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Original Article

Area Optimized Spiral Cantilever Array for Ultra Low Power Piezoelectric MEMS Energy Harvesting

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Abstract - *This work presents an approach to embed an array of spiral cantilevers with different resonant frequencies on a silicon substrate layer, with all four sides fixed. The effect of four-square spiral cantilevers on modes is discussed when connected in series and parallel combinations to form an array. For geometric optimization, up to 9 spiral element harvesters are analyzed, and the maximum harvested power is achieved by connecting four spiral elements. The total harvested power of 3.5 µW is obtained over the frequency band 264 Hz to 272 Hz. The normalized areal and volumetric power density were found to be 5.17×10−3 µW/mm2• g2• Hz and 1.15 µW/mm3• g2• Hz, respectively.*

Keywords - *Cantilever, Energy harvester, MEMS, Piezoelectric, Power Density, Spiral Array.*

1. Introduction

Over the last few decades, the use of renewable macro energy harvesting systems, such as solar and wind energy, has become increasingly prevalent [1]. Mechanical vibration is one of the most frequent types of ambient energy found in civil structures, machines, and the human body, among other places. Several transduction mechanisms can be used to convert mechanical vibration into usable electrical energy. So far, electrostatic, electromagnetic, and piezoelectric-based harvesters have been realized for these purposes [2]. Nowadays, with the recent breakthroughs in ultra-low-power electronics, piezoelectric- based energy harvesters have received huge attention in the research community. Piezoelectric-based Micro-Electromechanical systems (MEMS) harvesters are considered the simplest solution in current MEMS technology, in which input environmental vibrations are directly converted into an output electrical voltage using piezoelectric materials [3-5].

The majority of documented piezoelectric energy harvesters employ a cantilever beam as a host structure and ambient vibration as a source. Additionally, the piezoelectric energy harvester does not require any external electrical input. The harvester's resonant frequency should match the surroundings' vibrational frequency in order to scavenge the maximum usable electrical power from that vibrating environment. The resonant frequency of the cantilever is frequently calibrated by introducing a proof mass at the tip [6]. Currently, to enhance the harvested power density at lower frequencies, substantial research is being conducted on different architectural designs and piezoelectric materials using various optimization techniques [7-9]. A piezoelectric cantilever-based harvester with a proof mass, operating at a Single Degree Of Freedom (SDOF), is modeled as a spring-mass-damper system. Although such a basic mechanical construction simplifies fabrication, it has a relatively limited operational bandwidth. Any slight change in the environmental vibration frequency results in a degradation of the harvester's efficiency [10]. An optimum solution to address the challenge of narrow bandwidth is to enlarge the operational bandwidth by using multiple cantilevers with different frequencies arranged in an array [11]. Each cantilever in the array can generate electrical power at its resonant frequency. The total harvested power is the sum of the outputs from a series or parallel connection of each harvester, with a wider bandwidth. As a result, MEMS energy harvesters must be able to operate over a wide frequency range while maintaining a high level of areal/volumetric power density.

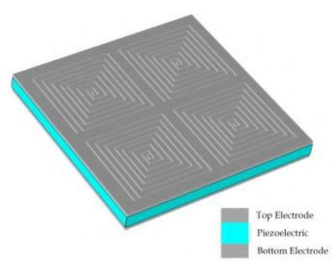
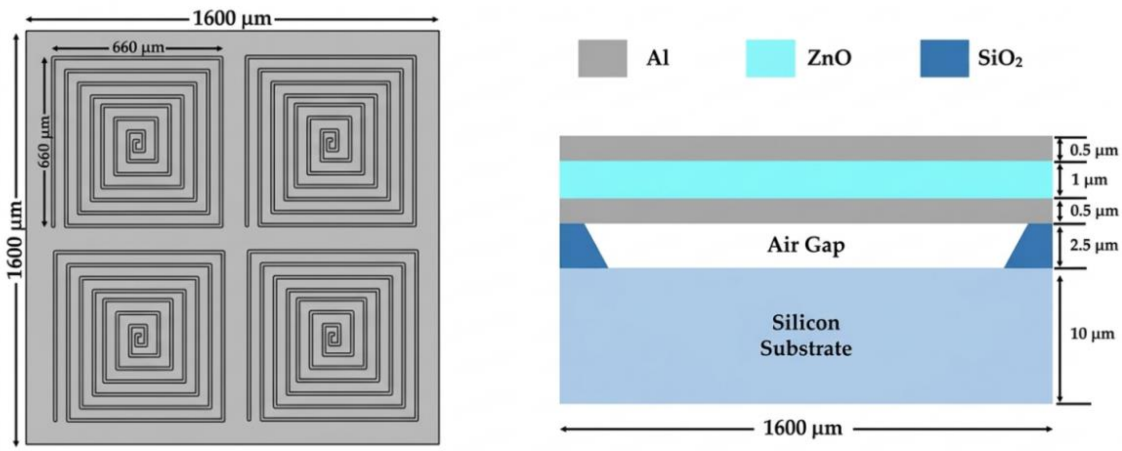


Fig. 1 Proposed 3D schematic of spiral array energy harvester



(a) (b)

Fig. 2 Top and side view of the proposed spiral array energy harvester

Various approaches to enhance the efficiency of broadband piezoelectric harvesters have been proposed to meet the power requirements of low-power electronic applications, such as wireless sensor nodes, wearable sensors, and implantable devices.

A simple spring-shaped piezoelectric energy harvester based on a binder clip is reported by Wu et al. [12]. However, the volume of these harvesters is increased by introducing a larger number of piezoelectric elements. A nonlinear approach is also introduced in several reported structures to broaden the bandwidth of the harvesters.

Ahn et al. [13] presented a piezoelectric harvester with a ball-shaped tip mass, and Huang et al. [14] studied performance improvements achieved by using magnetic force to achieve high-order stiffness. These nonlinear harvesters are mostly built with bulkier magnets and are incompatible with the designs of MEMS-based harvesters. A few research studies based on different-shaped macroscale cantilever designs have been proposed in recent times. Liu et al. [15] reported a d_{31} mode S-shaped unimorph energy harvester, which scavenges power upto 1.117 nW at 27.4 Hz.

Additionally, several studies have documented various forms of cantilevers, such as rectangular, trapezoidal, and quadrilateral, as well as their optimization methodologies [16-18]. Recently, a spiral-shaped unimorph energy harvester by Song et al. [19] and an Archimedean bimorph energy harvester by Piyarathna et al. [20] have been reported. These harvesters outperform all other non-conventional MEMS piezoelectric energy harvesters at lower frequencies. Moreover, these harvesters operate at multimodal frequencies, and their frequency bandwidth can be increased by using an array of these designs. In that context, the harvester proposed in this work is the array of square spiral cantilevers based on a piezoelectric energy harvester with improved normalized power density.

2. Proposed Energy Harvester Design

The array of four spiral cantilever elements based energy harvester is reported in the work. The total harvested power scavenge went through the normalization by the square of input acceleration, resonant frequency, active volume, and area, denoted as “Normalized Volumetric/Areal Power Density (NVPD/NAPD)”. Energy harvesters that were previously available either had a larger power output or a lower frequency of operation, depending upon device dimension and material. The precise demand, however, is for high power density at ultralow resonant frequency. The effective method for achieving this demand is suggested in the work.

Figure 1 shows a proposed four-element spiral array-based energy harvester. A unimorph square plate of 1600 µm x 1600 µm using the layers of Zinc Oxide (ZnO) sandwiched between the two Aluminum (Al) electrodes is designed. A square spiral cut of 0.1 µm is carved on the plate to form a fixed-free spiral beam. Each element of the square spiral has seven turns and exhibits an areal dimension of 660 µm x 660 µm as shown in Figure 2 (a). Figure 2 (b) shows the complete harvester design grown over the silicon substrate layer with an air gap in the deposited oxide layer. All the side surfaces are kept fixed, and an input vibration of 1g is applied to the entire geometry. The displacement, stress, strains, and electric potential for different modes are thoroughly investigated through simulation.

3. Analytical Study and Model Simulation

A 3D model of the harvester with a different spiral element is designed using COMSOL Multiphysics 5.3a MEMS CAD tool. The three layers of top and bottom electrode with piezoelectric material are deposited over the substrate layer, and a spiral cut is made on the layers to form the cantilever structure. For geometrical optimization, the harvester array of 1, 2, 4, 6, and 9 spiral elements is analyzed. All the boundary and initial conditions are kept zero, and a free tetrahedral mesh is applied to the domains. Firstly, eigenfrequencies of different mode shapes are estimated through simulation. As shown in Figure 3, the first eigen frequency of the harvester when either of the elements S1, S2, S3, and S4 is ON was obtained to be 264 Hz, 266 Hz, 270 Hz, and 272 Hz, respectively. The displacement on the cantilever is increasing linearly with a minimum at the fixed end and a maximum at the free end. Based on varying input acceleration, the stress is induced over the harvester design.

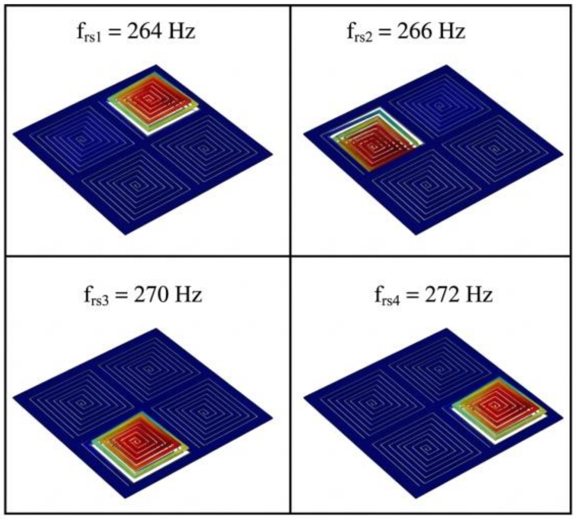


Fig. 3 FEM simulation result obtained for the first eigen mode when either of the spirals is switched ON

The stress, in turn, results in the volumetric strain and electric potential across the top electrode of the harvester as given in Table 1. The first eigen mode of each harvester in the array exhibits a minimum resonant frequency, maximum stress, and strain.

The maximum performance is achieved for the seven turns of the spiral harvester. Further increase in the turns will yield the dominance of the torsional mode in the beam and decrease the output harvested power. The charges that appear on the top electrode produce an electric field, which in turn allows the charges present in the electrode to be free.

Table 1. Stress and Strain across the harvester when any of the cantilevers is ON

Elements	Maximum Stress (x 10^7 N/m^2)	Volumetric Strain (x 10^{-5})
S1	14	2.5
S2	12	1.9
S3	5	0.8
S4	1	0.1

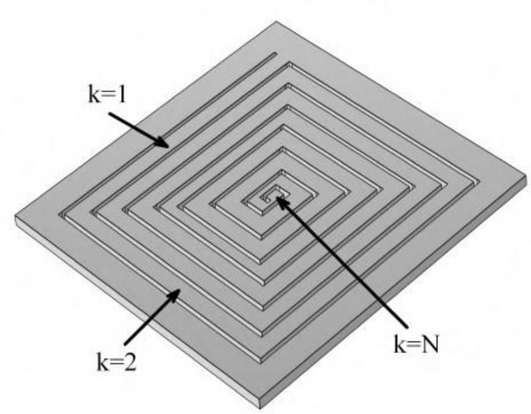
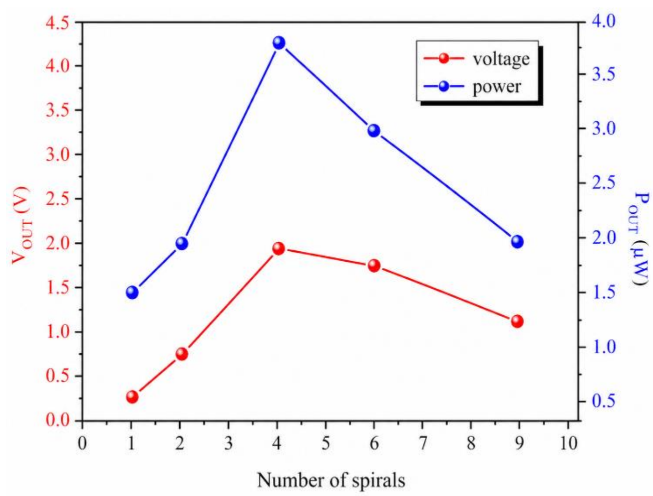
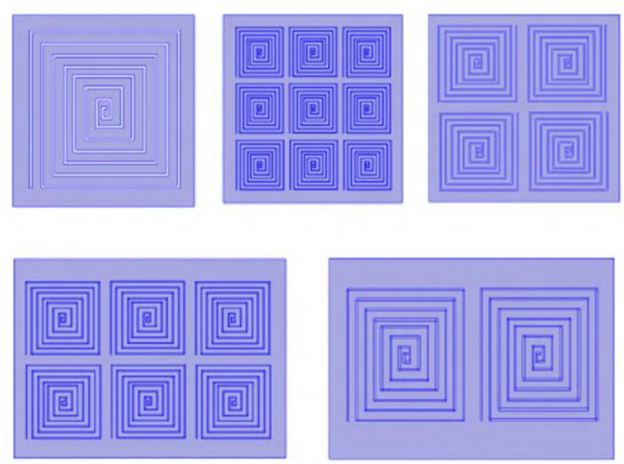


Fig. 4 Beam arrangements from fixed (k = 1) to tip of the last one (k = N) free to move



(a)



(b)

Fig. 5 Harvested voltage and power with variation in the number of spiral elements

The theoretical analysis of the harvester is done with the use of a lumped parameter model expressed in [21, 22]. The structure of a multibeam is divided into N single beams, where each beam's end is connected to the starting point of the next beam, as shown in Figure 4. The total output power P_{OUT} on a resistive load (R_L) is given by

$$P_{OUT} = \frac{V_{OUT\,(TOTAL)}^2}{2R_L} \quad (1)$$

Where

$$V_{OUT\,(TOTAL)} = \sum_{n=1}^{N} V_{OUT(n)} \quad (2)$$

and n=1,2,3, and 4 (for this work)

$$V_{OUT(n)} = \frac{\ddot{Y}\iota x_b \kappa \omega_b M_t}{(k_t + ic_t\omega_b - \omega_b^2 M_t)\left(\frac{1}{R_L} + \omega_b C_e\right) + i\omega_b \chi\kappa} \quad (3)$$

The base displacement and frequency are denoted as x_b and ω_b. c_t represents equivalent viscous damping, k_t is equivalent stiffness, M_t is equivalent mass, χ is the mechanical coupling constant, κ is the electrical coupling constant, and C_e is electrode capacitance, which are defined as

$$\chi = -\sum_{K=1}^{N} \frac{E_{11} d_{31} b}{2h_p} (h_c^2 - h_b^2)\left[\phi_K' \Big|_{L_1}^{L_2} - \phi_K' \Big|_{L_2}^{L_3}\right]$$

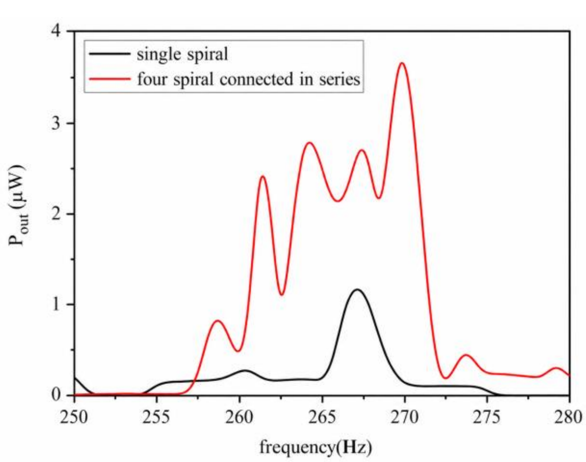
$$\kappa = -\sum_{K=1}^{N} E_{11} d_{31} b h_{pc} (h_c^2 - h_b^2)\left[\phi_K' \Big|_{L_1}^{L_2} - \phi_K' \Big|_{L_2}^{L_3}\right]$$

$$C_e = \sum_{K=1}^{N} \frac{\varepsilon_{33}^S b L_k}{h_p}$$

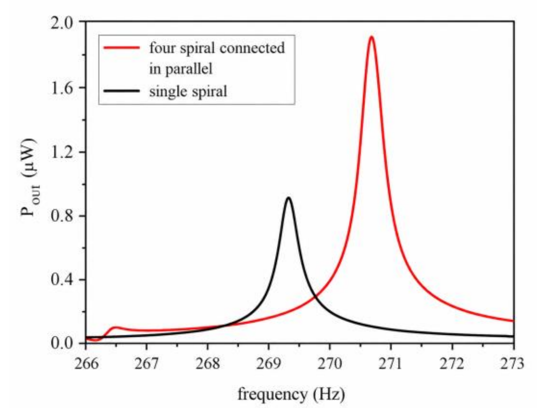
where N represents the total number of beam segments, E_{11} is the elastic modulus, φ is the normalized mode, h_c, h_b, and h_{pc} are the distances from the neutral axis to the top, bottom, and center of the piezoelectric layer, L_1, L_2, and L_3 are the locations of boundaries of the electrode.

4. Results and Discussions

In this work, the performance of an array with four square spirals has been analyzed. The harvester consists of seven square spiral turns, which are connected in series or parallel using an aluminum electrode that sandwiches the ZnO material.



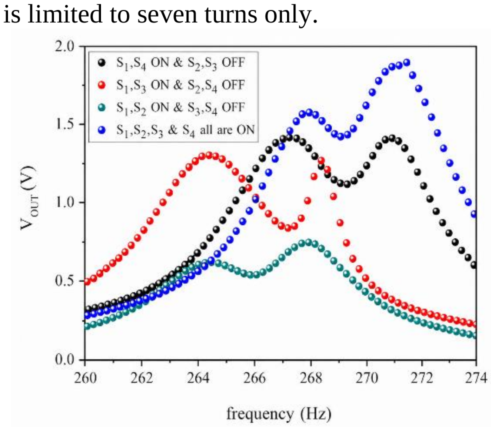
(a)



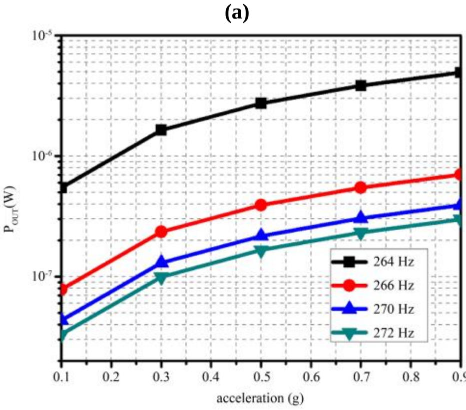
(b)

Fig. 6 (a) Harvested output power dependence on frequency for a single and series-connected four-spiral harvester (b) for a single and parallel-connected four-spiral harvester

The top and bottom aluminum electrodes are connected using the electrical circuit physics of COMSOL Multiphysics. In FEM simulation, firstly, an investigation of eigen frequency is performed to estimate the resonant frequency of each element of the four-spiral array harvester. The frequency domain analysis of the harvester reveals that on increasing the number of turns beyond seven, the resonant frequency of the single element increases significantly, and hence the proposed design is limited to seven turns only.

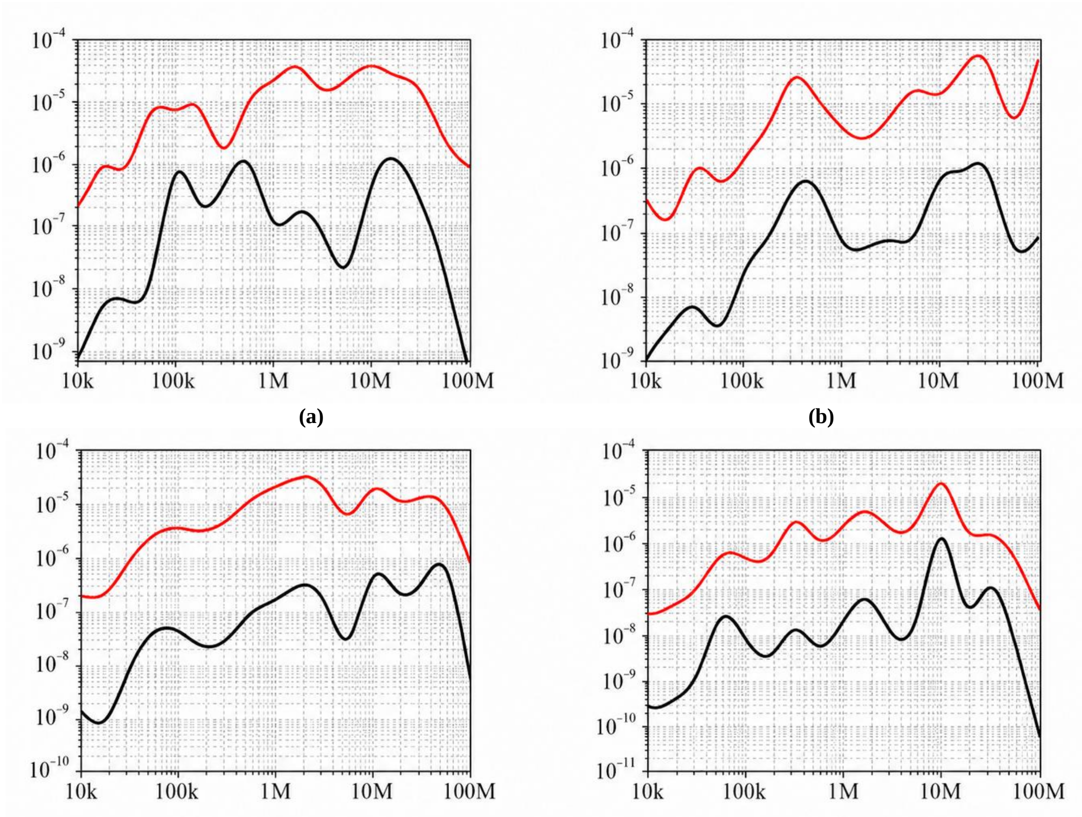


(a)



(b)

Fig. 7 (a) Frequency band shifting by connecting a spiral element in mixed patterns (b) Output power for varying input acceleration and load resistances



(a) (b)

(c) (d)

Fig. 8 Output electrical and Input mechanical power with varying load when individual element (a) S_1, (b) S_2, (c) S_3, (d) S_4 is ON.

In order to obtain maximum harvested power, the optimized value of load resistance is estimated through simulation. The performance comparison of 1, 2, 4, 6, and 9 spiral elements with equal geometrical area, a four-element array harvester is made, and it is found that the maximum harvested voltage and power are obtained at the four-element array harvester, as can be seen in Figure 5. As the element number is increased above four, the eigen mode shape of one element dominantly affects the neighboring spiral element and severely decreases the output voltage.

The characteristic of an array of multiple spiral elements is examined step by step through simulation. Firstly, the performance of a series-connected spiral element is analyzed. Figure 6(a) and (b) shows the dependence of output harvested power on driving vibration frequency for a harvester with a single spiral element and four spiral elements. In comparison to a single spiral harvester, the output power for a four-spiral harvester increased by nearly four times with a wider bandwidth. The total output power with an optimum load of 5 MΩ connected to it is obtained to be 3.5 µW, having a wider bandwidth from (266, 268) Hz to (264, 272) Hz. The performance of the parallel-connected elements has also been analyzed. It is found that due to a change in the electrical boundary condition, the resonant frequency gets shifted by nearly 2 Hz as the number of spirals is changed from 1 to 4.

Figure 7(a) shows that the frequency band gets shifted as the spirals are connected in a mixed pattern. The results show that the harvesting capability increases with a wider bandwidth by connecting the four spiral elements, and the maximum voltage is obtained when all S1, S2, S3, and S4 are ON. The performance of the proposed spiral array harvester is also investigated for different input accelerations. As the Input vibrating acceleration increases, the harvested power for each spiral element also increases, as shown in Figure 7(b). Figure 8 shows the input mechanical and output electrical power for all four spiral elements with varying load resistance. For the respective optimum load resistance of the spiral elements, the power conversion efficiencies are obtained to 21% for S1, 19.6% for S2, 19.1% for S3, and 17.8% for S4.

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5. Conclusion

An array of four square spiral elements cantilever is investigated for realizing a low-power energy harvester. The eigen mode shapes with stress and strain distribution were investigated through an FEM simulation environment. By connecting the spiral elements in both serial and parallel, the performance of the proposed array harvester is analyzed. The first eigen mode frequency of S1, S2, S3, and S4 is found to be 264 Hz, 266 Hz, 270 Hz, and 272 Hz, respectively, with a wider bandwidth of 10Hz. It is also observed that the harvested voltage decreases as the number of spirals is increased beyond 4. The NAPD and NVPD were found to be 5.17×10^{-3} μW/mm²• g²• Hz and 1.15 μW/mm³•g² Hz. The total output power of 3.5 μW is harvested when the spirals are connected in series, which is sufficient to provide add-on power to the microelectronic devices in wireless sensor networks.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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