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A Novel Double Layer Cantilevers Harvester for Vibration Energy

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Abstract

This paper reported a double layer cantilever harvester powered for vibration energy. A space layer between the PZT beam and the support silicon beam is existed, leading to the double layer cantilever structure. Such structure can allow the more strain generated by the piezoelectric layer due to the existing of space layer, and the output voltage is further increased. The formula of output voltage is then derived from the piezoelectric effect equation and vibration model. And the formula verifies the relationship of voltage and structure parameter. And the simulation in micrometer lever is used to discuss the relationship. Finally, the prototype is assembled and measured to verify the feature of the device. Experimentally, the 3.8V output voltage and 16.9uW output power is acquired.

Keywords: *Energy harvester, Piezoelectric effect, Double layer cantilever, Space layer*

1. Introduction

Wireless sensor network is a special peer-to-peer network with some advantage such as good concealment, fast deployment, and high tolerance [1, 2]. The network is consisted of large amount sensor nods with the feature of tiny dimension, small power and low cost. To delay the nods lifetime, the nods directed a large segment of energy research towards seeking alternative sources to power and maintain them. As a candidate, the vibration energy is a popular choice due to its pervasive existence [3-5]. Because of small size, low power consumption (milliwatt level), low unit cost, and the possibility of circuits' integration, micro-piezoelectric vibration energy harvesting is regarded as one of the promising device to power for wireless network nodes [6]. Lefeuvre Elie, *et al.,* discussed the relation between the charge, volume and frequency, and the result showed that the charge increases in direct proportion to the device volume [7]. Jing-Quan Liu, *et al.,* prepared the PZT film harvester array with MEMS technology to improve the frequency range and output power [8]. The harvester can generate the 3.98μW power and can load the resistor and supply the DC direct current. Jeong, *et al.,* reported a two-layered piezoelectric bender device for micro-power generator [9]. Their result showed that the inherit frequency of device decrease in the decrease of top piezoelectric layer, which provide a feasible solution to improve the narrow frequency response of sing linear cantilever energy harvester.

To improve the device efficiency and response band wind, some native structure is becoming the hot point due to the most current research focus on the single linear cantilever structure. Erturk, *et al.*, reported the L shape cantilever to brand the response frequency which changes the cantilever geometry structure to decrease the difference of first two order frequency [10]. Roundy, *et al.*, used the triangle shape to replace the rectangle to enhance the

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device performance, and the output power can increase 30% [11]. KOK, *et al.*, prepared a free standing thick film piezoelectric energy harvester. Different from the mutil-layer cantilever with support structure, the free standing harvester just include the PZT thick film and the Ag/Pd electrode layer, which remove the support layer's restrict and provide the PZT material's freedom [12].

This paper design a double layer cantilever harvester powered for vibration energy. The structure is composed of two bottom support beam and a top piezoelectric beam separated by a space layer, *i.e.*, gap. The existence of gap helps to increase strain generated by the piezoelectric layer due to the piezoelectric layer having the larger bending amplitude without the less restrict from the support beam. When the force is applied, the device vibrates and the piezoelectric beam can generate the large strain, and the device structure is shown in Figure 1. To achieve more accurate analysis, a model based on the spring-mass vibrating system is, above all, established in this paper. Based on this model, we select the right bending mode for the formulas of spring constant, resonant frequency, shape function, and design criterion. And the characteristic of double layer cantilever is also discussed. This model is verified by discrete component model and experiments afterwards.

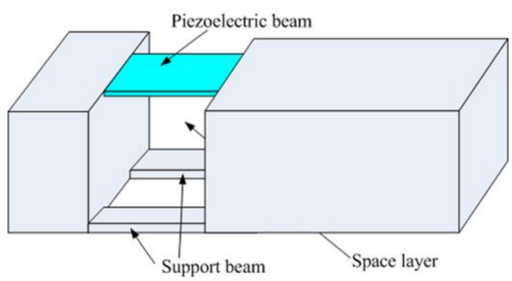

Figure 1. Structure of Double Layer Cantilever Harvester

2. Modeling and Analysis

The energy harvester convert the mechanical strain of piezoelectric layer generated the mechanical strain due to the forced vibration into the electricity output. Neglected the structure of double layer cantilever harvester, the "spring-damper-mass" vibrating system proposed by Williams and Yates is considered to research the electrical characteristic. The structure of vibrating structure including mass and spring is shown in Figure 2.

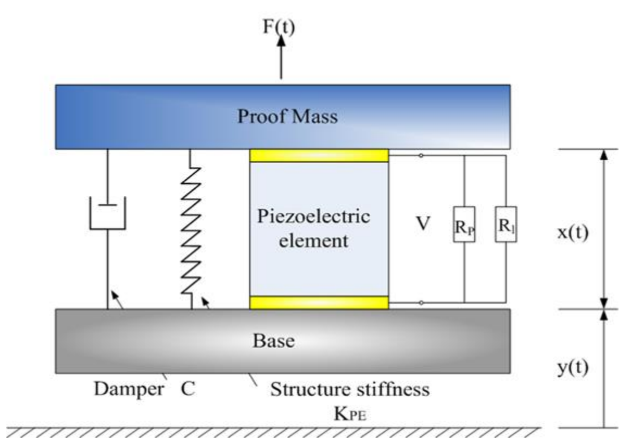

Figure 2. Model of a Vibrating Structure Including a Piezoelectric Element

In the Figure 2, m is the magnitude of proof mass, x is the relative displacement of proof mass, y is the input displacement of ambient vibration, C is the overall damping coefficient, K_{PE} is the system rigidity, ω_n is the inherent frequency. $M\ddot{y}(t)$ is the applied force including the restoring force introduced by piezoelectric layer, restoring force introduced by spring, and the viscous force of damp. Finally the input displacement of ambient vibration is given by $y = A\sin(\omega t)$, where ω is ambient vibration frequency. R_l is the load resistor, R_P is the leakage resistance of piezoelectric layer and paralleled connection with R_l. V(t) is the voltage across the resistor, and αV is the Piezoelectric coupling force introduced by αV. The formula is express as:

$$M\ddot{x}(t) + C\dot{x}(t) + K_{PE}x(t) + \alpha V = -M\ddot{y}(t) \qquad (1)$$

In this paper the d_{31} mode is selected, that is, the electric field is along with the 3 direction, and that of mechanical strain and stress is 1 direction. As a result, the equation is expressed as

$$\begin{cases} \sigma_1 = c_{31}^E \delta_1 - d_{31} c_{31}^E E_3 \\ D_3 = d_{31} c_{31}^E \delta_1 + \varepsilon_{33}^s E_3 \end{cases} \qquad (2)$$

where, σ_1 is the mechanical stress, δ_1 is the mechanical strain, c_{31}^E is the Young's modulus of piezoelectric material, E_3 is the electric field intensity, D_3 is the electric displacement, ε_{33}^s is the dielectric constant of piezoelectric material, d_{31} is the strain constant.

Use the Eq. (1) and Eq. (2), the formula can be expressed as:

$$\begin{cases} K_{PE}x(t) + \alpha V = c_{31}^E A k_b \dfrac{x(t)}{t_p} + d_{31} c_{31}^E A \dfrac{V(t)}{t_p} \\ i(t) - d_{31} c_{31}^E A k_b \dot{x}(t) + \varepsilon_{33}^s \dfrac{A}{t_p} \dot{V}(t) = 0 \end{cases} \qquad (3)$$

where A is the effective area of piezoelectric layer, and k_b is the constant of displacement and strain $\delta_1 = k_b x(t)$.

With the Laplace transform, the Eq. (3) can further expressed as

$$|V| = \frac{\dfrac{d_{31} c_{31}^E t_p k_b}{\varepsilon_{33}^s}}{\sqrt{\left(2\xi_m \omega_n{}^2\right)^2 + \left(\dfrac{d_{31}^2 c_{31}^E t_p}{\varepsilon_{33}^s}\omega_n^2 + \dfrac{2\xi_m \omega_n t_p}{R_l \varepsilon_{33}^s A}\right)^2}} Y \qquad (4)$$

where, ξ_m is the system damp ratio, ω_n is the frequency of system, Y is the input acceleration. Furthermore, the optimum resistance R_l is derived:

$$R_l = \frac{2\xi_m t_p}{\varepsilon_{33}^s A \omega_n \sqrt{4\xi_m^2 + \left(\dfrac{d_{31}^2 c_{31}^E t_p}{\varepsilon_{33}^s}\right)^2}} \qquad (5)$$

Based on the Eq. (4), the output voltage is inversely proportional to the device frequency, and is direct proportion to the parameter k_b. Furthermore the geometric parameters of device can also affect the voltage and power. Since k_b is the constant between the proof mass displacement and strain generated by the piezoelectric layer, the constant k_b should be derived.

In this paper, the bending of mass is neglected, and to simplify the analysis, the rigid boundary condition for both PZT beam and support beams is assumed. The neutral plane coordinate is firstly defined. Supposed the origin coordinate locate the middle of device, Z_1

and Z_2 are the middle planes coordinates of the bottom and top beams respectively, and Z_C is the neutral plane. Based on the static's theory, the neutral plane coordinate Zc of double layer beam can be expressed as:

$$Z_c = \frac{E_1 A_1 Z_1 + E_2 A_2 Z_2}{E_1 A_1 + E_2 A_2} \quad (6)$$

Here, E_1, E_2, A_1 and A_2 are respectively defined as the Young modulus and cross-sectional area of bottom beam and top beam. A_1 is equal to the product of width w_1 and thick t_1 of bottom beam. A_2 is the product of width w_2 and thick t_2 of top beam. Thus, the distance between the middle of top beam and neutral plane d_1, and the middle of support beams and neutral plane d_2, can be expressed as:

$$\begin{cases} d_1 = \dfrac{E_2 A_2 (Z_2 - Z_1)}{E_1 A_1 + E_2 A_2} \\ d_2 = \dfrac{E_1 A_1 (Z_2 - Z_1)}{E_1 A_1 + E_2 A_2} \end{cases} \quad (7)$$

In practice, we can observe two deformation modes: rotational movement and translational movement. For the rotational movement, the movement can be referred to the pure bending, and the cantilever rotate at the free end. From the theorem of multilayer structure cantilever, rotary inertia of parallel axis is obtained by $I_R = I_i + A_i (d_i)^2$. The bending rigidities of rotational movement can be expressed as $I_R = I_1 + A_1 d_1^2 + I_2 + A_2 d_2^2$, and I_i is rotary inertia of the i layer beam, d_i is the distance of the i layer beam to neutral plane.The bending angle is θ, and the shear force F_R is zero, bending moment is can be expressed as $2M_R = ma(l + L)$,and l is the length of piezoelectric beam and support beams, L is the length of proof mass.

For the translational movement, the mass remains in horizontal direction after deforming, this means the force experienced by the beam include both the shear force and bending moment. Since the shape of proof mass can't ignore, the beam is defined the shear beam with two ends fixed. Thus, the shear force is constant, that is $F_T = ma$. And the bending moment is a linear function of the horizontal position, $2M_T = ma(2x - l)$, at the middle of the beam the bending moment is zero.

Thus the total bending moment at the X end is $2M = ma(2l + L - 2x)$.

Thus the average stress of effective area of piezoelectric layer can be expressed as:

$$\sigma(x) = -\frac{ma(l + \frac{L}{2} - x) d_2}{I} \quad (8)$$

The strain can be expressed as:

$$\delta(x) = -\frac{ma(l + \frac{L}{2} - x) d_2}{EI} \quad (9)$$

Based on the Euler-Bernoulli equation,

$$\frac{d^2 w(x)}{dx^2} = \frac{M(x)}{EI} \quad (10)$$

Use the equation of (6),(8) and (8), k_b can be expressed as:

$$k_b = \frac{6 L d_2}{(4l + 3L) l^2} \quad (11)$$

Based on the Eq. (4) and Eq. (11), a conclusion can be derived that the constant k_b is inversely proportional to the length of cantilever, and is direct proportion to the gap d_2 , that is, the voltage V is direct proportion to the gap d_2 .

3. Optimum Design

To obtain the better performance, some parameters of suspended beam structure should be considered, especially in MEMS scale. The Figure 3 shows the relationship between output voltage and the cantilever length and the proof mass length. The voltage is range from 2 mV to 42 mV. And the length of proof mass is from 250 um to 400 um and that of double layer beam of 10 um to 160um, respectively. As shown in Figure 3, the smaller thickness of support beam can lead to the higher voltage, when the value is larger, the voltage has an increase with the increase of the thickness of proof mass.

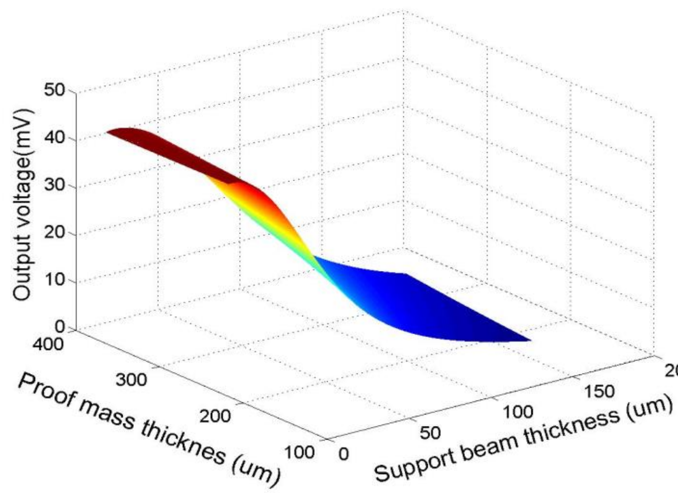

Figure 3. Relationship between Voltage and Thickness

Assumed the fixing value of support beam 100μm, the thickness ratio of proof mass T to support beam is from 2 to 4, a increasing relationship is also can be observed, shown in Figure 4. Thus, a conclusion can be derived that the voltage of suspended beam structure is affected by the thickness of proof mass and the support beam. We also can conclude that the larger gap between the top beam and support beam helps generate more voltage.

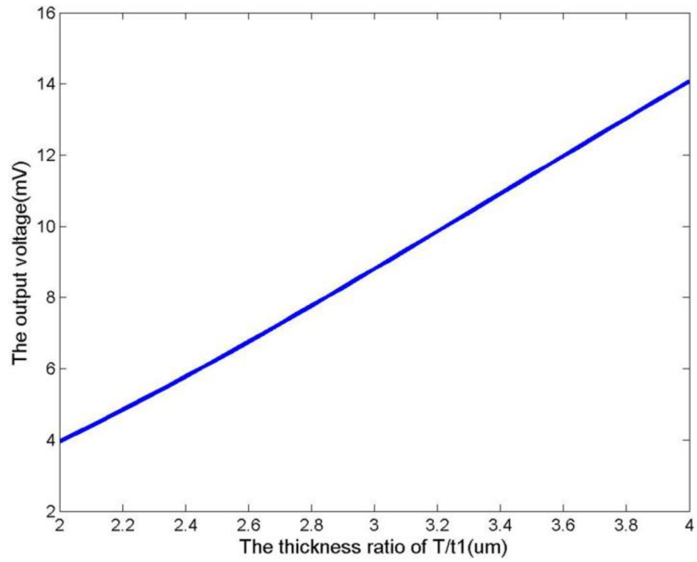

Figure 4. The Voltages with Different Ratio

4. Measurement

In order to verify above analysis result, the millimeters lever prototype is fabricated. To obtain the similar performance with silicon material, some candidate materials should be considered. The bottom beam and mass is fabricated with 45# steel, since its mechanical property is very similar to that of silicon. The measurement system picture is shown in Figure 5. The device was fixed to a vibrator (SINOCERA JZK-2), which is used to generate mechanical vibrations. Sinusoidal signals were applied to the vibrator at various frequencies. The voltages from the energy harvesting device were monitored by an oscilloscope (YOKOGAWA DL850) at the same time, and the non-contact doppler vibrometer (Vibroducer V1002) is used to measure the contrastive voltage. The experiment frequency is 328.0 Hz, and the peak output voltage is 15.5V, shown in Figure 6.

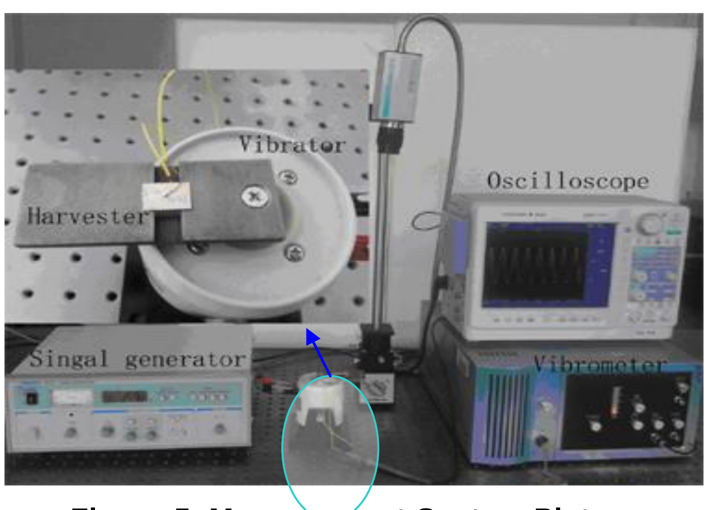

Figure 5. Measurement System Picture

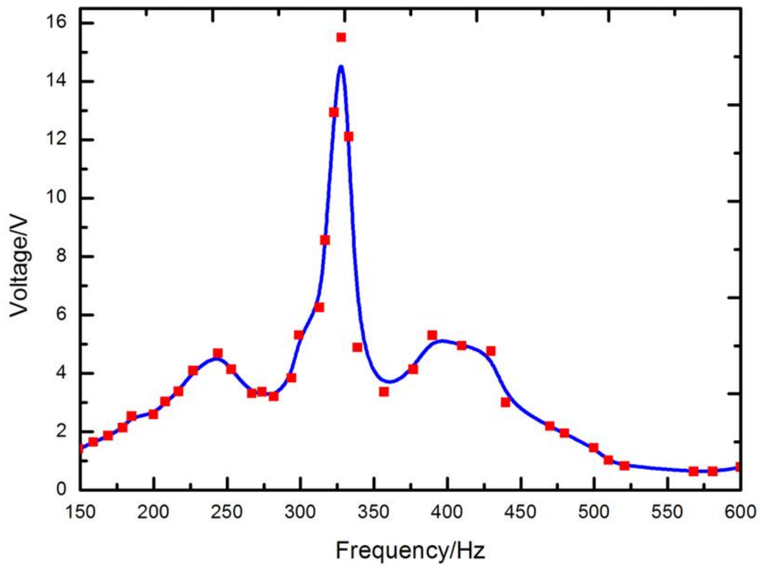

Figure 6. Frequency Response of Double Layer Cantilever

Since the output voltage from PZT is sinusoidal, this voltage needs to be rectified with diodes, and capacitor is charged by this energy harvester. The plot of charging voltage/power is shown in Figure 7. The value of the capacitor was 100μF. The capacitor voltage collected from the energy harvester is 3.8V.And the 16.9 μW maximum power is also derived.

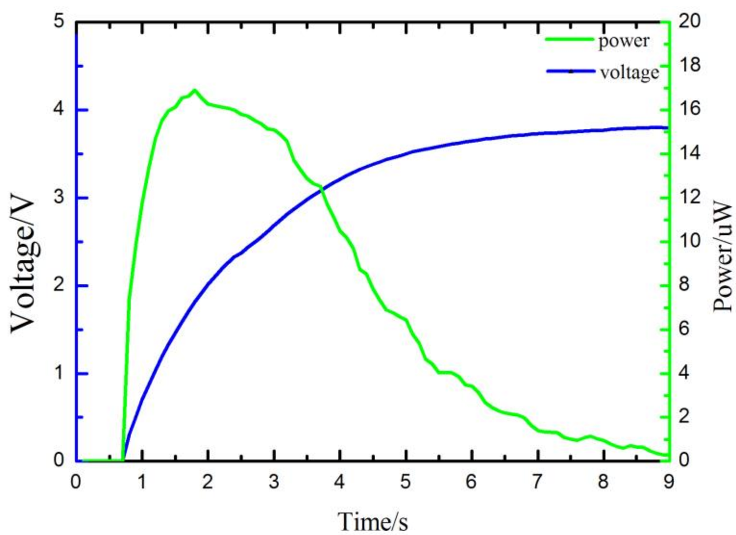

Figure 7. Plot Charging Voltage/Power of the Capacitor

5. Conclusions

Double layer cantilever harvester for vibration energy is designed by inserting the space layer between the top PZT beam and bottom support beam. Thus the top piezoelectric layer without the restriction of support beamr is freedom to generate more strain and more charge. Furthermore, the modeling analysis, prototype fabrication and measurement are discussed in this paper. Based on the piezoelectric effect and the "spring-damper-mass" vibrating model, the formulation of voltage of double layer cantilever is derived. The optimum result indicated that the structure parameter of device can affect the output voltage in micrometer scale. Accordingly, the acquired prototype is assembled. The prototype can generate the 3.8V output voltage and 16.9μW output power. The experiment frequency is 328.0 Hz.

Double layer cantilever energy harvester can gain the optimum voltage by adopting the response frequency with parameter of device. Furthermore, comparing to the single linear cantilever, this structure energy harvester is significance, especially in the improving the piezoelectric strain field for its space structure. With MEMS technology, this double layer cantilever harvester will decrease deeply the volume of power device, improve the transfer efficiency. Furthermore, it can integrate with the wireless sensor nodes which expand the lifetime of sensor nodes.

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