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Using a MEMS pendulum to measure the gravity gradient in orbit: a new concept for a miniaturized Earth sensor

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Abstract

We present the fabrication and test results of a novel inertial sensor for use onboard satellites, to obtain the Earth vector. Current state-of-the-art Earth sensors determine the Earth vector by imaging the Earth's horizon in the IR. This requires multiple optical heads on different faces of the satellite, with associated mounting and thermal considerations. The MEMS-based approach reported here is based on measuring the gravity gradient vector by measuring the gravity gradient torque on a 4 cm long Si-pendulum. This approach eliminates the need for multiple external access ports, allowing a compact sensor to be situated anywhere inside the spacecraft.

Keywords: Earth sensor; gravity gradient torque; inertial sensor, satellite

1. Sensor Design and Fabrication

The force of gravity reduces according to the inverse square law with the distance from the center of the Earth. This produces a torque on an elongated body in orbit around the Earth, called the Gravity Gradient Torque (GGT). The expression for GGT is given by [1],

$$GGT = 2\ GMass_{EARTH}\ I\ \sin(2\psi)\ /\ 3\ Radius^{3}_{ORBIT} \qquad (1)$$

where G is the gravitational constant, I the maximum moment of inertia of the elongated object, and ψ the angle between the Earth normal and the axis of minimum moment of inertia as seen in Figure 1.

1.1. Sensor Design

We use a pendulum that is attached to the satellite by a soft suspension. Under GGT, the pendulum rotates relative to the satellite, reaching an equilibrium position given by the GGT and the spring constant of the

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suspension. The rotation angle of the pendulum due to GGT depends on the angle to the Earth normal, and by sensing this displacement we can determine this angle, one of the two components of the Earth normal vector. For the inertial sensor mass we choose a barbell shape. This design maximizes the moment of inertia I and allows a differential readout scheme to be readily implemented.

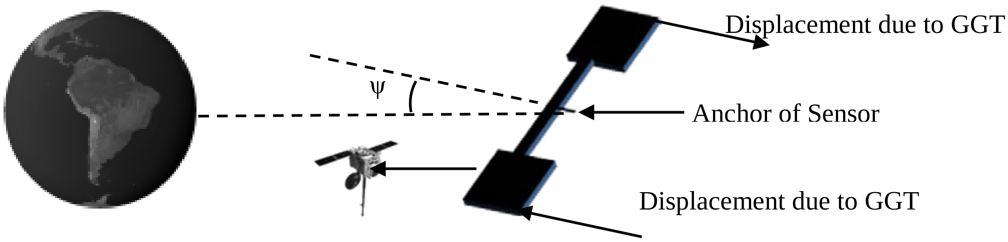


Fig. 1. The MEMS based Earth sensor on board a satellite. Its displacement depends on the angle ψ of its axis of minimum moment of inertia to the Earth normal

We use a mass of outline dimensions 1 × 4 cm^2 fabricated from both the device and handle layers of an SOI wafer (100 μm, 1 μm, 500 μm) whose weight is 0.33 g. The GGT on this mass is of order 1×10^{-13} N.m. To obtain a measurable displacement from this minute torque we suspend this mass by a very compliant spring, of dimensions 1 mm length, 15 μm wide, 100 μm deep, fabricated from the device layer of the SOI wafer. Though a larger pendulum mass with a softer spring results in a better SNR [2], the limiting factor for the size of the mass is both the need to fabricate several sensors per wafer, and the need to fabricate and test the sensor in a one gravity environment, which is more challenging for very large dimensions.

1.2. Microfabrication of the Earth sensor

With such a large mass suspended from a compliant spring, it can break off under routine handling unless it is constrained. The principal challenge of the fabrication process was to build in the restriction of motion of the sensor mass, so that the mass is protected before final release. The device and handle layers are etched using DRIE. The device layers has stoppers are etched into it which restrict the motion of the sensor mass in the X-Y plane. The chips are released from the wafer after the DRIE steps using HF vapor release, but keeping the sensor mass still attached to the chip via the buried oxide. To restrict motion in the Z plane, a Pyrex chip with spikes giving 30 μm clearances is bonded to the handle layer of the frame in a step similar to that in [3]. In the final step, using HF vapor release the sensor mass is released from the chip. It is constrained to a maximum displacement of 30 μm prior to the release (Figure 2). The fabricated sensor is seen in Figure 3.

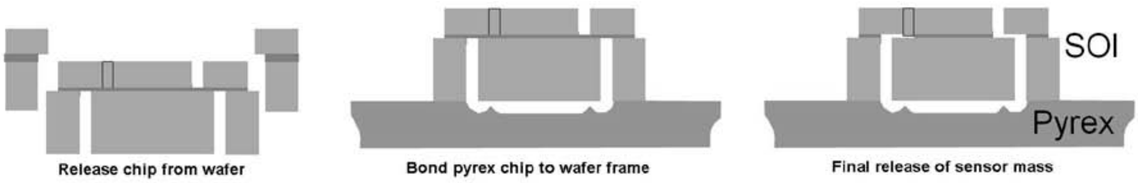


Fig. 2. Schematic of the last assembly steps. To prevent the spring from breaking during fabrication, the proof mass is only released in HF vapor after the SOI chip is bonded to an etched Pyrex wafer.

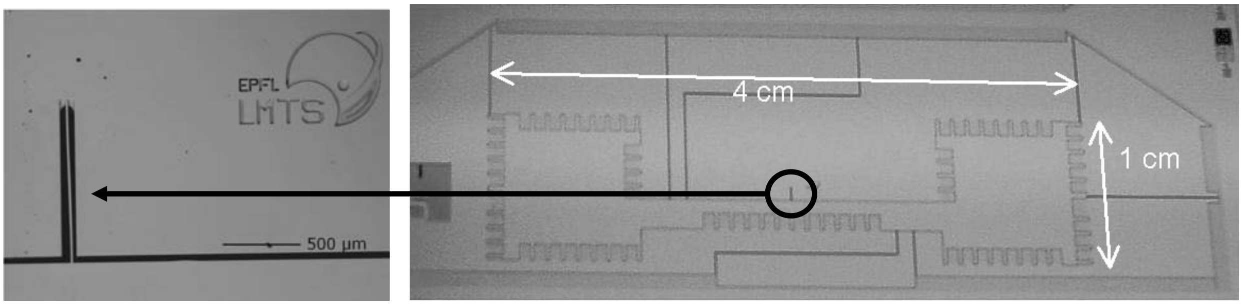


Fig. 3. (a) SEM image of the 1mm long, 15 µm wide, and 100 µm deep spring etched into the device layer of the SOI wafer. (b) Optical micrograph of the deep reactive ion etched silicon pendulum mass.

2. Detecting the displacement of the Earth sensor

The barbell is displaced on the order of nanometers due to GGT. To detect this displacement we use an integrated fiber based interferometer [4]. To build the interferometer, we etch a groove into the device layer of the SOI wafer during DRIE with clamps to hold the fiber in the groove. The fiber can be positioned at a known distance from the sensor mass as seen in Figure 4.

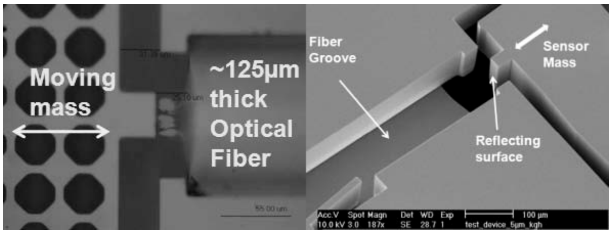


Fig. 4. (a) Top view of fiber interferometer integrated onto a test chip with 635 nm laser light exiting and being reflected back into single-mode fiber. (b) SEM image of fiber mounting and interferometer geometry on a fabricated MEMS Earth sensor.

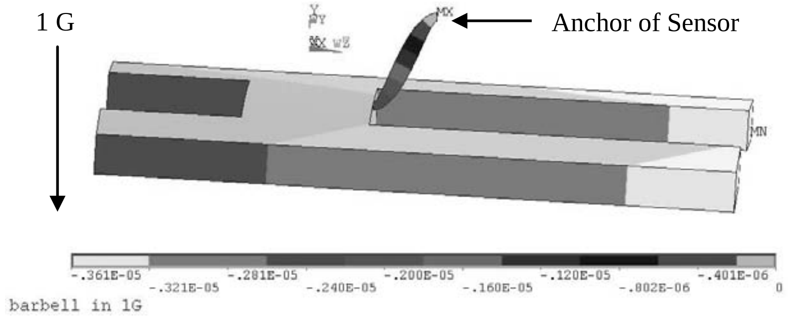
3. Testing the Earth Sensor

3.1. Test Setup

With its length of 1 mm and width of 15 µm, the spring of the sensor is designed to be compliant to GGT in the plane of the chip. Its depth of 100 µm is intended to make the sensor rigid in the direction of gravity for on-Earth testing. The barbell mass is distributed around the spring such that the mass remains parallel to the Earth's surface when the sensor is placed flat (Figure 5a). This enables the sensor mass to be freely suspended. The sensor is mounted on a rotary stepper motor stage capable of 1.25 millidegree resolution (Figure 5b). The stage is rotated until the chip is flat enough and the sensor mass is free to move. Using a piezo driven tilt stage, arc second tilts are applied leading the same nm scale motion expected from GGT in zero gravity.

3.2. Testing the displacement readout

When the tilt stage is moved through very small angles, the sensor mass moves by nm relative to the fiber tip. The tilt due to the piezo stage was recorded using a laser positioned to reflect light off the chip onto a Position Sensitive Detector (PSD) and could be controlled from 0.000 ° to 0.014 °. Using FEM, the displacement of the sensor mass relative to the fiber tip was determined to be 21 nm for the maximum tilt. The resulting change in the photocurrent at the measuring photodiode of the fiber interferometer is recorded for this 21 nm displacement of the sensor mass (Figure 6) as the device is tilted, yielding an interferogram showing that nm motion can readily be detected with this device.



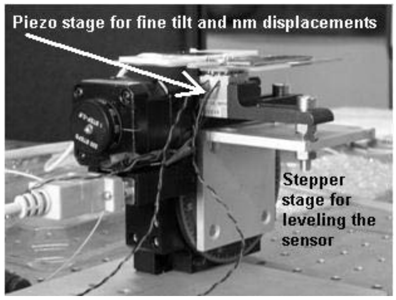


Fig. 5. (a) FEM simulation with ANSYS showing the side view of the barbell. It can be seen that the mass sags by only a few microns in one gravity. (b) The test stage with the sensor mounted on top of a piezo stage, which is in turn mounted on a rotary stepper motor stage

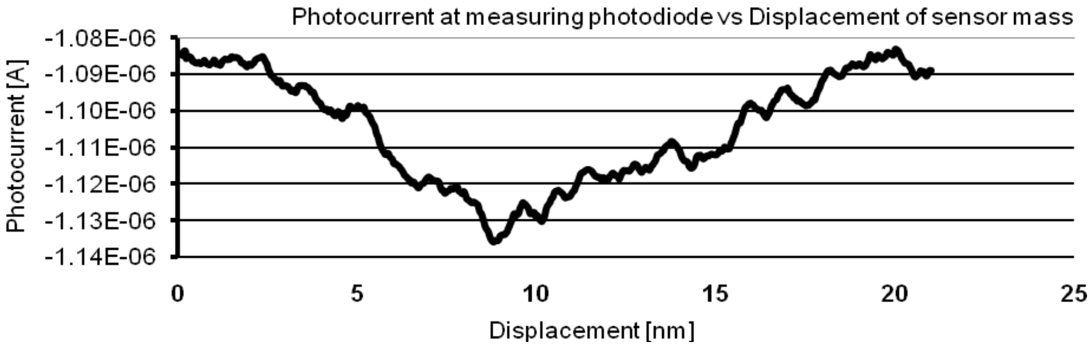


Fig. 6: Photocurrent at measuring photodiode, of the fiber interferometer of Earth sensor, as the tilt of the tip-tilt stage piezo is increased, leading to up to 21 nm displacement. The interferogram allows a position readout accurate to of order 1 nm.

4. Conclusions

We were able to fabricate and test in a one gravity environment a sensor designed to detect torque in microgravity. The fabrication process that has been developed will allow more robust sensors in the future without reducing the sensitivity. Figure 6 shows that the photocurrent changes significantly as the sensor mass moves in the 10 nm range. The accuracy is on the order of roughly 1 nm with the direct measurement of the photocurrent. The accuracy can be improved by adopting closed loop techniques and phase sensitive detection. In orbit such as sensor will determine the angle between the spacecraft and the Earth with approximately 1° accuracy.

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