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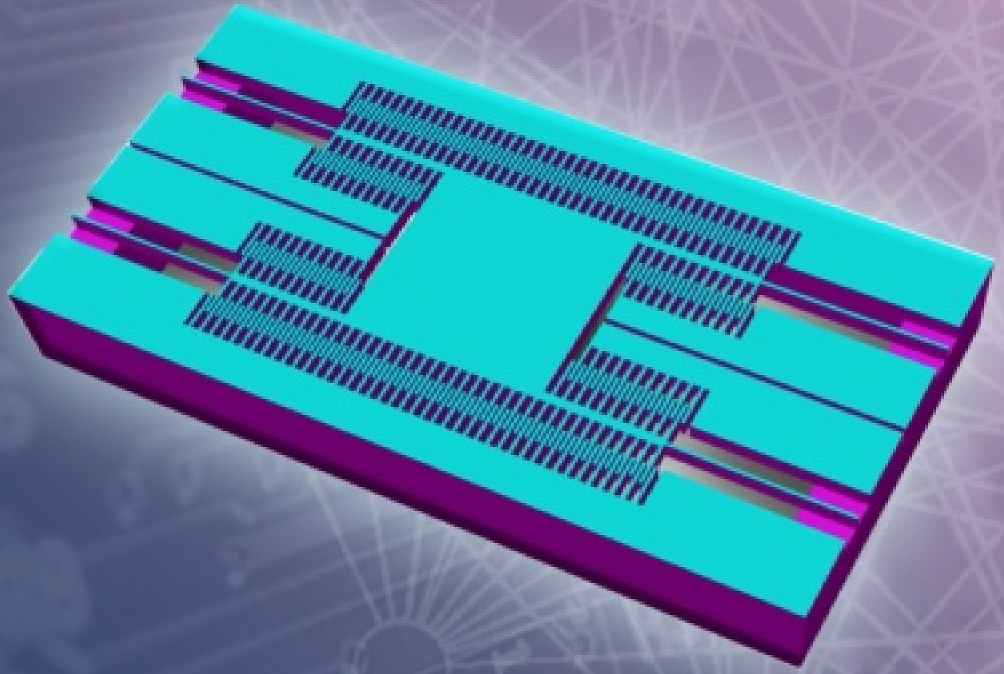

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Trapezoidal Electrodes Array for Electret-Based Electrostatic Energy Harvester

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Abstract: Electrode structure design plays a significant role in the development of an energy harvester device. In this paper, a design and modeling of a new electrode structure of an electrets-based electrostatic energy harvester is introduced. A Trapezoidal shape electrodes structure, interleaving with one another couples with a rectangular electrets structure stacked on top of the electrodes, are modeled and analyzed thoroughly using the standard analysis tool and later simulated with a Finite Element Analysis tool (FEA), the CoventorWare. Two types of FEA analysis are conducted, the mechanical and electrostatic analyses. Results of the theoretical analysis indicate that the average output power of the trapezoidal electrodes energy harvester is approximately 1 mW in response to the input vibrations of 20 Hz and 1 g acceleration. Further mechanical and electrostatic analyses conducted on the model with FEA show that the trapezoidal electrodes structure resonates at the frequency of 113 Hz and induces 1895 pC of charge from 450 VDC electrets surface potential. Parameters obtain from these analyses will be used as a reference for physical device fabrication using a standard 0.35 µm CMOS-MEMS process technology, hence a proactive optimization approach taken towards device fabrication. *Copyright © 2012 IFSA.*

Keywords: Electrets, MEMS energy harvester, Trapezoidal electrode, Finite element analysis.

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1. Introduction

Energy harvesting system is a process which converts the ambient energy sources such as vibrations, solar, thermal and RF energies into a useful electrical energy. An energy harvesting topic has gain extensive research interest recently, mainly driven by the needs of alternative power sources for ubiquitous sensor networks and low power portable devices. Some examples of the energy harvesting applications are wireless sensor nodes (WSN) used to monitor structural health of bridges, home/building energy management system (HEMS/BEMS), automotive sensors such as tire pressure monitoring systems (TPMS), and wearable biomedical devices such as pacemakers and hearing aid. Studies conducted by researchers [1-4], believed that the energy harvester could make significance contribution to the reduction of battery consumption which leads to a reduction of hazardous waste from batteries.

Among the available energy sources mentioned, vibration source which originates from the mechanical motion is of special interest due to its abundance in nature. Energy conversion method from vibration to electrical energy, also called the transduction mechanisms, can be categorized into electrostatic, electromagnetic and piezoelectric as described in [2]. Among the transduction mechanisms mentioned, electrostatic conversion method has significance advantages when considering a device for miniaturization, it's called the micro energy harvester in [3]. However, the electrostatic method has its own drawbacks, whereby a separate voltage source is required to provide consistent charge to the electrodes as mentioned in [4]. Hence, to overcome this drawback, an *Electrets* which is a type of dielectric material, is deposited on one of the electrodes and then charged with a *Corona* charging method as discussed in [5]. The charging process provides a surface charge potential with constant electrostatic field, hence is called a *quasi-permanent* charged material.

An electrets energy harvester is fundamentally a variable capacitor made up of parallel plate electrodes placed on top of each other while the electrets material is deposited on one side of the electrodes as described in [6]. In this paper however, other type of electrode structure is introduced, called the Lateral Electrode Structure. In this structure, the harvesting electrodes are placed adjacent to each other. The electrodes are placed on a seismic mass connected to beams which acts as a mechanical spring. The electrets layer, on the other hand, is placed on the opposite side of the harvesting electrodes as shown by Fig. 2 and also reported in [7]. Using the concept of the lateral electrodes structure, a Trapezoidal Electrode Structure is later designed, modeled and analyzed in detail where the results are to be compared to the literature [8], hence will be the focus of this paper.

2. Electrodes Design

2.1. Conventional Electrode

A common electrode structure used on the existing electrets energy harvester is shown in Fig. 1. The harvesting electrode called the upper electrode is located at the top side of the structure whereas the electrets is deposited on the opposite side electrode called the lower electrode. The upper electrode is attached to a seismic mass which moves in response to the ambient vibration as a result of resonance. One of the disadvantages of the conventional electrode structure is its limited displacement of the seismic mass, hence would produced relatively lower output power, typically below 1 mW range [5,7].

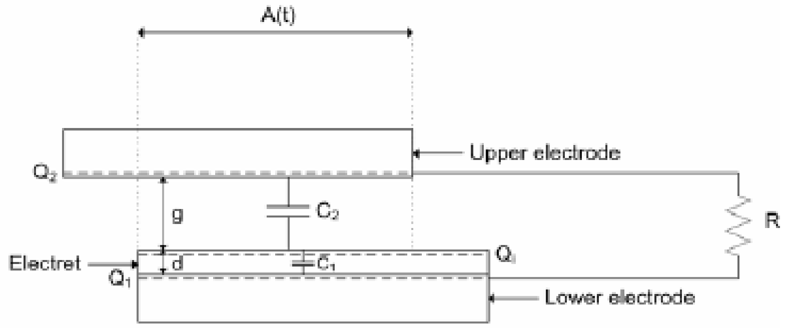


Fig. 1. Topology of a conventional electrode structure [9].

2.2. Lateral Electrodes Structure

Okamoto et. al [7] explored another type of electrode structure called the lateral electrode as shown in Fig. 2. This structure has both of its harvesting electrodes called the Work Electrodes (WE), with rectangular shaped, placed laterally adjacent to each other, whereas the electrets layer is placed on the opposite side of the work electrodes on a different structure as discussed detail in [7]. This electrets layer is deposited on a seismic mass, which displaces laterally in response to the ambient vibration whereas the harvesting electrodes remain stationary. The detail layouts of the lateral electrodes structure are shown in Figs. 2, 3 and 4. The main advantage of this structure is larger displacement of the seismic mass can be achieved; hence a relatively higher output power can be generated as compared to the conventional electrode structure.

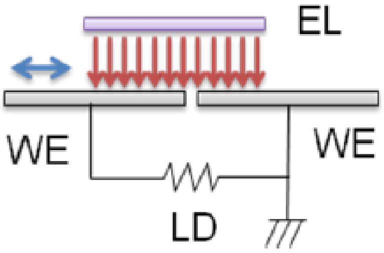


Fig. 2. Lateral electrodes structure as in [7].

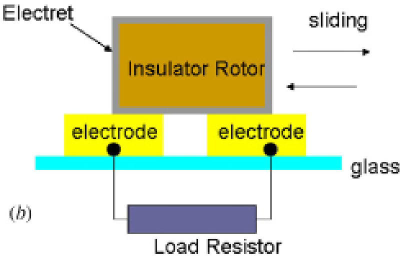


Fig. 3. Lateral electrodes structure with electrets rotor as described in [6].

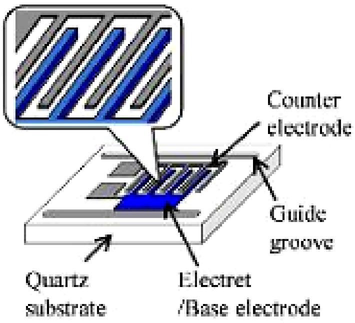


Fig. 4. Blow out view of the rectangular shaped lateral electrodes as in [10].

2.3. Trapezoidal Electrodes Structure

Trapezoidal electrodes are the new type of electrodes structure leveraging from the concept of lateral electrode but designed with a trapezoidal shape which functions as a transducer for the electrets-based electrostatic energy harvester as depicted in Fig. 5. The Trapezoidal electrodes structure consist of two work electrodes placed adjacent to one another attached on a seismic mass, which resonates in response to an input vibration. The electrets layer, on the other hand, is placed on the opposite side of the electrodes, on a stationary structure separated by air gap. Obviously, the significant difference of this structure as compared to the lateral structure mentioned is the shape and the arrangement of the electrodes.

The complete layout of the trapezoidal electrodes structure and the electrets layer are shown in Fig. 6. In this paper, an extensive modeling and analysis of this structure are conducted thoroughly in order to comprehend its theoretical performance with respect to the affected parameters. From the analysis, it is found that the major advantage of this structure is that the electrets and electrodes layers are independent of each other, i.e. some critical parameters can be controlled without affecting others such as electrodes-electrets gap, electrets thickness and surface area to name a few. Hence, this electrodes structure is adopted throughout the modeling process.

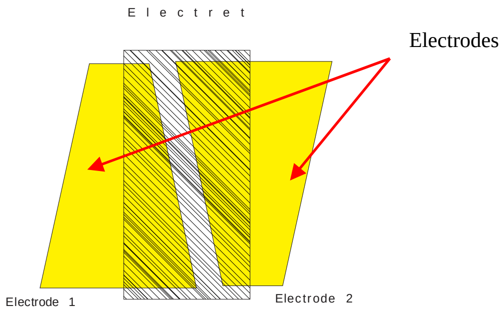


Fig. 5. The new trapezoidal electrodes structure concept.

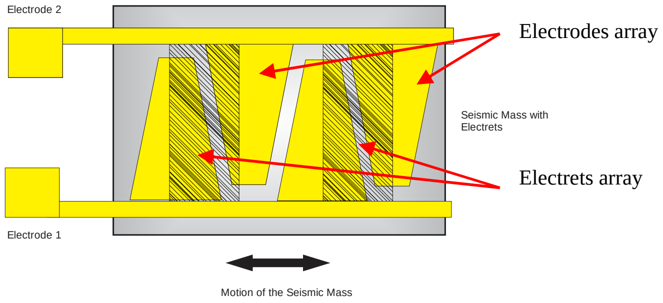


Fig. 6. The trapezoidal electrodes structure complete design.

3. Mathematical Model

To understand the electrical energy generation process with the trapezoidal electrodes concept, an equivalent model of the system is developed which consists of a mass-spring-damper and variable capacitors as shown by Fig. 7 and Fig. 8 respectively.

To analyze the mechanical and electrical modules of the energy harvester, an Ordinary Differential Equation (ODE) of motion is utilized. The mechanical equation is derived from Newton's Second Law whereas the electrical equation is deduced from Kirchhoff's Voltage Law. The equations to represent a complete mechanical to electrical conversion of the energy harvester are as follows:

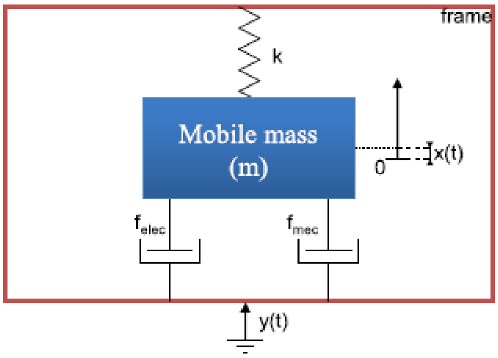


Fig. 7. Equivalent mechanical model of the energy harvester system as in [9].

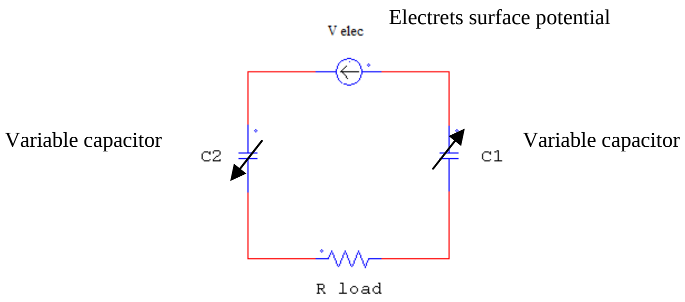


Fig. 8. Electrical model of the trapezoidal electrodes structure.

$$m\ddot{x} + b\dot{x} + kx + f_{elec} = -m\ddot{y} \tag{1}$$

$$f_{elec} = \frac{1}{2}\frac{q(t)^2}{C(t)} \tag{2}$$

$$C(t) = \frac{\varepsilon A(t)}{g} \tag{3}$$

$$\ddot{y}(t) = a(t) = \omega^2 Y Sin(\omega t), \tag{4}$$

where m denotes the seismic mass, b the mechanical damping coefficient, k the spring stiffness, $x(t)$ the corresponding displacement of the seismic mass with respect to the stationary electrodes, $\ddot{y}(t)$, $a(t)$, Y and ω are the displacement, acceleration, amplitude and angular frequency of the ambient vibration, f_{elec} the electrostatic force generated by the variable capacitors, $C(t)$ the variable capacitor, g the air gap between the electrodes and the electrets, $q(t)$ the electric charge, $A(t)$ the electrodes surface area, $\varepsilon=\varepsilon_r\varepsilon_o$, dielectric constant of the electrets material, which is a product of relative permittivity of the electrets material and the permittivity of the air (8.85E-12 F/m) respectively.

Applying the concept of conservation of charge on the electrets and the electrodes surface area using the following equation

$$Q_{el} = Q_1(t) + Q_2(t) \tag{5}$$

where

$$Q_1(t) = \tilde{\sigma}A_1(t) \text{ and } Q_2(t) = \tilde{\sigma}A_2(t) \tag{6}$$

are the charges present on the designated electrode 1 and electrode 2 respectively. The charge induced on the work electrodes called the induced surface charge density is given by

$$\tilde{\sigma} = -\frac{(d\sigma_{el} - \varepsilon V_{el})}{(d + \varepsilon_r g)}, \tag{7}$$

while the implanted surface charge density of the electrets from the Corona charging method is given by

$$\sigma_{el} = \frac{V_{el}2\varepsilon}{d}. \tag{8}$$

Hence, the voltage generated by the energy harvester model is therefore given by

$$\mathrm{V(t)} = -\frac{Q_1(t)}{C_1(t)} + \frac{Q_2(t)}{C_2(t)}. \tag{9}$$

The induction current is the current that flows through the load resistance and is defined as the time derivative of the electric charge as given by

$$I(t) = \frac{dQ(t)}{dt} = \frac{V(t)}{R}. \tag{10}$$

Substituting (9) into (10) yields

$$I(t) = \frac{gV_{el}}{R(d + \varepsilon_r g)}[A_1(t) - A_2(t)], \tag{11}$$

where R is the load resistance, V_{el} the electrets surface voltage and d the thickness of the electrets material. Further simplifying (1) yields a final equation for the mechanical motion,

$$\ddot{x}(t) = -\frac{b}{m}\dot{x}(t) - \frac{k}{m}x(t) - \frac{q(t)^2 g}{2m\varepsilon A} - a(t) \tag{12}$$

Using (10), the average output power P(t) of the energy harvester can be derived as below

$$P_{average} = \frac{1}{t_{end}}\int_0^{t_{end}} R\left(\frac{dQ(t)}{dt}\right)^2. \tag{13}$$

The basic functionality of the trapezoidal electrodes energy harvester can be further studied by constructing a block diagram of the model utilizing (11) to (13) with Matlab/Simulink tool as shown in Fig. 9.

To further evaluate the performance of the trapezoidal electrodes energy harvester model, a simulation is conducted using the benchmark parameters as in [11]. The subsequent sections of this paper discuss the detail analysis of the electrets energy harvester model using the trapezoidal electrodes structure with respect to all other related parameters shown in Table 1 and Table 2.

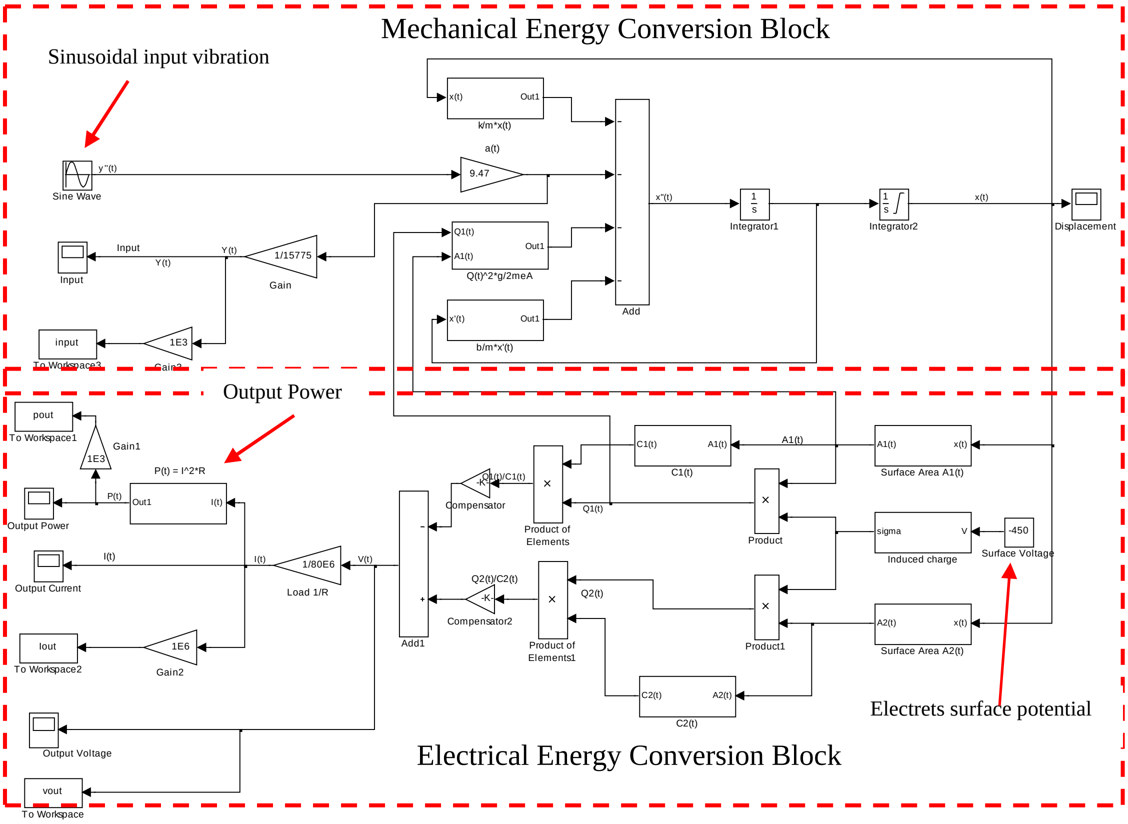


Fig. 9. Matlab/Simulink block diagram of the theoretical model of the Trapezoidal electrodes harvester.

Table 1. Relationship of the output power and device intrinsic parameters

Parameters	Relationships with output power
Surface Voltage	Directly proportional – power increases with increasing surface voltage
Load Resistance	Inversely proportional – power decreases with increasing load
Electrodes- Electrets Gap	Inversely proportional – power decreases with increasing gap
Electrets Thickness	Inversely proportional – power decreases with increasing gap
Seismic Mass Displacement	Directly proportional – power increases with increasing displacement
Input Acceleration	Power increases and saturates
Electrodes Surface Area	Directly proportional – power increases with increasing surface area
Input Frequency	Maximum power occurs at resonance frequency

Table 2. Theoretical parameters used to generate 1 mW targeted output power.

Output Power (mW)	Parameters	Values	Units
1	Surface Voltage	-450	V
	Load Resistance	80	MΩ
	Electrodes to Electrets Gap	50	μm
	Electrets Thickness	9	μm
	Seismic Mass Displacement	3.6	mm
	Input Excitation	0.6	mm
	Input Acceleration	9.47	m/s^2
	Electrodes Surface Area	100	mm^2
	Input Frequency	20	Hz
	Seismic Mass	1	mg

4. Analytical Model

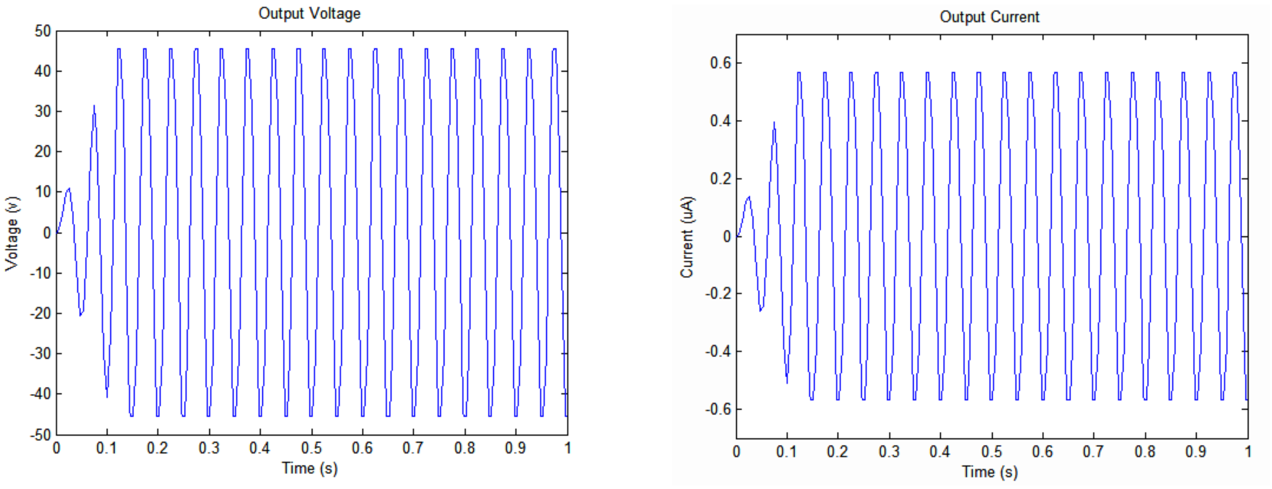
4.1. Theoretical Analysis

To understand the correlation between the output power and the affected parameters of the trapezoidal electrodes energy harvester, the parameters such as surface voltage, electrets thickness, electrets-electrodes air gap, load resistance, seismic mass displacement and electrodes dimensions, are characterized by varying their values accordingly. Results of the characterization, as in Table 1, indicate the relationship of each parameter to the output power, e.g. the surface voltage, seismic mass displacement and electrodes surface area are directly proportional to the output power whereas the load resistance, electrodes-electrets gap and electrets thickness are inversely proportional to the output power.

To roughly harvest 1 mW of power from the model as a targeted output, values of each parameter corresponds to the intended power are compiled and tabulated as in Table 2. Next, the closest values of each parameter to yield the targeted power, called the optimized values, are derived from the model and showed in Table 3. Eventually, the said parameters are re-entered into the Matlab/Simulink model and the plots of the outputs are generated as shown in Fig. 10 and Fig. 11.

Table 3. Optimized parameter values used for the model.

Parameters	Symbol	Values	Units
Spring Stiffness	k	15.79	N/m
Mobile Mass	m	1	g
Mechanical Damping	b	6280	µNs/m
Air gap	g	50	µm
Electrode Surface Area	A	25	mm^2
Load Resistance	R_L	80	MΩ
Acceleration of vibration	a	9.80	m/s^2
Electrets Surface Voltage	V_{elec}	-450	V
Ambient Vibration	f	20	Hz
Dielectric Thickness	d	2	µm



(a) (b)

Fig. 10. Theoretical outputs of the trapezoidal electrodes structure: (a) Voltage, (b) Current.

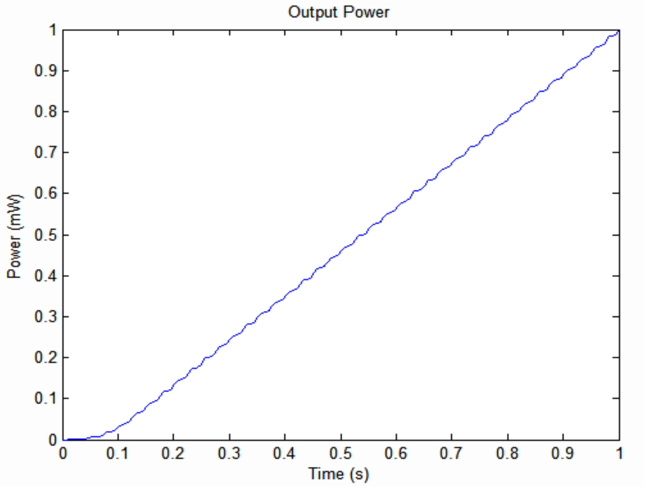


Fig. 11. Average output power harvested from the trapezoidal electrodes.

The results obtained from the simulation infers that the Trapezoidal Electrodes structure concept introduced and described in this paper, is theoretically feasible to harvest electrical energy from the ambient vibration and capable to generate the output power better than the conventional and lateral electrodes structures.

4.2. Finite Element Modeling and Analysis

Modeling and analysis of the trapezoidal electrodes structure are carried out with a Finite Element Analysis (FEA) tool, called the CoventorWare® 2010 [12]. The analyses are carried out in two separate stages, the mechanical and electrostatic.

In order to understand the mechanical responses of the trapezoidal electrodes structure, a design of the resonator structure is created with CoventorWare® Designer module, utilizing the layout editor as shown in Fig. 12. The resonator comprises of a seismic mass, where the trapezoidal electrodes resides, and two long beams placed at each side of the seismic mass, called the ‘Serpentine’ typed beams, are anchored and fixed at the end of the structure. The overall dimension of the structure is 25 mm^2, with 25 µm beam width, 300 µm beam gaps and 100 µm thickness.

A 3D model is later created using the ‘Designer’ module of the CoventorWare® as shown by Fig. 13. Using the parameters from [11] and Table 4, a mechanical simulation and analysis are carried out with the ‘Analyzer’ option of the CoventorWare®. From the simulation, there are several possible displacement modes observed such as lateral, transverse and torsion. Results of the simulation show that the lateral displacement mode, i.e. mode 1, is the most dominant mode where the maximum displacement value recorded is 94 µm, and resonates at the frequency of 113 Hz in response to 100 Hz and 1g (9.8 m/s^2) input vibrations as shown by Fig. 14 and Fig. 15. Hence, the serpentine beam resonator structure which holds the trapezoidal electrodes, is suitable for used as a conversion mechanism for a vibration-based energy harvester.

Similar to the mechanical analysis described earlier, an electrostatic analysis is conducted next with CoventorWare®, to comprehend the charge transfer characteristic. This simulation requires both the trapezoidal electrodes and the electrets structures designs. The trapezoidal electrodes structure is drawn to a specific dimension of 20 × 40 × 100 µm (Top × Base × Height) whereas the rectangular electrets structure are drawn to a dimension of 40 × 100 µm (Width × Length), both layouts are arranged in an array pattern as shown in Fig. 16 and Fig. 17 together with their respective 3D models. The trapezoidal electrodes are positioned on the seismic mass of the resonator structure whereas the electrets are placed on another structure such that the electrode and the electrets are constructed in a vertical arrangement.

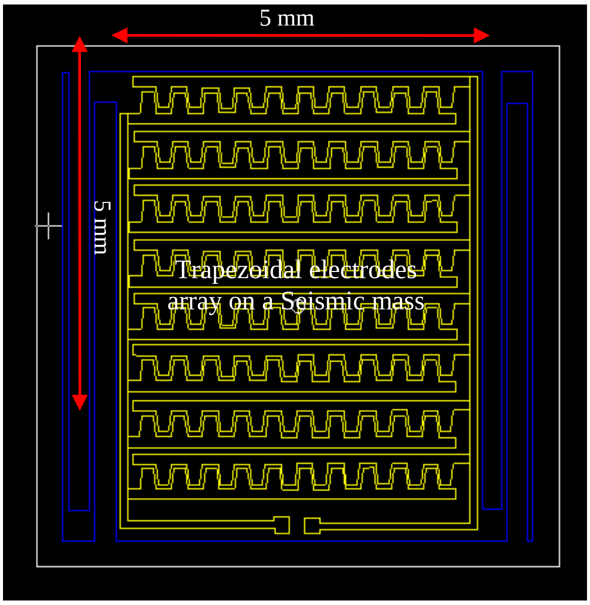


Fig. 12. Layout of the resonator structure for mechanical analysis

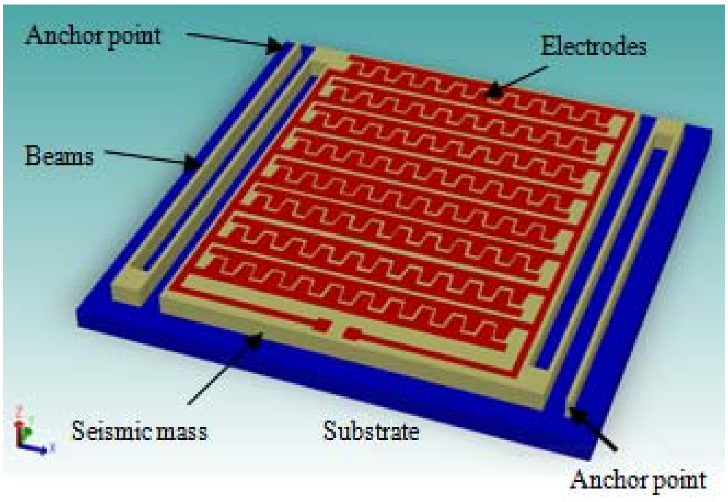


Fig. 13. A 3D model of the resonator structure.

Table 4. Input parameters used for FEA mechanical analysis.

Parameters	Symbol	Values	Units
Input Acceleration	a	9.80	m/s^2
Ambient Vibration	f	100	Hz
Resonator Mass	m	3.26E-6	kg
Spring Constant	k	0.085	N/m
Damping Coefficient	b	1.17E-4	Ns/m
Quality Factor	Q	20	-

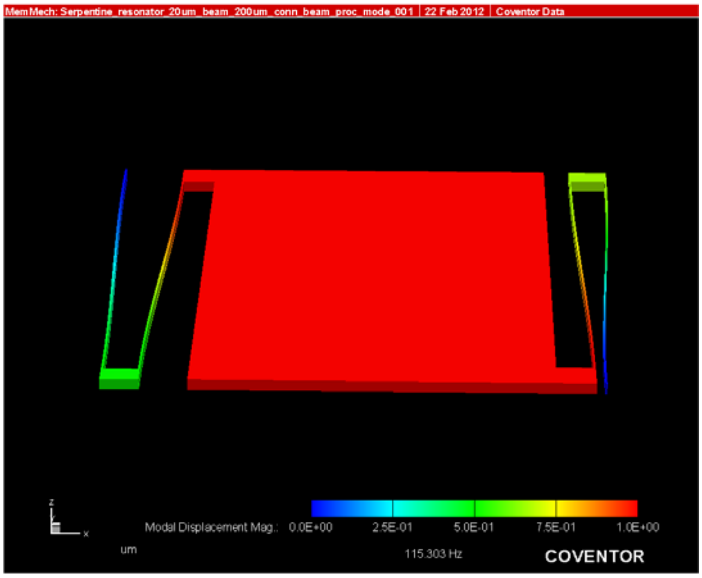


Fig. 14. Deformation of the resonator structure in the lateral mode.

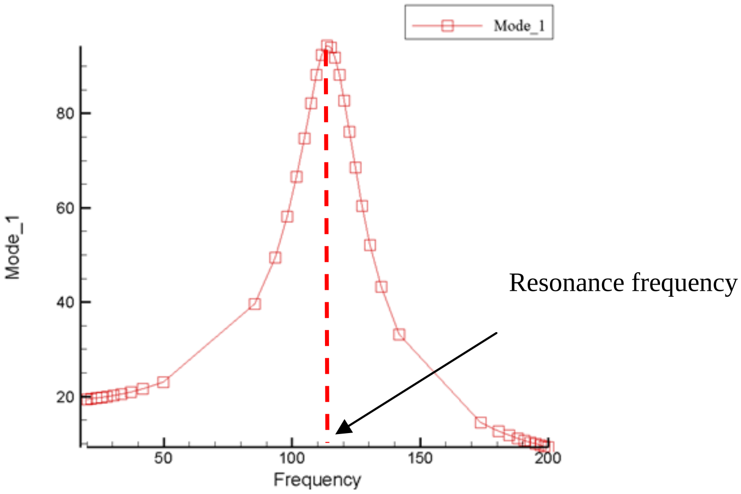


Fig. 15. Frequency response of the resonator lateral mode displacement

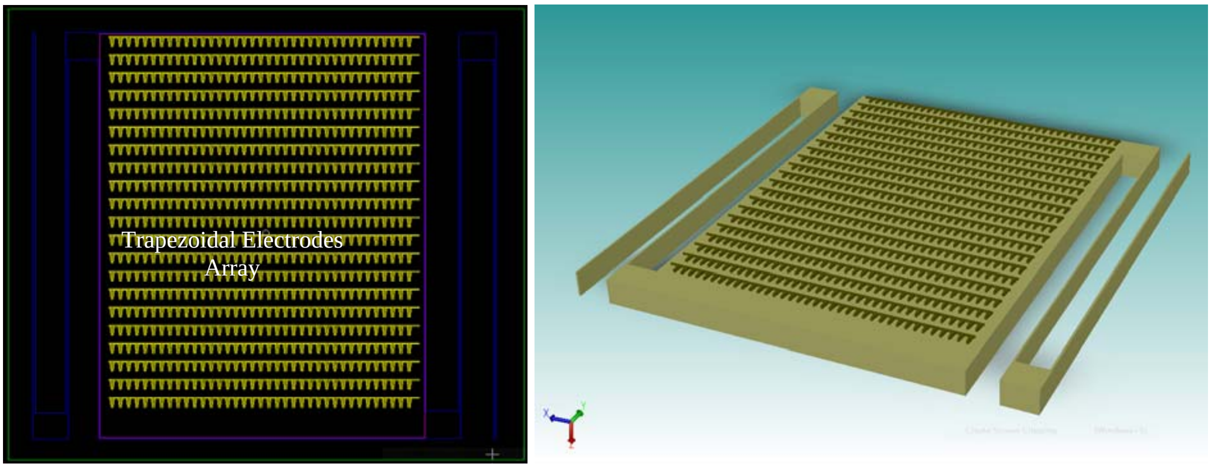


Fig. 16. Layout and 3D model of the trapezoidal electrodes structure.

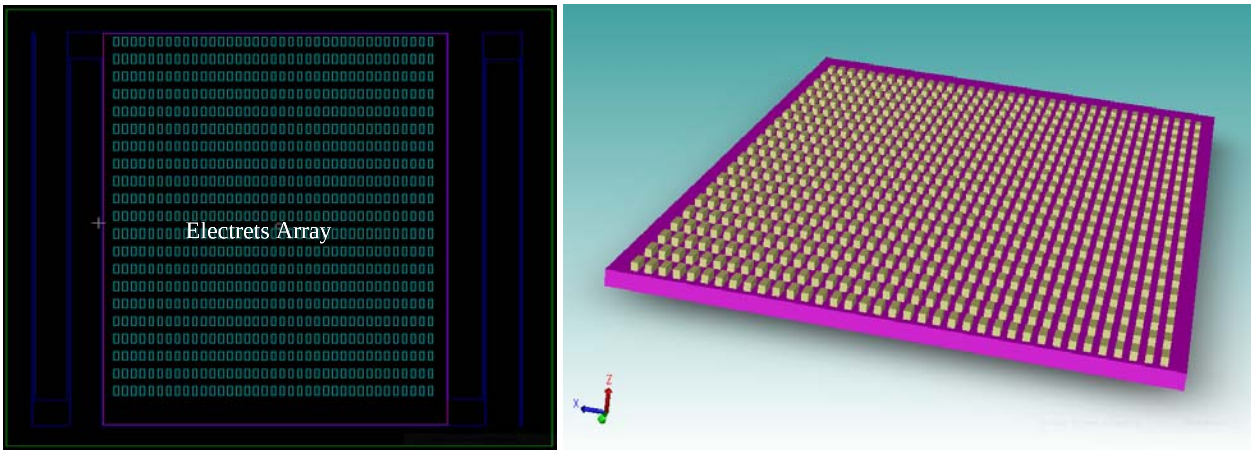


Fig. 17. Layout and 3D model of the electrets structure.

The surface potential of the electrets is set to 450 VDC in the 'MemElectro' boundary condition setting of the CoventorWare®. Next, both of the structures are integrated into one main structure while maintaining a 10 µm air gap separation between them, then the simulation begins. The outcomes of the electrostatic analysis are the measurement of the capacitance value and the charge density induced on the trapezoidal electrodes, results show 4.21 pF and 1895 pC respectively. The induced charge density on the electrodes structure are due to the charge transfer from the electrets surface potential as described detail in section 3 and shown by Fig. 18.

From this simulation, the electrostatic analysis conducted on the trapezoidal electrodes structure indicates that the structure is capable to induce charges from the electrets surface, hence some voltages and current are present if the electrodes are connected to a resistive load. Comparing the capacitance value obtained from this analysis, 4.21 pF, with the mathematical model using the Matlab/Simulink, 3.6 pF, the difference shown between the theoretical and FEA is only 15 %. Hence, as far as the analysis is concerned, this FEA modeling correlates well with the theoretical analysis. These results will be further compared to the physical device currently fabricated on 0.35 µm CMOS-MEMS process technology.

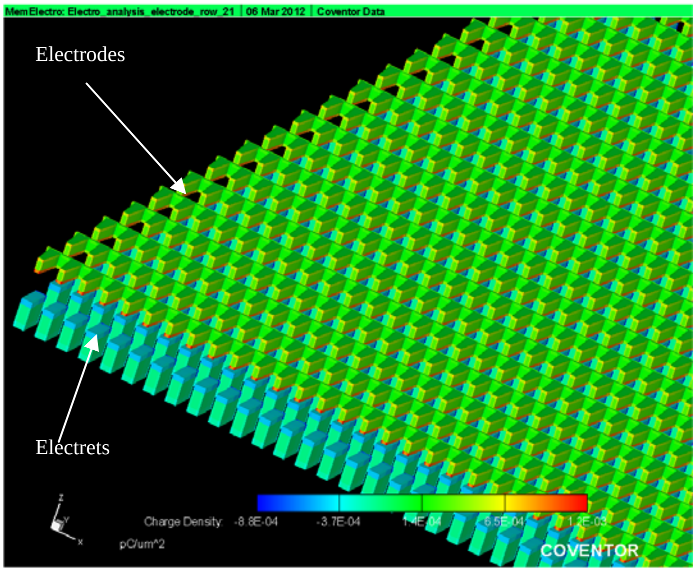


Fig. 18. Electrostatic charge induced on the trapezoidal electrodes.

5. Conclusions

In this paper, the Trapezoidal electrodes structure for used on the electrets-based electrostatic energy harvester has been designed, modeled and analyzed thoroughly. Initial analysis on the theoretical model shows that the trapezoidal electrodes structure is capable to harvest approximately 1 mW of output power using frequency as low as 20 Hz and 1 g acceleration as the input vibrations. Further mechanical and electrostatic analyses conducted with FEA indicates that the trapezoidal electrodes with its rectangular electrets structure counterpart, resonates at 113 Hz and induces 1895 pC of charge from 100 Hz input vibration and 450 VDC surface potential respectively.

Thus, the trapezoidal electrodes structure analyses described in this paper is capable to convert the mechanical vibrations from the ambient into electrical energy and able to generate the output power better than the conventional and the lateral electrode structures.

Acknowledgements

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References

[1]. Y. Suzuki, Development of MEMS Energy Harvester with High-Performance Polymer Electrets, in *Proceedings of the 10th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications Power MEMS 2010*, Leuven, December 1, 2010.

[2]. P. D. Mitcheson, E. M. Yeatman, G. K. Rao, A. S. Holmes, T. C. Green, Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices, in *Proc. of the IEEE*, 96, 9, 2008, pp. 1457-1486.

[3]. S. P. Beeby, M. J. Tudor, and N. M. White, Energy harvesting vibration sources for micro systems applications, *Meas. Sci. Technol.*, Vol. 17, 2006, pp. 175-195.

[4]. R. Mialtu, M. Sararoiu, Electret based capacitive MEMS vibration-to-electric energy harvesting, in *Proc. of the International Semiconductor Conference, CAS 2009*, Vol. 1, 12-14 Oct. 2009, pp. 219-222.

[5]. Y. Arakawa, Y. Suzuki, and N. Kasagi, Micro Seismic Power Generator Using Electret Polymer Film, *PowerMEMS 2004,* Kyoto, Japan, pp. 187-190, 2004.

[6]. T. Tsutsumino, Y. Suzuki, N. Kasagi, K. Kashiwagi, and Y. Morizawa, Micro Seismic Electret Generator for Energy Harvesting, in *Proc. of the 5th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications PowerMEMS 2006*, Berkeley, 2006, pp. 279-282.

[7]. H. Okamoto, T. Onuki, K. Mori, H. Kuwano, Improving An Electret Energy Harvester By Redirecting The Electric Field, in *Proc. PowerMEMS,* 2008, pp. 11-14.

[8]. H. W. Lo, Y. C. Tai, Parylene-based electret power generators, *J. Micromech. Microeng.,* Vol. 18, 10, 2008, 104006.

[9]. S. Boisseau, G. Despesse, A. Sylvestre, Optimization of an electret-based energy harvester, *Smart Materials and Structures*, Vol. 19, 7, 2010.

[10]. T. Takahashi, M. Suzuki, T. Hirata, N. Matsushita, R. Yoneya, J. Onishi, T. Nishida, Y. Yoshikawa, S. Aoyagi, Electret energy harvesting based on fringe electrical field change inside trenched ferroelectric, Micro Electro Mechanical Systems (MEMS), in *Proceedings of the IEEE 24th International Conference*, 2011, pp. 1305-1308.

[11]. M. R. Ahmad, M. H. Md Khir, Design, Analysis and Fabrication of Electret-Based Micro-Electromechanical Systems Energy Harvester, 3rd NPC2011, *Universiti Teknologi PETRONAS*, 2011.

[12]. CoventorWare Designer and Analyzer version 2010, http://www.coventor.com

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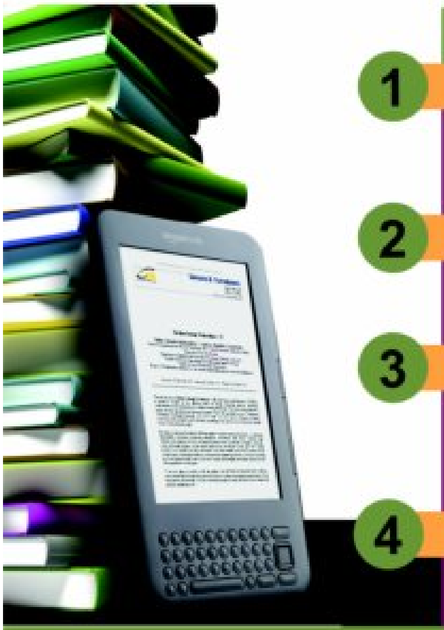

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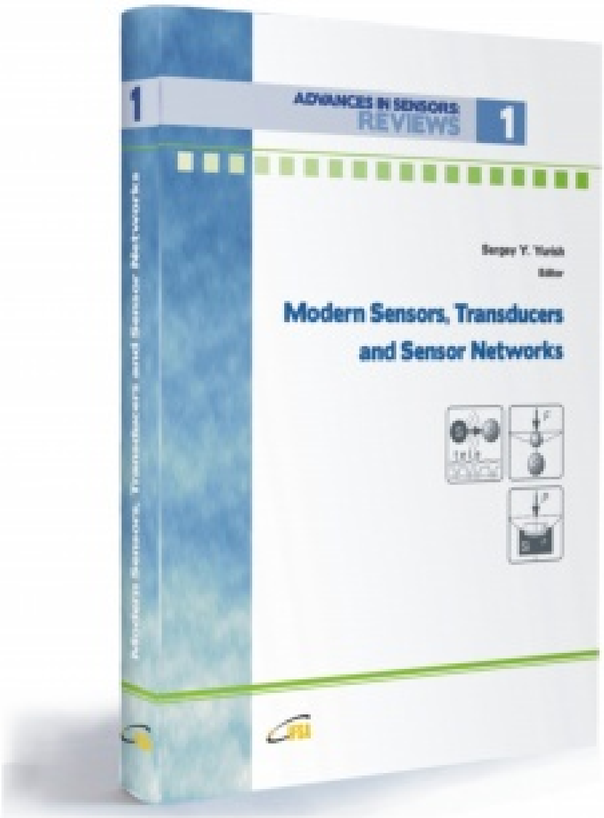
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