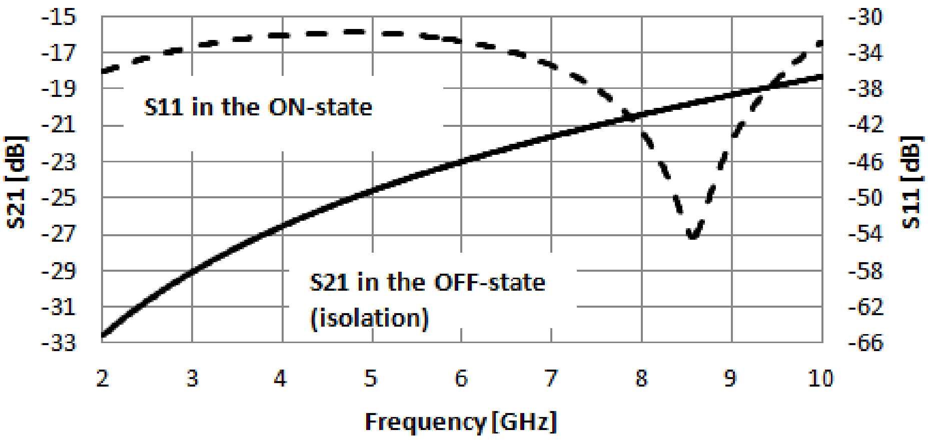


Fig. 7. Numerical electromagnetic simulated performance of the switch in Fig. 6

Conclusion

This paper has introduced enabling technologies for implementing low cost RF MEMS switches on LTCC substrates. Cantilever beams have been manufactured and characterised; measurements agree well with both theory and numerical simulations. A design configuration for an RF MEMS switch using this beam has been proposed and will be fabricated and tested shortly.

References

[1] S. Pranosatit and S. Lucyszyn, “Self-assembled screen-printed microwave inductors”, *IEE Elec. Lett.*, vol. 41, no. 23, pp. 1287-1288, Nov. 2005

[2] S. Di Nardo, “RF MEMS switches built on LTCC”, *CTB Working Group on Hybrids, MCMs, interconnection and micropackaging*, ESA/ESTEC, Noordwijk, May 2007

[3] M. F. Shafique, K. Saeed, D. P. Steenson and I. D. Robertson, “Laser prototyping of microwave circuits in LTCC technology”, *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 12, pp. 3254-3261, Dec. 2009

[4] D. Robben, S. F. Peik, T. Henning, M. Becker and K. Froehner, “Laser machined microsystems for active frequency selective surfaces”, *IEEE MTT-S*, Montreal, Canada, pp. Jun. 2012

[5] F. Vollertsent, I. Komelt and R. Kalst, “The laser bending of steel foils for microparts by the buckling mechanism – a model”, *Modell. Simul. Mater. Sci. Eng.*, vol. 3, pp. 107-119, Jan. 1995

[6] J. L. Ocana, M. Morales, J. A. Porro, J. J. Garcfa-Ballesteros, O. Garcia, C. Molpeceres, M. Holgado, “Short pulse laser shock microforming of thin metal MEMS components”, *Lasers and Electro-Optics 2009 and the European Quantum Electronics Conference (EQEC)*, Munich, Germany, Jun. 2009