Supplementary Materials

In the spirit of open-source hardware, we are making the drawings and a list of construction materials for this specific sensor available, so that others might duplicate and improve it, or simply use it for educational purposes.

Of necessity, certain commercial equipment, instruments, or materials are identified in the supplementary materials (see table labeled Materials) in order to specify the sensor and its construction adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

If you are interested in making one of these sensors, and have questions, please feel free to contact Jon Pratt via email: jon.pratt@nist.gov. If you are interested in the dynamic optomechanical calibration technique and would like a copy of the software, please contact Stephan Schlamminger via email: stephan.schlamminger@nist.gov.

The Computer-Aided Design (CAD) drawings that can be obtained are for the following components:

Parallelogram oscillator 573 Hz; Ceramic mounting block; Sensor mounting block

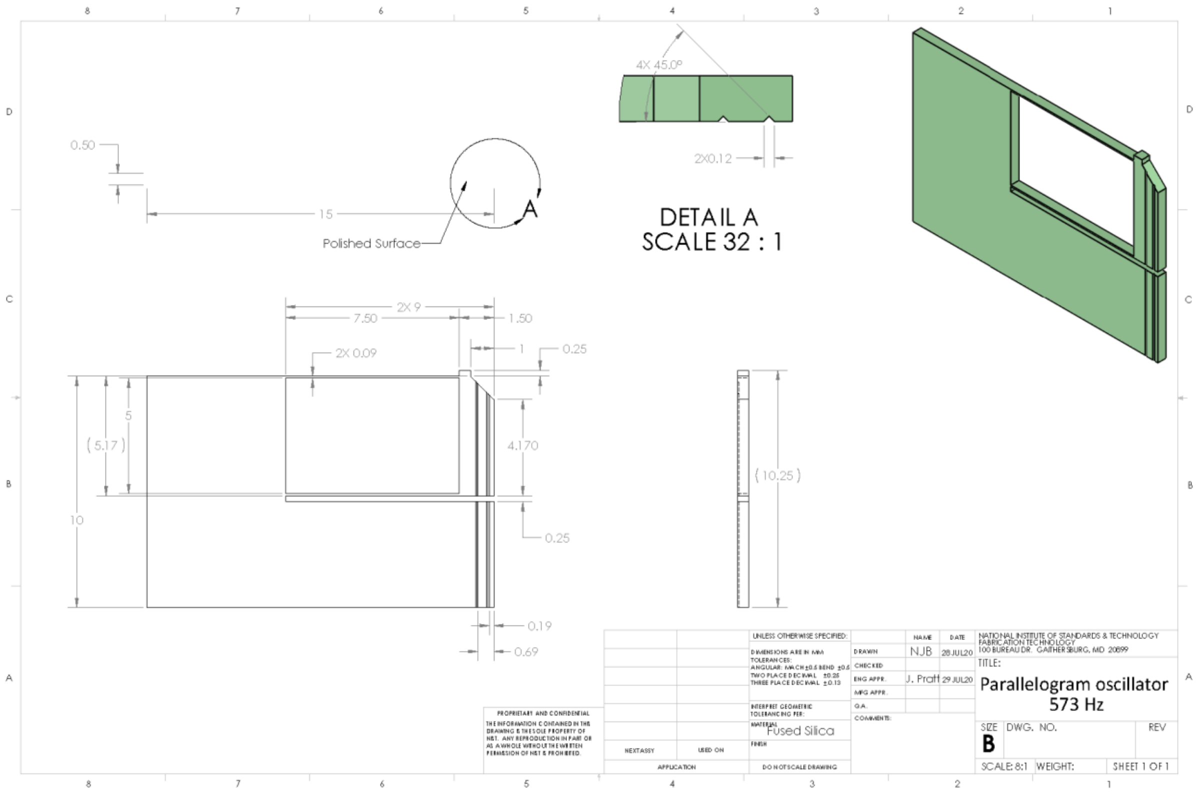
The drawings are dimensioned in inches, but with the SI equivalent expressed in mm shown in square brackets, e.g. 1 in [25.4 mm]. JPEG images of these CAD drawings are included here for convenience.

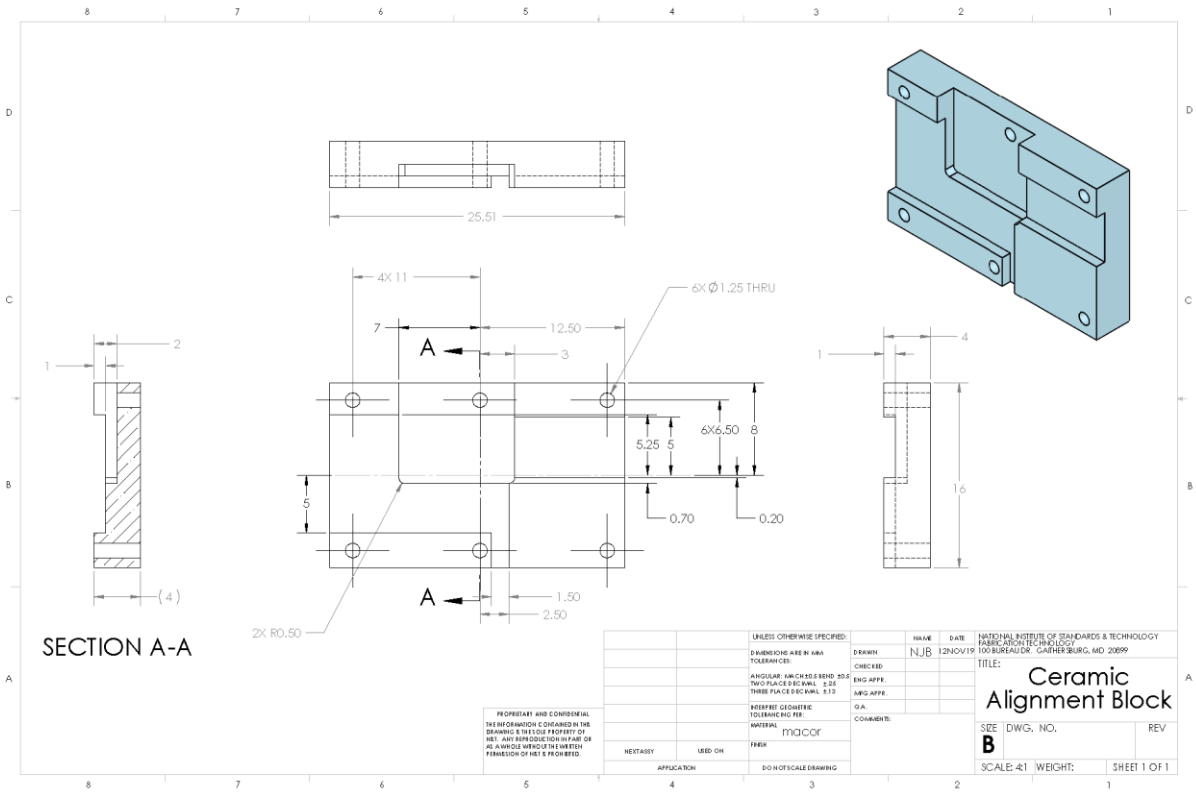
Drawings and/or STEP files can be requested directly from the NIST Manufacturing Technology Division. Send an email to nolan.brandengurg@nist.gov referencing this paper and Jon Pratt.

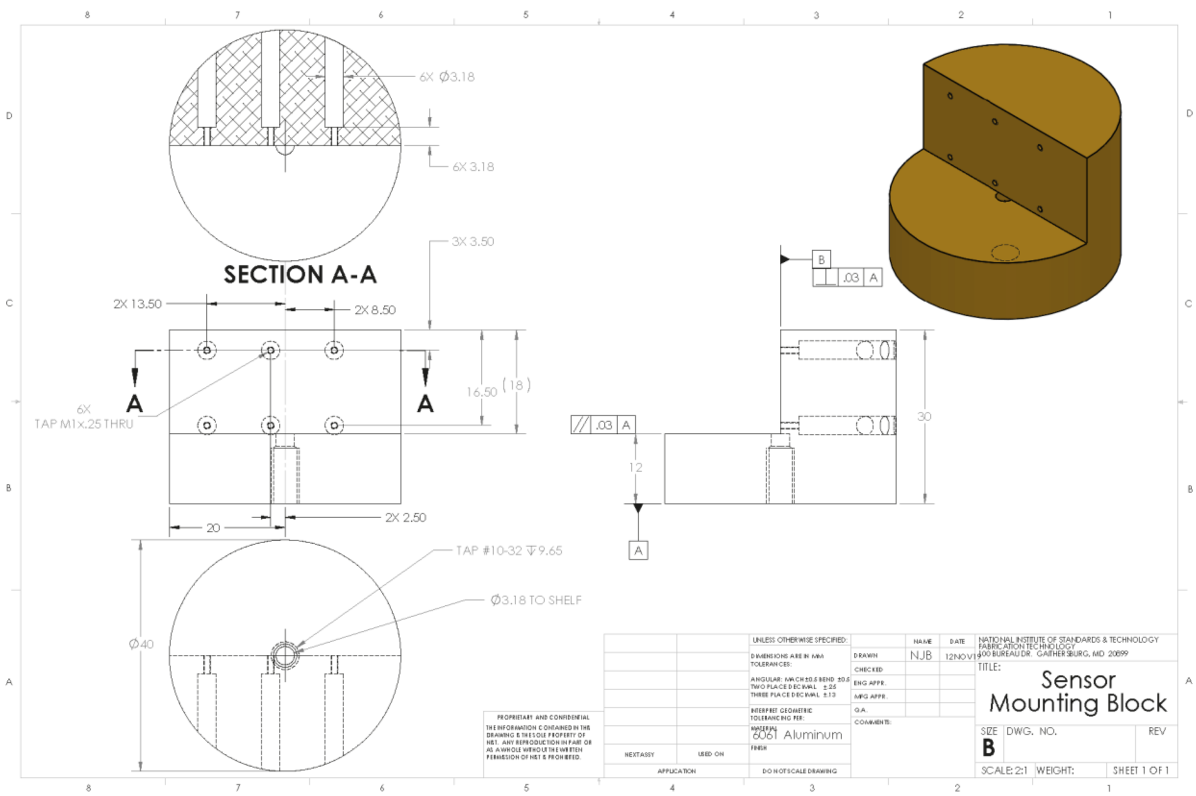
A partial list of materials and vendors used to perform the work in this paper is included as a table.

A brief section concludes the supplementary materials that restates the mechanical design philosophy and assumptions from the paper, provides analytical approximations for other vibratory modes of the parallelogram oscillator, and offers some informal observations about the accelerometer construction as fodder for future improvement.

Dimensioned Drawings







SECTION A-A
6X Ø3.18
6X 3.18
3X 3.50
2X 13.50
2X 8.50
16.50
(18)
6X
TAP M1x.25 THRU
A
A
20
2X 2.50
TAP #10-32 ⌴ 9.65
Ø3.18 TO SHELF
Ø40
B
.03 A
.03 A
12
30
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
NAME
DATE
DRAWN
NJB
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061 Aluminum
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY
FABRICATION TECHNOLOGY
TITLE:
Sensor
Mounting Block
SIZE
B
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1

Table of Materials

Component	Material/Model	Vendor
573 Hz Parallelogram Oscillator, per drawing	Fused silica	Translume
Ceramic mounting block, per drawing	Macor	NIST Fabrication Technology Division (FTD), NIST Gaithersburg, MD, USA, Nolan Brandenburg, Technical point of contact
Aluminum mounting post	6061 T6 Al	NIST FTD
Tunable laser	81640A (now obsolete)	Agilent (Keysight)
Polarization Insensitive Isolator Dual Stage	FS-3-13/15-X	FS.com
2X2 FBT splitter, Steel tube, 50/50 Fiber coupler	FBT-ST-N-SMxN	FS.com
Fiber optic adapter	AD-FCA-SM-SX-SQSOO-FS	FS.com
Fiber optic cleaver	FS08-C	FS.com
FC/APC patch cable	1550BHP-Custom; Custom Patch Cable - Fiber: 1550BHP, Tubing: None, End 1: FC/APC, End 2: FC/APC, Length: 2 m	Thorlabs
Photodetector	PDA10CS2	Thorlabs
Can opener for laser diodes	WR1	Thorlabs
Norland Optical Adhesive	NOA61	Thorlabs
UV Curing Unit with driver unit and handheld optical source	CS20K2	Thorlabs

Mechanical design principles and assumptions

We had the following in mind:

1) **The sensor mechanics should be well approximated by a single degree of freedom simple harmonic oscillator** composed of a mass connected to a reference frame by a spring.
2) **The mass should be "rigid"** and calculable from the volume and density of the material. We used a simple prism that was approximated for initial design by a solid rectangular parallelepiped. All additional features and dimensions shown on the drawing of Parallelogram Oscillator 573 Hz (S1) were employed as described in the paper to evaluate the final design.
3) **The spring should be "massless" and provide the restoring force while constraining the motion of the mass to a "single" coordinate**. Like the mass, it should be calculable from material properties and geometry. We used a parallelogram leaf spring and Euler-Bernoulli beam theory in the paper.

Ideally, the mass and spring form a composite structure that is a monolith of the same material. We concede that there is no such thing as a perfectly rigid mass, or a massless spring, but for a first approximation, we assumed that the block of glass that formed the mass was infinitely stiff compared to the slender spring elements, and that the effective mass of the leaf springs was negligible compared to that of the rigid mass element. A better next approximation might be to lump 1/3 the mass of the leaf springs with the moving mass, particularly in the happy event that the manufacturing process is sufficiently precise to warrant such attention to detail.

We used parallel leaf springs to constrain motion of the mass, taking care not to over constrain. Designs that over constrain, such as designs that include parallel leaf springs mirrored across the sensor center line, risk the potential for thermal buckling, midplane stretching, and a host of other issues, including nonlinear resonant behavior.

The fundamental mode frequency of the beams is verified to be at least an order of magnitude greater than the resonant frequency of the composite oscillator. For example, we used fixed-fixed beams where the fundamental mode frequency is,

$$f_1 = \frac{22.734}{2\pi}\sqrt{\frac{EI}{l^3}\frac{1}{m_b}}$$

where m_b is the mass of the beam. For sensor S_1, f_1=9 094 Hz > 10 x 573 Hz.

It is impossible to completely constrain the motion to a single coordinate, so we must consider the potential for the mass to move in other directions, and for these motions to be falsely detected. We use two strategies to minimize this cross-axis sensitivity: a uniaxial detection scheme and mode spreading.

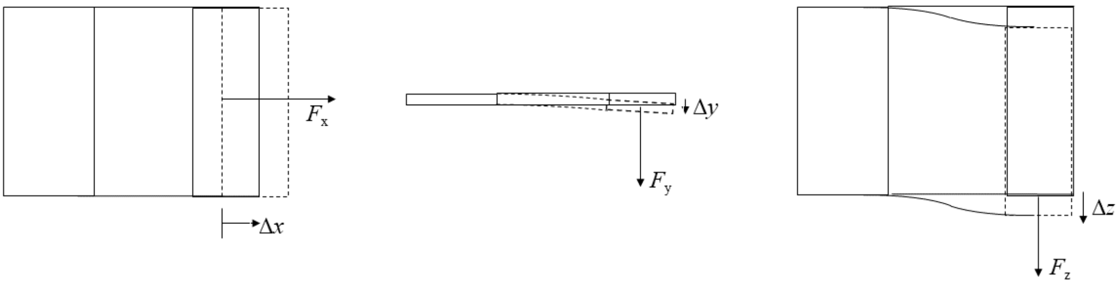
The fiber interferometer detection scheme is uniaxial to the extent that motion of a plane mirror in a direction orthogonal to z does not change the detected cavity length. Of course, the mirrors have errors in alignment, since the cleaved surfaces may not be completely perpendicular to the motion axis. In this case, orthogonal motions produce spurious signal. The fiber cleaver can regularly achieve cleaves that are perpendicular to the fiber axis within less than 20 mrad, but we lack a tool to confirm this for a specific cleave. Considering the case of simultaneous unitary on and off-axis acceleration at the base of the accelerometer, such angular misalignment is predicted to produce a relative error signal in the detected z-axis acceleration on the order of 2 %. Such simultaneous acceleration is not expected in a testing environment, but for general sensing applications, inspection of the cleaves to reduce the potential for such errors seems prudent. We further note that the detection cavity is parallel to *z*, but displaced from the center of mass along *y*, producing a so-called Abbé offset. Furthermore, the center of gravity of the seismic mass is not located in line with the point of attachment of the leaf spring, so that acceleration in z produces a torque that can, in principle, excite such rotations, though in this case both the offset mass and offset distance are small, and appeared to be of little consequence in our experiments. Such offsets should be analyzed and further minimized in future designs.

We attempted to make off-axis mechanical stiffness at least an order of magnitude greater than on axis, or

$$\frac{k_{off\ axis}}{k_z} = \frac{f_{off\ axis}^2}{f_z^2} > 10,$$

a procedure sometimes referred to as mode spreading. The analytical approach employed here is to consider the mechanism deflection under static load in each of the orthogonal directions and infer the ratio of frequencies from the relevant leaf spring stiffnesses, as illustrated below

Mechanism deflections under static loads



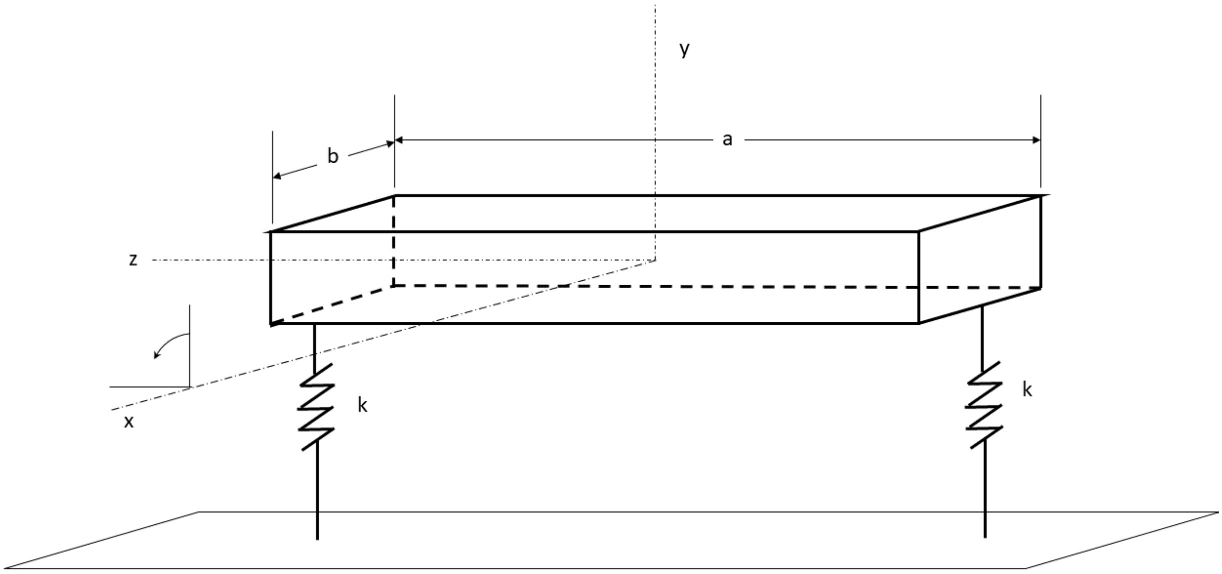
Relevant leaf spring stiffnesses and ratios

$$k_x = \frac{EA}{l_s} = \frac{Ebh}{l_s} \qquad k_y = \frac{3EI_z}{l_s^3} = \frac{Eb^3h}{4l_s^3} \qquad k_z = \frac{12EI_y}{l_s^3} = \frac{Ebh^3}{l_s^3}$$

$$\frac{k_x}{k_z} = \left(\frac{l}{h}\right)^2 \qquad \frac{k_y}{k_z} = \frac{1}{4}\left(\frac{b}{h}\right)^2$$

From inspection, k_x more than achieves our goal, and does not warrant further consideration. The ratio of k_y to k_z is dominated by the ratio of the beam cross section dimensions, simply 1/4 $(b/h)^2$=8.65. The result falls a little short of our stated goal and will be re-evaluated in future designs.

Finally, consider a rigid body rotation about the *x* axis, as illustrated using the Lumped Model below,



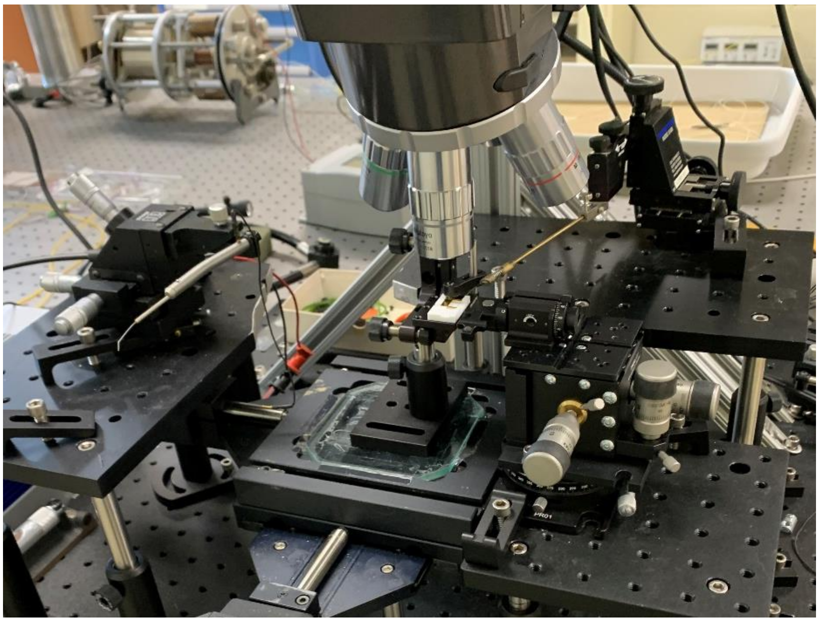
The two leaf springs apply a restoring torque and have an effective torsional stiffness $\kappa=k_y a^2$=0.0061 N/rad. The rotational frequency is $f_\theta = \frac{1}{2\pi}\sqrt{\frac{\kappa}{I}}$ =2896 Hz where *I* in this expression is the *mass* (not area) moment of inertia for a rigid plate (overestimate ignores some of the features), or $I = m/12\ (a^2 + b^2)$ where *a* =5.17 mm, *b* is 0.5 mm, and *m*=8.19 mg.

The above analyses were based on many simplifying assumptions. In practice, the rigid mass will deform, and the leaf springs will bend and *twist* (which we haven't accounted for). We concede that a finite element approach might do a considerably better job. However, for this simple structure, our approach provides an intuitive feel for how choices in geometry influence the resulting frequencies. For instance, it appears we can achieve a greater mode spreading simply by increasing the ratio b/h of the beam elements in the future.

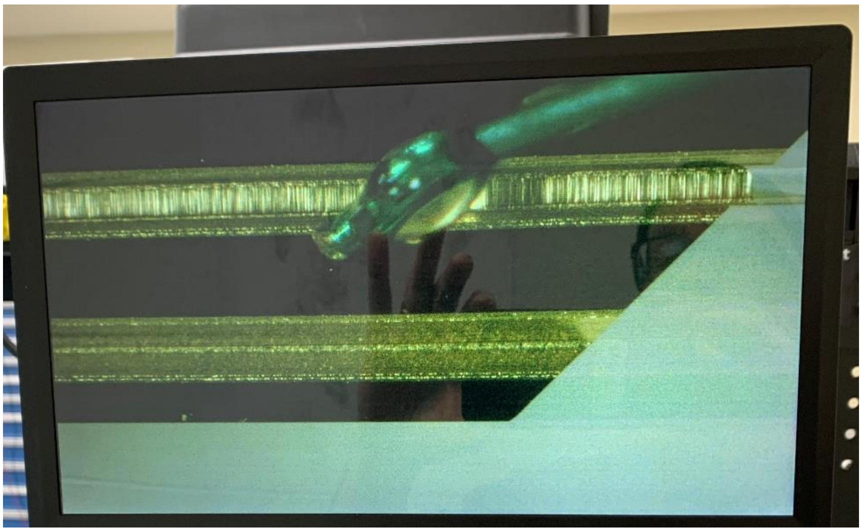
Notes on construction

The oscillator is the key to the sensor, and you can't make a sensor without it. Your fabrication options are limited to two companies, one in the US, one in Europe (unless you invest in the Femtoprint machine [16]). Fortunately, the part is very light, and seems to ship well, in either case. This specific part is a design we have made in the US for nearly a decade. Reference this paper, offer to supply the STP file for this oscillator, and ask for a quote. Make multiple copies if you can afford to. That helps reduce the per part cost, and makes the oscillator feel a little less precious, when a screwdriver slips from its slot.

The mounting of optical fibers in v-grooves is greatly aided by fiber alignment stages and a long standoff microscope, such as the set up in this photo:



A barely perceptible drop of UV cure epoxy on fine magnet wire (120 micrometer diameter) is all that is required to hold the fibers in place. Dip the tip of the wire in the epoxy. The amount that remains on the wire is enough.



We typically apply the drop near the fiber entry point and watch it wick along the fiber from the entry to the detection end under a microscope before curing. Surface tension seems to halt the glue at the v-groove terminus.

Many variations on the mounting hardware are possible. We encourage people to use the drawings provided here as a launch point for brainstorming. We use ceramic material or Invar for the sensor holder, because it is good to have a thermal match to the fused silica. We used frit bonding to glass substrates in the past [7]. That process is no longer easily available to us, and we are interested in exploring the monolithic approach of [11].

We admit that both the mounting block and post in this paper are clumsy. The mounting screws to affix the ceramic piece to the aluminum mount are hard to access, and screw drivers have an alarming tendency to slip out of the standard metric screws, which is unfortunate around a delicate oscillator. Rethinking the design to allow counterbored screw holes seems like a much better and obvious approach, on further reflection. We could simply use glue, but the idea was to have one mounting post that could work with a variety of sensor holders, and to avoid inevitable contamination during disassembly (glue dissolves when the part is soaked in solvent but can redeposit on all surfaces). In order to stud mount the sensor in a specific rotational orientation about the z-axis using our mounting post, you will need to create shims to adjust the thread engagement (a washer cut out of a NIST fundamental constants card worked well for this paper!). We put an initial premium on having the total center of mass on the shaker axis. An offset of the sensor holder that would allow a simple through hole in the aluminum body would ruin this symmetry, but it would make attachment in any rotation about the shaker axis much easier, and the slight offset of the center of mass seems unlikely to cause a problem for a shaker.

You will need to find a shop to make the mounting parts, if you decide to use them. We emphasize that the parts should be fabricated to the tolerances specified if you are going to preserve the accuracy of the subsequent alignments. These are not extreme tolerances, and shops with these capabilities are not difficult to find in the US and around the world, but they may be scarce in some locales. We have limited experience using internet vendors. But you are encouraged to send the STP files and get quotes from any of the many vendors on the vast world wide web. In principle, anywhere the internet and mail service reach, contract discrete part manufacturing is at your disposal! Let us know if you try this option. We’re curious to hear about the results.