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Improved Bandwidth MEMS Dual-Resonant Electromagnetic Energy Harvesting

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Abstract— In this article, analysis of dual-resonant electromagnetic micro generator is performed. Also, output power, bandwidth and performance of dual-resonant systems are discussed. Multi-resonant micro generator exhibits higher bandwidth in comparison with resonant mode structure. The micro generator is designed to convert 1 – 3 Hz heart beat mechanical vibrations to output electrical power. MEMS technology is utilized to construct the device in tiny dimensions. Finite Element Analysis (FEA) software is utilized to determine the mechanical and electromagnetic characteristics of the power harvester. For 2 Hz and 2.1 Hz resonant frequencies, the output power of 0.30568 µW and 0.33746 µW are achieved, respectively. The maximum overall output power is 0.3794 µW. The achieved results illustrate that, the dual-resonant system exhibits better and wider frequency response in comparison with resonant system.

Keywords— Electromagnetic micro generator, dual-resonant, mechanical vibrations, electrical power, MEMS (Micro Electro Mechanical Systems), FEA.

I. INTRODUCTION

Micro generators are suitable replacement for limited lifetime energy sources and batteries. Where, micro power harvester could supply electrical devices such as implantable biomedical devices, wireless sensors, monitoring systems and etc. [1-3]. Hence, desire for energy source substitution is dismissed and maintenance is not required [4-6].

Different techniques could be utilized to improve the frequency response of micro generator. Single resonant system has limited bandwidth. Hence, multi resonant design could develop the bandwidth of system.

In this work, a dual-resonant electromagnetic micro power generator is designed. Two resonant modes are designed to improve the limited bandwidth of single resonant. Cut off frequency of each resonant modes are aligned together to improve the bandwidth. Frequency response of each resonant system compensates each other to achieve higher bandwidth. In resonant mode design, a coil is attached to generator housing and a magnet is connected to frame with a spring. Vibration of housing oscillates the magnet and deviation of magnet flux passing through coil cross section generates output electrical power in terminals of the coil. The proposed dual-resonant device consists of magnet and coil, which are attached to the generator housing with two different suspension system. Consequently, two different resonant frequencies could affect the micro generator and output power is available for two different bandwidths. The resonant frequency and bandwidth of two resonant modes are aligned to satisfy a final improved and desired frequency response.

A novel dual-resonant method is studied to improve the frequency response of the micro generator. The designed dual-resonant system exhibit two different bandwidth, where, output power is available. The attained results illustrate that dual-resonant system exhibits higher bandwidth in comparison with resonant system. Also, MEMS structure is utilized to design the micro power harvester in tiny dimensions and the final device could be used for implantable biomedical systems.

Rest of the paper is organized as follows, Section I contains the introduction. Section II contain the related work of the research. Section III contain the Dual-Resonant Electromagnetic Micro Generator Design and Modelling. Comparisons and discussions are made in section IV. Finally, conclusion is demonstrated in section V.

II. RELATED WORK

Different types of energy conversion methods are used to design micro power generator. These methods are electromagnetic [7-10], piezoelectric [11, 12] and electrostatic [13, 14]. Low internal resistance, high output current, flexible configuration and varied structure are advantages of electromagnetic energy conversion method. Hence, in this study, electromagnetic micro power generator is designed [15, 16].

According to the literature, the most common designed micro generator is resonant mode devices. Resonant mode micro generators could scavenge the mechanical vibrations at specific resonant frequency with limited bandwidth. A little change in mechanical vibration frequency, could affect the performance of the system and results in decrease of output power, significantly. Consequently, modification of bandwidth is required to improve the performance of system and achieve higher output power for different mechanical vibration frequencies. In this article, a new procedure is proposed to increase the limited bandwidth of generator. This method is utilization of multi-resonant system [1, 8]. Multi-resonant configuration could generate output power for different resonant frequencies and bandwidth. Hence, for different frequencies the output power is available and the frequency response is improved.

III. DUAL-RESONANT ELECTROMAGNETIC MICRO GENERATOR DESIGN AND MODELLING

Single resonant micro generator has a specific resonant frequency and limited bandwidth. A new method to improve the frequency response is multi-resonant design. Multi-resonant micro generator could scavenge the mechanical vibrations with different resonant frequencies. In this study, dual-resonant micro generator is designed. The advantages are discussed and comparison with resonant micro generators is made. To design a dual-resonant system, there should be two resonant modes. Electromagnetic micro generator consists of a magnet and a coil. Where, deviation of magnet flux, passing through coil cross section generates output electrical power. To achieve two resonant modes, the magnet and the coil are connected to generator housing utilizing two different springs. Vibration of frame, excites the magnet and the coil at two different frequencies and generates output power. A typical structure for dual-resonant system is shown in Figure 1 [17].

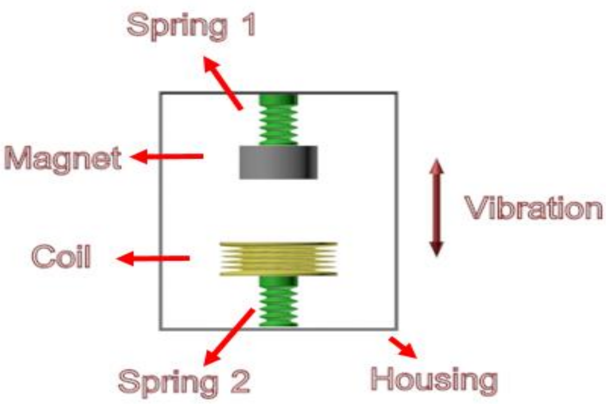


Figure 1. A typical structure of dual-resonant electromagnetic micro generator.

Dual-resonant electromagnetic micro power harvester consists of magnet, coil, housing and two suspension system. Magnet and coil are connected to housing with two different suspension system. Each suspension system is adjusted on different resonant frequencies and bandwidth. Hence, mechanical vibrations at two resonant frequencies and bandwidth could be converted to output electrical power. The resonant frequencies and bandwidth are aligned to have overall desired frequency response. This method improves the bandwidth of the micro generator. The mechanical model of dual-resonant system is demonstrated in Figure 2.

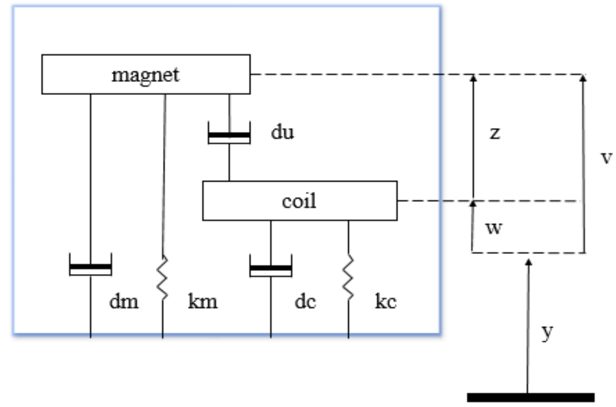


Figure 2. Dual-resonant system modeling.

Where, z is difference between position of magnet and coil, the displacement of frame is denoted as y, v is displacement of magnet to frame and w is displacement of coil to frame. The modeling equations are:

$$m_m\ddot{v}(t) + d_m\dot{v}(t) + d_u\dot{z}(t) + k_m v(t) = -m_m\ddot{y}(t) \quad (1)$$

$$m_c\ddot{w}(t) + d_c\dot{w}(t) - d_u\dot{z}(t) + k_c w(t) = -m_c\ddot{y}(t)$$

z(t) = v(t) – w(t)

where, m_m and m_c are magnet and coil mass, respectively. The equivalent circuit for generator is shown in Figure 3. The demonstrated circuit in Figure 3, shows the model of coil, which is connected to a resistance load (R_{Load}). Also, internal characteristic of coil, which, is composed of EMF voltage source, coil inductance (L) and internal resistance of coil (R_{Coil}) is demonstrated in Figure 3.

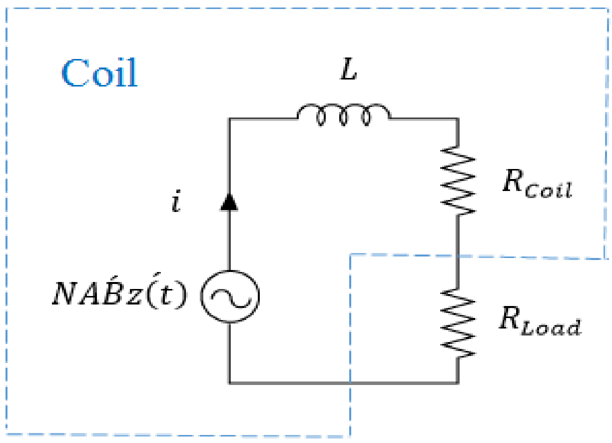


Figure 3. Equivalent circuit of the proposed electromagnetic micro generator.

where, i is current, L is coil inductance, R_{Coil} is coil internal resistance, R_{Load} is load resistance, N is coil turns, A is coil cross section area, $\acute{B} = dB/dz$, B is magnetic field of magnet passing through coil cross section and $\acute{z}(t)$ is derivative of relative displacement of magnet to coil.

The voltage induced in the coil (Electro Motive Force) is $\varepsilon = NA\acute{B}\acute{z}(t)$. Assume, $R = R_{Coil} + R_{Load}$. So, the electrical damping factor could be calculated as:

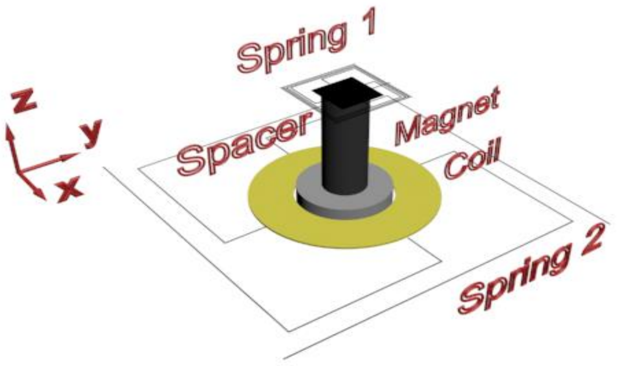
$$d_u = (NA\acute{B})^2/(R + Ls) \tag{2}$$

So, the output power could be calculated as $P \approx V_{load}^2/R_{Load}$. Where, V_{load} is voltage of the resistance load terminals, which is approximately $\varepsilon/2$, where, imaginary part of coil impedance is neglected, and coil internal resistance is equal to load resistance to deliver maximum output power to load.

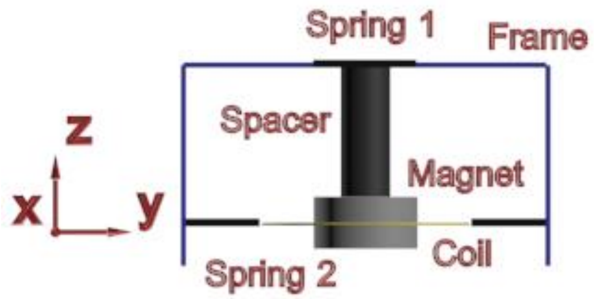
There should be two different resonant modes to design dual-resonant configuration. The dimensions of the micro generator are assumed to be less than few cm. The feature size is about mm or µm. The design procedure is as follows:

- Different structures for coil and magnet are simulated.
- For a specific constant volume, final structure for coil and magnet are achieved.
- Two different suspension systems are simulated for the magnet and the coil.
- The two resonant frequencies are tuned.
- A design is performed to gain maximum mechanical vibration amplitude.

The proposed dual-resonant device is shown in Figure 4. The proposed device consists of magnet, planar coil, spacer, frame and two springs. Two springs as suspension system creates two different resonance frequency for the device. Relative motion of magnet and coil, changes the magnetic flux of magnet passing through coil cross section. Generation of output electrical power is result of magnetic flux variation, which is passing through coil cross section. Resonant frequencies of spring 1 and spring 2 are adjusted on 2 Hz and 2.1 Hz, respectively. At input frequency of 2 Hz, spring 1, spacer and magnet vibrates by means of frame vibration and generates output power. At input frequency of 2.1 Hz, spring 2 and coil oscillates due to frame vibration and generates output power. Hence, input mechanical vibrations at 2 Hz, 2.1 Hz and around it could be converted to output electrical power. Two resonant frequencies and bandwidth are tuned to satisfy the overall improved frequency response.



(a)



(b)

Figure 4. (a) The proposed dual-resonant electromagnetic micro power generator, (b) cross section view of dual-resonant device with frame.

3.1. Mechanical modelling of dual-resonant micro generator

Mechanical model of dual-resonant system consists of two suspension system. Each suspension system is a spring, which suspends magnet and coil, separately. Magnet and spacer hang spring 1 and coil hangs spring 2, as shown in Figure 4. Every spring consists of four folded beam. The design procedure of suspension system is discussed in follow. Firstly, a beam with quarter stiffness of final suspension system is designed. Then, to achieve minimum volume of spring, a folded beam is constructed. To attain high linear vibration amplitude, desired stiffness and required resonant frequency, four folded beam are connected together to build suspension system. A membrane is attached to the folded beams to operate as a plate. So, spacer-magnet connection and coil could be established on each membrane, separately. The spacer creates adequate space for magnet and coil vibration. The maximum attainable vibration amplitude is equal to the spacer height. The resonant frequency for magnet and coil is predicted to be 2 Hz and 2.1 Hz, respectively.

Estimation of resonant frequency is essential to find the output performances. The maximum output power is generated at mechanical resonant frequency of system. Using COMSOL software [18] the resonant frequency of practical device is achieved. The resonant frequency for magnet vibration is 2.0681 Hz as shown in Figure 5. The dimensions could be changed to maintain the resonant frequency between 1 – 3 Hz. Hence, heart beat energy could be scavenged and converted to electrical power [19]. Top view of Spring 1 is shown in Figure 6. The dimensions are shown in Figures 5 and 6: beam width and spacing is 50 µm, beam and membrane thickness is 7.5 µm, membrane width and length is 2 mm, spacer radius is 950 µm, spacer length is 5 mm, magnet radius is 2 mm, and magnet height is 2 mm.

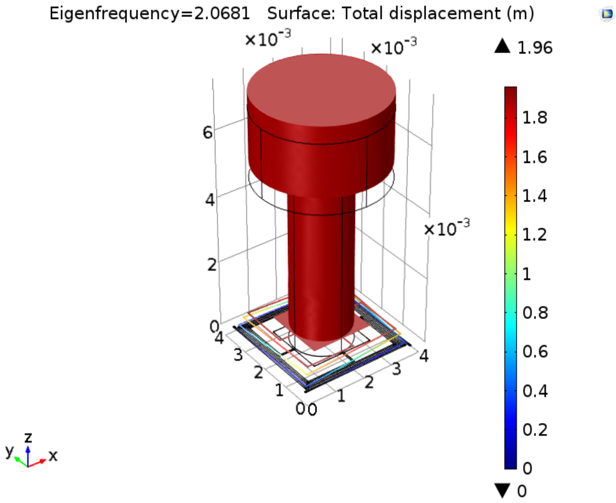


Figure 5. Resonant frequency of the suspension system of the magnet.

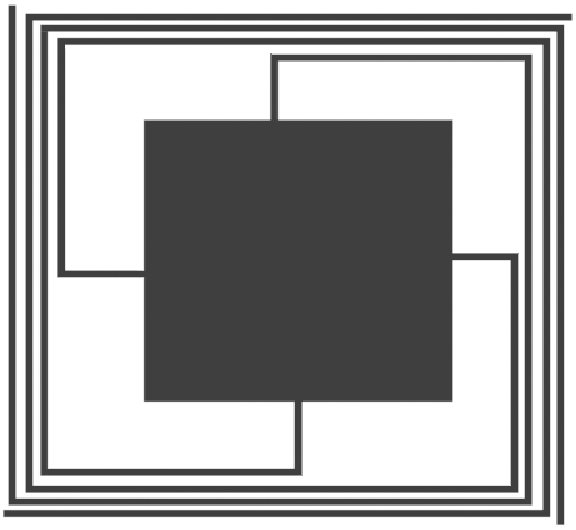


Figure 6. Spring 1.

To satisfy the overall frequency response of the micro generator, coil resonant frequency is tuned 0.1 Hz higher than magnet resonant frequency (2.1 Hz). The resonant frequency for coil vibration is 2.1642 Hz, which is estimated using FEA software COMSOL [18], as shown in Figure 7. Top view of spring 2 is demonstrated in Figure 8. As shown in Figure 7 and 8, folded beam width and thickness are 50 µm and 12 µm, respectively. Inner and outer radius of the plate are 2.1 mm and 4 mm, respectively.

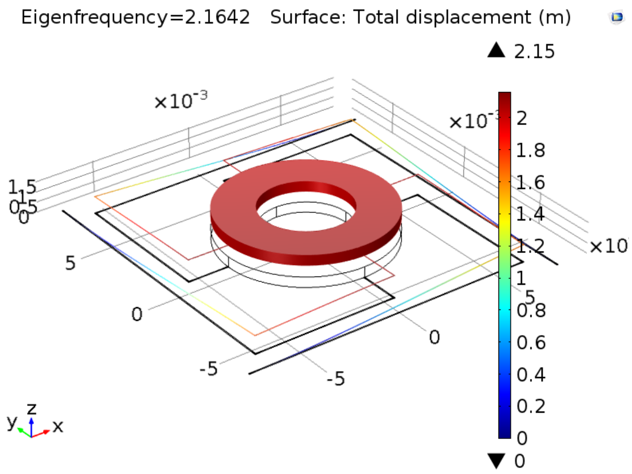


Figure 7. Resonant frequency of the suspension system of the coil.

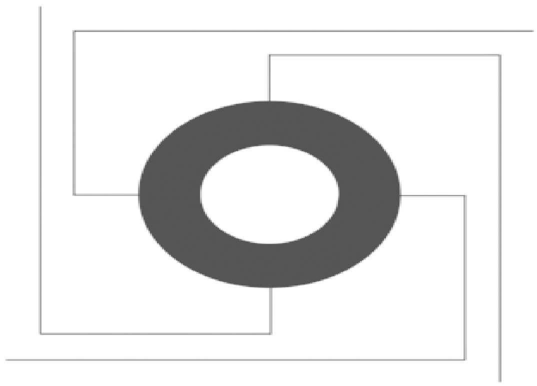


Figure 8. Spring 2.

The planar springs are designed to achieve specific resonant frequency between 1 – 3 Hz. Also, four folded beams are used to have linear motion and high vibration amplitude of about 5 mm. The parameters that is assumed in this section to evaluate the resonant frequency and stiffness of the beam, could be varied. These parameters are beam width, beam length, beam thickness, utilized materials, dimension of magnet, position of magnet, dimension of coil and other properties. The parameters should be adjusted to achieve a specific or optimum resonant frequency and stiffness.

3.2. Electromagnetic modelling of dual-resonant micro generator

Mechanical vibrations are applied in z axis direction of the frame, hence, magnet and coil are oscillated in z axis direction. The proposed electromagnetic structure of dual-resonant system, which consists of magnet and planar coil, is shown in Figure 9. Design parameters are as in follow: coil inner radius is 2.1 mm, coil outer radius is 4 mm, coil turn is 40, magnet radius is 2mm, so air gap is maintained 0.1 mm, magnet height is 2 mm, vibration amplitude is 5 mm, load resistance and internal resistance of the planar coil is 5 Ω, for coil, copper track width and space width is 25 µm, track height is 102 µm. Dimensions of the planar coil are shown in Figure 10.

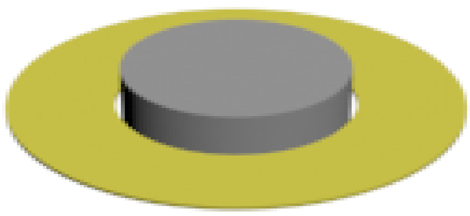


Figure 9. Electromagnetic structure of dual-resonant micro generator.

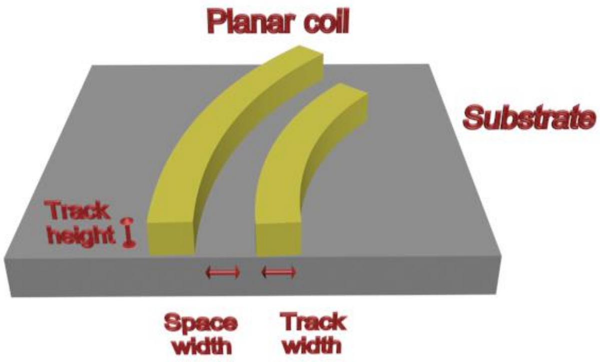


Figure 10. Planar coil dimensions.

For calculation of the output power, an initial position is assigned to the magnet or coil and then the magnet or coil is released to vibrate freely. Vibration amplitude of magnet to frame or coil to frame is equal to initial position. For one cycle of vibration, the output power is calculated. The output power is estimated using Flux software [20]. The simulated output power for magnet vibration at 2 Hz is 0.30568 µW and for coil vibration at 2.1 Hz is 0.33746 µW.

3.3. Output performance of dual-resonant micro generator

Two resonant mode generators are aligned together to improve the overall bandwidth. Two resonant frequencies are 2 Hz and 2.1 Hz. The bandwidths are aligned to compensate each other. Cut off frequencies of each resonant system are approximately tuned on the same frequency, to achieve a higher final bandwidth. The overall frequency response is combination of two single resonant modes.

Frequency response of dual-resonant system is demonstrated in Figure 11. In Figure 11, for resonant mode of the magnet at 2 Hz, the output power is shown with green line. For resonant mode of the planar coil at 2.1 Hz, the output power is demonstrated with blue line. The overall output power is sum of two resonant modes, which is shown with red line in Figure 11. The resonant frequency and bandwidth of each resonant system could be varied to cover a specific or desired bandwidth. The overall frequency response is wider than each single resonant modes. The results exhibits that, dual-resonant micro generator has higher and improved bandwidth.

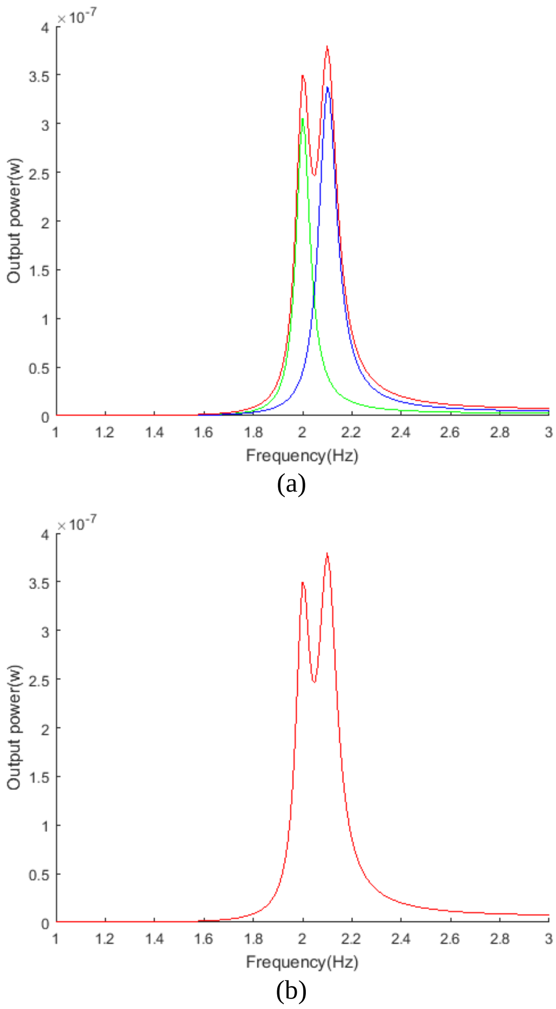


Figure 11. Frequency response of dual-resonant micro generator; (a) with two resonators, (b) energy harvesting bandwidth.

IV. COMPARISONS AND DISCUSSIONS

In this article, dual-resonant electromagnetic energy harvesting systems is designed and comparisons are made. As mentioned, resonant mode micro generator has specific resonant frequency and bandwidth. Limited bandwidth is the main disadvantage of resonant mode system. To overcome the disadvantage, multi-resonant system is recommended, where, different resonant frequency and bandwidths compensates each other. The achieved multi-resonant system has higher bandwidth and high output power at different excitation frequencies. The achieved results in this work, illustrates that dual-resonant system has better performances in comparison with resonant micro generator. The maximum achieved output power is 0.3794 µW at 2.1 Hz. Also, the bandwidth is improved to approximately 0.3 Hz.

In comparison with prior work, Mallick et al. [21] presents an electromagnetic energy harvesting generator with multi frequency design, where the output power is reported to be 0.22 µW. In the proposed work, at input vibration frequency of 2.1 Hz, the overall output power is 0.3794 µW, where, higher than reported in the literature.

The micro generator is designed in tiny dimension utilizing MEMS technology. MEMS supports to design the electromagnetic micro generator in minimum volume. Hence, the output power density is maximized. This makes the designed device to be suitable for implantable biomedical devices.

V. CONCLUSION

In this article, a novel configuration for electromagnetic micro power generator is proposed to improve frequency response and bandwidth of the system. The method is dual-resonant system. This method could improve the frequency response and bandwidth of the device. The obtained results, demonstrate that dual-resonant micro power harvester has higher bandwidth in comparison with resonant design. The maximum achieved output power is 0.3794 µW at 2.1 Hz. Also, the bandwidth is improved to approximately 0.3 Hz. To achieve the optimum volume for implementation of the power harvester, the device is designed in MEMS dimensions. This method could generate electrical power to supply different types of electronic devices and systems.

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