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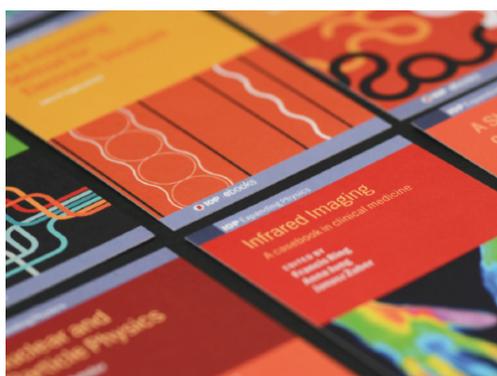
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Design and Simulation of Bistable Microsystem with Frequency-up conversion effect for Electrostatic Energy Harvesting

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Abstract. This work is dedicated for the study of energy harvesters implemented in form of microelectromechanical systems (MEMS) used to harvest ambient vibrations for powering standalone electronic devices. The previewed application is to power a leadless pacemaker with mechanical energy of the heartbeat, which requires the amount of power typically more than $1\mu\text{W}$. The target of the presented article is to combine the effect of bistability and non-linear coupling by electrostatic effect in order to achieve the high value of bandwidth at the low frequency under the low accelerations. Such system is expected to bring high power density performance. This study is performed mostly by numerical simulation.

For the present day energy harvesting is viewed as a promising and innovative alternative for the batteries in the task of powering a wide variety of standalone devices. The examples could be found in different fields: starting from the infrastructure monitors and sensor networks up to biomedical applications.

Conception and design of the energy harvesting device that will be able to deliver $>1\mu\text{W}$ of power under the low frequency excitation (20-30Hz) with acceleration of $1g$ is in the scope of this work. Such parameters are not very far from the values of the human heartbeat, so the presented device could serve as a starting point in development of the mechanism capable of powering the pacemaker [1]. Numerous examples of the energy harvesters operating with such input parameters had already been proposed, but generally they are not compatible with biomedical applications due to the size [2] and use of magnetic elements [3]. However, introducing the non-linearity in electrostatic energy harvester could produce a dramatic effect on its performance [4].

In the bistable system, the switching between stable positions depends only on the value of the external applied force [5], and it could be used to access the low frequencies keeping the bandwidth high for the external excitation.

It had been clearly demonstrated that maximum power that can be converted by an inertial power generator is proportional to the operational frequency of the transducer [6]. So, the frequency-up conversion is a promising strategy to increase the output power value.

Design of the device and the simulation of its performance is presented in this paper.



1. Design of the Frequency-up conversion System

Presented energy harvester using bistable electrostatic frequency-up conversion system consists of two suspended masses with bistable and linear springs, variable capacity attached to linear oscillator and two pair of electrodes: one to impose bias between to oscillators and separately another one to apply voltage on variable capacity. Oscillator with bistable springs gets excited from the vibrating medium - it serves as a seismic mass, then comes into contact with linear oscillator which leads to electrostatic pull-in followed by accompanied movement and, finally, pull-out. As a result, energy is transmitted from a seismic mass to the transducer that is attached to linear oscillator. Thus, independent oscillation after pull-out is a source of produced electrical energy.

Bistability of an oscillator is achieved by using a double curved beam spring geometry. The switching forces are chosen to be 1.3mN and 0.5mN for the double curved beam mechanism. For the variable capacitance part, a gap closing finger geometry was implemented as it seems to be an optimal solution to maximize the amplitude of capacitance variation keeping the limited maximum displacement. Stoppers are placed in order to prevent the electrostatic stitching.

The schematics of the device is shown on the Fig. 1.

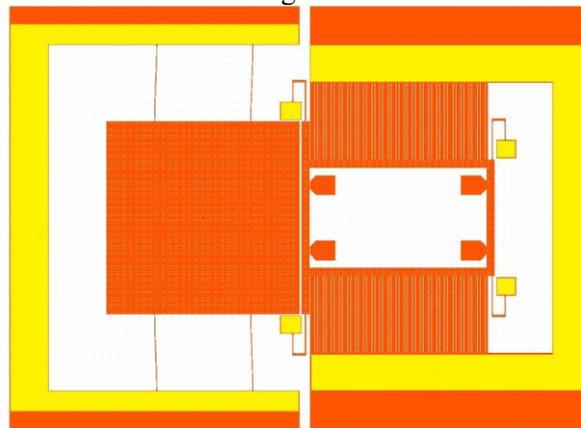


Figure 1. Bistable electrostatic energy harvester with frequency up-conversion. Mechanical oscillator with bistable springs is presented on the left side, linear resonator with comb fingers is on the right side. Orange represents silicon, yellow – gold contacts.

Device dimensions are 1.5cm x 1cm x 85µm. Total device volume is 0.013 cm³, which is much lower than limiting value of 1cm³, so it is compatible with previewed application. Summary of device parameters is presented on Table 1.

Parameter	Value
Curved beam length, mm	2
Capacitive finger length, mm	2
Seismic mass, g	0.22
Stopper proximity distance, µm	1
Inter-finger distance, µm	20
Linear oscillator resonant frequency, Hz	4000
C _{max} , pF	102
C _{min} , pF	10

Table 1. Summary of designed parameters.

2. Modelling the Dynamics

To simulate the highly non-linear dynamics of the coupled two oscillators system with frequency up-conversion the equivalent circuit approach is used. Using electrical circuit simulation is a simple way to confine the multiphysics phenomena in electrical equations, with easy way to include a variety of non-linear effects (springs softening and hardening) [7]. Equivalent circuit had been implemented in LTspice IV. Its electrical parameters correspond unambiguously to the basic mechanical properties of both resonators (such as spring stiffness, damping and mass), and, thus, the same evolution equations are solved [8]. Electrostatic contact between two movable parts was simulated as for the ideal capacitor. Schematics of equivalent circuit is shown on the Fig. 2.

The non-linearity of bistable mechanism was simulated by adding a restoring force of double curved beam in the oscillator circuit. The non-linear stiffness coefficients had been obtained from the finite element model developed in ANSYS©. This model allows simulating the time evolution of the displacement of both movable masses in the frequency up-conversion system.

Biasing voltage between two oscillators was set to 1.2V. The displacement of seismic mass and linear resonator with excitation of 1g at 25Hz is shown on the Fig. 3.

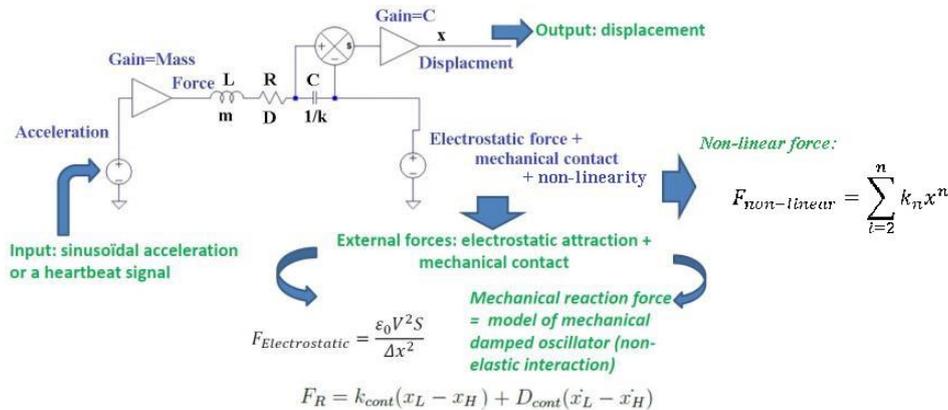


Figure 2. Equivalent circuit of bistable oscillator used to simulate the displacement evolution.

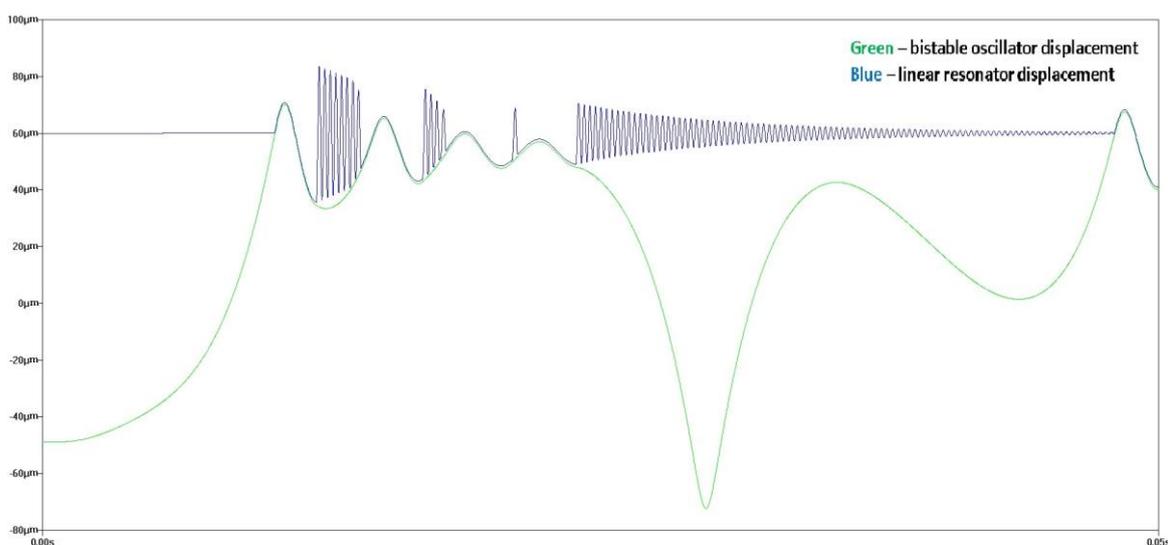


Figure 3. Spice simulation that indicates electrostatic frequency up-conversion in the system of two mechanical oscillators. Displacement of the bistable resonator (green) and linear resonator (blue).

The notion of bandwidth for non-linear systems still remains ambiguous. Here we will use this term in order to describe the frequencies at which the bistable mechanism could be switched. Keeping the same 1g acceleration, the sweep and selective frequencies analysis had been performed. Both revealed that with given parameters seismic mass could be excited at frequency range of 1-100Hz, which could be explained by highly non-linear nature of bistable mechanism, which is mostly sensitive to applied inertial force, but much less to the frequency of excitation.

3. Energy Harvesting Simulations

To evaluate the power output of the energy harvester, a simple model of the interface circuit with biasing capacitor, diode rectifier and energy storage capacitor had been chosen [9]. Results of simulated power output as a function of biasing capacitor voltage and store capacitor voltage are shown on the Table 2.

V bias / V store	Harvested power, μW
8V/4V	0.93
10V/5V	1.5
12V/6V	2.4

Table 2. Simulated power output as a function of biasing voltage.

Maximum biasing voltage had been chosen to impose slightly smaller attraction force in transducer in comparison to restoration force of the linear spring. Thus, with the highest simulated biasing voltage applied to the transducer, the power density could reach the value of $185\mu\text{W}/\text{cm}^3$.

4. Device Fabrication Procedure

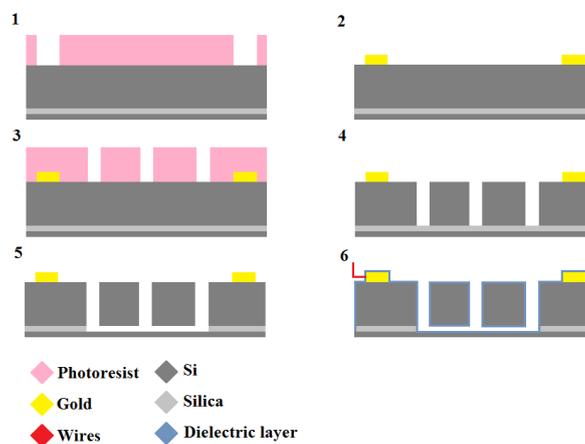


Figure 4. Schematic representation of electrostatic frequency up-conversion system fabrication process (not for scale).

The system discussed before had not been fabricated yet, however fabrication technique had already been developed and tested on prototypes. Device is previewed to be created on 4-inch SOI wafer of $85\mu\text{m}$ device thickness layer with classical Si technologies that are easily accessible for industrial implementation. The offered process flow is shown on the Fig. 4.

First, the Ti35ES photoresist is deposited by spin-coating, which is followed by UV lithography and development (Fig. 4, 1). Next, gold layer thin film is evaporated on the wafer and lift-off process is performed (Fig. 4, 2). After, next step of S1828 photoresist spin-coating and UV lithography is made (Fig. 4, 3) and device is shaped with deep reactive ion etching (DRIE) of Si layer (Fig. 4, 4). Finally,

the MEMS is liberated with HF vapour etching of buried oxide layer (Fig. 4, 5). The wires are bonded to gold electrodes, and atomic layer deposition of thin dielectric layer is done (Fig. 4, 6).

5. Conclusion

In the present article, a design of the bistable electrostatic energy harvester with frequency-up conversion mechanism is offered and its performance is simulated. As stated by the results obtained, seismic mass with bistable springs is expected to be sensible to the excitations at low frequencies with the broad band and at relatively low amplitude (of the order of 1g). An equivalent circuit had been used in order to simulate the run of both mechanical and electrical parts of the energy harvester. Simulated harvester output is exceeding the value of 1 μ W. The power output is highly dependable on the voltage applied to the variable capacitor. Energy harvester is previewed to be produced in form of MEMS device with classical clean room technologies on SOI wafer. An optical and electrical characterization set-ups are created and tested on trial devices – so, both dynamics of the oscillators and final power output could be measured.

However, the main future challenge for the bistable springs based system is the gravitational offset that interferes in the device dynamics if it is not positioned horizontally. Up to now, it is considered to be a major issue not only for the presented system, but for a number of MEMS in general and it is a target for the future development.

Acknowledgements

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