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Monomorph piezoelectric wideband energy harvester integrated into LTCC

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Abstract

In this paper the first fully LTCC embedded piezoelectric vibration harvester is demonstrated and characterized. Using ordinary LTCC processes a 39 mm × 39 mm × 3 mm package containing 25 mm co-fired PZT discs was made. Three laser cut beams of different lengths provided a 5.4% frequency bandwidth for 3 dB attenuation and a power of 32 μW at 1 g acceleration delivered into a 33.9 kΩ resistive load. The packaged structure was compared to a bare monomorph reference sample and showed less crosstalk, better frequency control and more power generated. The experiments showed that integration of LTCC and PZT bulk materials by co-firing is a very feasible way to realise energy harvesters for wireless technologies, sensors and autonomous System-On-a-Package.

Keywords: PZT; Functional applications; Actuators; Sensors; Mechanical properties

1. Introduction

In today's world of complicated machines and portable applications, as well as in possible future autonomous and smart devices, there is a need for small, reliable and cost effective power sources to supply countless sensors, actuators and data transmitters. The simplest solutions using battery or cable connections are not always the cheapest or the easiest ones, and are sometimes not feasible at all. In some instances these problems can be solved by using small and portable energy harvesters transforming mechanical energy to electrical energy. Whether it is a mobile phone, a washing machine or a bridge over the sea, their continuous or occasional vibration can generate power to charge the batteries or capacitors for continued utilisation.[1,2]

The piezoelectric effect, discovered in the XIX century by the Curie brothers, has been broadly utilised in numerous applications such as gas igniters, hydrophones, modern skis and advanced systems for optical and nanotechnology applications.[3] Whenever there is a need to change the electrical energy into precise movement or deformation or *vice versa*, the piezoelectric effect is one of the most versatile and feasible way to realise it. Piezoelectric transducers used for energy harvesting can be efficient and extremely compact solid state structures to be utilised in the vibrating machines, vehicles and motors but their high efficiency range is limited to the mechanical resonance frequency, thus limiting their feasibility.[1,2] Another challenge is that harvesters will often be exposed to harsh environments such as moisture, solar radiation, temperature differences and chemicals, which can severely degrade their properties and lifetime. In order to obtain stable harvester and sensor functions with long lifetimes a suitable package solution is needed. For this purpose low temperature co-fired ceramic (LTCC) is a widely utilised option as a durable and hermetic package material which enables easy fabrication of even complicated shapes and reliable electronic circuitry, including buried interconnections and passive electronics.[4,5] Previously, piezoelectric actuators have been utilised in LTCC as embedded actuators in order to realise integrated active components in reliable package material.[6–9]

In this paper, a Heraeus Heralock 2000 LTCC system has been utilised together with commercially available bulk PZT to realise new fully LTCC embedded wideband piezoelectric vibration harvesters. This approach aims for an integrated system including a reliable and hermetic package, a circuit board for electronics and an active piezoelectric harvester structure to be realised in the same process. The harvesters obtain wideband operation by laser micro-machined LTCC and piezoelectric beams with varying length. The electromechanical properties of

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realised structures functioning both as actuators and harvesters were characterized and analysed.

The generated power of 32 μW at 1 g acceleration by the realised energy harvester is already sufficient to constantly power, for example, a LM19 temperature sensor (National Semiconductors, USA) requiring 24 μW of power or LIS3DH 3-axes accelerometer requiring 27.5 μW of power with typical settings and 50 Hz sample rate (STMicroelectronics, Switzerland).[10,11] Alternatively, the energy can be used to charge a reservoir and then use the accumulated energy for data transmission bursts. In such approach the harvester can collect enough energy in 21–28 min, for example, wireless data transfer by ZigBit 900 module with 1.8 V and 15/20 mA supply in RX/TX mode and below 6 μA in power save mode (Meshnetics, Atmel Co., USA).[12] Furthermore, greater power could be generated with further development of the harvester and improved electronics.

2. Theory and design

The wideband piezoelectric energy harvester presented here utilises multiple resonating beam topology where the resonance frequency of a single arm n can be expressed as

$$f_{res,n} = 2\pi\sqrt{\frac{k_n}{m_n}} \tag{1}$$

where k_n is the effective spring constant of the beam and m_n is its effective mass. The resonance frequency of the beam also has a relation

$$f_{res,n} \propto \frac{1}{l^2} \tag{2}$$

where l is the length of the cantilever. Therefore, by varying the length of the beam, i.e. the area moment of inertia, the resonance frequency can be adjusted. This quadratic relation is evident when considering Eq. (1) and noting that

$$k_n \propto \frac{1}{l^2} \tag{3}$$

and

$$m_n \propto l \tag{4}$$

for beams with uniform cross-sections. The difference between the resonance frequencies of adjacent beams is

$$f_n - f_{n-1} = \alpha\xi f_{n-1}, \quad 0 < \alpha < 2 \tag{5}$$

where ξ is the damping coefficient of the material and α an overlapping parameter. When α is set to 0, all beams have the same resonance frequency and the bandwidth of the harvester is at its minimum and the produced current at its maximum. When the parameter is set to 2, the resonances of the adjacent beams are spaced by their full bandwidth and therefore the bandwidth of the harvester is at its maximum. By using Eqs. (2) and (5) a recursion

$$f_{res,0} = f_{res,0}, \quad l_0 = l_0, \quad f_{res,n} = (\alpha\xi + 1) f_{res,n-1}, \quad l_n = \frac{l_{n-1}}{\sqrt{\alpha\xi + 1}} \tag{6}$$

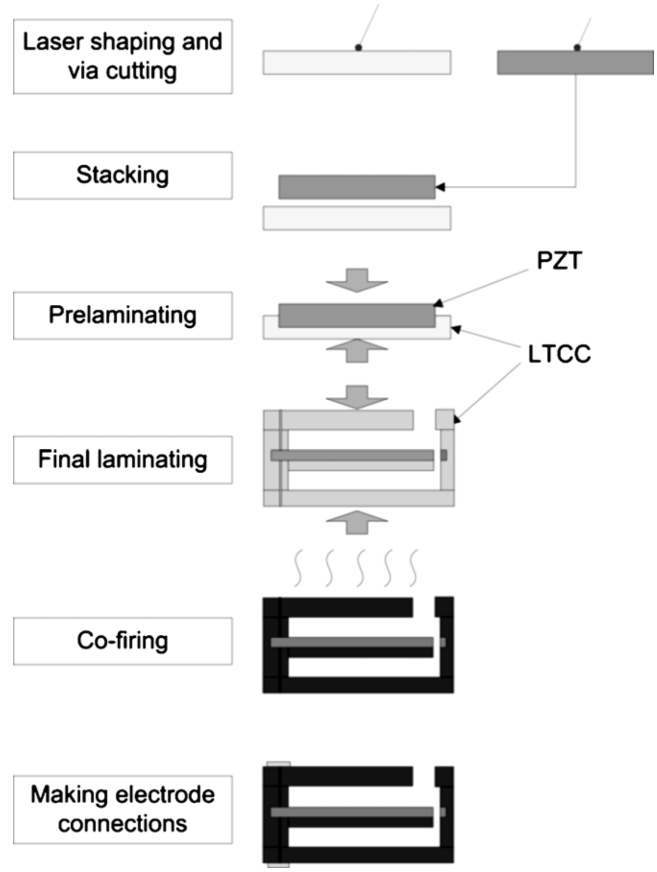

Fig. 1. Flowchart of the manufacturing process.

can be obtained from which the desired lengths for the beams can be calculated. The starting point for the recursion is the length of the beam l_0 and the resulting resonance frequency $f_{res,0}$, which can be obtained by analytical means, by finite element method (FEM) modelling or by measurements. The prototype in this work was designed to have three beams with lengths of 18 mm, 17.78 mm and 17.56 mm calculated from Eq. (6) with $\alpha = 1$ and $\xi = 0.025$. The width of the beams was 3 mm and the designed overall bandwidth of the configuration would be 7.5% (with 3 dB attenuation) from the resonance frequency of the middle beam.

3. Experiments

Two different samples were manufactured using the LTCC process presented in Fig. 1. Commercially available PZT PZ29 discs (Ferroperm A/S, Denmark) with diameter of 25 mm and thickness of 375 μm were laser cut into the designed shape and their electrodes were trimmed accordingly with a Nd:YVO_4 laser (Siemens Microbeam 3200, Siemens AG, Germany). In the case of the reference sample, bulk piezoceramics were first uniaxially laminated with a Heraeus Heralock 2000 LTCC system (W.C. Heraeus GmbH, Germany) having a corresponding diameter and a thickness of 390 μm. Lamination was carried out at 75 °C under 100 bar pressure for 10 min. The laminated PZT–LTCC structure was then cut with the laser in order to create precisely the structure with 3 cantilevers as designed, without alignment errors which could have occurred during stacking and lamination. The samples were sintered in a Nabertherm box furnace (Nabertherm GmbH, Germany) using the standard Heralock sintering profile provided by the supplier.[13]

After the reference sample, the LTCC packaged version was made with the difference that the PZT and LTCC were both cut before lamination. Then thin sheets of LTCC were stacked together with the PZT using aligning pins and laminated. The lamination was carried out in two steps, first laminating the part with PZT and the lid separately, and then joining them together in a final lamination process. Pre-lamination of the lid took place in an isostatic lamination chamber (IL-4012 Isostatic lamination system, Pacific Trinetics Corp.) at 75 °C under 100 bar for 10 min, while pre-lamination of the PZT was carried out in a uniaxial press with the same parameters. The final prototype consisted of 30 LTCC layers, as presented in Fig. 2.

Laminated samples were inspected optically for any abnormalities and then sintered as described for the reference sample.

After sintering, electrical connections for both reference and packaged structures were made with conductive silver paint. Final sintered samples are shown in Fig. 3. Subsequently, the samples were poled by applying a 2.5 V/μm electric field for 30 min at 60 °C.

Measurements in both actuator and harvester modes as a function of frequency were carried out using the system shown in Fig. 4 based on a fibre-optic laser vibrometer OFV-5000 (Polytec GmbH, Germany), an electromagnetic mini shaker (Bruel & Kjær, Denmark) and a bridge rectifier. Power generation was measured at resonance as a function of resistive load.

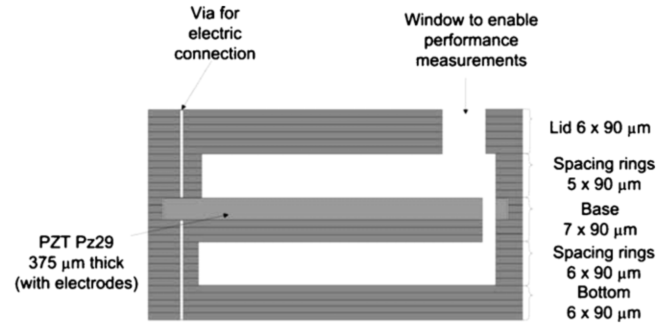

Fig. 2. Schematics of LTCC packaged harvester (not in scale).

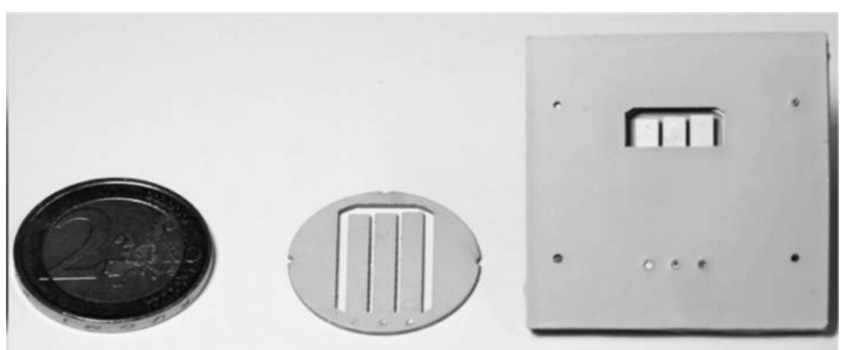

Fig. 3. Pictures of final sintered harvester samples.

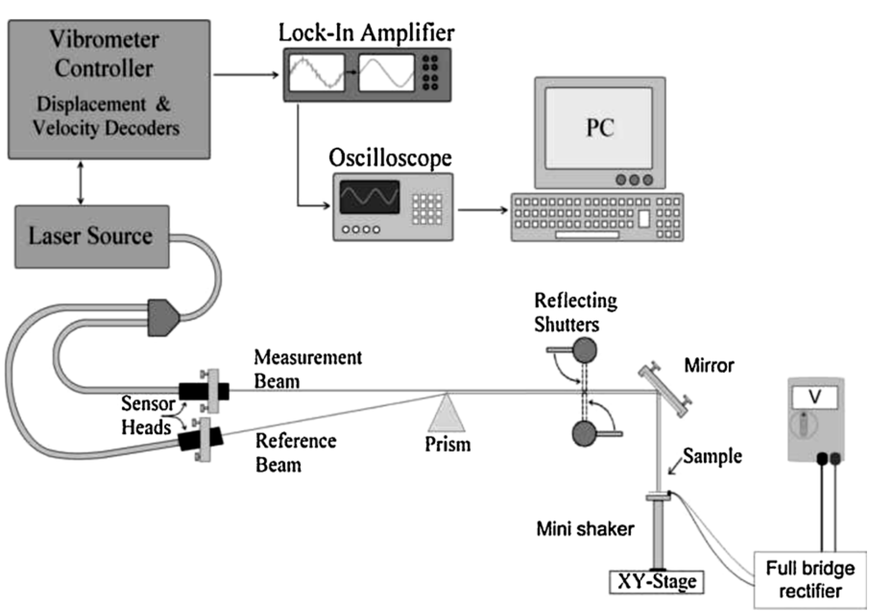

Fig. 4. Schematics of the measurement system.

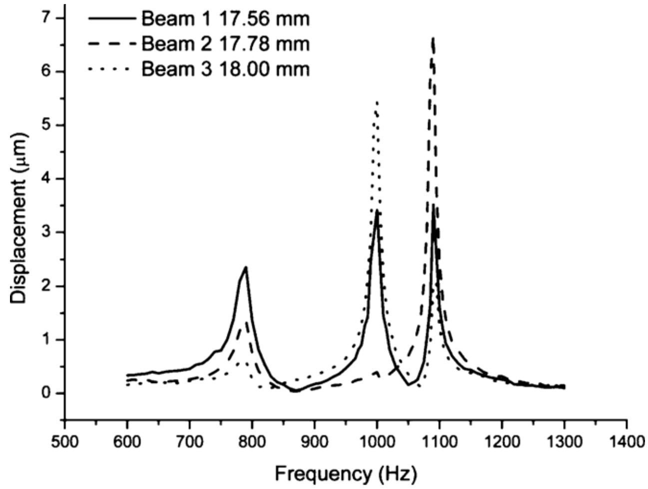

Fig. 5. Displacement of the reference sample as a function of frequency in actuator mode with 1 V_{pp} sinusoidal signal.

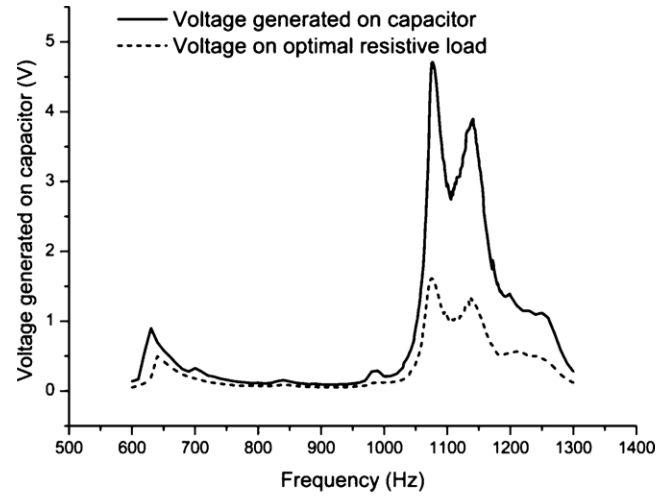

Fig. 6. Voltage generated by reference structure into the capacitor as a function of frequency.

4. Results and discussion

Performance of the reference sample when the beams were actuated independently (Fig. 5.) exhibited significant discrepancies from the designed values. Resonance frequencies were 790 Hz, 1000 Hz and 1090 Hz instead of calculated 790 Hz, 809 Hz and 830 Hz and corresponding Q_m values were 19, 100 and 83. The discrepancy between the calculated and measured resonance frequencies is expected to be mainly a result of large crosstalk between the beams and their mechanical base having too low stiffness and therefore poor mechanical isolation. However, it should be noted that also changes in material properties might exist due to pre-stressing effect resulting from 0.2% sintering shrinkage and mismatch of thermal expansion of the PZT and LTCC. This may increase the area moment of inertia of the structures but also change mechanical properties of the material.[14] These effects can be lowered thorough improved processing steps during manufacturing as well as design guidelines taking such parameters into account.

The largest displacement of 6.68 μm was measured for the middle beam (Beam 2) at a frequency of 1090 Hz while the shortest beam (Beam 1) presented similar displacement for all three resonance frequencies. In this case the adjacent beams interfered with each other, thus altering the performance. This is clearly seen in the case of the longest beam (Beam 3) where the resonance frequency was shifted towards higher frequencies and the displacement was smaller than that of the middle beam.

Next, the voltage was measured across a 1 μF capacitor after the rectifier by driving the reference structure with 1 μm peak-to-peak displacement in the mini shaker. Result presented in Fig. 6 shows two significant peaks at 1077 Hz and 1140 Hz and a small peak at 630 Hz. This exhibits a clear discrepancy compared to the structure's behaviour as an actuator, assuming that the two significant peaks refer to the two larger peaks on the actuator performance plot. At 1077 Hz all three beams generated 4.69 V measured after the bridge rectifier. In addition, the voltage as a function of frequency was measured with an optimal resistive load on the capacitor. Results are shown in Fig. 6.

Different resistive loads, from 149 Ω to 510 kΩ were tested to find the optimal impedance for the harvester. Generated power as a function of resistive load is presented in Fig. 7a. A 99.6 kΩ resistor had the closest match with the impedance of the sample, producing the highest power of 25.9 μW at 1076 Hz. Generated power as a function of frequency for this optimal load is presented in Fig. 7b. Moreover, it was noticed that the resistive load slightly shifts the resonance to lower frequencies due to the difference in the electric circuit influencing the stiffness of the beams. In the case of the low-frequency peak, the shift was 10 Hz while in the two higher frequency peaks the shift was 2 Hz.

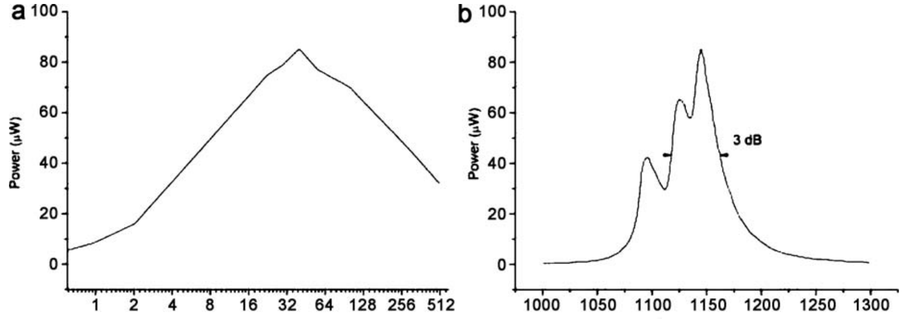

Fig. 7. (a) Generated power as a function of resistive loads. (b) Overall power generated by three beams of the reference sample as a function of frequency with 99.6 kΩ resistive load.

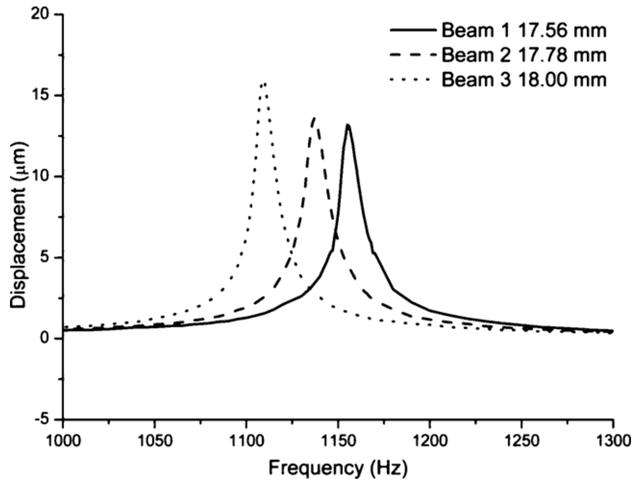

Fig. 8. Displacement of the packaged sample as a function of frequency in actuator mode with 1 V_{pp} sinusoidal signal.

The same investigations were carried for the structure packaged into the LTCC. Displacement of the beams as a function of frequency when driven by a 1 V_{pp} sinusoidal signal is presented in Fig. 8.

The resonance frequencies correspond to the lengths of the beams and can easily be distinguished at 1109 Hz, 1137 Hz and 1155 Hz frequencies while the corresponding Q_m values were 110, 94 and 105, respectively. Using formula (5) and assuming 1100 Hz as the base frequency, the resonances should be 1100 Hz, 1137 Hz and 1165 Hz, respectively, which implies an error of less than 9%. When comparing this with the error of 20% in the reference prototype the packaged harvester exhibited significantly improved control over the resonance frequencies and overall performance. This is a consequence of greatly decreased cross-talk, due to increased stiffness of the mechanical base, having a dominating effect in the performance.

The generated voltage in the 1 µF capacitor (after the rectifier) when driving the packaged structure with 1 µm peak-to-peak displacement is shown in Fig. 9.

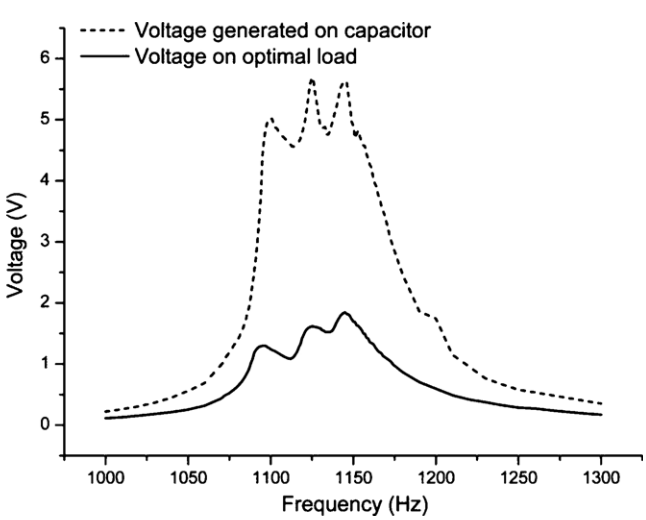

Fig. 9. Voltage generated by packaged structure into the capacitor as a function of frequency.

Table 1
Summarized performance of reference and packaged harvesters.

Sample	No package	Package
Centre frequency [Hz]	1076.0	1147.0
Bandwidth [%]	2.7	5.4
Voltage output [V]	4.7	5.6
Total generated power [µW]	25.9	85.0
Power output per 1 g of acceleration [$\mu W\,g^{-1}$]	11.5	32.0
Power density per area of piezo [$\mu W\,g^{-1}\,cm^{-2}$]	7.2	20.0

The behaviour with no resistive load resembles the actuator performance. The resonance frequencies of all three beams are clearly visible and differ only slightly from the designed values. The generated voltage was at a similar level to that produced by the reference sample. The optimal resistive load for the harvester was found to be 39.9 kΩ, producing the highest power of 85 µW at 1147 Hz. Generated power as a function of resistive loads and frequency are presented in Fig. 10a and b, respectively. The resistive load reduced the first resonance frequency by 2 Hz, while the highest resonance frequency was increased by 3 Hz.

The 3 dB bandwidths of the packaged and reference harvester were 5.4% and 2.7%, respectively, as shown in Table 1, while the designed value was 7.5%. In the packaged harvester the difference in the measured and calculated bandwidths are largely due to lower assumed Q_m factor compared to measured one, i.e. bandwidth of individual beam is narrower thus decreasing the overall bandwidth. In the case of reference sample also the discrepancies in the resonance frequencies decreased greatly the obtained overall bandwidth from the calculated one. The overall performance of the LTCC packaged sample was much better than that of the reference sample. The stiff package diminished the mechanical cross-talk between the beams resulting in well defined peaks in actuator mode. This sample also presented ~2.6 times higher performance in terms of generated energy and power density per piezoelectric volume. Furthermore, the available power at 5.4% bandwidth of the packaged sample was twice the amount of power available at 2.7% bandwidth of the reference sample.

The 5.4% bandwidth and 85 µW of the three beam structure exhibited promising results in comparison to that presented in Ref. 15 having 35 beams and 17.5% bandwidth and producing 0.4 µW. AlN based MEMS piezoelectric energy harvesters have also been previously developed.[16] The cantilever type harvester with seismic mass obtained maximum output power of 60 µW at 572 Hz and 2 g acceleration as an unpackaged version. However, when the harvester was packaged the output power decreased to 22 µW and 2.1 µW with open and closed packages, respectively, due to air damping. In the case of the solution presented in this paper, closing of the package had no effect on the performance of the structure. Thick film cantilever harvesters, presented in Ref. 17, whose length was identical to the longest beam in our structure, generated 84 nW under 1 g acceleration at the resonance frequency while a multilayer structure with total thickness of 168 µm delivered 40 µW under 0.5 g of acceleration.

The presented monomorph type piezoelectric energy harvester integrated into LTCC showed very good results which

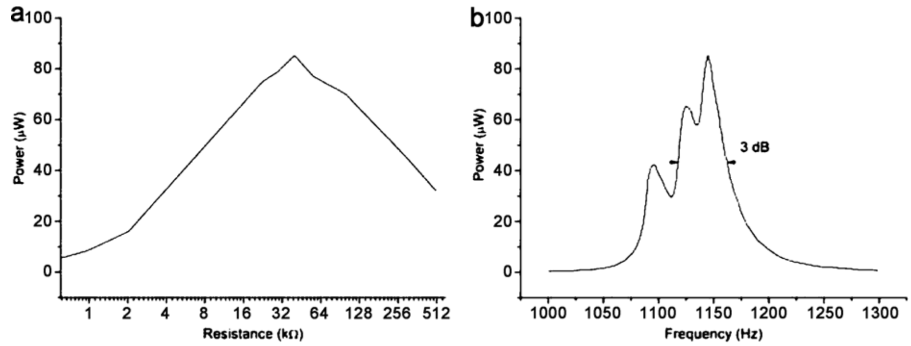

Fig. 10. (a) Power generated by packaged structure into the capacitor as a function of different loads. (b) Overall power generated by three beams of the packaged sample as a function of frequency with 39.9 kΩ resistive load.

can be significantly improved and tailored according to requirements, for example, by adding additional mass at the tips thus increasing the stress level for the cantilevers and changing the lengths, by varying the thickness of the LTCC passive layer and also by varying the number of the beams. This allows the production of a wide range of broadband harvesters designed and optimised for specific applications. Moreover, the LTCC package will not only isolate the piezoelectric from the ambient conditions, but will also allow integration of suitable electronics, including sensors and data transmitters, creating a fully autonomous System-On-a-Package.

5. Summary and conclusions

This paper demonstrates that co-firing of PZT bulk ceramics in "non-shrinkage" LTCC such as Heralock 2000 is a successful method for packaging and embedding piezoelectric materials. Standard procedures used in LTCC manufacturing were sufficient to produce a compact and rugged package with suitable electrical connections and capability to protect the PZT from different environments. It also enhanced the properties of the energy harvester by the provision of good mechanical isolation. Furthermore, 32 μW and 5.4% bandwidth at 3 dB was obtained for an LTCC embedded piezoelectric energy harvester which can be utilised in autonomous sensors and data transmitters in various environments. By adopting the presented method, and downsizing and adjusting the frequency range for specific applications, it is possible to create a mass-producible self-powered LTCC based autonomous sensor system for harsh environments and different applications.

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