Geotechnical Inclinometer Sensors in Optical MEMS

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We have designed, fabricated and tested small and cost-effective tilt meter sensors for structural health monitoring using simple and inexpensive MEMS technology and fiber-to-chip assembly. The packaged devices show excellent linear response and angular resolution as low as 0.014 mm/m (14 µrad).

Inclinometers are used in a variety of monitoring applications in civil and geotechnical engineering. Together with strain, displacement and pressure, tilt is one of the most important indicators of structural health and performance. Currently, the most used tilt sensors are based on electrical sensors, which suffer from significant limitations for uses where electromagnetic disturbances are present, for example in proximity of train lines or in structures subject to lightning strikes. The maximum cable length is also limited for electrical sensors, which poses a problem for the monitoring of very large structures, in particular dams and dykes.

Optical fiber sensors are typically used to address those limitations thanks to their insensitivity to electro-magnetic interference and the ability to transmit information over long distances. Some optical fiber inclinometers have been developed in the past but are typically bulkier and more expensive than the conventional sensors and offer inferior performance. Existing fiber optic tilt sensors are based on conventional mechanical concepts with mechanical pendulums applying strain to a sensing optical fiber. Because of the fiber rigidity, large masses are required in the pendulum and this makes the sensors bulky and expensive.

In collaboration with Smartec SA we have developed the inclinometer concept which is based on a miniature, MEMS seismic mass that moves when the sensor axis rotate in respect to the earth gravity vector (Figure 1). The mass movement induces a variation of a Fabry-Perot (FP) cavity gap. The tilt meter sensor extracts the information on the gap by analyzing the optical spectrum coming from the FP cavity formed by a fixed optical fibre and a movable MEMS mirror. Thus, the sensor measures the inclination through calculation of the FP gap.

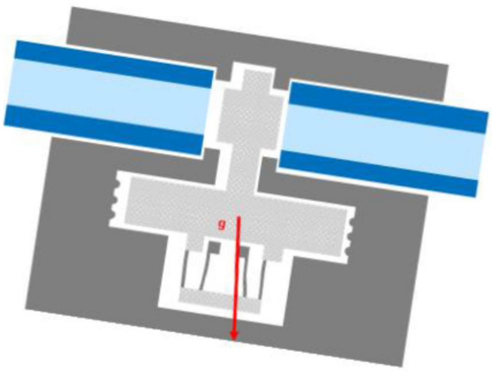

Figure 1: A concept for a Fabry-Perot optical MEMS inclinometer.

A module based on a single Fabry-Perot cavity is already sufficient for most of the applications. However, in some cases a module based on a dual Fabry-Perot cavity (as shown in Figure 1) is required; in presence of thermal expansion a single cavity module would not be sufficient to discriminate a gap variation due to module rotation or due to thermal dilation. With two cavities operating in opposition when the module is subjected to rotation and operating in synchronous for thermal expansions, the two contributions can be separated.

Following COMSOL simulations (mechanical performance) and ZEMAX simulations (optical performance), the microfabrication of the sensing chip is performed following a simple 3-mask process based on silicon-on-insulator wafers, standard photolithography, dry etching and HF release steps. An example of a fabricated chip is shown in Figure 2.

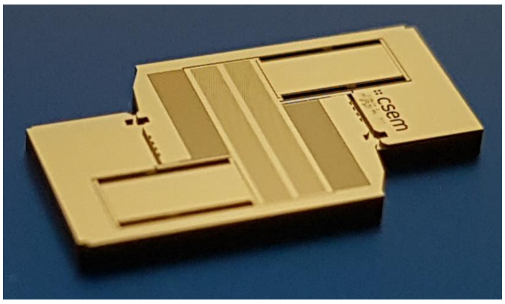

Figure 2: Fabricated silicon inclinometer chip from SOI wafer.

Custom designed supports made in PEEK material are used to house the silicon chip and to attach the multi-mode optical fibres (62.5 / 125 / 250 µm). The non-hermetic assembly procedure has been performed on a 5-axis stage while actively monitoring the intensity and quality of the optical signal exiting the fibres.

The inclinometer prototypes are tested in laboratory conditions after preliminary stress, shock (500g) and thermal cycling tests (-40°C - 80°C), which did not affect the sensor performance. The typical calibration curve of a packaged chip is plotted in Figure 3. It shows a relation between the FP gap distance and the chip tilt. The sensors are designed to work in a max ±5° range. The values simulated in COMSOL and experimental results are in excellent agreement, giving the highest sensitivity in a range around 14.5 µrad/nm. Considering that the developed read-out module can detect 1 nm displacements, this value translates to 14.5 µrad angular resolution (0.014 mm/m). The obtained sensitivity is far below the target performance set by the client to 100 µrad, typically stated for state of the art optical fibre inclinometers.

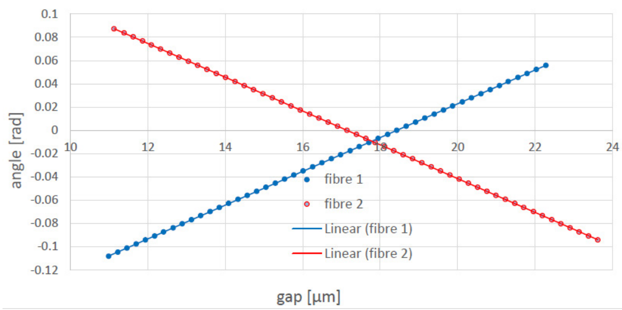

Figure 2: The linear fitting of the inclinometer calibration curve.

The inclinometer devices are currently undergoing additional field testing and characterization as a preparation for the device 2nd level packaging and industrialization.

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