Journal of Engineering and Applied Sciences 10 (6): 137-142, 2015
ISSN: 1816-949X

Modelling of New PZT Energy Harvester for Non-Traditional Geometry with a Lower Resonance Frequency

[1,2]N. Siddaiah, [1]K.S.N. Murthy, [2]D.V. Rama Koti Reddy, [1]T. Vijay Srinivas, [2]S. Krishna Chaitanya and [1]A.L.G.N. Aditya
[1]Department of Electronics and Communication Engineering, K L University, Vaddeswaram, Andhra Pradesh, India
[2]Department of Instrument Technology, College of Engineering, Andhra University, Andhra Pradesh, India

Abstract: Harvesting the energy from environmental resources has become a very prominent role in generating power for various applications. There are many ways to extract the energy, in this study, the charge generation was done through the piezoelectric method using a cantilever beam. This beam will sense the vibrations with very low frequencies (in order of <1 kHz) and generates the charge accordingly. This technology is used for both portable and wearable devices. Energy harvesting through piezoelectric devices is very economical since it does not use any external power supply. In this study, a unimorph cantilever in macro scale with non-traditional geometry is investigated for charge generation. COMSOL multi-physics 4.3 is the software which is used for the simulation and analysis. The piezoelectric energy harvester comprises of an active Piezoelectric layer (PZT-5 H) on the top and a steel substrate at the bottom. The results of the traditional geometry which is rectangular shape and the proposed (T) structure are compared. Simulation results shows that the proposed structure has a very low resonant frequency and higher average strain.

Key words: Piezoelectric energy harvester, COMSOL multi-physics, cantilever, unimorph, resonant frequency

INTRODUCTION

Whenever the battery drains it should be either replaced or recharged which is very inconvenient when we need them most. So, in order to avoid this, self powered devices are invented which are known as energy harvesters.

The main theme of energy harvester is to run the self powered electronic systems by harvesting the ambient energy which mostly is the vibrations. There were many methods which will convert mechanical energy to electrical energy among them the most prominent in order to generate ac power are electrostatics, electromagnetic and piezoelectric methods. Among all the available sources of energy in the environment vibration energy is the one which is mostly wasted.

The capacitance of the harvester will change according to the frequency of the vibrations. That means the separation between the plates will vary according to the vibrations providing a variable capacitance so this phenomenon is used in the electrostatic method of energy harvesting (Ching *et al*., 2002; Williams and Yates, 1995). In the electromagnetic method, the variation of magnetic field around the conductor to induce voltage in it. This can be done by using a cantilever and permanent magnets (Chalasani and Conrad, 2008). When piezoelectric material is subjected to stress or strain it generates electric charge. By these ways the generation and storage of power can be done through these general methods (Bindu and Potdar, 2014).

In this study, piezoelectric method is adopted to generate the electrical form of energy. This method requires less cost since it does not require any external power supply. Whereas electrostatic and electromagnetic methods require external power supply in order to begin the system. Thus, piezoelectric technology has a eminent role in wearable and implantable medical applications and other applications which requires a very accurate and sensitive analysis.

Majority of the piezoelectric energy harvesters uses a cantilever beam structure. Generally cantilever is clamped at one end and free at the other end. Fixed-free beam is the another way to indicate cantilever beam. The cantilever beam consists of one or more layers which are laid on an elastic layer. The elastic layer prevents the piezoelectric layer from the cracks that appear because of the vibrations and to increase the elasticity of the material. The cantilever structure can be unimorph, bimorph and multimorph, depending on the type of application they were chosen.

Corresponding Author: N. Siddaiah, Department of Instrument Technology, College of Engineering, Andhra University, Andhra Pradesh, India

In this study, a unimorph cantilever structure with non-traditional geometry modelled and simulated. COMSOL multi-physics is the software used for the conversion of the mechanical energy into electrical energy. COMSOL creates the suitable environment for the energy harvester and makes it easy to observe the variations in strain energy, charge, terminal voltage along the length and width of the sensor.

THEORETICAL BACKGROUND

Piezoelectric materials produce electricity when they are subjected to mechanical strain. There were four forms of piezoelectric constitutive equations which are mentioned by the IEEE standard on piezoelectricity. They were stress-charge form, strain-charge form, stress-voltage form, strain voltage form. In this study, the strain-charge form is used and the governing equations are as:

$$S = S^E T + d\bar{E} \quad (1)$$

$$D = dT + \varepsilon^T \bar{E} \quad (2)$$

Where:

- T = Stress
- S = Strain
- D = Charge-density displacement
- E = Electric field
- S^E = Elastic compliance tensor
- dT = Electro-mechanical coupling factor

The term d in the first equation is the electro mechanical coupling factor which provides the conversion from mechanical energy to electrical energy.

The piezoelectric energy harvester can be designed in two different modes, one is longitudinal mode where the polarization of the beam is parallel to the piezoelectric substrate. The other mode is transversal mode where the polarization of the beam is perpendicular to the piezoelectric substrate.

Among all the parameters the most important parameter is frequency. The frequency of the vibrations in the environment is very low (lower than 1 kHz). The sensitivity of the sensor I will be reduced drastically if the energy harvester is designed for high resonant frequencies. So, there is a necessity to design the energy harvester for lower resonance frequency applications. So, the resonance frequency of the given structure must be much closer to the frequency of environmental vibrations.

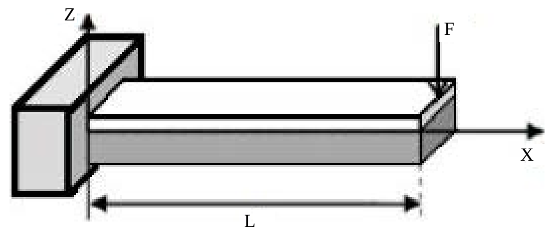

Fig. 1: Configuration of piezoelectric cantilever beam

The cantilever beam has different modes of vibrations and each mode has different resonance frequency. The deformation of the cantilever beam is also depends on the frequency. Out of all those modes the first mode has lowest frequency and provides the maximum deformation and provides more electrical energy (Fig. 1). The resonance frequency of any structure is calculated by the following equation:

$$f_n = \frac{v_n^2}{2\pi}\frac{1}{L^2}\sqrt{\frac{D_p}{m}}$$

where, $m = \rho_p t_p + \rho_s t_s$. Since, we are considering the first mode of vibration the first mode coefficient V_n is equal to 1.875 m is the mass per unit area which is calculated by the thickness and density of the piezoelectric layer and steel substrate.

The mass per unit area m depends on the thickness and density of the material. Different materials have different densities so as there will be change in the mass of the given structure comprises of different materials, thus there will be change in resonant frequency of that structure.

Bending modules (D_p) which is a dependent function on young's modules and also thickness parameters of the used materials in designing the structure is given by:

$$D_p = \frac{E_p^2 t_p^2 + E_s^2 t_s^2 + 2E_p E_s t_p t_s (2t_p^2 + 2t_s^2 + 3t_s t_{sp})}{12\,(E_p t_p + E_s tS)}$$

Where:

- E_p and E_s = The young's modules of the piezoelectric layer and the substrate layer
- t_p and t_s = The thickness of piezoelectric layer and substrate, respectively

Hence, the frequency is inversely proportional to square of length and directly proportional to square root of thickness of piezoelectric layer and substrate.

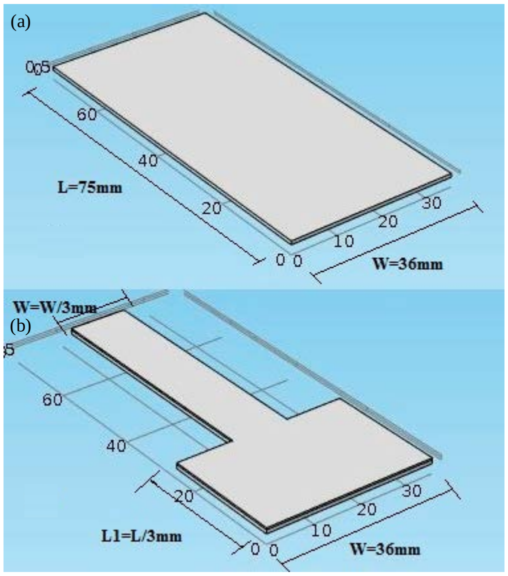

Fig. 2: a) Rectangular geometry and b) proposed geometry

COMSOL multi-physics: Using COMSOL the piezoelectric energy harvester with proposed geometry and rectangular geometry are modelled using the piezoelectric devices. The modelling of the whole structure is done in 3D as shown in Fig. 2a and b.

Domain settings: The whole geometry is divided into two layers which are also called as sub-domains. The bottom layer is filled with steel substrate and the top layer is filled with Lead Zirconate Titanate (PZT-5H).

Boundary conditions: One end of the cantilever, i.e., W/3 end is clamped and the other end is unclamped which makes that part of cantilever free to vibrate. The vertical faces of both the layers are set to the fixed constraints. Because in this study we only considering the transverse mode of vibrations. The floating potential is applied at the upper surface of the piezoelectric layer and ground is applied to the bottom layer of the piezoelectric layer to acquire the d31 mode. Zero charge constraint was applied to all other faces of the structure. The body load of F (0.1 N) is applied in z-direction to the piezoelectric layer which induces the strain. To find the charge, the floating potential should be disabled and terminal should be added to the piezoelectric layer by means of using physical interface.

Meshing: The structure is changed into a group of small blocks and given to the solver for finite element analysis. In this study, a tetrahedral structure elements were used as shown in Fig. 3.

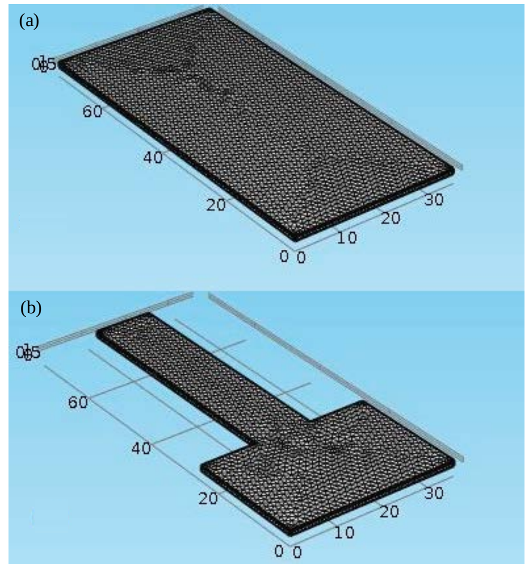

Fig. 3: Regular and proposed geometries after meshing

STUDIES AND RESULTS

Eigen frequency analysis: After the meshing is completed the geometry is now ready for all the studies. Studies are nothing but the eigen frequency analysis along length, width and thickness of the geometry to observe what is the resonant frequency of the geometry and how does it change for different geometries. The stationary analysis is to observe the variation of strain energy, output voltage, output charge and output energy for the geometry along length and width. In Fig. 4, the first 4 eigen frequency modes of the proposed structure are shown in Fig. 5-7.

Stationary analysis: The charge, voltage and energy produced depends on the length and width of the structure. The variations in charge, voltage and energy along length and width for both rectangular and proposed geometries are compared and plotted in the graphs shown below. Figure 8-13 represent the variations in strain energy, output voltage, terminal charge and output energy for the rectangular and proposed geometries along length and width.

Figure 8-13 show that the strain analysis was done for the same dimensions of rectangular and proposed geometries. It is witnessed that the proposed geometry has large strain and higher terminal voltage and higher charge when compared to the rectangular geometry (Table 1-4). Figure 14 and 15 show the output energy for both rectangular and proposed geometries.

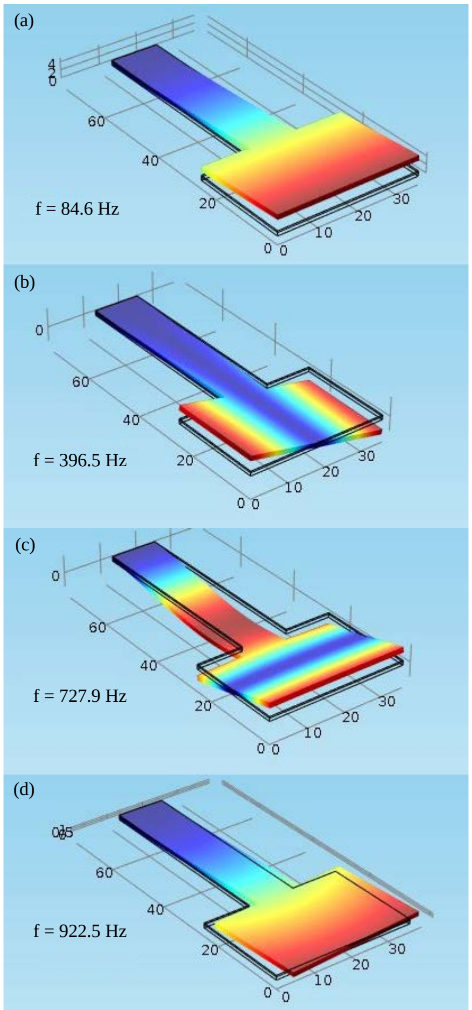

Fig. 4: a) First mode; b) second mode; c) third mode and d) fourth mode

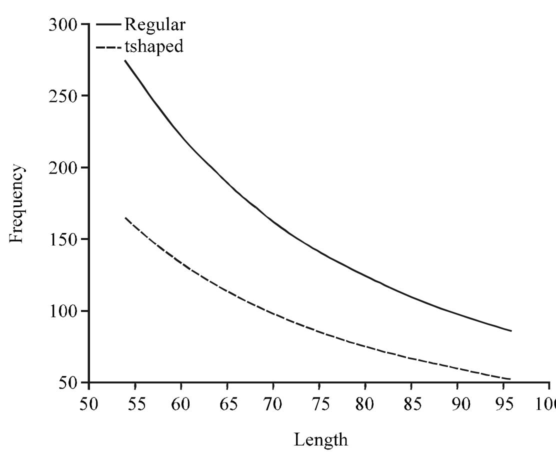

Fig. 5: Resonance frequency vs. beam length at W = 36 mm, t_p = 0.4 mm

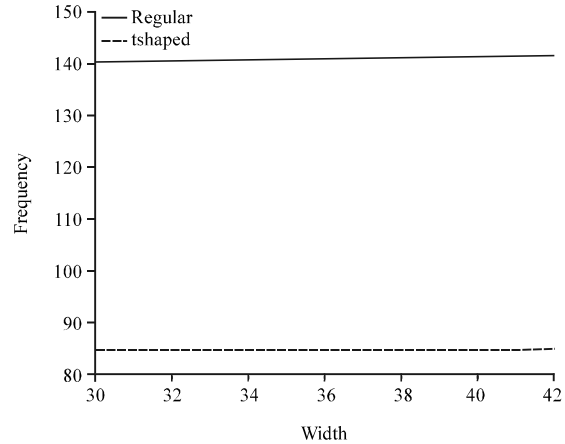

Fig. 6: Resonance frequency vs. beam width at L = 75 mm, t_p = 0.4 mm

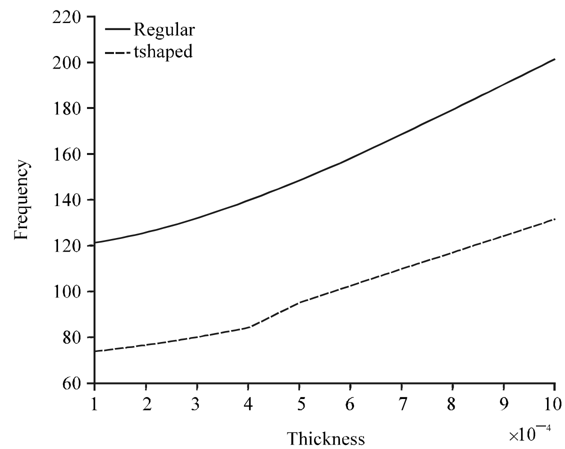

Fig. 7: Resonance frequency vs. beam thickness at L = 75 mm, W = 36 mm

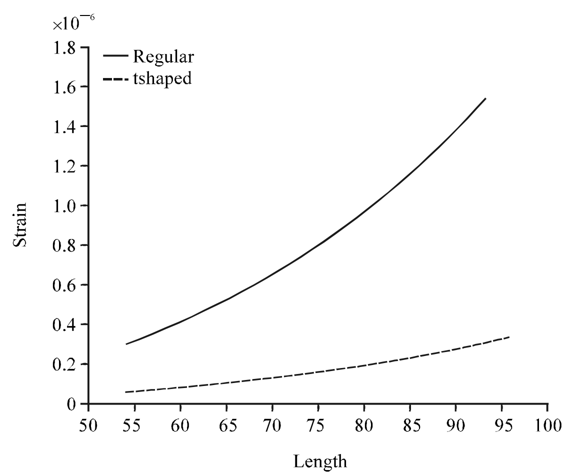

Fig. 8: Strain energy vs. beam length at W = 36 mm, t_p = 0.4 mm

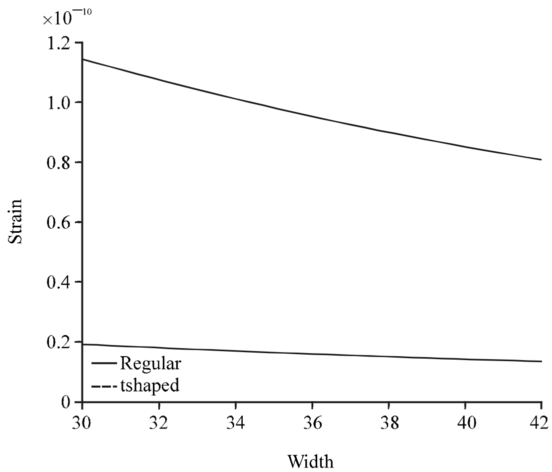

Fig. 9: Strain vs. width at L = 75 mm, t_p = 0.4 mm

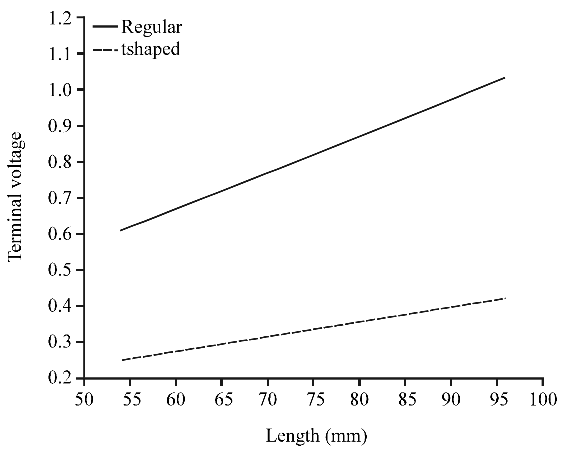

Fig. 10: Output voltage vs. beam length at W = 36 mm, t_p = 0.4 mm

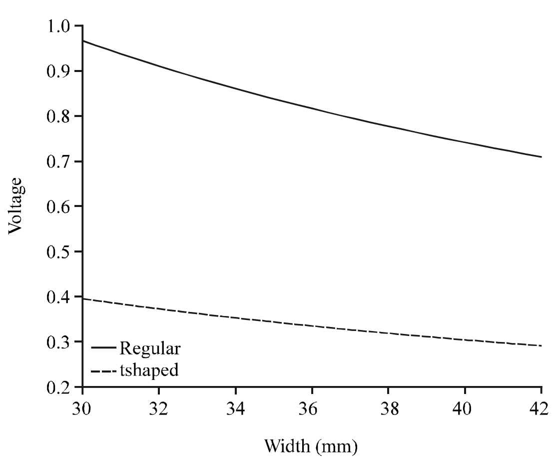

Fig. 11: Output voltage vs. beam width at L = 75 mm, t_p = 0.4 mm

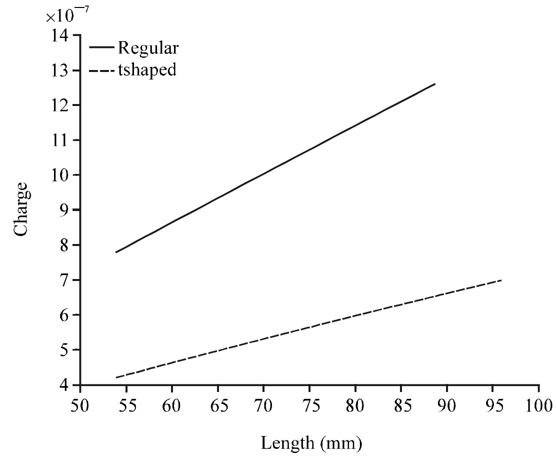

Fig. 12: Charge vs. beam length at W = 36 mm, t_p = 0.4 mm

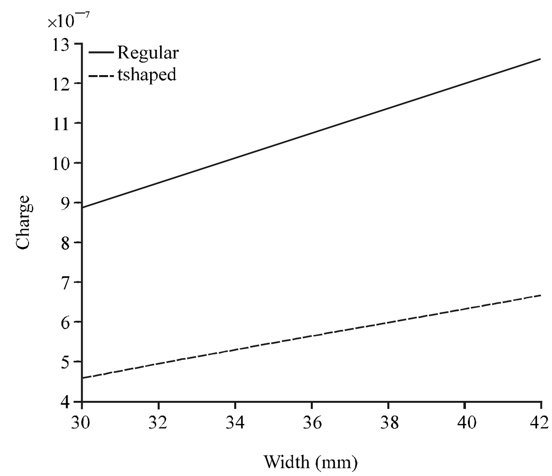

Fig. 13: Output charge vs. beam width at L = 75 mm, t_p = 0.4 mm

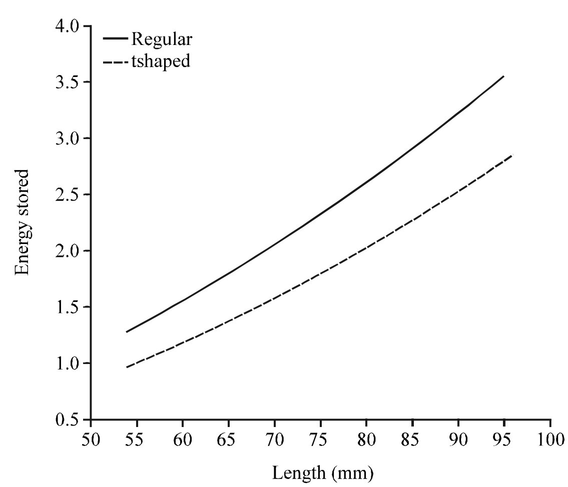

Fig. 14: Output energy (J) vs. beam length at W = 36 mm, t_p = 0.4 mm

Table 1: Values of charge, voltage and energy for rectangular geometry along length

Length (mm)	Output voltage (v)	Output charge (f)	Output energy (J)
54	0.24728	7.75843e-7	9.5925e-008
60	0.27206	8.60478e-7	1.1705e-007
66	0.29663	9.44864e-7	1.4014e-007
72	0.32122	1.02829e-6	1.6515e-007
78	0.34557	1.11127e-6	1.9201e-007
84	0.36962	1.19366e-6	2.2060e-007
90	0.39377	1.27556e-6	2.5114e-007
96	0.41783	1.35644e-6	2.8338e-007

Table 2: Values of charge, voltage and energy for rectangular geometry along width

Width (mm)	Output voltage (v)	Output charge (f)	Output energy (J)
30	0.39313	8.86414e-7	1.7424e-007
33	0.36060	9.78122e-7	1.7636e-007
36	0.33339	1.0699e-6	1.7835e-007
39	0.31008	1.16148e-6	1.8008e-007
42	0.28994	1.25253e-6	1.8158e-007

Table 3: Values of charge, voltage and energy for proposed geometry along length

Length (mm)	Output voltage (v)	Output charge (f)	Output energy (f)
54	0.60713	4.19071e-7	1.2722e-007
60	0.66700	4.6133e-7	1.5385e-007
66	0.72744	5.02704e-7	1.8284e-007
72	0.78767	5.4335e-7	2.1399e-007
78	0.84824	5.83093e-7	2.4730e-007
84	0.90906	6.21595e-7	2.8253e-007
90	0.97029	6.59433e-7	3.1992e-007
96	1.03133	6.96368e-7	3.5909e-007

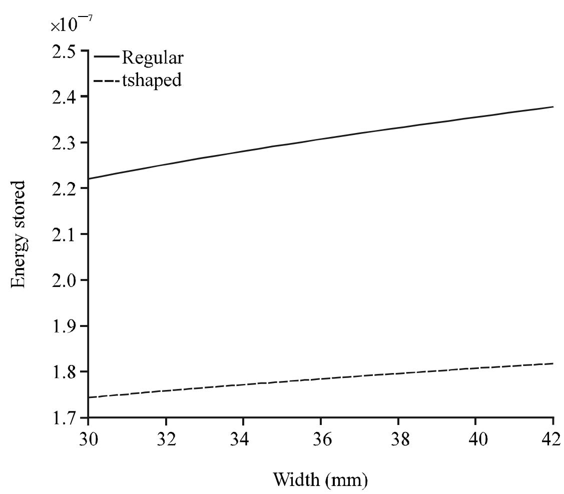

Fig. 15: Output energy vs. beam width at L = 75 mm, t_p = 0.4 mm

Table 4: Values of charge, voltage and energy for proposed geometry along width

Width (mm)	Output voltage (v)	Output charge (f)	Output energy (J)
30	0.96782	4.5859e-7	2.2192e-007
33	0.88581	5.11116e-7	2.2638e-007
36	0.81787	5.63306e-7	2.3036e-007
39	0.76074	6.15418e-7	2.3409e-007
42	0.71165	6.6752e-7	2.3752e-007

CONCLUSION

An energy harvester based on piezoelectric cantilever with dimensions 75×36×0.4 mm is designed and simulated in COMSOL multi-physics.

The simulation results (strain, resonant frequency, voltage, charge and energy) sensitivity were analyzed versus proposed cantilever design parameters (L and W) variations and compared with the results of rectangular shape cantilever.

The proposed geometry can operate from 55-130 Hz and generates output voltage within the range of 0.5-0.75 V.

The proposed geometry has a lower resonant frequency while achieving higher output voltage and energy than the rectangular one.

REFERENCES

Bindu, R.S. and M. Potdar, 2014. Study of piezoelectric cantilever energy harvesters. Int. J. Innovative Res. Dev., Vol. 3.

Chalasani, S. and J.M. Conrad, 2008. A survey of energy harvesting sources for embedded systems. Proceedings of the Southeastcon, 2008. April 3-6, 2008, IEEE, Huntsville, AL pp: 442-447.

Ching, N.N., H.Y. Wong, W.J. Li, P.H. Leong and Z. Wen, 2002. A laser-micromachined multi-modal resonating power transducer for wireless sensing systems. Sensors Actuators A. Phys., 97: 685-690.

Williams, C.B. and R.B. Yates, 1995. Analysis of a micro-electric generator for Microsystems. Proceedings of the 8th International Conference on Solid-State Sensors and Actuators, June 25-29, 1995, Sweden, pp: 369-372.