MEMS based Nonlinear Monostable Electromagnetic Vibrational Energy Harvester for Wider Bandwidth

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Abstract. This paper reports a wideband vibrational energy harvesting scheme using a MEMS based nonlinear electromagnetic transducer. The nonlinearity is incorporated in the proposed device through the stretching strain in addition to the bending of the fixed-guided configured beams of the designed structure. The thin spring structure is fabricated on Silicon-On-Insulator substrate with device layer thickness of 50   m. The MEMS spring structure is packaged and characterized with wire wound copper coil (NE1) and micro fabricated double layer copper coil (NE2) for comparison. Measurement results show that ~80 Hz half power bandwidth is obtained for the fabricated devices with maximum load powers of 2.8   W (NE1) and 0.4   W (NE2) respectively at 0.5g which improves the 'power-bandwidth gain' to one of the highest among reported works.

1. Introduction

With advancement of low power electronics, the speculated 'Internet of Things (IoT)' has opened up a window to visualize a connected world of tiny, autonomous Wireless Sensor Nodes (WSNs), which would transform our surrounding into an intelligent and responsive environment. To enable the 'fit-and-forget' operation of the WSNs, scavenging electrical energy from ambient vibrations has gained major attention. Nonlinear oscillation based Vibrational Energy Harvesters (VEHs) [1-8] have received enormous attention recently due to their inherent ability to improve the off-resonance performance compared to a resonant system. In this work, we have developed stretching strain based nonlinear monostable VEH which is much compact and easy to implement at MEMS scale.

2. Design and FEM Analysis

We have designed our devices in such a way that the nonlinearity appears due to stretching of the spring arms in addition to the bending strain in a fixed-fixed beam configuration. The resultant spring force of such beam, which consists of two parts, one due to bending (F_b) and the other due to stretching (F_S) has been calculated analytically and is given by [4]

$$F = F_b + F_s = -\frac{Y}{L^3} W d^4 \left[\frac{d_f}{d} + \frac{18}{25}\left(\frac{d_f}{d}\right)^3\right] \quad (1)$$

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Where, L, W, d and Y are length, width, thickness and Young's modulus of the beam and d_f is the beam tip deflection. For large amplitude oscillations (d_f>d), the stretching terms become significant and nonlinearity appears. We have designed the device in such a way to exploit this stretching based nonlinearity that results in wideband response. The thin spring configuration on silicon potentially brings the different fundamental modes of the designed structure close together. As shown in Fig. 1, the first three modes of the proposed device are 406 Hz (out-of-plane vibration), 425 Hz (torsional) and 512 Hz (torsional in different direction) respectively as obtained from the FEM analysis in COMSOL Multiphysics. The closely spaced resonance modes interact between themselves and enhance the otherwise wideband output frequency response due to high nonlinear stiffness of the device.

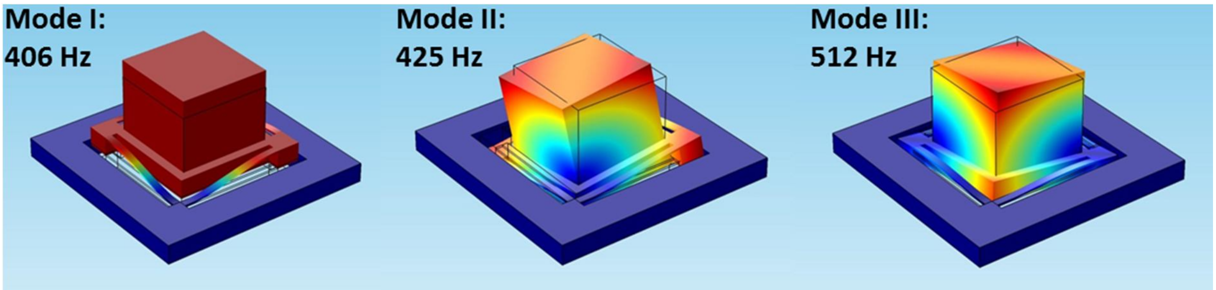

Figure 1. First three vibrational modes of the MEMS nonlinear spring structure.

3. Fabrication

The designed spring structure is fabricated on a Double Side Polished (DSP) <100> Silicon-on-Insulator (SOI) wafer with device layer thickness of 50 m, 3 m buried oxide (BOX) and a handle layer of 450 m using a double mask process. The device layer defines the thickness of the spring arms. The fabrication starts by thermally growing oxide layers on front and back side of the wafer which act as the mask layer during front and back etch. The front side is then patterned and developed using a first mask and the exposed oxide sites are etched using Plasma Enhanced Reactive Ion Etching (PERIE) to reach the device layer silicon. Same is performed in the back side of the wafer using a second mask. The device layer silicon is etched using Deep Reactive Ion Etching (DRIE) till the BOX layer to define the thin spring structure. Lastly, the handle layer is etched from the back using DRIE to release the MEMS structure. The microscopic images of the fabricated spring structure are shown in Fig. 2.

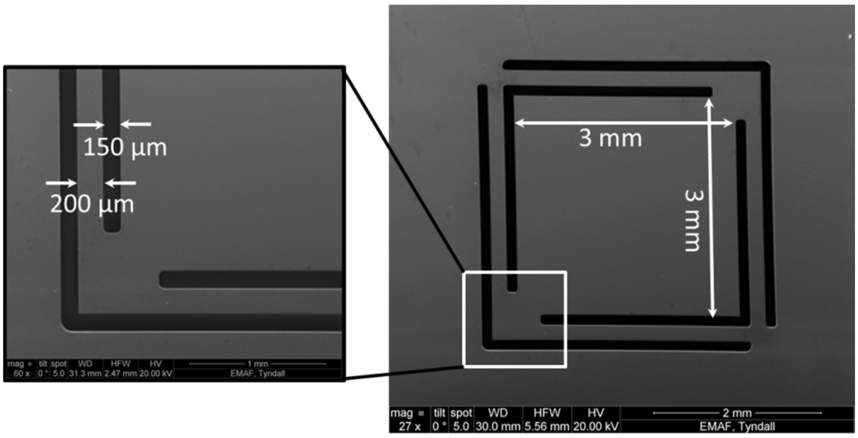

Figure 2. SEM image of the Nonlinear Spring fabricated on SOI substrate.

The double layer electroplated copper coil is fabricated on a separate Silicon substrate [9]. The fabrication process starts by sputtering Ti/Cu (20/200 nm) seed layer on silicon. The substrate is then patterned and the first layer of copper is electroplated and resist is stripped off. Using a second mask, via layer is patterned and copper is again electroplated to fill the via. Next, SU-8 insulation layer is spun to isolate the bottom copper tracks from the top layer. Similar seed layers as the bottom is sputtered on SU-8. The corresponding layer is patterned again, top layer copper is electroplated and the resist is stripped off. Finally another layer of SU-8 is spun to provide passivation to the structure. The track width, the inter-track gap and the height of each track of the coil is 10 m each. The square coil has an outer dimension of 2.8×2.8 mm^2. The Microfabricated coil is shown in Fig. 3(a) which has 144 turns with the coil resistance of 192 Ω.

The micro-fabricated spring structure and coil are packaged together to form the MEMS based nonlinear electromagnetic energy harvesting device. A small NdFeB block magnet (2.5×2.5× 2 mm^3) is epoxy bonded onto the movable paddle which provides mass (9.83×10^{-5} Kg) to the oscillator. The device is characterized at different level of integration to report a comparative study. First, the nonlinear spring structure is packaged with a wire wound copper coil having comparable dimensions to the micro coil. The wire wound coil with 3mm outer diameter, 0.5 mm thickness and 25 m wire diameter, has 560 turns and a coil resistance of 140 Ω. The packaged MEMS devices [Fig. 3(b)] have a volume of 0.14 cm^3.

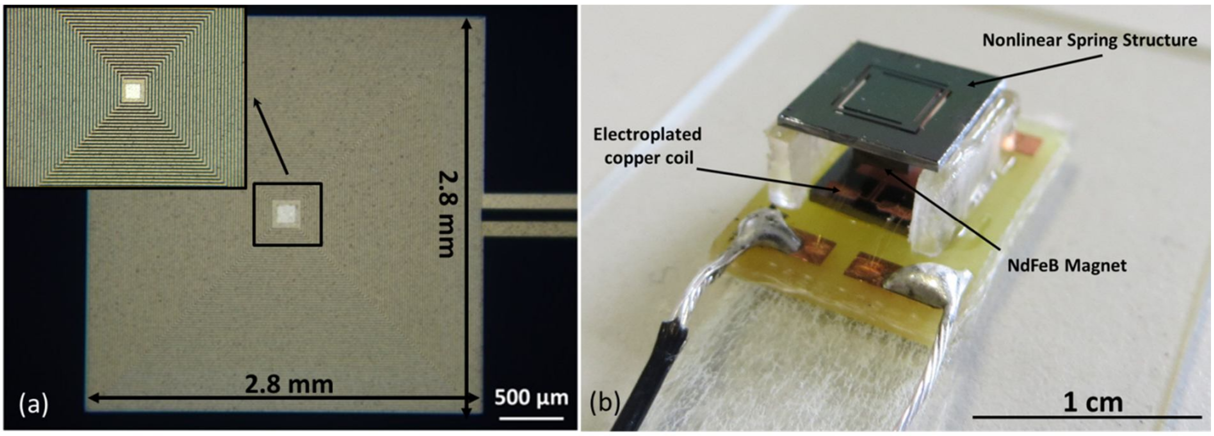

Figure 3. (a) Microscopic image of the micro-fabricated coil. (b) Packaged device (NE2) on chip for testing.

4. Characterization & Discussions

The two prototypes, one with wire wound coil (NE1) and the other one with the micro coil (NE2) are tested under swept sine input vibrations under different acceleration levels (0.1g, 0.2g and 0.5g; g=9.8 m/s^2). The electrical damping due to the small size magnet and coil assembly is found to be smaller than the parasitic damping. Thus the optimized load for both the prototypes are equal to the respective coil resistances i.e., for NE1 it is 140 Ω and for NE2 the same is 190 Ω respectively. The load power vs frequency response of the prototypes under different acceleration levels are shown in Fig. 4 as the frequency is swept in the forward direction. As mentioned in section 2, the first three vibration modes of the designed spring are relatively close. The large deflection, stretching strain nonlinearity will be stronger for the first out-of-plane vibration mode. However since the other two modes (torsions in two opposite directions) are also out-of-plane, the nonlinear contribution due to those two modes also adds up. Consequently, very wideband response is achieved and the corresponding wideband nature escalates with the input acceleration. At 0.5g, the peak load power of 2.8 W is obtained with NE1 with a half power bandwidth of 78 Hz. Peak load power of 0.4 W is obtained with prototype NE2 along with a bandwidth of 82 Hz. The slight fall of the bandwidth of NE1 can be due to the comparatively larger electrical damping produced from the wire wound coil with large turn numbers than a micro coil.

As a figure of merit of wideband energy harvesters, the concept of Power Integral is introduced before [6]. It is the area under the load power-frequency curve at a fixed acceleration level and is defined as $(\boldsymbol{P_f = \int P_L . df})$ where P_L is the load power and f is the frequency. In MEMS based systems, the power is normally significantly reduced due to the scaling of the active material whereas the bandwidth increases due to the larger nonlinearity because of the thinner spring structure. In the following Table, we provide a comparative study of some of the reported MEMS energy harvesting devices along with our work. The efficient nonlinear spring design in our device produces sufficient wideband response, which results in large power integral values.

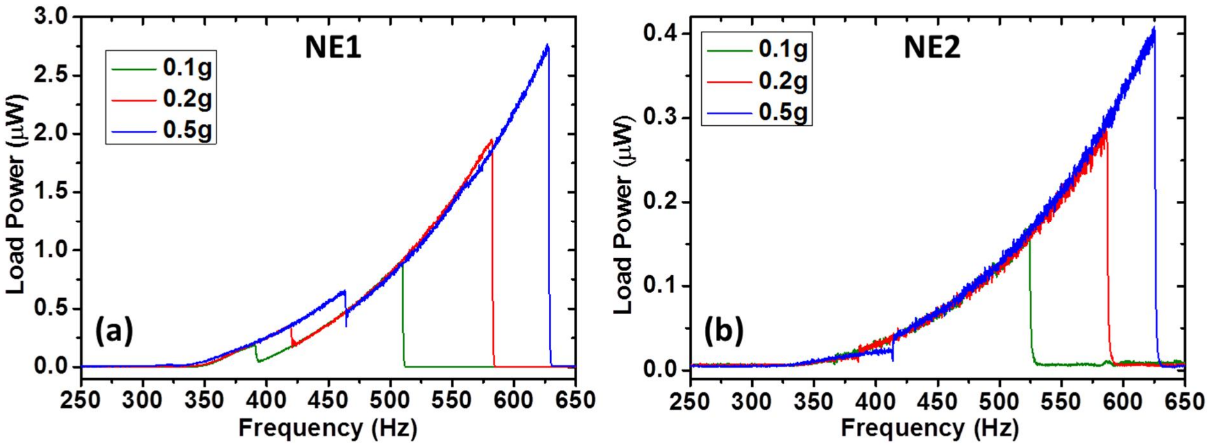

Figure 4. Load power vs frequency response of the two prototypes under different accelerations for respective optimized load resistances: (a) NE1 for 140 Ω load and (b) NE2 for 190 Ω load.

Table 1. Comparison of Power Integral for different MEMS nonlinear energy harvesters.

Reference	Type of Transduction	*Volume (cm^3)*	Acceleration (g)	*Power Integral (W-Hz)*
7	EM	0.032	3g	1.8
8	PZ	0.016	0.6g	2.8
10	ES	0.042	1g (35V bias)	164
11	EM	0.158	1g	0.02
NE1	EM	0.14	0.5g	840
NE2	EM	0.14	0.5g	123

5. Conclusions

In summary, this paper reports a bandwidth widening scheme using a MEMS based monostable nonlinear electromagnetic vibration energy harvesting device. The nonlinearity is incorporated in the proposed device through the stretching strain in addition to the bending of the fixed-guided configured beams of the designed structure. The thin spring structure is fabricated on SOI substrate with device layer thickness of 50 m. The device is tested with wire wound copper coil (NE1) and micro fabricated double layer copper coil (NE2) for comparison. Testing results show that ~80 Hz half power bandwidth is obtained for the fabricated devices with maximum load powers of 2.8 W (NE1) and 0.4 W (NE2) respectively at 0.5g which enhances the 'power-bandwidth gain' to one of the highest among reported works.

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