Integrated Optics Inclinometers for SHM

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ABSTRACT: 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. Inclinometers are also used to monitor subsurface movements and deformations. In this contribution we present the development, qualification and testing of a novel fiber optic inclinometer based on integrated optics microfabrication. The new device offers performances in line with the standard electrical tilt sensors, is small and light and is compatible with existing Fabry-Perot readout modules already used to measure other optical fiber sensors (e.g. strain, temperature, displacement and pressure sensors).

1 INCLINOMETERS

Currently, the most used tilt sensors are based on electrical sensors (see figure 1). These electrical technologies have limitations in their use when electromagnetic disturbances are present, e.g. 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 EM 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, Ferdinand (2000), He, Shaoling, et al. (2010), Inaudi, Glisic (2002), Todd, M. D., et al. (1998).

Typical applications include:

- Detecting zones of movement and establish whether movement is constant, accelerating, or responding to remedial measures,

- Verifying stability of dams, dam abutments, and upstream slopes during and after impoundment,

- Monitoring settlement profiles of embankments, foundations, and other structures (horizontal inclinometer),

- Detect differential settlements in buildings and bridges that produce a tilt of the structure,

- Monitoring of Oil & Gas structures such as off-shore platforms, risers.

There is a market need for a small, accurate and cost-competitive tilt sensor that can be used as a stand-alone product or in combination with other existing optical fiber sensors.

Such an optical inclinometer will enable new applications that are currently impossible or impractical to address with conventional electrical sensors. This includes in particular the monitoring in environment with strong electromagnetic disturbance (e.g. close to generators and power lines) or in explosive environments (oil wells, off-shore platforms, chemical plants). Besides the civil engineering and geotechnical applications, other potentially interesting markets will be explored, such as patient movement monitoring during MRI procedures.

Figure 1. Typical electrical / MEMS inclinometers.

2 SENSOR DESIGN

The sensor design of the new optical tilt sensor is based on a silicon micro-machined sensing element. This enables a significantly smaller, cheaper and more reliable sensor compared to existing fiber optic sensing tiltmeters.

The silicon chip is manufactured on 150 mm wafers with a chip area is 40 mm2. This means about 300 chips per wafer. Considering a chip yield of 70%, it makes about 200 chips per wafer.

The main scientific and technological objectives of the project are:

- Design, simulation and fabrication of a silicon based optical inclinometer sensor. The sensor will be interrogated via two optical fibers by a remote electronics. The sensor has to be fully compatible with existing Fabry-Perot sensing interrogators. The sensor incorporates a silicon sensing part and U-groove channels to accommodate and hold in place the optical fibers.

- Design and fabrication of 1st level package to accommodate the optical MEMS sensor.

- A second level packaging solution to accommodate the packaged (first level package) inclinometer module. Those packaging is devoted to surface mounting and borehole installation respectively.

The main specifications for the optical tilt sensor are reported in Table 1.

Table 1. Key specifications of the optical tilt sensor

General specification	Value
Silicon chip dimensions	Target area: ~40mm^2 Fabricated on 150mm SOI wafers Chip lateral size: < 15mm No constraints on the longitudinal dimension
Operational temperature range	-40°C to +80°C
Angular measurement range	± 10 deg
Angular measurement resolution / accuracy	0.1 mm / m (100 micro rad)
Optical fibers	Single-side access on the sensor head
Distance between sensor head and electronics	1 km
Optical gap	12 to 18 microns of full scale tilt measurement
Optical fibers	Multimode Single-side access Fiber must exist vertically from the MEMS chip

2.1 Fabry-Perot sensing

FISO Technologies' patented white-light cross-correlator offers a unique and powerful way to make absolute Fabry-Perot cavity length measurements with astonishing accuracy and linearity, providing consistency time after time. The principle behind this sensing technology is actually quite simple although some technical details have to be considered in order to manufacture such device. A light source, namely, a bright incoherent light source, is first injected and guided into a multimode optical fiber and then into an input of a coupler which acts as a 50/50 power splitter. One output is linked to the fiber optic sensor through an optical connector at the signal conditioner front panel. Then, the light travels through the lead optical fiber until it reaches its tip, where the sensor is assembled.

The core of the sensor is a Fabry-Perot interferometer, a technology that has been well-known in the optical scientific community for over a century, having been used in many research applications such as physics and astrophysics. It is constituted by two parallel, perfectly flat, semi reflecting mirrors separated by a given gap. The light passing through a first mirror is reflected back and forth a very large number of times between the two parallel mirrors. However, at each reflection, a small fraction of the incident beam escapes the interferometer creating a large number of parallel beams of light emerging at the same angle at which they entered the interferometer. In the free space, they could be focused to form an image by a converging lens creating a constructive interference by the multiple beams which produce very bright and sharp interference fringes. Their spacing will depend on the optical path (that is related to the distance separating the parallel planes and the refractive index between those planes) and naturally on the light wavelength. Thus if a physical parameter to be measured by the sensor changes the optical path difference (OPD) of the Fabry-Perot interferometer, the light escaping this interferometer will be encoded according to this variation.

Figure 2 shows the Fabry-Perot interferometer working principle.

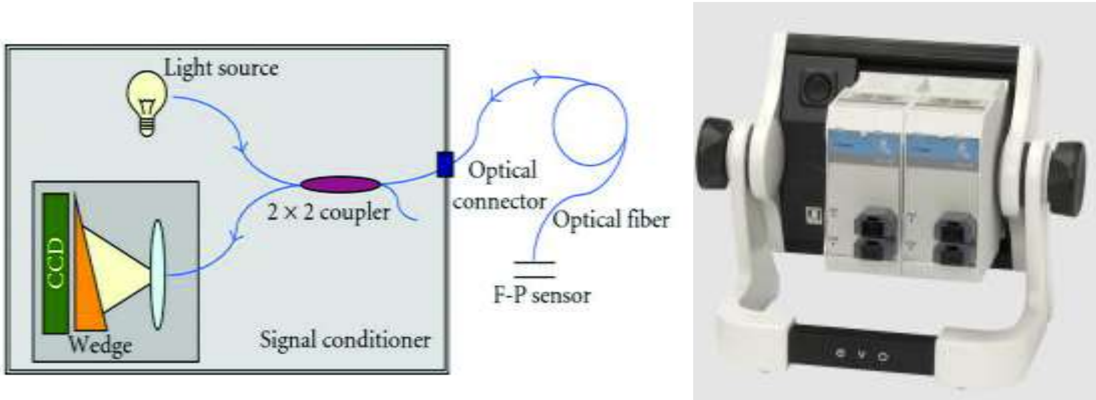

Figure 2: Schematic description of the Fabry-Perot absolute measurement signal conditioner using white-light interferometry (left). Examples of Fabry-Perot readout (right).

2.2 Device design

The proposed device is based on a CSEM process platform that is used for several other products, like for example watch components. The concept of the proposed inclinometer is shown in Figure 3. The optical sensor is based on a seismic mass that moves when the sensor axis rotate in respect to the earth gravity vector. The seismic mass movement induces a variation of a Fabry-Perot cavity gap; by reading such variation with a white light interferometric module, the information on the rotation angle can be extrapolated.

A module based on a single Fabry-Perot cavity is already sufficient for most of the applications; in some cases, a module based on a dual Fabry-Perot cavity is required: in fact, in presence of thermal expansion a single cavity module wouldn't 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.

Figure 3 shows the principle of the transduction of a rotation into a variation in the Fabry-Perot cavity dimensions.

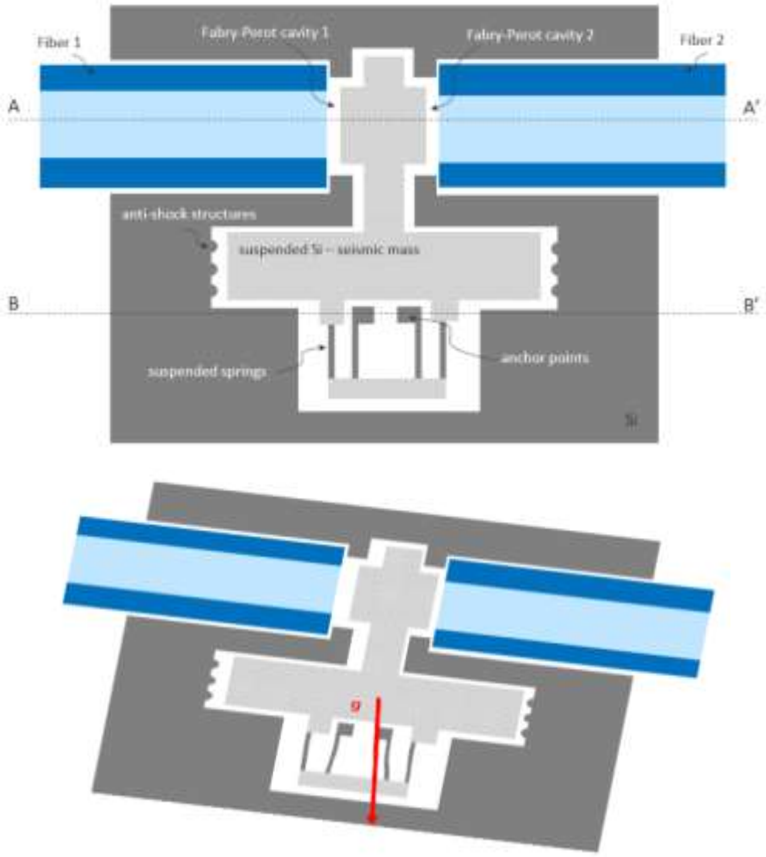

Figure 3: Schematic description of the Fabry-Perot absolute measurement signal conditioner using white-light interferometry. Steady state for the sensor when the seismic mass direction of movement is perpendicular to the earth gravity vector. When the sensor is subjected to a rotation, the gravity causes a lateral movement of the seismic mass, thus a variation in the Fabry-Perot cavity dimensions.

3 PROTOTYPE CHARACTERISATION

The optoinclino pototypes are assembled on a PEEK package, connected with two glass fibers with ST connector; 2 meters, 62.5 / 125 / 250 µm, temperature range: -40°C to 85°C.

Figure 4 shows a completed device.

The manufactured chips are tested in the laboratory conditions. The testing setup is installed on the optical table which has vibration isolation, see Figure 5. The testing setup consists of:

- The inclination stage, whose angle is manually changed,

- The angle reader, used for the calibration of the tested chips (right),

- The FP gap readout module, to which can be attached up to 4 different channels (left),

- The optinclino chip to be tested, attached with a screw to the stage (encircled in blue).

Figure 4: Completed device with 1st level package.

Figure 5. The optical setup for the characterization of the manufactured chips.

Each of the chips has two fibers attached, allowing two chips to be measured simultaneously on a single readout module. The readout module is connected to the computer and is capable of monitoring the quality of the signal coming from the chip and saving the results upon the end of the measurements. This feature was used for the signal stability measurements over few hours or overnight. As for the characterization of the inclinometer performance the following characterization method was used:

- The chip was positioned roughly at 0° with respect to the vertical axis,

- The angle was changed manually in steps of 0.2° (sometimes larger, but always to have more than 20 points) and values from the readout module for both fibres have been recorded,

- After reaching the saturation region on one side, the angle was reset to roughly 0° and the measurement was repeated in the opposite direction for angles.

The typical values of a measured chip are plotted in Figure 6. It is clear from the figure that the calibration curve has three distinct regions: linear, non-linear and saturation. The chips are designed to work in a max ±5° range (some less depending on the design i.e. on the beam stiffness).

Both channels of the chip work and have the same slope in the linear regime. The two calibration curves are not intersected at exactly 0°, which is only due to the non-perfect initial alignment of the chip to the inclination stage. In addition, the chip is not always perfectly vertically assembled on a chip holder.

Higher order polynomial fits to the raw data points have been performed until the error bar stabilizes and does not drop any further. As a general rule the 4th order polynomial fit did not show much improvement to the cubit fit. Figure 7 shows the residual error after a cubic fit has been applied. It can be noticed that the residual error is below 0.1 mrad in line with the project target.

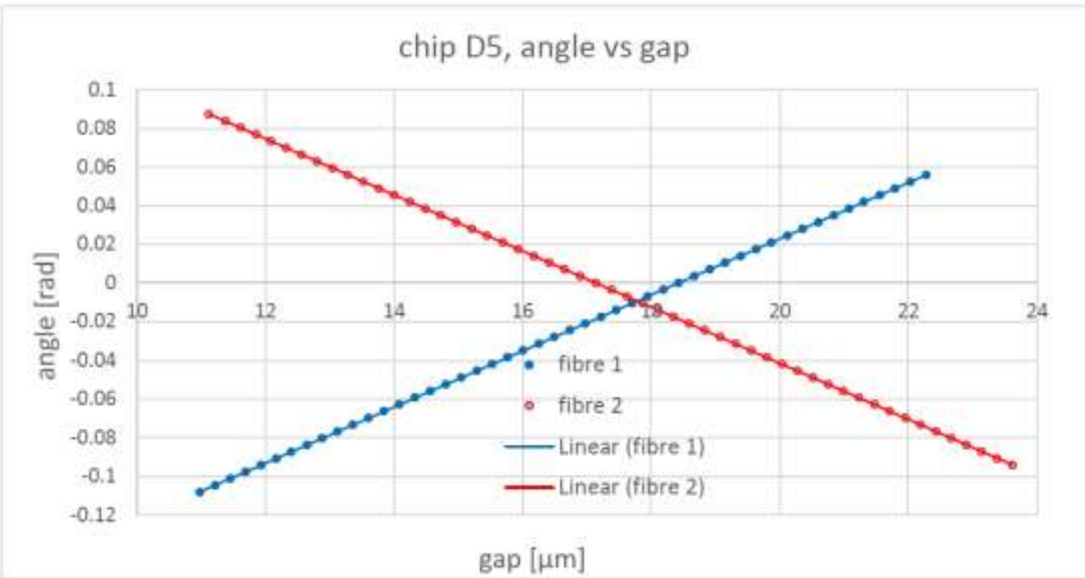

Figure 6. Optical characterization curve for chip D5. Sensitivities are estimated to be 11.68 µrad / nm.

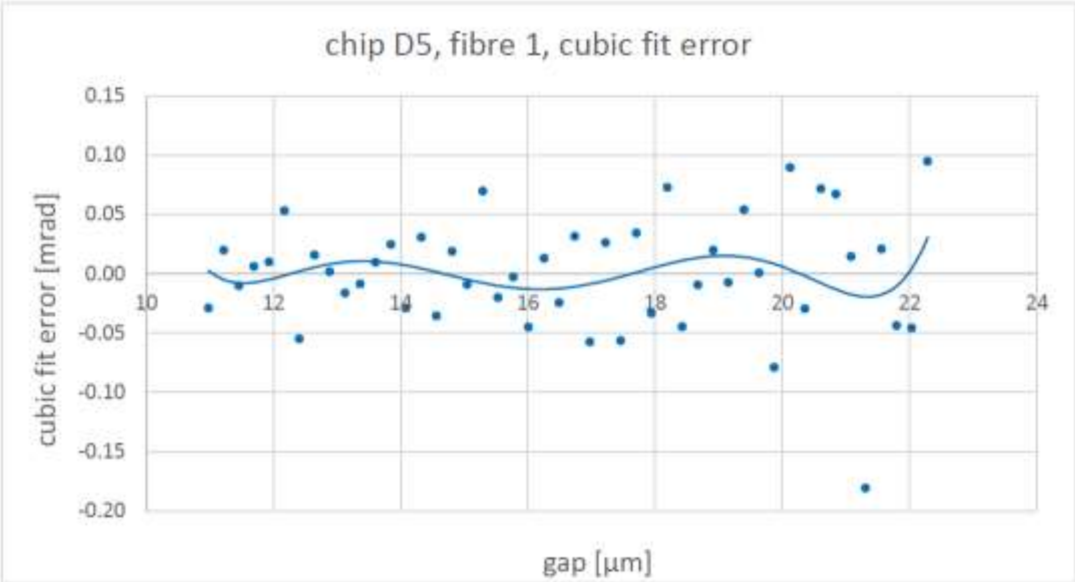

Figure 7. Cubic fit error for chip D5.

4 CONCLUSION

The presented fiber optical inclinometer meets the project goals of developing a small and cost-effective tilt meter that can be used in combination with other optical fiber sensors based on Fabry-Perot Technology, such as strain, piezometers, displacement and temperature sensors. The sensors are currently undergoing additional laboratory and field testing.

5 REFERENCES

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