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Design Optimization of Mems Based Piezoelectric Energy Harvester For Low Frequency Applications

[1] Roohi Singh, [2] Anil Arora
[1][2] Department of Electronics and Communication Thapar Institute of Engineering and Technology Patiala, India.

Abstract- **Cantilever based piezoelectric energy harvester received great demand in last recent years. These are mostly made of thin film technology and different configurations as unimorph and bimorph for sensor and actuator applications. In this paper, analysis and comparison of two widely used cantilever design in MEMS energy harvesting devices i.e. wide beam structure and narrow beam structure have been done. Aluminum Nitride (AIN) is chosen as a piezoelectric material due to its CMOS and biocompatibility. To study the output of the design, Finite Element Modeling was used. The power density obtained based on the volume of the structure was 14.8 µ W/cm3 for the wide beam structure and 0.10 µ W/cm3 for narrow beam structure individually. In selecting a device, bandwidth is also a vital parameter. An array of cantilever structure resulted in a bandwidth of 4 Hz for the wide beam structure and 8.1 Hz for narrow beam structure respectively.**

Index Terms: — Energy harvesting, Micro-Electro-Mechanical System (MEMS), Piezoelectric unimorph, Finite Element Modeling (FEM), Aluminum Nitride (AIN), Energy Harvester (EH).

I.INTRODUCTION

With recent progress in Micro-Electro-Mechanical System (MEMS) based piezoelectric energy harvesting device have been prevailing for portable electronics and wireless sensor networks [1]. Wireless sensors requirement as input is a low power which can be sustained by the conventional batteries and the non-conventional i.e. piezoelectric and the electromagnetic energy generation if the circumambient media is vibrating in nature [2-3]. This vibration may range as of Hz (line human body movements) to KHz (like various rotary machines).

This paper focuses on the design of piezoelectric MEMS-based energy harvesting device.

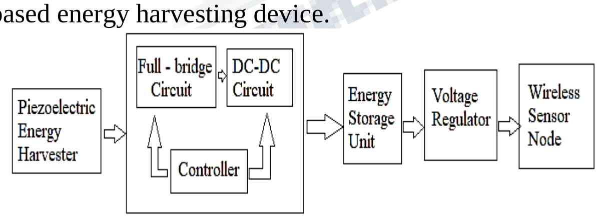

Figure 1 Piezoelectric Energy Harvesting System

Piezoelectric energy harvesting system as shown in Figure 1 actually consists of energy unit, conversion unit, storage unit and wireless sensor unit can be powered for some time period.

Using piezoelectric materials to convert mechanical energy into electrical energy is not the new idea but the piezoelectric generators remain bounded for the low power field as large stresses are accepted by piezoelectric ceramics but their strain is very meager which results in a limitation of material quantity usage. The recent progress of wireless system and wearable electronics combined progress in the low power electronics domain encouraging researchers on recycling of ambient energies [4-6]. Wireless devices have various advantages like it is easy to implement, very flexible, able to ease the placement of wireless devices in the remote locations [7].

An alternate solution to power the wireless system is the kinetic energy generators like vibration-based energy harvesters. This piezoelectric energy harvester (EH) device's power density and its efficiency strongly depend on frequency as it generates maximum power as output at the resonance frequency. The aim of energy harvester should be the low-frequency fundamental mode over the higher frequency as output power has an inverse relation with the vibrational mode's frequency. Various techniques can be used to achieve the low resonance frequency such as the choice of piezoelectric material, the design of the EH, design configurations and circuitry of conditioning the energy harvester. Traditionally, in energy harvesting devices cantilever structures are used. Due to brittleness and stiffness of Silicon, fabrication of low-frequency EH device can be difficult as they need a large mass which results in an increase in the stress on the beam, as a result, there is a decrease in the robustness of the structure. Nonetheless, the stress is decreased at low acceleration and there is an increase in robustness of the structure. For this reason,

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
Vol 5, Issue 7, July 2018

silicon (Si) based MEMS cantilevers put up to be ideal for low acceleration applications.

The main focus of device optimization of EH is on increasing power and bandwidth. It is necessary to increase the amount of power for accurately power the wireless sensor networks. One technique to increase the efficiency of power is to optimize the circuitry of energy harvester. The other technique is by energy harvesting device, this paper is condensed on this technique [8]. Optimizing the power from piezoelectric energy harvesting device is met by augmenting the structure dimension of the cantilever and optimizing the piezoelectric material.

In this paper aluminium nitride (AIN) is used over other piezoelectric materials (Lead zirconate titanate, zinc oxide, polyvinylidene fluoride). Aluminum nitride was chosen because of its CMOS compatibility. AIN is more compatible with silicon semiconductor technology and this material has high resistivity. Moreover, AIN is biocompatible. The quality of AIN can be determined by dielectric constant and piezoelectric properties, which influence the material ability to convert the mechanical strain in electrical power.

The other key aspect desired from energy harvester is wide bandwidth. The Silicon based energy harvesting devices gain large quality factor which in turn limits it's applications in real life. Various efforts have been done in order to increase bandwidth [9-10], most of the efforts are on the basis of damping factor. Even though if there is an increase in the damping, it results in higher bandwidth, in fact, it also has the negative impact of lowering the quality factor which in turn decrease the power generated by the device. Another method is to make an array of the cantilever structure with varying frequency. Size and shape of the structure affect the bandwidth. When there is an increase in the cantilever structure in a given area it results in the increase in bandwidth.

This paper emphasis on the comparison of two cantilever structures which are designed for the low power and low-frequency applications. The cantilever structures are the narrow and wide rectangular design. This paper compares the power and their bandwidth individually. This paper examines the most two common aspects of energy devices from two commonly used structures and compares its results. To examine the results (stress, resonant frequency and power generated) of the piezoelectric device finite element modeling has been used.

II. THEORETICAL CONSIDERATIONS

When the piezoelectric materials are either stressed or deformed, they generate a voltage across the material. The mechanical and electrical behavior can be modeled by the equations as [11]

$$S = s^{E}T + dE \qquad (1)$$

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

Where S is the Mechanical strain, T is the Mechanical stress, E is the Electric field, D is the Electric displacement, s^E is the matrix of elasticity under condition of constant electric field(indicated by superscript E), ε^{T} is the permittivity matrix at constant mechanical strain(indicated by superscript T), d is the piezoelectric coefficient matrix. Thus equation (1) and (2) describes the reverse and direct piezoelectric effect, respectively. The most convenient way of modeling the piezoelectric elements is by modeling both the mechanical and electrical parts of piezoelectric system as the basic circuit elements. Transformer is for the electromechanical coupling [15].

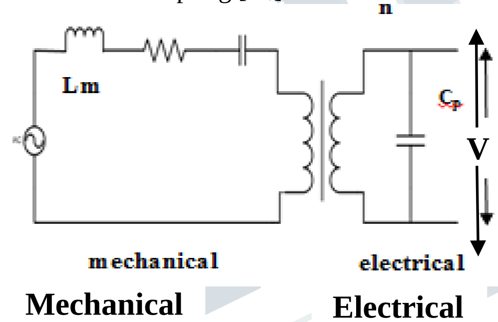

Figure 2 Circuit representation of piezoelectric EH generator

In Figure 2, Inductor and capacitor plays a kind of role in exchange of electrical, potential and kinetic energy, bounce back and forth energy and the currents in device. Resistor governs the losses. Resistor, capacitor and inductor together forms the mechanical part of the device. L_m represents the mass of inertia, R_p represents the mechanical damping and C_p represents mechanical stiffness, AC source is stress generator, V is voltage across the device.

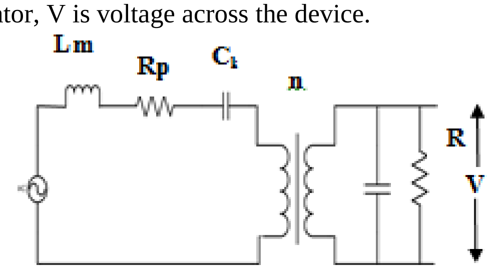

Figure 3 Circuit representation of piezoelectric energy harvester generator with resistive load

A resistive load is required to measure the amount of power which is been delivered to the load (device) as shown in Figure 3. Resistive load is necessary to measure the power generated by the piezoelectric energy harvester device.

The cantilever model can be used in two modes 33 and 31 as shown in Figure 4. [11]

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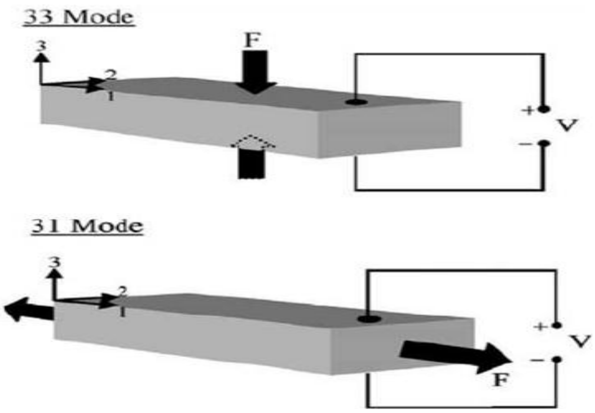


Figure 4 Mode 33 and 31

The 33 mode (compressive mode) means that the voltage is obtained in the 3 direction which is parallel to the direction of applied force, whereas in 31 mode (transverse mode) means that the voltage is obtained in 1 direction perpendicular to the applied force direction.The most preferred mode is 31 mode in energy harvesting applications as tip mass is added to the end of the beam increases the strain and compliance thus decreasing the resonance frequency, as the d_{31} coefficient is lower than the d_{33} coefficient.

A cantilever beam has a various mode of vibration as shown in Figure 5. Each cantilever beam hasa different resonance frequency. The first mode of the vibrating cantilever beam posses the highest electrical energy as the deflection is more in this mode moreover has the lowest resonance frequency.The low resonance frequency is close to the physical vibration sources and as such more power is produced at lower frequencies.Generally, the first resonant mode is preferred over the others [12].

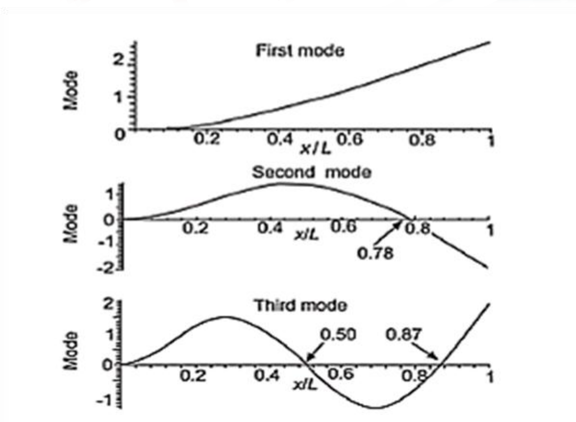


Figure 5 Different modes of the vibrating beam

The equation of the resonance frequency f_o for the cantilever beam based on Euler-Bernoulli beam theory is [13]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The stiffness coefficient k is

$$k = \frac{8EI}{l_2}$$

where m is mass, E is moment of inertia and I is area of moment of inertia of cantilever and piezoelectric layer.
or resonance frequency f_0 is also given by

$$f_0=\frac{1}{2\pi}\frac{t}{L^2}\sqrt{\frac{Y}{\rho}}$$

Where Y is Young’s modulus, t is thickness and L is the length of the cantilever beam and ρ is the mass density.
The energy harvester is integrated across an electrical circuit with the resistive load. The power can be calculated across the load resistor as [13]

$$P = V_{rect}\left(\frac{2\alpha}{\frac{\pi}{2}+RC_p\omega_p} + \frac{\frac{\pi}{2}+RC_p\omega_r}{\alpha R}\right)$$

Where C_p is the piezoelectric output capacitance, V_{rect} is the rectified voltage, ω_r is the resonance angular frequency, R is the resistance, α tells the electrical and mechanical coupling properties of piezoelectric material.
which results in

$$P = \frac{V^2}{R} = \frac{\left(\frac{0.5V}{\sqrt{2}}\right)^2}{R}$$

III. GEOMETRICAL MODELING

COMSOL Version 5.2, MEMS MODULE is used to simulate the model for the values of resonant frequency and output power. The cantilever structure used in this paper covers a wide beam and narrow rectangular beam.

The acceleration of the device is customary as 0.2 g for a wide beam and 0.4 g for narrow beam rectangular structure [12], the wide beam had an overall area which is 8.4 × 7mm whereas the narrow beam structure had 7.5 × 0.5mm. All layers used in the formation of piezoelectric energy harvester design had a thickness of 0.1 μm for Pt, 0.5 μm for AIN and 1 μm for Al respectively. Proof mass is made up of silicon Figure 6 shows the order of layer in piezoelectric cantilever beam.

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
Vol 5, Issue 7, July 2018

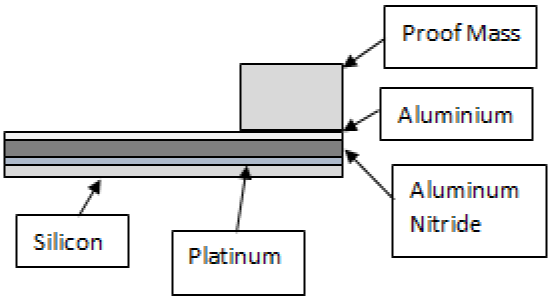


Figure 6 Structure of piezoelectric layer of the cantilever beam

In this paper the load is taken as 850 k ohm in order to calculate the power generated by the cantilever beam as shown in Figure 7.

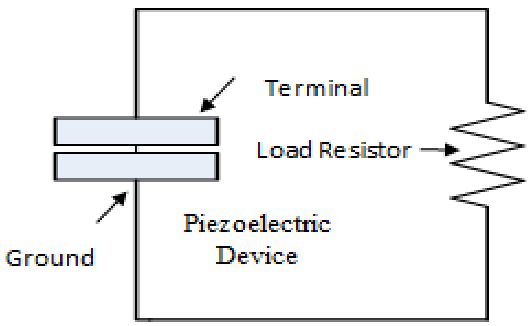


Figure 7 Circuit Diagram of Piezoelectric devices in COMSOL

Table1. Material used in simulation and Parameters

Silicon parameters (Si)

Name	Value	Unit
Density	2329[kg/m^3]	kg/m^3
Young's modulus	170e9[Pa]	Pa
Poisson's ratio	0.28	1

Platinum parameters (Pt)

Name	Value	Unit
Density	21450[kg/m^3]	kg/m^3
Young's modulus	168e9[Pa]	Pa
Poisson's ratio	0.38	1

Aluminium parameters (Al)

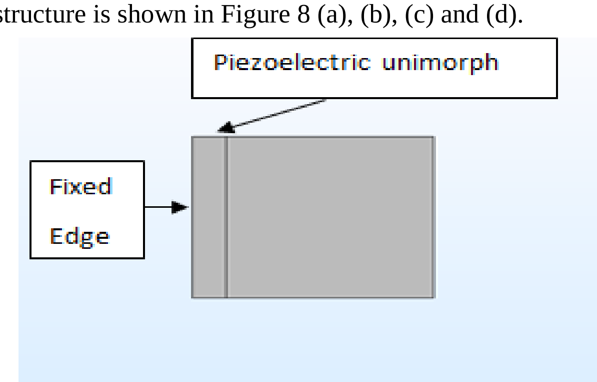
Name	Value	Unit
Density	2700[kg/m^3]	kg/m^3
Young's modulus	70.0e9[Pa]	Pa
Poisson's ratio	0.35	1

Aluminum Nitride (AIN)

Property	Value
Density[kg/m^3]	3300
Coupling matrix (C/m^3) $e_0 = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{bmatrix}$	e_{31} -0.58 e_{33} 1.55 e_{15} -0.48
Relative permittivity constant matrix (F/m) $\begin{bmatrix} \varepsilon_{11}^T & 0 & 0 \\ 0 & \varepsilon_{11}^T & 0 \\ 0 & 0 & \varepsilon_{33}^T \end{bmatrix}$	$\varepsilon_{11}^T 9.20817\times 8.85\times 10^{-12}$ $\varepsilon_{33}^T 10.2566\times 8.85\times 10^{-12}$
Elasticity matrix (GPa) $c_0 = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{15} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix}$	c_{11} 410 c_{12} 149 c_{13} 99 c_{33} 389 c_{44} 125 c_{66} 125
Relative permittivity	9

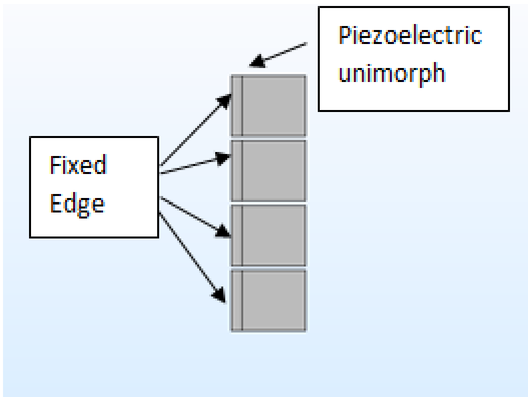
IV. SIMULATION RESULTS

Simulation and model-ling of vibrational based piezoelectric energy harvester is conducted in COMSOL 5.2. The two (wide cantilever beam and narrow cantilever beam) piezoelectric cantilever beam structure has been analyzed, one end of the device is clamped and the other end is free to move as it have proof mass on it. Frequency, Voltage, Power and Power density has been calculated using COMSOL 5.2. The schematic wide and narrow beam structure is shown in Figure 8 (a), (b), (c) and (d).

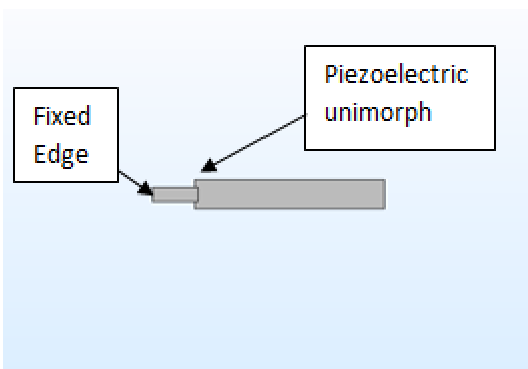


(a)Schematic of the wide single cantilever beam

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
Vol 5, Issue 7, July 2018



(b) Schematic of the wide array cantilever beam



(c) Schematic of the single narrow cantilever beam

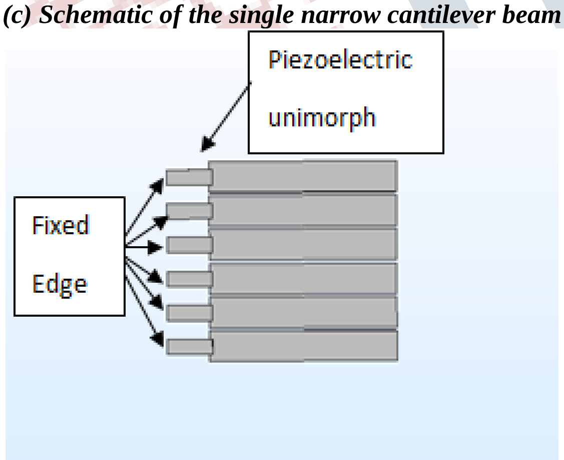
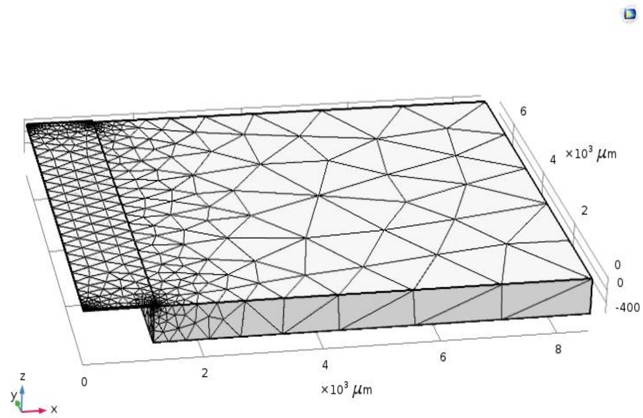
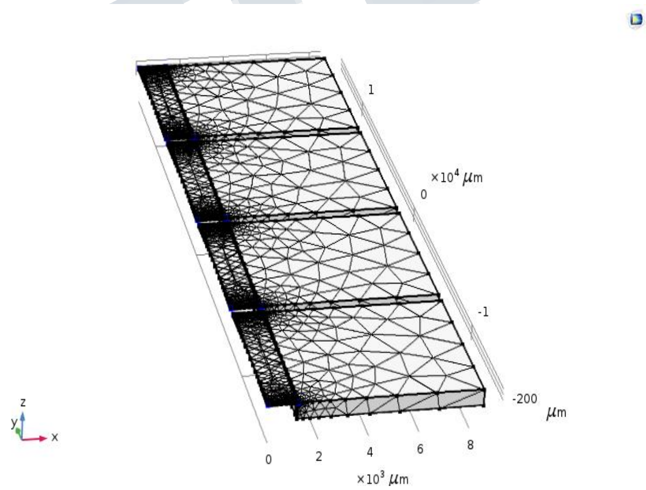


Figure 8 (a), (b), (c), (d) Schematic of wide and narrow cantilever beam structure

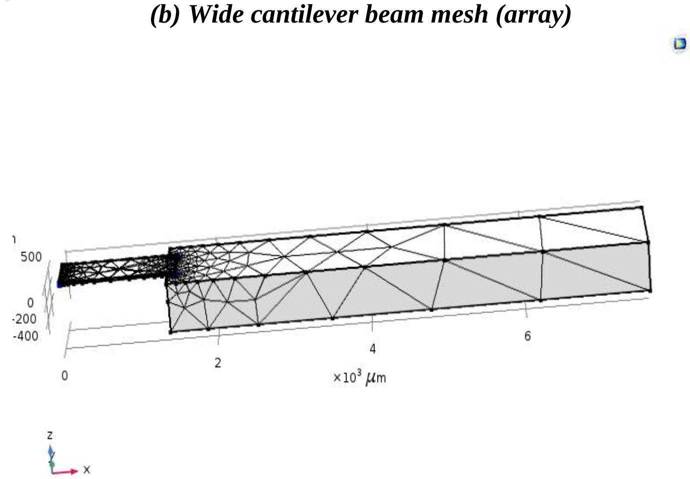
The application of meshing defines the correlation between the 3-D structure and reference structure, involves solving of mesh smoothing equations inside the COMSOL to define the coordinate transformations of the beam. Free tetrahedral meshing is used for meshing the model as shown in Figure 9 (a), (b), (c) and (d).



(a) Single wide cantilever beam mesh

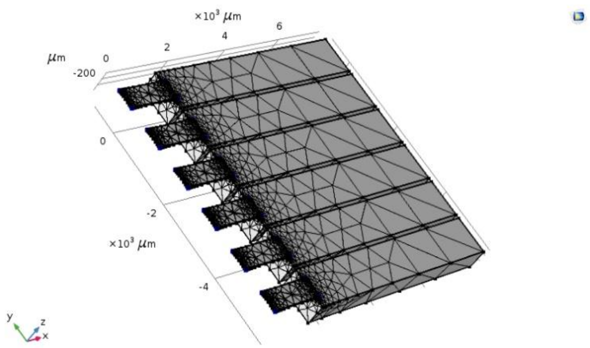


(b) Wide cantilever beam mesh (array)



(c) Single narrow cantilever beam mesh

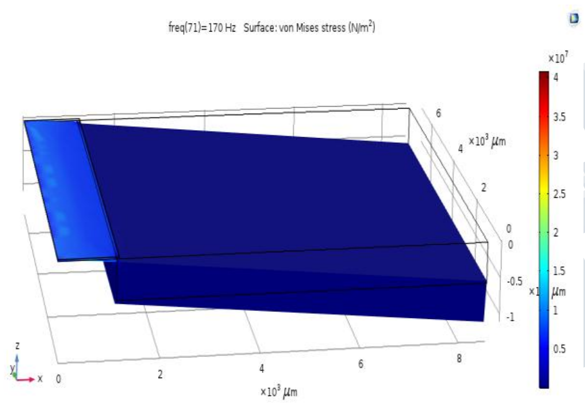
International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
Vol 5, Issue 7, July 2018



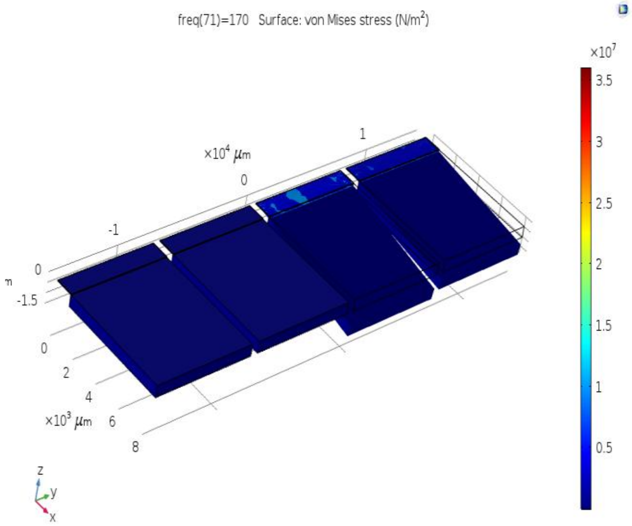
(d) Narrow cantilever beam mesh (array)

Figure 9 (a) (b) (c) (d) Mesh model in COMSOL 5.2

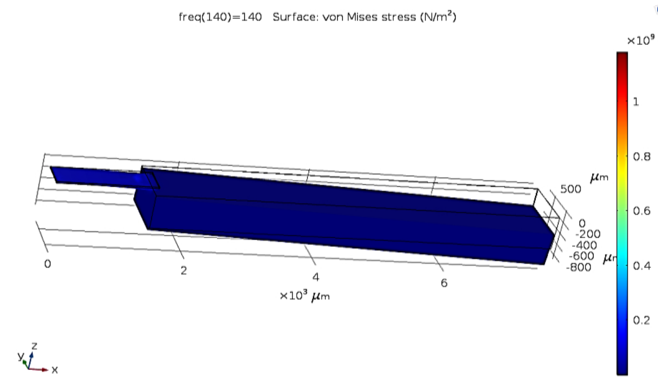
The stress generated on single wide and narrow cantilever beam are shown in Figure 10 (a) and Figure 10 (c) ,and array cantilever beam are shown in Figure 10 (b), Figure 10 (d)



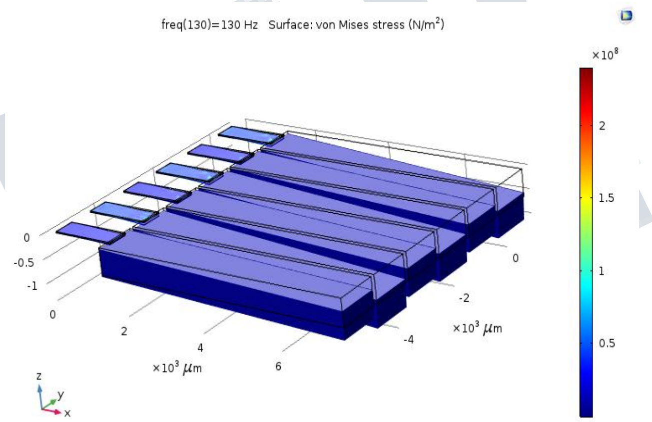
(a) Stress on the single wide cantilever beam



(b) Stress on the wide array cantilever beam



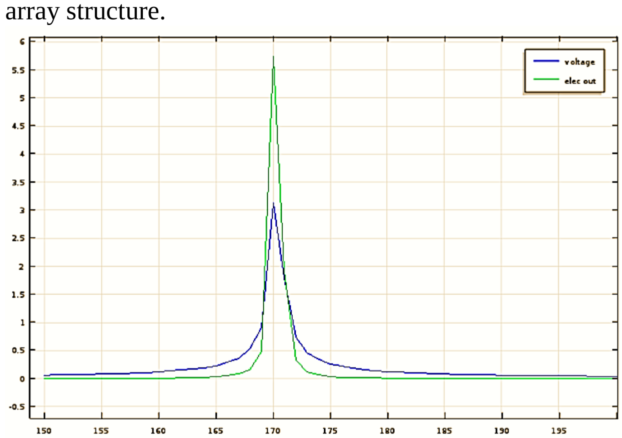
(c) Stress on the single narrow beam



(d) Stress on narrow array cantilever beam

Figure 10 (a), (b), (c), (d) Stress on single and array cantilever beams

Figure 11 (a) and Figure 11 (c) shows the graph between frequency and voltage, frequency and power for single cantilever structure, Figure 11 (b) for the wide cantilever beam array and Figure 11 (d) for the narrow cantilever beam array structure.



(a) Simulation result of single wide cantilever beam

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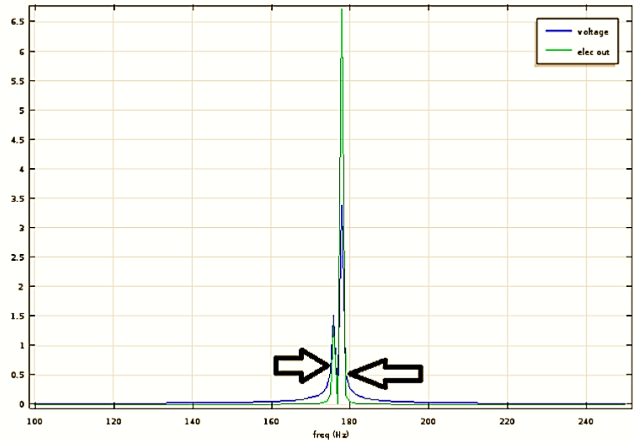
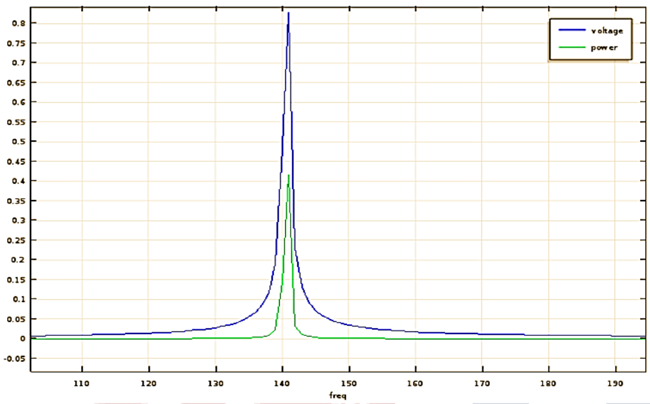
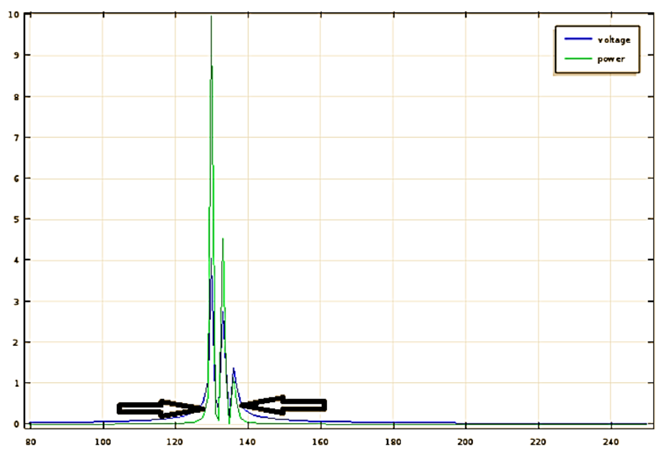
Vol 5, Issue 7, July 2018



(b) Simulation result of array of wide cantilever beam



(c) Simulation result of narrow cantilever beam



(d) Simulation result of array of narrow cantilever beam
Figure 11 (a), (b), (c), (d) Simulation results showing the voltage and power vs. frequency

Figure 11 (a) and Figure 11 (c) shows the graph between frequency and voltage, frequency and power for single cantilever structure, Figure 11 (b) for the wide cantilever beam array and Figure 11 (d) for the narrow cantilever beam array structure.

Table 2 Voltage and Power obtained from the cantilever structures

Architecture	**Voltage (V)**	**Electric Power (μW)**	**Frequency (Hz)**
Wide beam cantilever structure	3.1	5.55	170
Narrow beam cantilever structure	0.85	0.42	142

From Table 2 the power generated was 5.55 μW for the wide EH cantilever structure and 0.42 μW for narrow EH cantilever structure which is close to the theoretical calculated power which is 5.652 μW and 0.425 μW respectively.
Figure 11 (b) shows the graph of voltage and power with respect to frequency for the array of the wide beam and Figure 11 (d) the narrow beam cantilever design. It is clearly seen that there is an increase in bandwidth and amplitude which is due to the combined result of all the wide beam and the narrow beam design in the array. As every cantilever beam have its resonance frequency and when the array is formed it gives results in combination which increases the bandwidth of the EH device as each beam is contributing in the results. Thus size and shape of the structure affect the bandwidth. As the number of cantilever structure in wide cantilever beam is four and in narrow cantilever beam is six, there is quite increase in the bandwidth when compared to the single beam structure of wide and narrow cantilever beam respectively. To get the wide bandwidth the number of cantilevers should be increased in future research.
The first aspect of energy harvesting device is the power density [14]

Power Density = $\frac{Pp}{V}$

Where P_p is peak electric power and v is volume.

Table 3 Power density of the structures

Architecture	**Power density ($\mu W/cm^3$)**
Wide cantilever beam structure	14.8
Narrow cantilever beam structure	0.10

From Table 3 can be seen the power density of single wide cantilever beam and narrow cantilever beam is 14.8 $\mu W/cm^3$ and 0.10 $\mu W/cm^3$. It is clearly seen in results that the wide beam piezoelectric cantilever structure had the highest power density than the narrow beam cantilever piezoelectric structure. The other feature of EH device is the bandwidth. In order to increase the bandwidth, various cantilever structures are used to form an array by varying the length which in return alters the resonant frequency between each cantilever structure. The results obtained from the array structure are shown in Figure 11 (b) and Figure 11 (d). It is clearly seen in the graph of Figure 11 (b) and Figure 11 (d), there is a low bandwidth of 4 Hz in wide beam and 8.1 Hz in narrow beam cantilever structure. For increasing bandwidth narrow structure EH devices are the best kind of cantilever structures over the wide structure EH devices, however, generate low power. The results demonstrate that the wide cantilever beam EH design delivers high power density and bandwidth is low in it, on the other hand, the narrow cantilever beam structure delivers high bandwidth and low power density. Thus optimum shape is depended on the utilization.

V. CONCLUSION

This paper examines the simulation outcome of the two aspects which are power density and bandwidth of MEMS-based energy harvesting device. Design using Finite Element Modeling (FEM) is validated by the results and further experiments can be done using the model in future. Various cantilever structures were designed and tested to operate on low frequency and on low acceleration. Each design cantilever of energy harvester type has its pro's and con's, and the conclusion of the results are wide beam structure is preferred to increase power density and a narrow beam for the wide bandwidth. High power density also has a disadvantage which is likely to fail where acceleration is high, as due to increasing stress which they experienced. Future work will be to optimize the two structures using finite element modeling described in this paper to widen the bandwidth and to obtain high power from device.

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