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Frequency Modulated Magnetometer Using a Double-Ended Tuning Fork Resonator †

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Abstract: A Lorentz force MEMS magnetometer based on a double-ended tuning fork (DETF) for out-of-plane sensing is presented here. A novel configuration using a hexagonal-shaped Lorentz force transducer is used, which simplifies the sensor configuration and improves its sensitivity. Frequency modulated devices were fabricated in an in-house process on silicon on insulator wafers (SOI) and then tested in vacuum. The final devices have a differential configuration and experimental characterization shows a sensitivity of 4.59 Hz/mT for a total input current (on the Lorentz bar) of 1.5 mA.

Keywords: MEMS; magnetometer; frequency modulated; Lorentz force

1. Introduction

Along the years, magnetic sensors have been widely used in numerous fields and several applications are reported, such as, magnetic resonance imaging (MRI) and magnetoencephalography [1]. In the literature, several technologies (magnetic tunnel junction, Hall-effect, anisotropic magnetoresistance, among others) have been presented, but their incompatibility with microelectromechanical systems (MEMS) fabrication processes have been an important downside [2]. Thus, MEMS magnetic sensors have become popular since they enable the possibility of integrating in a single chip accelerometers, gyroscopes and magnetometers [3]. Those sensors compose the multiaxis measurement units (IMUs) that are popular for navigation and their performance enhancement is of high importance in autonomous driving, for instance. MEMS magnetometers for in-plane [3,4] or out-of-plane [2,3] measurements were already presented, but no frequency modulated devices using DETF resonators were found. Additionally, the sensor developed is encapsulated in vacuum, enabling integration compatibility with some devices (i.e., gyroscopes), thus decreasing the chip size and production costs.

2. Magnetometer Design

The magnetic sensor here presented is composed by two components, a double-ended tuning fork (DETF) and a Lorentz force bar. This transducer produces a force (F) proportional to the length of the beam (l), the bias input current (I_b) and the magnetic field (B).

$$F = l * I_b * B \quad (1)$$

The resulting force induces a stiffness change in the DETF beams and thus a frequency shift in their natural frequency that is proportional to the external magnetic field. Since the force can be positive or negative accordingly to the direction of the field, a bi-directional sensing is available.

Nonetheless, the use of a DETF and a Lorentz force transducer can be challenging because of the high axial stiffness of the DETF and the low elastic constant of the Lorentz bar, in such conditions, the lack of spring compliance jeopardizes the force coupling. For this reason, an optimization of the Lorentz bar shape and features' dimensions was performed using parametric design linked with a FEM tool. A theoretical sensitivity of 0.25 Hz/mT for a bias current of 1mA was simulated on a hexagonal-shaped Lorentz force transducer (see Figure 1). In the final design, a differential configuration was implemented to double the sensitivity and eliminate common mode errors (i.e., temperature dependency). The differential configuration is composed by two DETF resonators and two Lorentz force transducers.

The devices were fabricated in an in-house two-masks SOI process with a 25 μm active layer (see Figure 2) and tested in vacuum.

Regarding the fabrication process, a layer of AlSiCu was deposited on top of the Lorentz bar to lower the resistivity of the current path and thus decrease the voltage applied and the resultant temperature. Additionally, the same alloy is used for all the electrical contacts.

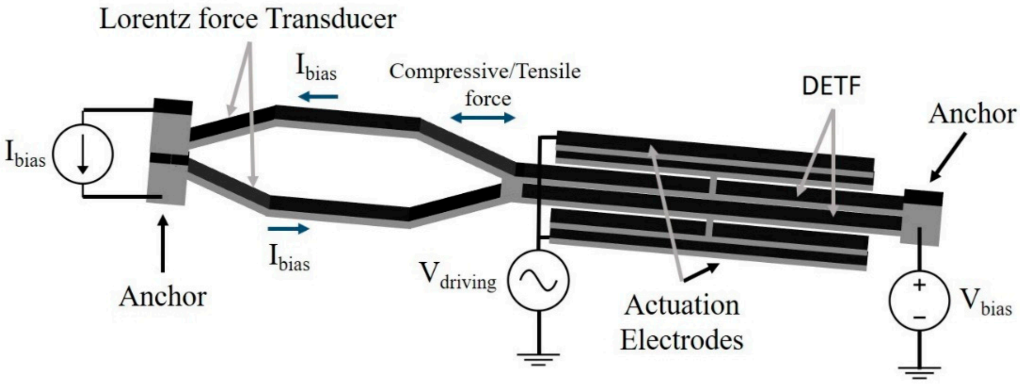


Figure 1. Scheme of the magnetometer composed by a DETF and hexagonal-shaped Lorentz force transducer. All the electrical connections used during the characterization are also represented.

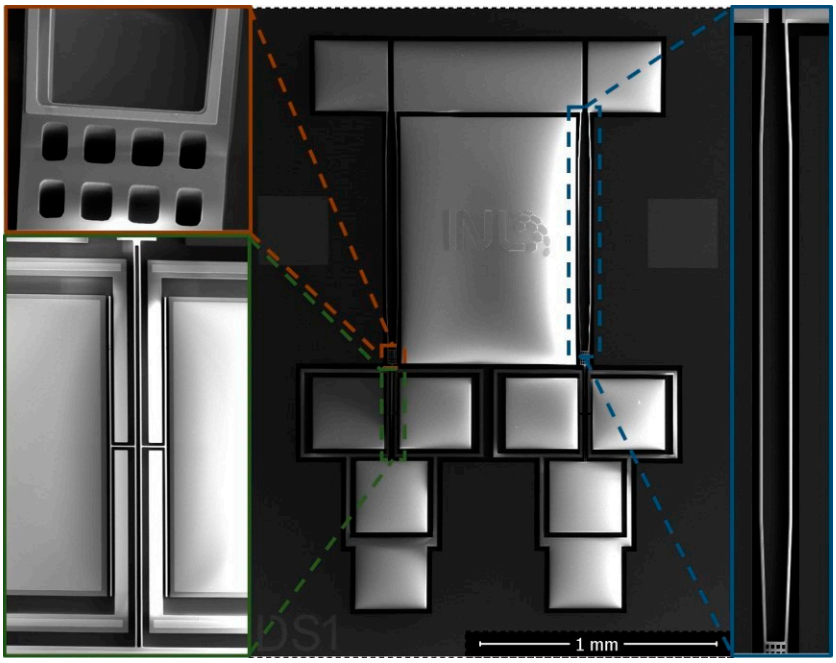
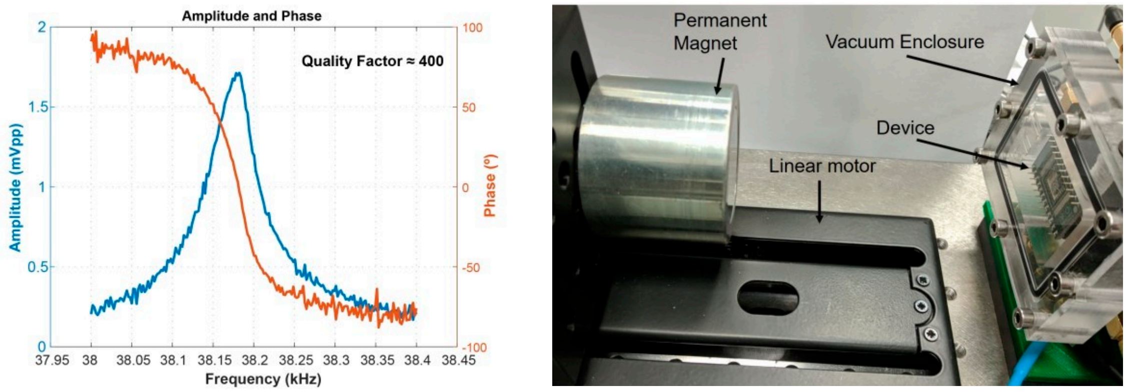


Figure 2. SEM image of the fabricated device.

3. Experimental Results

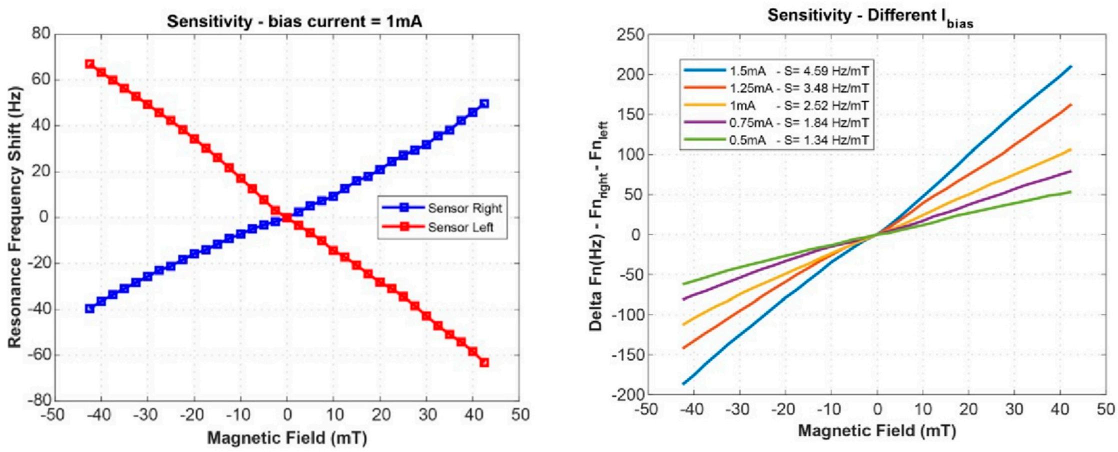
After fabrication, the devices were inserted in a vacuum chamber and characterized at low pressures. Resonance frequencies around 38.2 kHz and quality factors close to 400 were experimentally measured using a lock-in amplifier and a transimpedance amplifier, as shown in Figure 3a. For sensitivity measurements, the devices were characterized on a setup composed by a permanent magnet (capable of magnetic fields above 100 mT) and a linear motor to change the distance between the magnet and the sensor (see Figure 3b). In addition, a reference Gaussmeter was strategically placed close to the device for calibration of the measurement system.



(**a**) (**b**)

Figure 3. (**a**) Amplitude and phase measurements of one DETF. (**b**) Picture of the measurement setup and its components.

The curve shown in Figure 4a represents the frequency changes of the two resonators in the differential configuration, when an external field is applied. The magnetometer is composed by a DETF on the left and another on the right, and since the current on their Lorentz bar flows on opposite directions, one is subject to tensile force while the second suffer from compressive force. This explains the behavior of the curves, where the resonance frequency is increasing on the right sensor while it is decreasing on the left device.



(**a**) (**b**)

Figure 4. (**a**) Resonance frequency changes for the left and right resonators for a bias current of 1 mA and (**b**) sensitivity of the frequency modulate sensor for different bias currents.

The sensitivity of the magnetometer for several bias currents flowing through the Lorentz force transducer was also evaluated, and experimental results are presented in Figure 4b. In fact, the sensitivity increases, as expected, for higher currents due to a higher force produced by the transducer. Though, the sensitivity is not increasing linearly for the higher currents and this effect still needs to be studied. A maximum sensitivity of 4.59 Hz/mT for a bias current of 1.5 mA (for each Lorentz bar) was experimentally measured.

The shift in the resonance frequency was measured using a closed-loop system composed by a Field-programmable array (FPGA) that in real time updates the driving frequency to the resonance frequency of the sensor. A proportional controller was implemented to perform such task and the output of the system is a voltage proportional to the frequency shift.

4. Conclusions

A magnetometer composed by a differential configuration of Lorentz bar transducers and DETF resonators is here proposed. The sensor shape was optimized using a FEM software linked with a parametric CAD design to enhance its sensitivity. The device was fabricated in an in-house process on SOI wafers with two-masks only. A characterization of the sensor response was performed for both resonators of the differential architecture when encapsulated in vacuum. A sensitivity of 4.59 Hz/mT was experimentally measured validating the concept. The simplicity and small core size of the sensor element (below 0.25 mm^2 for the differential configuration) are a huge benefit of the proposed approach.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kumar, V.; Ramezany, A.; Mahdavi, M.; Pourkamali, S. Amplitude modulated Lorentz force MEMS magnetometer with picotesla sensitivity. *J. Micromech. Microeng.* **2016**, *26*, 105021, doi:10.1088/0960-1317/26/10/105021.
2. Laghi, G.; Marra, C.R.; Minotti, P.; Tocchio, A.; Langfelder, G. A 3-D Micromechanical Multi-Loop Magnetometer Driven Off-Resonance by an On-Chip Resonator. *J. Microelectromech. Syst.* **2016**, *25*, 637–651.
3. Li, M.; Ng, E.J.; Hong, V.A.; Ahn, C.H. Single-structure 3-axis lorentz force magnetometer with sub-30 nT/sqrt(Hz) resolution. In Proceedings of the IEEE 27th International Conference on Micro Electro Mechanical Systems (MEMS), San Francisco, USA, 26–30 January 2014; pp. 80–83.
4. Dellea, S.; Laghi, G.; Langfelder, G.; Longoni, A.; Minotti, P.; Tocchio, A.; Zerbini, S. Off-resonance operation of in-plane torsional MEMS magnetometers. *Procedia Eng.* **2014**, *87*, 819–822.