A New High-Sensitivity Differential *X*-Axis FM Accelerometer

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***Summary*— In this work, we propose an innovative high-performance Micro-Electro-Mechanical Systems (MEMS) *z*-axis Frequency Modulation (FM) accelerometer able to achieve a sensitivity higher than 1000 Hz/g around a carrier value of 180 kHz, with a 1120x608 μm^2 footprint only. The new device exploits the mechanical stiffness modulation induced on two in-plane flexural resonators by the torsional deformation of the two proof mass suspension springs to differentially measure an external *z*-axis acceleration. This concept, enabled by the Thelma-Double process by STMicroelectronics, is successfully demonstrated through preliminary experimental tests.**

Keywords*— MEMS, z-axis accelerometer, Frequency Modulation, high-sensitivity, differential readout

I. Introduction

Frequency Modulation (FM) sensing has gained through recent years a consistent maturity thanks to its inherent stability to electronic drifts and its quasi-digital output [1]. In a FM accelerometer, the frequency shift induced by an external acceleration on a resonating mechanical component is chosen as the output quantity. Different mechanisms have been exploited so far to correlate the external acceleration to the frequency shift of the accelerometer resonant components. Among them, one can mention *(i)* electrostatic modulation, *(ii)* mechanical modulation and *(iii)* inertia modulation.

Electrostatic modulation relies on the softening effect caused by parallel-plates electrodes to modulate the mechanical stiffness of the resonant components and thus their resonant frequency as a consequence of the proof mass displacement induced by the external acceleration. Due to pull-in instability phenomena that can affect devices working according to such principle, the electrostatic stiffness term is usually kept much lower than the mechanical counterpart, thus resulting in typically low scale-factors. On the other side, electrostatic modulation well complies with out-of-plane sensing thanks to the possibility of having vertical facing electrodes toward a suspended proof mass.

By focusing on FM *z*-axis accelerometer, electrostatic modulation has been exploited in [2] to achieve a 31.65 Hz/g sensitivity through a 6.9mm x 5.3mm footprint, in [3] to obtain a sensitivity of 70 Hz/g with an encumbrance of 2mm x 3mm, while in [4] and [5] a sensitivity of 10Hz/g and 1.3Hz/g is reached by significantly reducing the device in-plane dimensions to 480μm x 700μm and 510μm x 600μm, respectively.

Mechanical modulation is instead usually implemented by inducing a tensile/compressive stress on the resonant components through the movement of the main proof mass as a consequence of the external acceleration. Induced stresses cause a shift of the resonance frequency and thus a measure of the external acceleration. To the Authors' best knowledge, the vast majority of mechanically modulated accelerometers available in the literature, implement in-plane sensing, being the application of the same principle to out-of-plane sensing practically impossible or very poorly efficient for single-structural-layer planar MEMS processes.

The few available designs exploit indeed multi-layer MEMS processes. As an example, mechanical modulation has been exploited in [6] and [7] to achieve a sensitivity of 813Hz/g (with a footprint in excess of 2mm x 8mm) and 35 Hz/g, respectively.

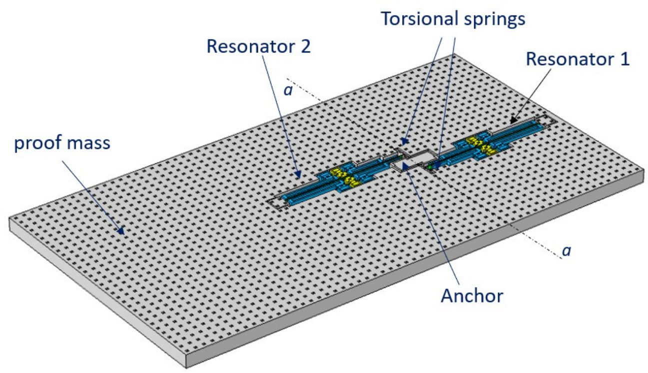
Mass modulating is finally the third possible FM principle. Despite being very promising to bypass the offset issue at its origin, to the Authors' best knowledge, only very few devices have been demonstrated so far [9].

Novel high-sensitivity solutions for *z*-axis accelerometers in small footprint are then required to answer the increasing market request of small high-performance sensors. Though not directly correlated, high-sensitivity often turns into low noise.

In this work, we exploit the Thelma-Double fabrication process recently proposed by STMicroelectronics to demonstrate a *z*-axis accelerometer able to measure the external acceleration according to the mechanical modulation principle. In particular, we overcome the state of the art by proposing the design of an high-performance MEMS z-axis FM accelerometer able to achieve a sensitivity of around 1000 Hz/g with a footprint of 1120 µm x 608 µm only.

In Section II the mechanical design will be described, experimental tests are instead summarized in Section III. Conclusions and future perspectives are finally reported in Section IV.

(a)



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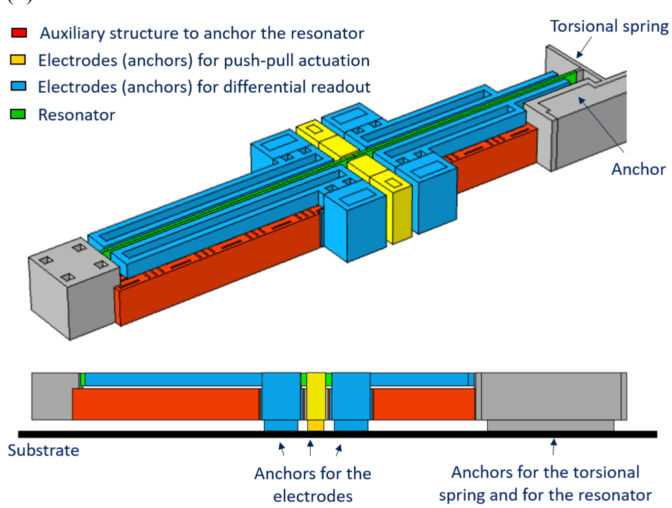


(c)

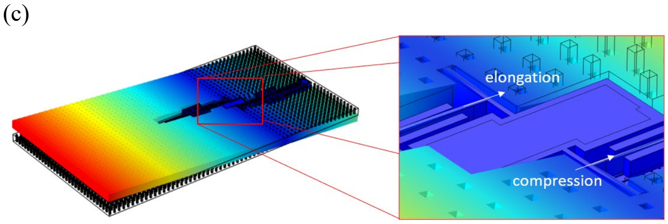


Fig.1 Schematic view of (a) the proposed accelerometer and of (b) the flexural resonator employed for the FM readout of the external acceleration. (c) Working principle of the FM accelerometer.

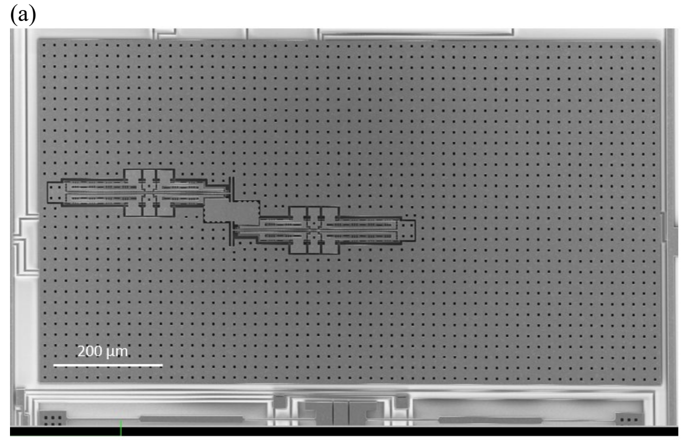
II. MECHANICAL DESIGN

In Fig. 1a, a schematic view of the proposed accelerometer is shown. Similarly to amplitude modulated *z*-axis accelerometer architectures, the mechanical structure consists of a rectangular proof mass (grey in Fig. 1a) suspended through two elongated torsional springs. Such springs are located off from the center of gravity of the structure to allow for a rotation of the proof mass around the *a-a* axis in Fig. 1a.

At rest, the proof mass is parallel to the underlying substrate with a gap of 1.8 µm. When an external *z*-axis acceleration acts on the accelerometer, the proof mass rotates around the *a-a* axis because of the inertial force.

To allow the frequency modulation functioning, two in-plane flexural resonators are also present in the accelerometer as shown in Fig.1a. Each flexural resonator (green in Fig. 1b) consists in an elongated beam connected to the torsional spring (grey in Fig. 1b) on one side and anchored to the central anchor of the device through an auxiliary structure (red in Fig. 1b) on the other side. The unique anchor for the entire accelerometer guarantees a robustness against fabrication-induced and thermal deformations which are usually sources of offset errors in FM accelerometers.

(a)



(b)

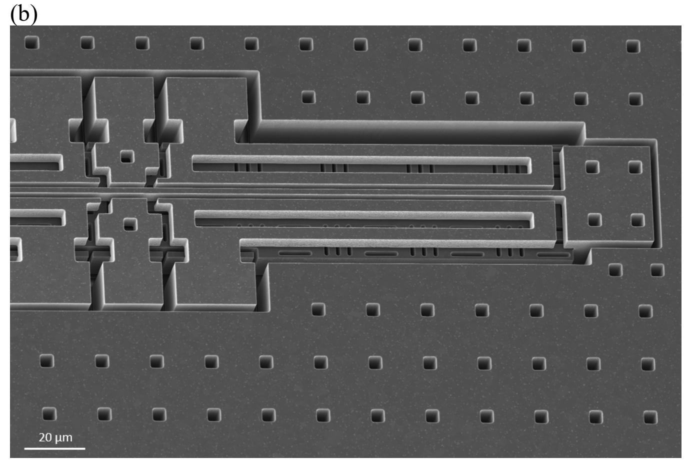


Fig.2 (a) SEM image of the proposed *z*-axis accelerometer. (b) Close-up view of one of the two in-plane flexural resonators.

The two in-plane resonators are kept in motion according to their first in-plane flexural mode through a push-pull electrostatic scheme (yellow electrodes in Fig.1b) and their frequencies are monitored through a differential electrostatic scheme (blue electrodes in Fig.1b). Note that geometric dimensions of the two resonators are chosen such as to resonate at around 180kHz.

Thanks to the different out-of-plane thickness of the resonators (8.2 µm) and the torsional springs (30 µm) allowed by the Thelma-Double fabrication process of STMicroelectronics [8], when the proof mass rotates around the *a-a* axis, one resonator is compressed and the other one is put under tensile stress as schematically shown in Fig. 1c. As a consequence, the natural frequency of the first resonator decreases and the one of the second resonator increases. Through a differential readout of the frequency shifts of the two resonators it is possible to measure the *z*-axis external acceleration.

The success of the proposed design resides in the capability to exploit in-plane flexural resonators to detect out-of-plane external accelerations, thus resulting in a better out-of-plane pull-in rejection than actual FM *z*-axis accelerometers.

III. Experimental Tests

The device has been fabricated through the Thelma-Double process by STMicroelectronics in polysilicon (E = 160 GPa, ν = 0.22, ρ = 2330 Kg/m^3).

The Scanning Electron Microscope (SEM) image is reported in Fig. 2a for the sake of clarity. Figure 2b shows instead a close-up view of one of the two in-plane flexural resonators adopted for the acceleration readout.

The fabricated accelerometer is then wire-bonded on a ceramic carrier and mounted on a Printed Circuit Board (PCB) for testing. The PCB hosts two harmonic oscillators, each based on a differential charge amplifier front-end, an analog phase shifter, and push pull drivers. The front-end amplifier is optimized in order to minimize noise, as it is the major source of phase noise in the loop.

The device is then tested under 1-g sine accelerations by mounting the system on a rate table as shown in Fig.3.

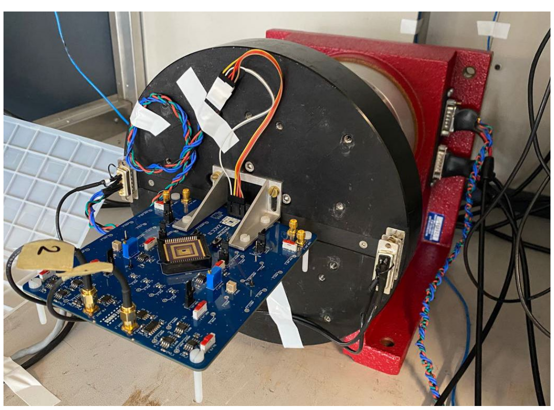


Fig.3 Experimental set-up employed for experiments.

The rate table is then slowly driven at a constant rate, so to modulate the inertial force on the device in a sinusoidal manner.

Preliminary results obtained by measuring the resonance frequency shifts of the two in-plane flexural resonators are summarized in Fig. 4a. As expected, the two resonators responses to external acceleration are in anti-phase to allow for a differential readout. For a better comparison, each of the two frequencies curves shown in Fig. 4a are reported after subtraction of the mean value. A differential sensitivity as large as 1450 Hz/g is achieved at a 11-V rotor voltage.

In Fig. 4b, the combined differential results, converted in terms of external acceleration amplitude, are shown.

An acceptable offset of 5g only is clearly visible from Fig. 4b. This is due to the different experimental natural frequencies of the two nominally identical resonators at 0 g, i.e. 184.2kHz and 176.6kHz, likely due to fabrication imperfections, e.g. different over etches on the two in-plane flexural resonators.

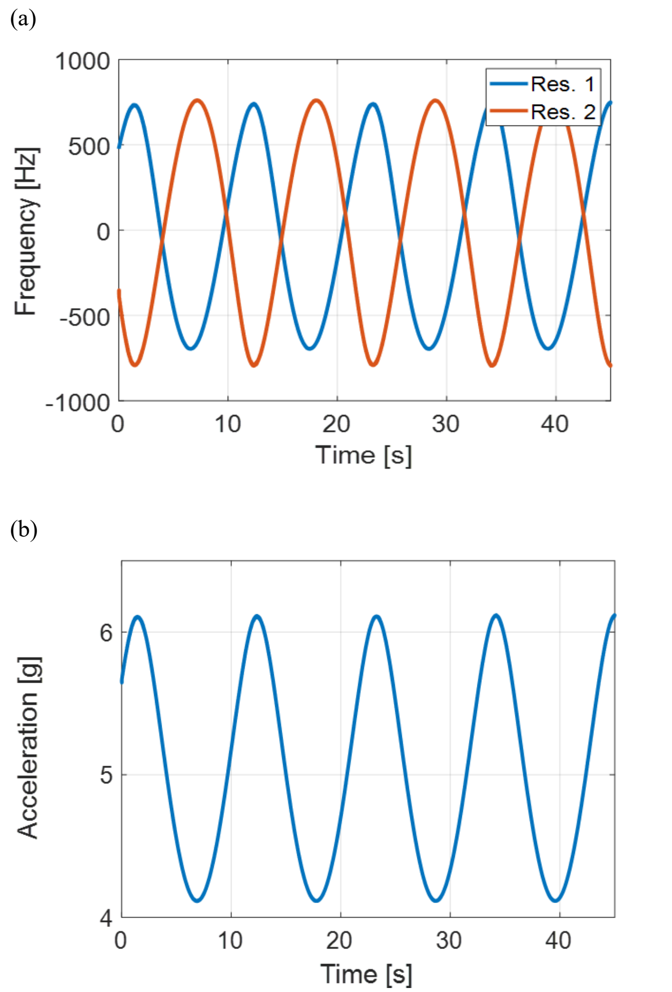


Fig.4 (a) Experimental natural frequency shifts of the two in-plane flexural resonators as a consequence of an applied sinusoidal *z*-axis acceleration ranging from -1g to +1g. A differential sensitivity of more than 1000Hz/g is obtained. (b) Differential acceleration measurements. An offset of around 5g is evidenced.

IV. Conclusions

An innovative high-sensitivity and compact *z*-axis FM accelerometer has been proposed, fabricated through the Thelma-Double fabrication process by STMicroelectronics and preliminarily tested. Experiments demonstrate a differential sensitivity, normalized to the rest frequency, of almost 1%/g.

The compact footprint of 1120µm x 608µm only and the central-anchoring system able to reject fabrication-induced and thermal pre-stresses make the present design very promising for future low-drift, high-end applications and put the basis for a new generation of FM *z*-axis accelerometers.

Future work will be addressed to the complete experimental characterization of the proposed device and to the comparison of experiments with numerical models.

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