LOW-FREQUENCY 2D RESONATORS
FOR VIBRATIONAL MICRO ENERGY HARVESTING APPLICATIONS

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Abstract: Vibration energy harvesting comprises electromagnetic, piezoelectric and electrostatic generators to convert ambient motion into electrical energy. Such devices typically include a mechanical resonator that amplifies the external vibration around its resonance frequency. For optimal harvesting, the external acceleration has to be aligned with the motion direction of the resonator. A shift of the acceleration direction or an irregular acceleration behavior along several directions reduce the energy conversion and harvesting efficiency. Since ambient vibrations mainly occur at lower frequencies, typically from 50 Hz to 350 Hz, this work presents the fabrication and characterization of two-dimensional low-frequency resonators. The devices are processed using standard micromachining technology. They are able to extract energy from ambient accelerations with arbitrary motional directions in the device plane.

Key words: Vibration energy harvesting, 2D resonators

1. INTRODUCTION

Resonators are commonly used in most of energy scavengers [1]-[3] that use electrostatic, piezoelectric or electromagnetic harvesting principles. The use of resonators is a simple possibility to extract energy from ambient motion and transform this energy into kinetic energy in form of oscillations of a seismic mass. These oscillations can then be damped by extracting energy when applying the selected harvesting principle. Previous resonators amplify the surrounding vibration around their resonance frequency in a single direction only [2]-[4]. For optimal harvesting, the external acceleration has to be aligned with the direction of the motion of the resonator. This is often delicate since the external vibration has to be characterized before. Furthermore, a shift of the acceleration direction or an irregular acceleration behavior along several directions prevent an efficient energy conversion and harvesting. Since ambient vibrations occur mainly in the range between 50 Hz and 350 Hz [5], this work presents the fabrication and characterization of two-dimensional (2D) resonators that vibrate at such low frequencies. The structures are obtained by using solely standard bulk micromachining technology. No additional mass added to the device is necessary to lower the resonance frequency into the applications frequency band. As the seismic mass of the presented resonators can move in two in-plane directions, these devices are able to extract energy from ambient accelerations with arbitrary motion directions in the device plane.

2. EXAMPLES OF 2D VIBRATIONS

To illustrate possible applications of the 2D resonators presented here, the body vibrations of an autonomous intelligent unmanned quadrocopter and a mechanical vacuum pump (Trivac D65BCS, Oerlikon Leybold, Germany) were characterized exemplarily. The setup for the characterization of the quadrocopter acceleration is shown in Fig. 1. It consists of a three-dimensional (3D) accelerometer fixed to the investigated object, a DC sensor supply, and an oscilloscope. The measured data is the average value of 100 measurements of the oscilloscope to filter out vibrations that are not permanently present. The obtained acceleration spectra are shown in Fig. 2. The inset in each spectrum shows the 2D time-dependent acceleration for a duration of 1 sec. The measured spectrum of the quadrocopter in Fig. 2 (a) has several peaks around 90 Hz, with accelerations of about

![Fig. 1: (a) General and (b) detailed view of measurement setup to characterize the body vibrations of an autonomous intelligent unmanned quadrocopter using a 3D accelerometer.](image-url)
0.08 g. The motion shows no preference for the $x$- or $y$-direction. In contrast, the spectrum of the vacuum pump shows one dominant peak at 50 Hz resulting from the power grid frequency in use in central Europe. The accelerations are 0.35 g and 0.14 g in the $x$- and $y$-direction, respectively. The inset for the vacuum pump data shows indeed a direction of maximum acceleration that is approximately along the $x$-axis. Its related maximum value is about twice as large as that along the $y$-axis. In case of a suboptimal alignment of a conventional one-dimensional (1D) vibration scavenger, a large fraction of the acceleration of the application would be wasted.

### 3. FABRICATION

The fabrication of the resonators uses a two mask process and is based on oxidized Si wafers as indicated in Fig. 3 (a). The silicon oxide has a thickness of 3 µm and is deposited by plasma enhanced chemical vapor deposition (PECVD). A photolithography step is followed by deep reactive ion etching (DRIE) of the wafer rear, as shown in Fig. 3 (b). The subsequent front photolithography, shown in Fig. 3 (c), defines the in-plane geometry of the resonator. The movable parts are released by the second DRIE step illustrated in Fig. 3 (d). The entire process makes it possible to tune the resonance frequency of the devices by simply varying the depth of the first DRIE step without changing the mask design. The fabrication of low-frequency resonators using micromachining technology is usually relatively difficult, since both large mass and low spring stiffness have to be combined. To address these issues, the full wafer thickness is used for the seismic mass, whereas the suspension springs do not have the same height. 2D resonators with resonance frequencies as low as 100 Hz have thus been realized. Scanning electron micrographs (SEM) of one fabricated structure with the device’s coordinate system are shown in Fig. 4, where the coordinate system of the device is indicated as well. A seismic mass with a diameter of 4 mm is suspended by a circular spring system. The width of each single spring is 10 µm and the height of the springs for this device was fabricated to be 235 µm, resulting in a DRIE aspect ratio of about 24. The maximum allowed travel range of the seismic mass is 150 µm.

### 4. CHARACTERIZATION

#### 4.1 Measurement setup

The measurement setup used to characterize the 2D mechanical behavior of the devices is shown in Fig. 5. A piezo-shaker ($P$-841, Physik Instrumente, Germany) is used to apply controlled vibrations to the
device. The shaker can be rotated in steps of 30° with respect to the resonator. Two motorized linear stages beneath the piezo shaker enable an easy positioning of the device under the measurement objective. The resonator under test and the excitational piezo shaker with the linear stages are placed inside a vacuum chamber with a glass window for optical access as shown in Fig. 5. For the in-plane motion detection of the seismic mass, a stroboscopic video analyzing system (MSA 400, Polytec, Germany) with nm-resolution is used. For energy harvesting devices, e.g. electret-based devices that are sensitive to moisture, a complete encapsulation of the electret and resonator is advantageous. The resonance behavior of the devices inside a vacuum encapsulation is different from the one at normal pressure, as air damping conditions change. The 2D resonators were characterized at both atmospheric pressure and in vacuum.

4.2 Measurement results

The results of the in-plane motion characterization are shown in Figs. 6 to 9. The x- and y-motions of the seismic mass for each frequency point are measured from 368.5 Hz to 376.45 Hz with a spectral resolution of 0.05 Hz using the stroboscopic measurement setup.

As an example, the measured seismic mass motions measured at 370.45 Hz, including the corresponding sinusoidal fits, are shown in Fig. 6. The in-plane motion is split into two perpendicular x- and y-components that are parallel to the device axes. The motion spectrum shown in Fig. 7 is derived by taking the peak-to-peak amplitude values of the sinusoidal fits for each frequency step. These spectra were obtained for an excitation of 6 nm applied to the device at 1013 mbar and 0.2 mbar. Two resonance frequencies of different oscillations modes are extracted. The two left peaks correspond to the x-mode, oscillating at 370.5 Hz. The two right-hand side peaks belong to the y-mode vibration, which occurs at 373.9 Hz. The two lower peaks measured at normal pressure show a quality-factor (Q-factor) of about 1400. The higher peaks measured in vacuum at a pressure of 0.2 mbar show an increase in the Q-factor to approximately 2500, as a result of the reduced air damping. Consequently, the frequency difference of the x- and the y-mode is 3.4 Hz. The performed FEM simulation using COMSOL 3.4, a finite element method (FEM) simulation tool, also shows a difference of the oscillation frequency with a slightly higher resonance frequency for the y-mode.

To characterize these two modes of motion, the device was excited with a peak-to-peak vibration in the x-direction and then along the y-direction with 21.4 nm corresponding to a peak-to-peak acceleration amplitude of $5.8 \times 10^{-3}$ g. The resulting in-plane oscillations for sinusoidal fits for one period are shown in Fig. 8. Two linear oscillations of the seismic mass with a 6°-divergence to the device axes are clearly identified. The graph also shows the simulated x- and y-mode directions. The modes simulated using the FEM are also linear oscillations and perpendicular to each other. The angular difference to the measured motion directions of the x- and y-mode is 6.3°. The device oscillates only in these two directions with

![Fig. 6: Measured displacement of the seismic mass in x- and y-direction at 370.45 Hz for an excitation of 21.4 nm in x-direction.](image)

![Fig. 7: Motion spectrum for the two orthogonal motion modes x and y at an input vibration of 6 nm and surrounding pressure of 1013 mbar and 0.2 mbar.](image)
amplitudes depending on the excitation angle.

In Fig. 9, the peak-to-peak amplitudes of the x- and y-motions are plotted for different excitation directions for a peak-to-peak driving amplitude of 21.4 nm. A schematic view of the resonator design is plotted in the background. The graph of the measured motion amplitude vs. excitation angle shows a point-symmetry to the origin and therefore device center. The maximum motion is about 30 µm for both directions and occurs at 0° and 60° and consequently at 180° and 240°. Figure 9 also illustrates the disadvantage of a 1D resonator compared to a 2D device when used for the extraction of ambient vibrations. Only the x- or the y-mode would be accessible for the extraction of external vibration. In the worst case, if the direction of motion is orthogonal to the input motion, only a small fraction of the available kinetic energy from the environment would be used. In contrast, for a 2D resonator, both in-plane directions can be accessed for harvesting applications. Therefore, kinetic energy from all directions in the device plane can be harvested by applying the desired vibration harvesting principle.

5. CONCLUSION

Low-frequency 2D resonators have been successfully fabricated using solely standard micromachining technology. These resonators are able to extract ambient kinetic energy from all directions in the device plane. The devices show two perpendicular linear modes of motion around 370 Hz. The Q-factor of the devices is about 1400 at atmospheric pressure and increases to 2500 at 0.2 mbar. The resonators can be used as a basis for electrostatic, electromagnetic and piezoelectric harvesting principles, among other applications.

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