OPTICAL MEMS-BASED SEISMOMETER ”WhiGS”

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ABSTRACT

Low-yield man-made seismic activity is difficult to detect and most often occurs in remote areas where seismic detection is weak. The Whispering Gallery mode based Seismometer (WhiGS), is an optical Micro-Electro-Mechanical System based (MEMS) instrument. The seismometer is a three-axis instrument, is compact, has low power consumption and is capable of unattended operation.

WhiGS exploits morphology-dependent optical resonance shifts in small dielectric spheres (<1 mm in diameter). These optical resonances, called whispering gallery modes (WGM), are extremely narrow, making the transducer highly sensitive to force ($< 10^{-9}$ Newtons). The MEMS sensing element in this seismometer has demonstrated an optical Q-factor of 10^7. As a result, the instrument is capable of measuring accelerations as low as 10 nano-g.

The engineering model to demonstrate the performance of the instrument has been built. Tests have demonstrated the sensitivity of the instrument. The development of the electronics is underway.

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Low-yield man-made seismic activity is difficult to detect and most often occurs in remote areas where seismic detection is weak. The Whispering Gallery mode based Seismometer (WhiGS), is an optical Micro-Electro-Mechanical System based (MEMS) instrument. The seismometer is a three-axis instrument, is compact, has low power consumption and is capable of unattended operation. WhiGS exploits morphology-dependent optical resonance shifts in small dielectric spheres (<1 mm in diameter). These optical resonances, called whispering gallery modes (WGM), are extremely narrow, making the transducer highly sensitive to force (< 10-9 Newtons). The MEMS sensing element in this seismometer has demonstrated an optical Q-factor of 107. As a result, the instrument is capable of measuring accelerations as low as 10 nano-g. The engineering model to demonstrate the performance of the instrument has been built. Tests have demonstrated the sensitivity of the instrument. The development of the electronics is underway.</td></tr>
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OBJECTIVES

Michigan Aerospace Corporation, in collaboration with Southern Methodist University, is developing a compact Whispering Gallery Seismometer (WhiGS). The sensing principle of the seismometer exploits the morphology-dependent optical resonance shifts of dielectric spheres to detect ground motion. These optical resonances are extremely narrow, making the transducer highly sensitive to ground motion. The small dielectric spheres are easily packaged into a small instrument capable of measuring accelerations as low as 10 nano-g.

The optical MEMS sensing element, typically a microsphere (with diameters in the range 200 to 1000 μm), is weakly coupled to an optical fiber, as shown in Figure 1a. The optical fiber, which carries light from a tunable laser, serves as an input/output port for the microsphere. When the microsphere comes into contact with an exposed section of the fiber core, light is coupled into the outer layer of the sphere, (Figure 1b). Its resonances are observed as sharp dips in the transmission spectrum as depicted in Figure 1d. When the sphere is compressed (as shown in Figure 1c), the wavelength of the resonances shifts.

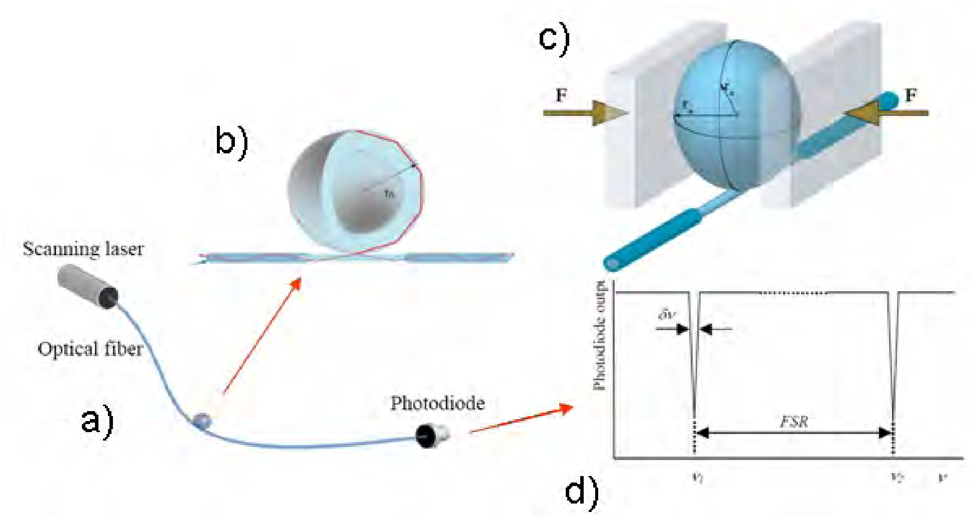

Figure 1: Principle of the WGM pressure-induced wavelength shift $\delta\nu$.

These optical resonances, also known as the "whispering gallery modes" (WGM), are extremely narrow and hence are highly sensitive to any morphological change in the microsphere. Other micro-resonator geometries, such as micro-discs, can be used as sensing elements in place of the microspheres.

The objectives include the fabrication of the dielectric microspheres, engineering model fabrication and preliminary tests, and instrument fabrication.

Objective 1:
The first objective of this effort is the experimental investigation of WGM characteristics of different-sized spheres (ranging from ~ 200 μm and 1 mm) and the fabrication of the microspheres. The candidate material to be used for the spheres is PDMS (commercially known as Sylgard 184). Different percentage of additives (cure agent) will be used to obtain different elastic modulus values and optical characteristics in order to determine the force sensitivity ranges that can be achieved and their suitability for the seismometer to be developed.

Objective 2:
The second objective was the fabrication of the engineering model to demonstrate the seismometer principle.

Objective 3:
The third objective entails the fabrication of the seismometer prototype.

RESEARCH ACCOMPLISHED

The transducer uses morphology-dependent optical resonances described by Benner and Hill (1988), WGMs in this case, investigated by Guan et al. (2006), to measure minute shape variations in dielectric spheres squeezed between the mass and the instrument base. Current studies by SMU using 0.7 mm spheres of another polymer, polydimethylsiloxane (PDMS), indicate that a force resolution of 10^{-8} N is possibly exploiting the same sensing principle. The dependence of the wavelength on the force is expressed as:

$$\delta F = \frac{\lambda}{Q}\left(\frac{d\lambda}{dF}\right)^{-1} \qquad (1)$$

where Q is the quality factor. The table below shows change of wavelength with force applied (dλ/dF) and the force resolution for several different sphere materials and dimensions. Polymer base-to-cure agent ratios of up to 60:1 were used in this investigation ($\frac{d\lambda}{dF} = 181 pm/\mu N$, ***Table 1***).

Our goal at onset of the program was to demonstrate the validity of the proposed concept using a bench test. To do so, a spring-proof mass assembly was designed, fabricated and tested to verify that

- The bandwidth extends over 40 Hz
- The spring is compliant enough to compress the sensing elements, i.e., the polymer microspheres
- And, the spheres register noticeable wavelength shifts at nano-g's acceleration.

The conceptual design of one axis of the seismometer is shown in Figure 2. The opto-mechanical assembly of the seismometer is composed of the spring-proof mass assembly and a polymer microsphere positioned between the proof mass and the seismometer base and an optical fiber to couple infrared light into the equatorial region of the microsphere. As the proof mass is set in motion by ground motion, the proof mass compresses a polymer microsphere. The morphological deformation of the microsphere under compression shifts the naturally occurring optical resonances in the sphere, proportionally to the physical deformation. The Q-factor of these optical resonances is ~10^7 thus providing the ability to detect acceleration as small as 10 nano-g.

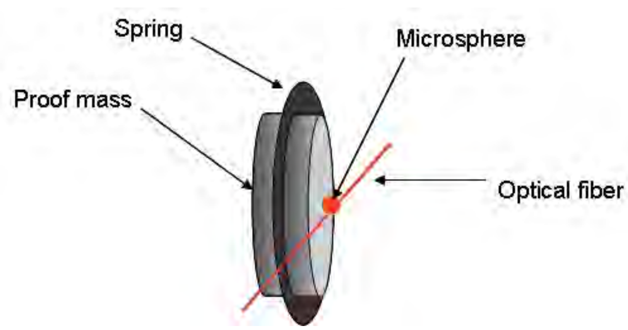

Figure 2. Whispering gallery mode based seismometer principle.

Table 1 lists the optimal characteristics for damping and sensitivity.

Table 1: Parameters for the mechanical design

Parameters	
Mass (kg)	0.01
Stiffness (N/m)	631
Resistance Constant (kg/s)	0.5
Sphere: PDMS	181 pm/μN
Q Factor (Mechanical)	5
Decay Modulus (s)	0.04

Spring Design

Finite element analysis was used to determine the optimal shape of the spring and the displacement. The spring must be sufficiently compliant to extend over a few nanometers and yet be stiff enough to ensure a flat response up to 40 Hz. The results of the spring design and deformation model is presented in Figure 3. The spring is composed of leaves that extend in the normal direction out of the plane of the spring. This design ensured radial stability under the gravitational acceleration. The thickness of the spring and the width of the slots define the spring stiffness, and two spring thicknesses were investigated.

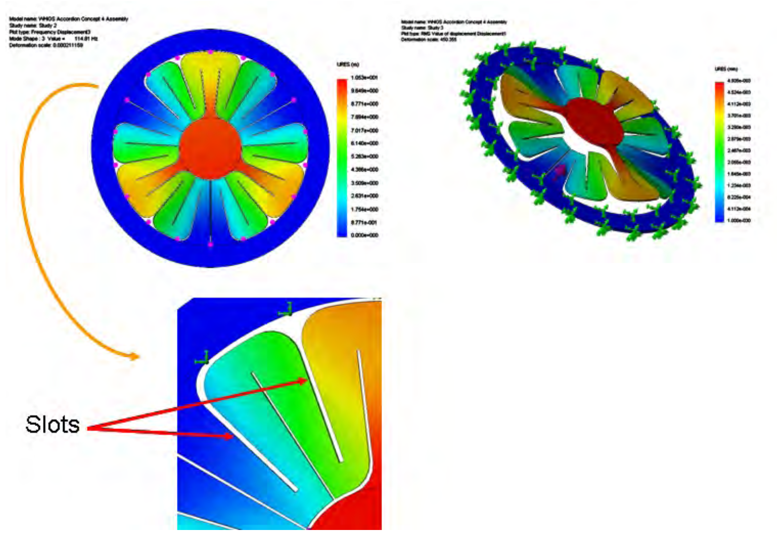

Figure 3. SolidWorks analysis of the spring design and deformation under static load.

Microsphere Fabrication

Our collaborator at Southern Methodist University, Professor Ötügen and his team, fabricated and delivered polymer (PDMS: polydimethylsiloxane) microspheres with curing agent ratios from 10:1 to 60:1. The curing agent ratio determines the hardness of the microsphere, 10:1 being the hardest. Figure 4 shows the microspheres held at the end of a fiber and a close up view of one of the spheres.

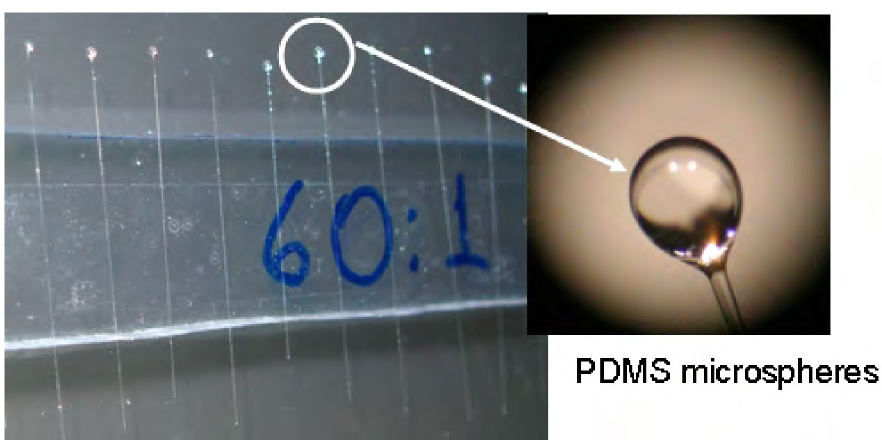

Figure 4 PDMS Spheres.

Accelerometer Design and Engineering Model

A prototype spring-proof mass assembly was fabricated and tested. Figure 5 shows a photograph of a spring and proof mass for the seismometer. The spring diameter is 0.88” (22 mm), thus very compact. The proof mass is 10 gm and fabricated out of tungsten. Springs of two different stiffness and slot widths were fabricated for testing.

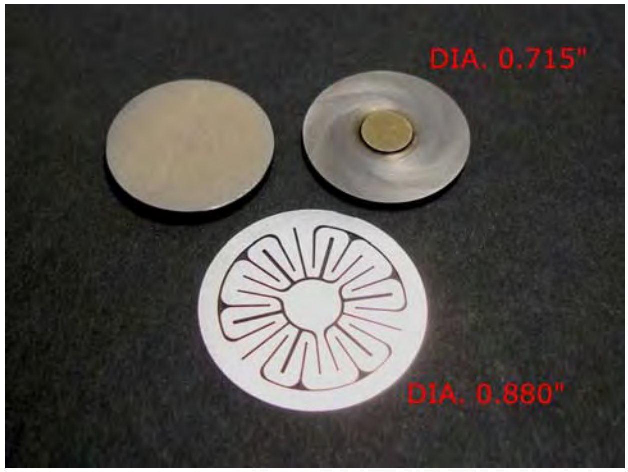

Figure 5 Spring and proof masses.

Test Results

A test rig, shown in Figure 6, was set up to measure the spring stiffness. The stiffness was measured by mass loading the spring with calibrated masses (against the gravitational acceleration) and measuring the elongation using a proximity sensor (placed under the spring). The results are shown in Figure 7. The spring stretched by 3.8 micrometer/gram, which provides a spring stiffness of 2.58 x 10^3 kg/s^2. For a proof mass of 10 gm, the resonant frequency is 80 Hz, sufficiently above the desired cut-off bandwidth at 40 Hz for the instrument. The spring elongation is a few hundred picometers, sufficient to generate a measurable shift in the whispering gallery mode resonance.

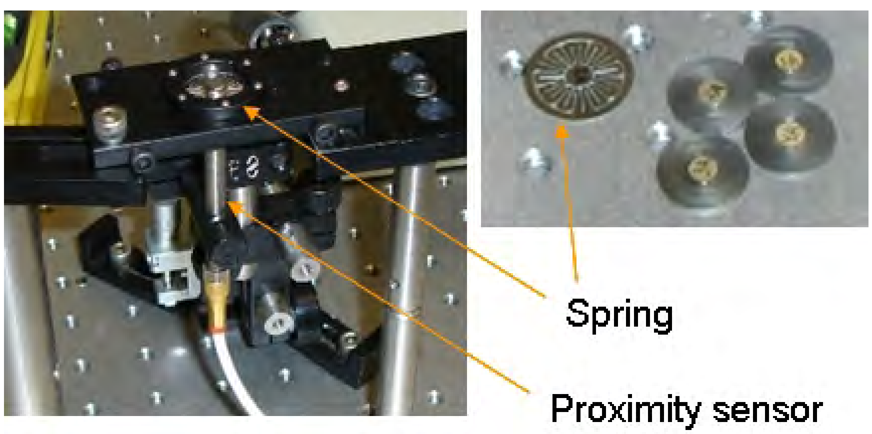

Figure 6. Test rig to measure the spring stiffness. (The tapped holes on the optical table are 1 inch apart).

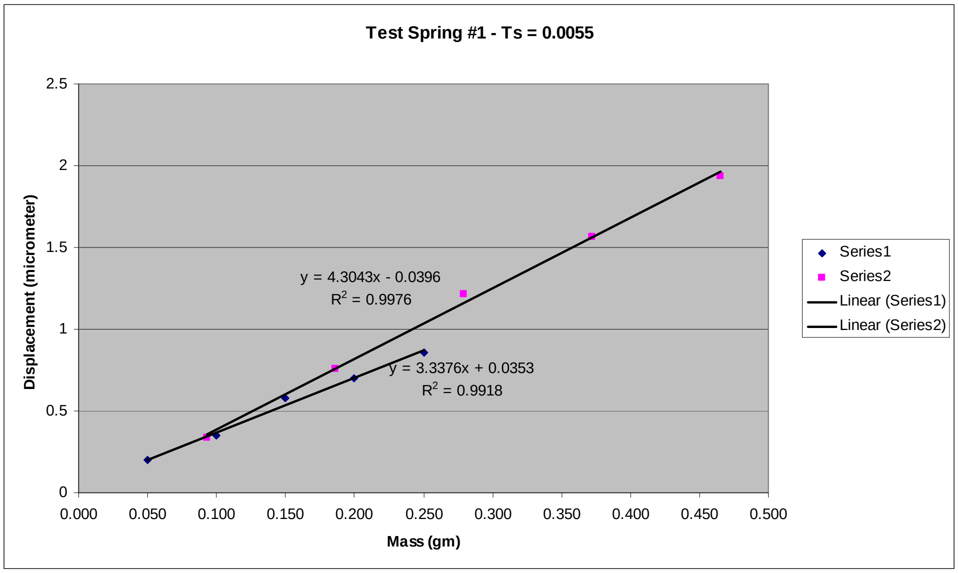

Figure 7. Test results to asses the stiffness of two springs.

Electronics

The development of the electronics entails the programming of an FPGA to digitize the output of the photodiode detector and track the resonance shifts caused by the deformation of the polymer microspheres under compression. The laser, laser driver and controller, fibers and photodiode detectors were assembled to characterize the laser performance and operating characteristics.

The laser has an integrated bias-t network inside the package that allows the use of an RF port on our laser diode holder to modulate the laser instead of using the modulation port on the laser controller. The lower cutoff frequency was near 650kHz therefore a capacitor was replaced to drive it with frequencies above 50kHz. The FPGA is currently being programmed for analog to digital conversion of the photodiode output.

The role of the processing electronics consists of identifying an optical resonance in the microsphere and tracking the wavelength shift of that resonance caused by the microsphere deformation, as shown in Figure 8. The processor instructs the driver controller to scan the current of the laser, and therefore the wavelength. The processor selects a resonance (dip in the detector output), and then instructs the driver controller to scan around the resonance. Once the processor is “locked” around a resonance, the current is dithered around that value.

Space conservation is paramount in the design of this small seismometer. The easiest way to conserve space is to reduce the number of pins and traces required for the circuit. All the components have been selected based on pin count and power dissipation. An analog-to-digital converter will be sampling the waveform detected from the photodiode. Parts are readily available with our constraints which dissipate roughly 3-5mW of power. The analog-to-digital converter would ideally be a serially-operated device to conserve the number of pins required for it to operate. Examples of such devices would be the AD7694 or the AD7685. A Field Programmable Gate Array (FPGA) was selected for this application (ACTEL Igloo Series). Assuming a 1-MHz internal clock rate and complexity similar to some of our other designs, the Igloo FPGA is expected to consume no more than 5mW of power. If for some reason the clock rate had to be increased to 5 MHz, the estimated power consumption would increase to about 15 mW (Table 2).

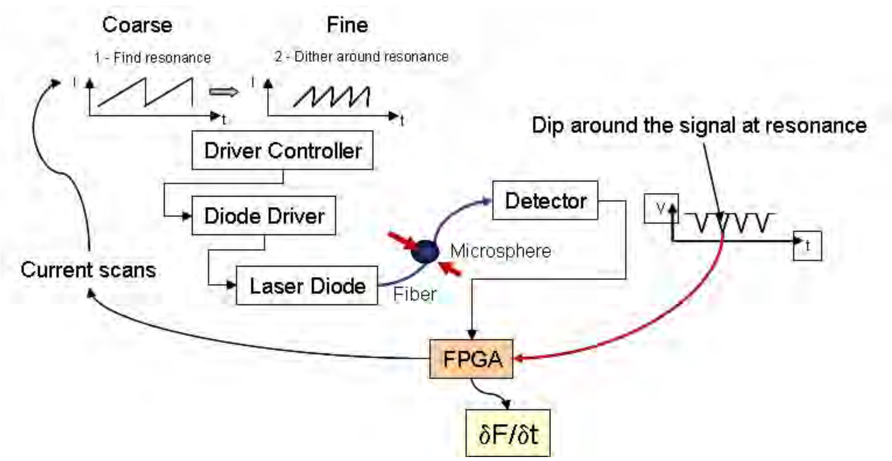

Figure 8. Functional diagram for the sensing element.

Table 2: Dissipation of the seismometer electronics components

Component	Dissipation (mW)
Laser Diode Controller	45
TEC Controller	100
Processor	15
Total	160

Our next effort entails installing a microsphere next to the proof mass and shaking the test assembly, as shown in the schematic in Figure 9. A shaker was purchased to test the instrument prototype.

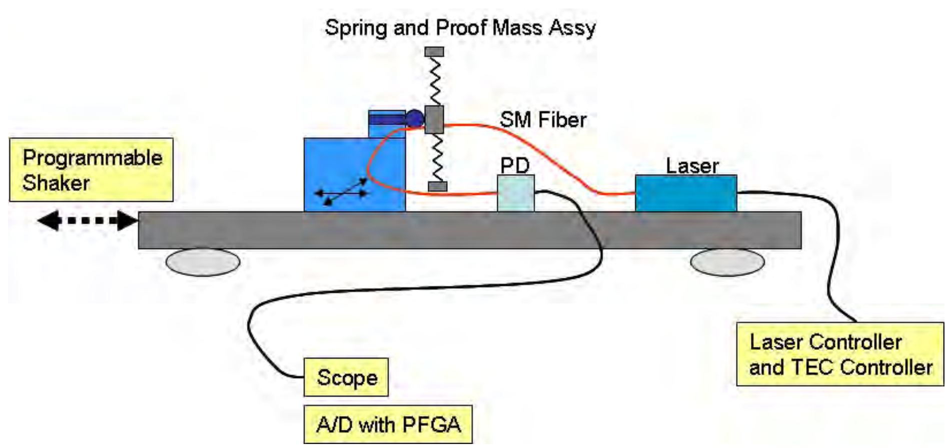

Figure 9. Schematic of test bench.

CONCLUSIONS AND RECOMMENDATION

The sensitivity of the sensing element was demonstrated using an engineering model. Results of photodiode outputs during acceleration will be pursued next.

REFERENCES

Benner, R. E.and S. C Hill (1988). Morphology-dependent Resonances, in *Optical effects Associated with Small Particles*, P.W. Barber and R.K. Chang, Eds., *Advanced Series in Applied Physics*, World Scientific.

Guan, G., S. Arnold and M. V. Ötügen, (2006). Temperature Measurements Using a Micro-Optical Sensor Based on Whispering Gallery Modes, *AIAA Journal* 44: 10, 2385–2389.

Ioppolo, T., U. K. Ayaz, U. K., and M. V. Ötügen (2009). High-resolution whispering gallery mode force micro-sensor based on polymeric spheres, Paper 2009-1450, 47th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, FL.