AN INTERFEROMETRIC MEMS SEISMOMETER: DESIGN AND TESTING

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ABSTRACT

Current nuclear explosion monitoring efforts focus on processing signals collected at teleseismic (>2000 km) and, increasingly, regional (200 to 2000 km) distances from relatively large source events. The transition from teleseismic to regional monitoring has required great efforts in signal processing techniques (because of the increased complexity of the regional signals) and monitoring station design (because of the expanded frequency range and increased sensitivity desired). Local seismic monitoring (0 to 200 km from the source event) is desired to push detection, location, and identification to significantly lower limits.

Effective local seismic and vibration monitoring will require small, easily deployed sensors that operate reliably, autonomously, and robustly, given deployment conditions. Placing sensors in the best locations to receive signals of interest may be very problematic. Local terrain, land use, and restricted access to the site may severely limit options for deployment. These factors drive size, power, and communications specifications for the sensor package, limiting choices among existing sensors to less sensitive devices. Miniaturization through micro-electromechanical system (MEMS) techniques is essential to build sensors of the size and capability needed.

The objective of this project is to develop technology needed to build a new seismic sensor that is very sensitive but extremely small. A prototype sensor will be developed through integration of a MEMS optical grating transducer with an optoelectronic source, photo detector, and associated electronics. In the near term, this sensor will be capable of motion detection on the order of 10 ng/√Hz over a frequency band of 0.1 to 50 Hz with a large dynamic range, while offering a factor of 10 reduction in size over existing technologies. The mid-term goal for this proposal is to reduce the noise floor down to 1 ng/√Hz. The longer-term goal is a noise floor of < 1 ng/√Hz (near the low-noise model), reduced lower bandwidth limit of 0.01 Hz, and further optimizations in size and power consumption. This will substantially increase sensitivity in very small, low power accelerometers.

OBJECTIVES

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The monitoring community needs for high-frequency sensors, with an emphasis on small sensors needed for local monitoring, were explored at the Air Force Research Laboratory (AFRL) Seismic Sensor Workshop in September 2004 (AFRL, 2004). The following sensor capability needs were identified at the workshop (Figure 1):

- Self Noise Below New Low Noise Model (NLNM)
- Dynamic range > 120dB
- Linear response > 60dB
- Frequency range at least 0.2 -40 Hz
- Power consumption < 100 mW
- Installation flexibility
- Low weight
- Small size
- Robustness
- Stability of response

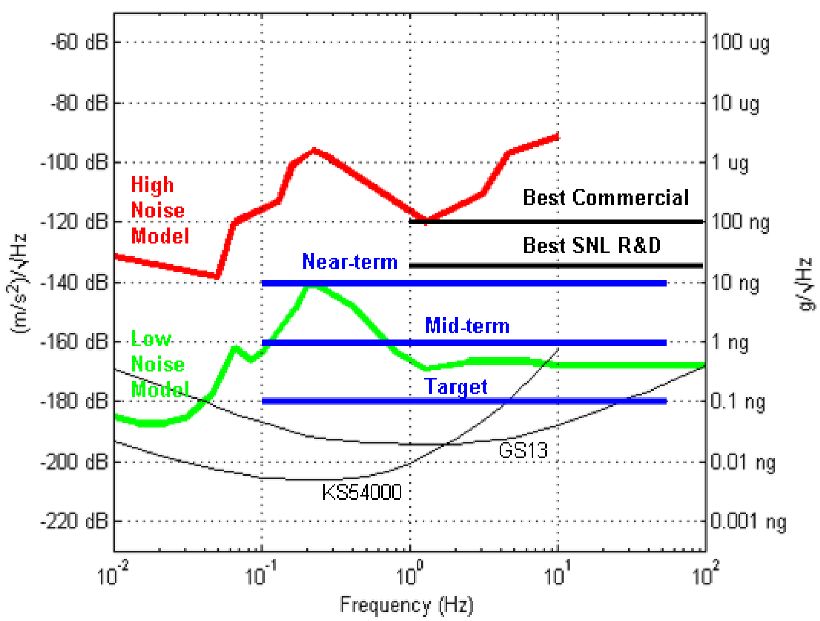

Figure 1. Comparison of projected MEMS accelerometer noise levels with the Low and High Noise Models. Current sensors are shown for reference.

Existing devices meet some combination of these requirements very well. Traditional short period seismometers easily meet the noise, dynamic range, linearity, and bandwidth requirements, but are larger and heavier than desired. Current small sensors (e.g., geophones, piezoelectric, or MEMS sensors) may meet the needs for emplacement flexibility, robustness, weight, size, and power, but do not deliver the sensitivity needed. Simultaneously addressing all of these specifications poses an extreme engineering challenge.

RESEARCH ACCOMPLISHED

Design Overview

The basis of the proposed inertial sensor system (Figure 2) is a motion detection transducer employing a fixed (or actuated) optical interferometer grating. The grating is made up of parallel lines of silicon. The individual grating lines are 1 μm wide and spaced 1 μm apart. A laser diode shines through this optical grating at a reflective surface on the proof mass frame.

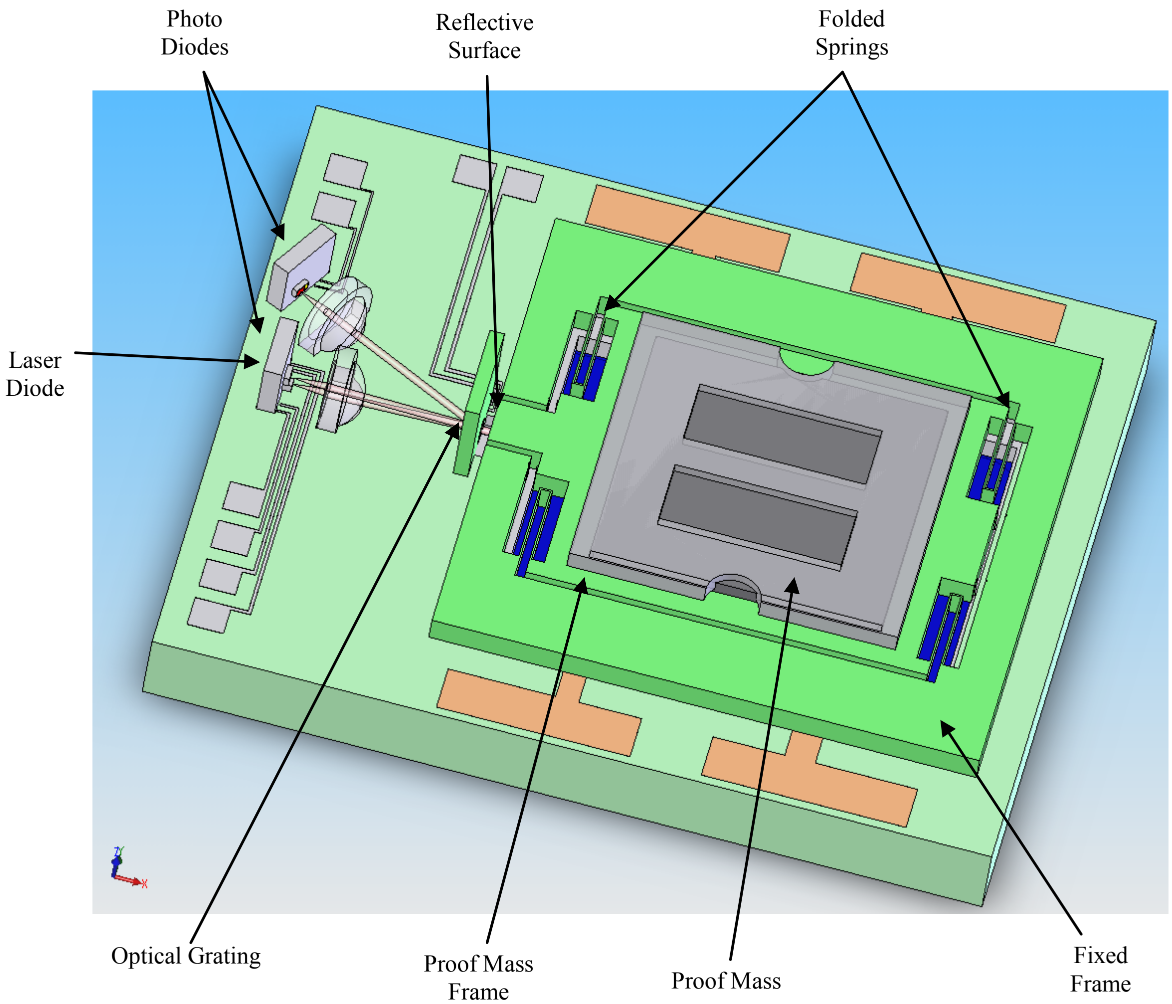

Figure 2. Proposed sensor design.

The proof mass frame on the opposite side of the grating is mounted to a fixed frame by folded springs. The proof mass frame is free to move in the direction of travel with the laser. Because of the optical detection method, the sensor will be insensitive to any cross axis or out-of-plane motion. A large mesoscale tungsten proof mass is positioned within the proof mass frame. Separating the assembly of the proof mass and the frame allows for the use of a significantly larger proof mass than would otherwise be possible using MEMS fabrication techniques.

Optical Detection

The reflective surface on the proof mass can be between 100 and 500 μm away from the optical grating. Depending upon the distance between the optical grating and the mass, some portion of the light from the laser will be reflected on-axis or diffracted off-axis from the direction of the incoming laser. For small changes in the spacing between the optical grating and the proof mass, a large change in the optical reflection is observed.

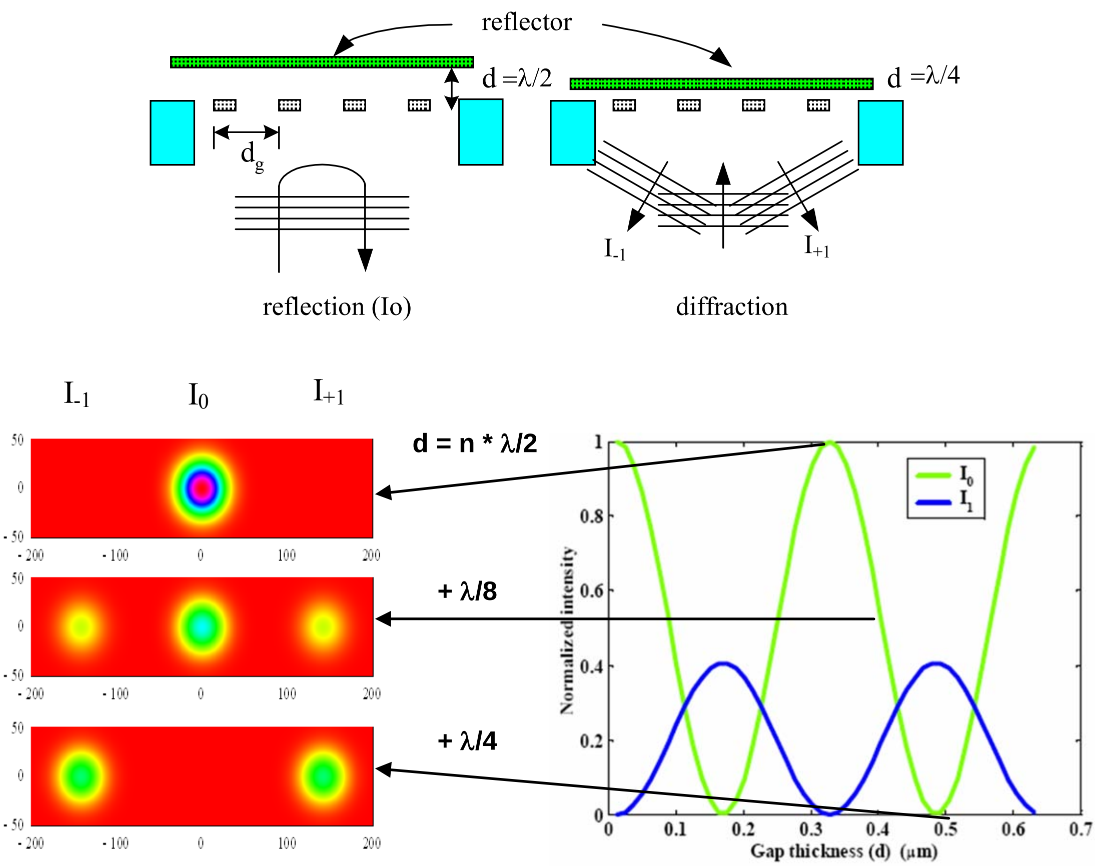

Figure 3. Images in the lower section show the variations in intensity of reflected and diffracted orders with the gap between the grating and reflector.

The most sensitive mode in which the optical displacement detection system can operate is in the +λ/8 position for the gap thickness. This corresponds to the point on the light intensity curve (Figure 3) at which the slope is the highest. Therefore, it is desirable for the sensor to operate at a gap size that is (n * λ/2) + λ/8 so as to maximize the optical sensitivity. The gap size can be controlled using feedback control.

There are several options for feedback control of the sensor. First, the optical grating can be actuated using electro-static force feedback. Second, the position of the proof mass can be controlled using magnetic force feedback. These feedback capabilities will make it possible to explore several different options for performing noise reduction, signal processing, and increasing dynamic range.

Two photo diodes will be positioned in the reflected (on-axis) and diffracted (off-axis) positions to measure the amount of reflected light (Figure 4). Typically, a small laser such as the one proposed, would be inherently noisy. In order to make them quieter, the laser would have to be significantly larger and precisely temperature controlled. However, by differencing both the reflected and diffracted light intensities, the common mode noise in the output of the laser diode can be minimized. The two photo diodes will still introduce some noise that is not common between their outputs; however, that noise is significantly less than the noise from the laser.

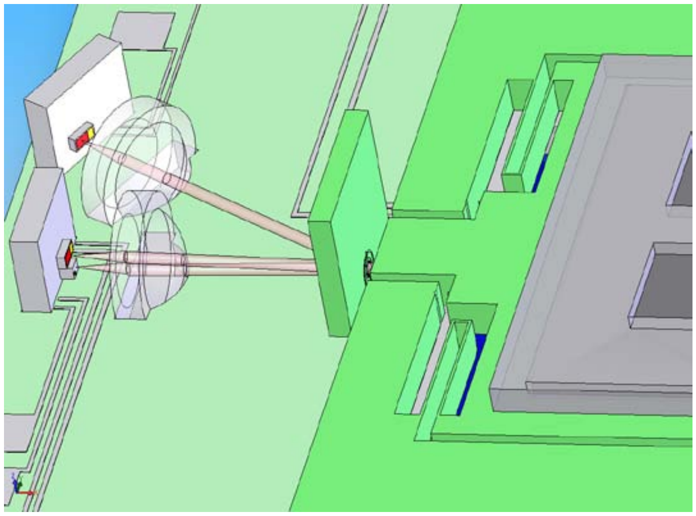

Figure 4. Laser and two photo diodes.

Self Noise

The theoretical self noise of this design is primarily driven by two physical limitations: thermal noise and optical-electronic noise. The thermal noise is due to the effects of atmosphere on the proof mass. As illustrated, the dominant source of noise (and resonant frequency of the system) is the thermal (Brownian) motion of the proof mass in a dissipative medium, which is a white noise source whose power spectral density is given by the relation shown in Equation 1:

Boltzman's Constant	k_B=1.38x10^{-23} J/K
Temperature	T = 300 K
Resonant Frequency	ω_o=314.16 rad/s (50Hz)
Quality Factor	Q = 1000
Proof Mass	m = 1 gram (10^{-3} kg)

$$a_n = \sqrt{\frac{4k_b T\omega_0}{Q\cdot m}}\frac{1}{\sqrt{Hz}} \qquad \approx 2.3\times10^{-9}\, m/s^2\sqrt{Hz}$$

$$0.2\ ng/\sqrt{Hz}$$

Equation 1. Thermal Noise

The optical-electronic noise is due to noise in the sensing mechanism for detecting the displacement of the proof mass relative to the optical grating shown in Equation 2:

Measured Displacement Noise	$x_n \approx 10^{-14}\, m/\sqrt{Hz}$
Spring Constant	k = 98.7 N/m
Proof Mass	m = 1 gram (10^{-3} kg)

$$k * x_n = m * a_n$$

Acceleration Noise

$$a_n \approx 9.8\times10^{-10}\, m/s^2\sqrt{Hz}$$

$$0.01\ ng/\sqrt{Hz}$$

Equation 2. Optical Electronic Noise

These estimates of the thermal and optical-electronic noise are illustrative of the desired performance levels. Parameters have been selected that are consistent with proven fabrication technologies and that match the desired set of requirements.

Fabrication Accomplished

In the first phase of fabrication, some of the individual components have been fabricated separately: a silicon frame, tungsten proof-mass insert, and the optical grating structure. In addition, a ceramic frame was designed and constructed to hold the components in place during testing. Subsequent fabrication phases will focus on further refinements to the components as well as integration of the components, laser diodes, and photo diodes onto a single die (Figure 5).

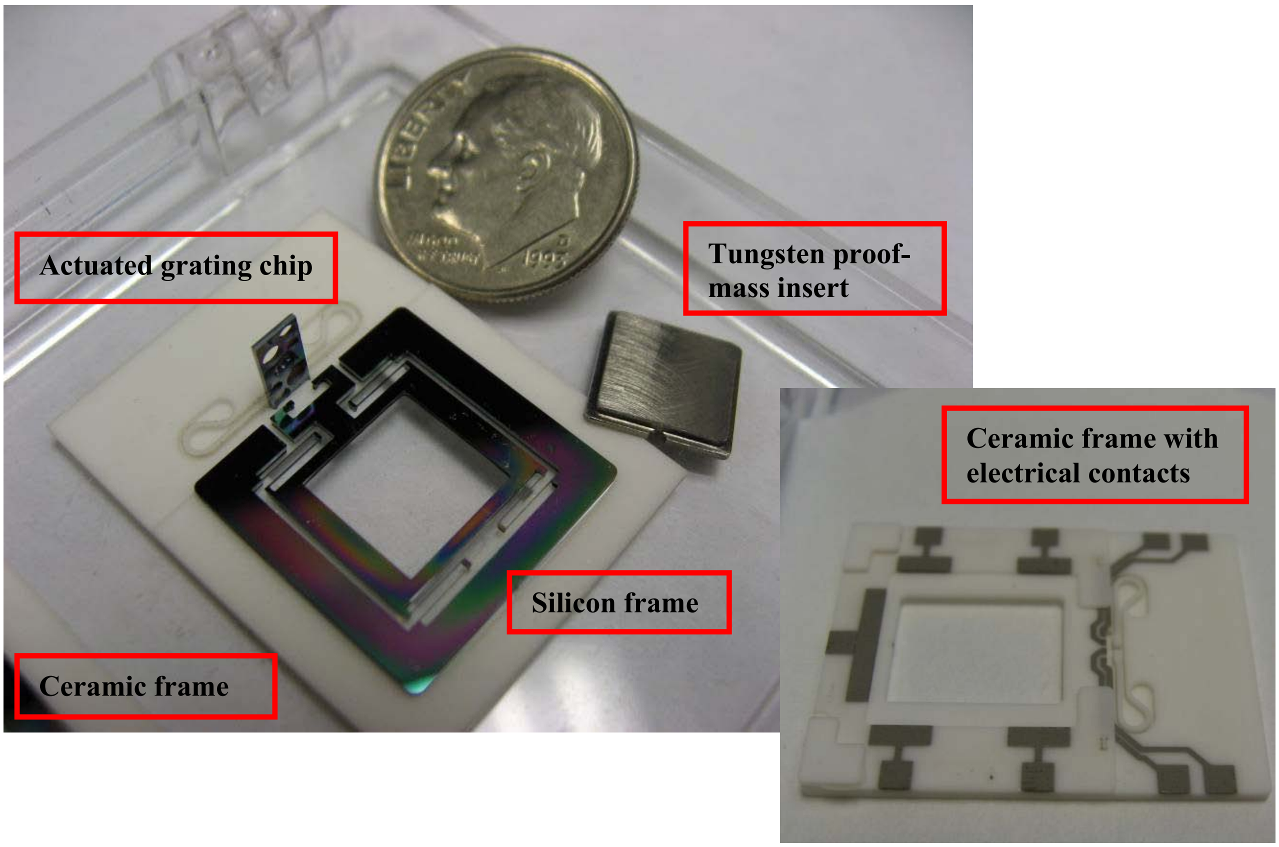

Figure 5. MEMS seismometer components.

Testing

We are in the early stages of assembling the test setup for the microseismometer. The first stage of functionality experiments is going to be performed in a laboratory environment and will focus on measuring the self-noise and response of the fabricated components. An external laser and photo detectors will be used to take measurements using the optical grating, reflective surface, and silicon frame. In addition, some amount of actuation of the grating chip will be possible as part of the testing.

The challenge in testing components such as these is that their targeted sensitivities are significantly below the ambient noise levels observed in a quiet laboratory environment. There are two approaches planned for resolving the sensor noise levels. First, multiple sensors can be co-located in the laboratory and coherence analysis used to attempt to identify their respective noises (Sleeman, 2006). This approach may have limited success given the high levels of noise expected in populated work areas and the ability to adequately co-locate sensors to ensure that they are all sampling a common signal. Second, we are planning on moving a breadboard version of the test setup into a quieter environment such as at the Sandia National Laboratories FACT site and/or the United States Geological Survey ASL tunnel. At either of these quieter locations, a broadband seismic reference sensor would be deployed to verify the response and sensitivity

CONCLUSIONS AND RECOMMENDATIONS

Work thus far has focused primarily on the design and development of the silicon frame. Processing of the silicon frame and other components has been carried out for the first design iterations. Further development and testing of the process and designs for the complete system are ongoing.

The current design has an expected shock tolerance on the order of 1000 g's. This level of shock tolerance is acceptable while the MEMS seismometer is operating at a fixed location. However, during handling, the components may be exposed to considerably larger shocks. To attempt to address this problem, we are also planning on incorporating an electrically actuated bistable locking mechanism into the device to enable increased mobility of the overall system. When engaged, this lock will prevent mechanical damage from large accelerations that can be encountered during handling.

The feedback control mechanism utilizing both the grating structure (electro-static) and the proof-mass (magnetic) will also be ready for testing in the next version of the device. Employing a feedback control system will result in a significantly larger linear dynamic range (> 120 dB) that will be needed for the target applications.

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