Development of a compact adjustable fiber collimator mount for optomechanical accelerometers

Ian Harley-Trochimczyk[a], Xiangyu Guo[a], Felipe Guzmán[a]
[a]Wyant College of Optical Sciences, The University of Arizona,
1630 E University Blvd, Tucson, AZ USA 85721

ABSTRACT

Precise alignment of laser beams used in heterodyne interferometry is vital and necessary to the precision, accuracy, and quality of the measurement, but off the shelf-based breadboard setups have a large physical footprint and many components that can introduce unwanted noise. Our lab creates optomechanical accelerometer devices including a fused silica resonator with a 5Hz natural frequency and uses a heterodyne displacement interferometer to readout the position of the test mass, which can then be used to determine the acceleration of the device. A novel compact fiber injector system design is presented here that reduces the footprint of the fiber collimator input of the heterodyne interferometer by an order of magnitude from a breadboard setup, down to 24 x 16 x 19 mm. This new injector system integrates both fibers of different frequencies directly onto the mount with the resonator, increasing stability and reducing entry points for vibrational noise while minimizing the optical path length difference between beams. Each beam can then be independently tilted and de-centered to maximize the fringe visibility at the output of the interferometer, using spring-loaded adjustment screws and secured in place with locking screws. An accelerometer using these injectors measured a displacement of 10^{-9} m/√Hz at 10^{-2} Hz in air with the test mass anchored, nearly identical to the previous breadboard setup while being much more compact and portable. I will present the design, integration onto an accelerometer, and the initial acceleration noise measurements taken using these fiber injector systems.

Keywords: Inertial sensor, accelerometer, optomechanics, resonator, fiber collimator, optical alignment

1. INTRODUCTION

Precise and stable alignment of input laser beams of an interferometer is necessary to obtain sufficient fringe visibility for good measurements in displacement measurement, metrology, and other applications. Our optomechanical accelerometers[1] use a heterodyne quasi-monolithic interferometer[2] to measure the displacement of a well characterized test mass and convert that displacement measurement into acceleration and force information, allowing these devices to be used as precise inertial sensors[3]. Highly sensitive, low-noise inertial sensors have applications to inertial navigation, geodesy[4], relative gravimetry[5], and noise characterization of gravitational wave detectors[6]. The optical readout system of the accelerometer consists of a single fiber-coupled laser source that is split in two and frequency modulated before passing through collimating lenses and entering the quasi-monolithic interferometer as free beams. The quasi-monolithic interferometer requires the beams to be parallel to the entrance prism face and exactly 5 mm apart. This alignment can be achieved with off the shelf fiber collimator lenses and optomechanical mounts and fixtures, but these setups have a large physical footprint, which can alter the optical path length between input beams introducing noise, and a high number of separate components and moveable parts, which are potential entrances for unwanted vibrations to enter the system and lower measurement sensitivity. We have developed custom compact fiber injector systems that remove the need for off the shelf adjustable mounts, reducing the physical footprint by an order of magnitude while preserving the acceleration measurement sensitivity of the device. This document discusses the design and testing of our fiber injectors, their integration into an optomechanical accelerometer system, and initial results comparing the acceleration measuring performance to an off the shelf fiber collimator alignment setup.

2. OPTOMECHANICAL ACCELEROMETER OVERVIEW

Our laboratory creates and works with optomechanical accelerometers of different materials, frequency measuring ranges, and optical readout methods. The focus here will be devices based on our lower frequency fused silica resonators, using

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the heterodyne quasi-monolithic interferometer based optical readout method. A resonator is made from a single piece of fused silica, a material with low damping and extremely high quality factor[7], that is etched to create a test mass attached to a main structure through thin flexures. The equations of motion of the test mass[5], which moves as a damped harmonic oscillator, can be used to extract acceleration information from displacement measurements of the test mass.

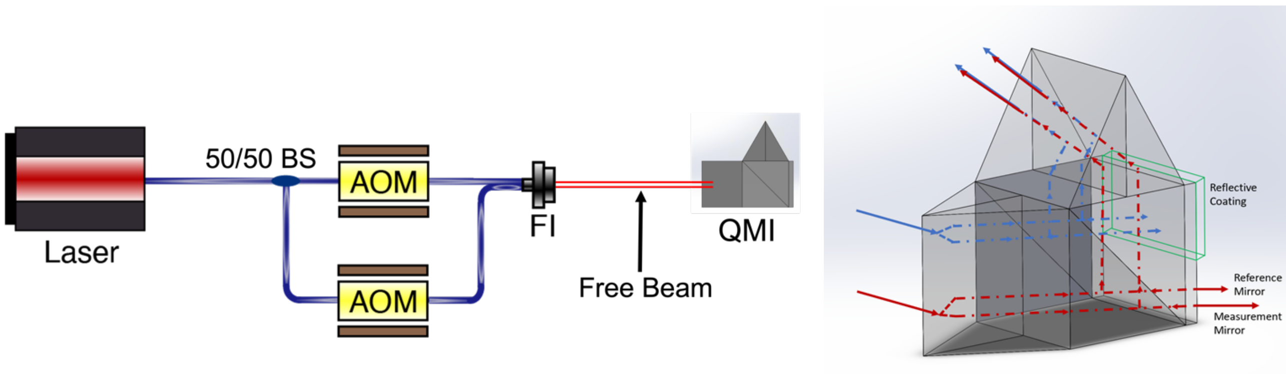

Figure 1. Left: Optical layout of optical readout input. FI = Fiber Injector, QMI = quasi-monolithic interferometer. Right[8]: quasi-monolithic interferometer diagram. Beams must enter parallel, 5 mm apart, and at proper location on prism face.

The optical readout of the resonator consists of a fiber-coupled laser source with the wavelength matched to the coatings on the quasi-monolithic interferometer (1064 nm and 1550 nm have been used and tested so far) that is split with a fiber beam splitter into two AOMs. Each AOM modulates the frequency of the laser, with the difference in modulation frequencies being the heterodyne frequency of the interferometer. The modulated beams then pass through fiber integrated collimating lenses, which are mounted into our fiber injector system where they can be injected into the quasi-monolithic interferometer at the required location and orientation and locked in place. Within the quasi-monolithic interferometer, the two beams are split into four, two comprising the measurement arm and two comprising the reference arm. Each arm interferes the beam reflected off the coating on the surface of the quasi-monolithic interferometer with the beam that reflects of an external mirror mounted on either the resonator frame (reference arm) or the test mass (measurement arm) and exits the quasi-monolithic interferometer to be directed onto a photodetector. The nominal alignment and subsequent in situ adjustment of the input beams is critical to obtaining a good fringe visibility as seen at the photodiode.

3. FIBER INJECTOR DESIGN

The design drivers behind the fiber injector systems were to create a system that is compact enough to be assembled into the same mount as the resonator and quasi-monolithic interferometer, that is adjustable enough to maximize fringe visibility at the output of the optical readout system from the nominal aligned position, and stable enough to not drift out of alignment over time. Our fiber injector reduces a large off the shelf setup with two 5-axis collimator mounts and an adjustable mirror mount and several posts and post holders, into a 24 x 16 x 19 mm device made of 3 parts and support hardware that gets integrated directly into the resonator mount.

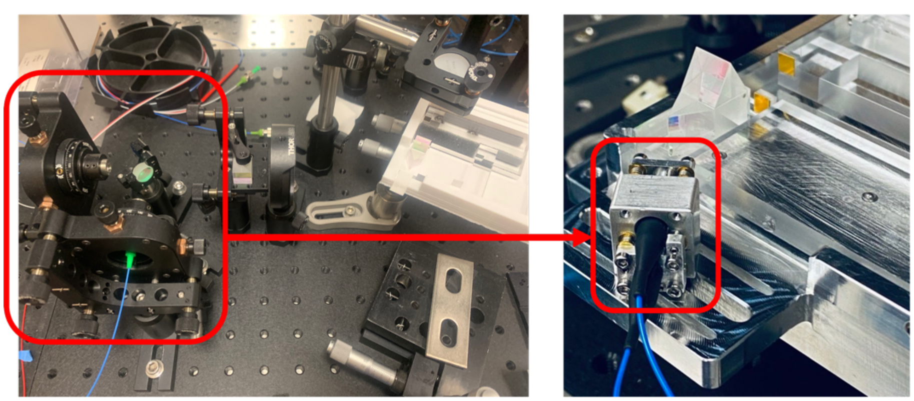

Figure 2. Off the shelf breadboard setup (160x160x200 mm) and integrated fiber injector system (24x16x19 mm).

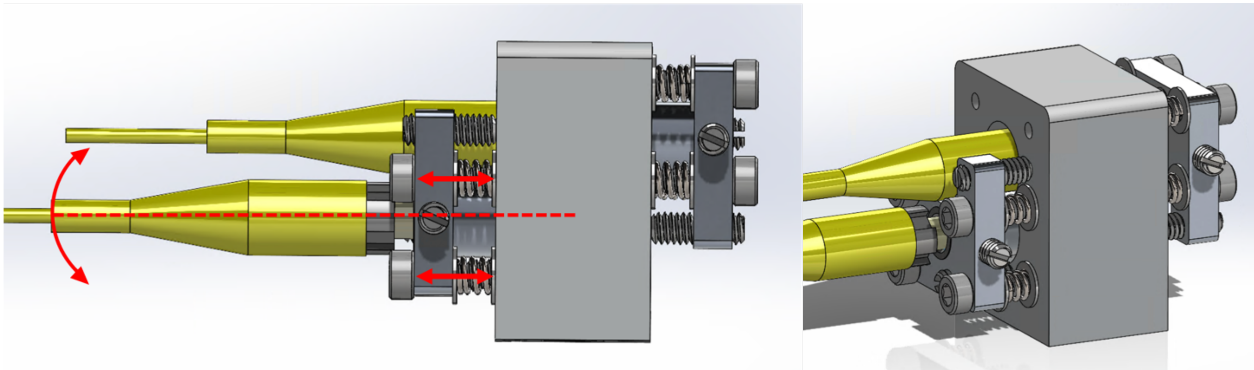

Figure 3. CAD Model of Fiber Injector. Adjusting screws tilts adjuster tube and changes the angle of that fiber collimator.

The fiber injector consists of a center mount block and two adjuster tubes, each one holding one of the two fiber collimators coming from the AOMs. They are on opposite sides to allow for adjustment access while maintaining 5 mm beam separation. Adapter tubes were also created to allow for both 4 mm and 3.4 mm diameter in-line fiber collimator lenses to be securely mounted in the fiber injector. Fibers can be rotated within the tube to align polarization axis and locked into place with a set screw. The adjuster tubes are mounted into the center mount block with springs to push them out against the bottom of the adjustment screws. The screws can then be tightened or loosened to change the angle of the fiber and therefore the angle of the beam incident on the quasi-monolithic interferometer entrance prism face. The adjuster tubes can move from 0.5 mm each direction from center in translation and can tilt 2.2 degrees away from the nominal center axis. Three set screws per adjuster tube can then be tightened to secure beam in position once aligned. One larger central screw secures, and two smaller support screws set the nominal angle of the fiber injector to the mount.

4. FIBER INJECTOR INTEGRATION

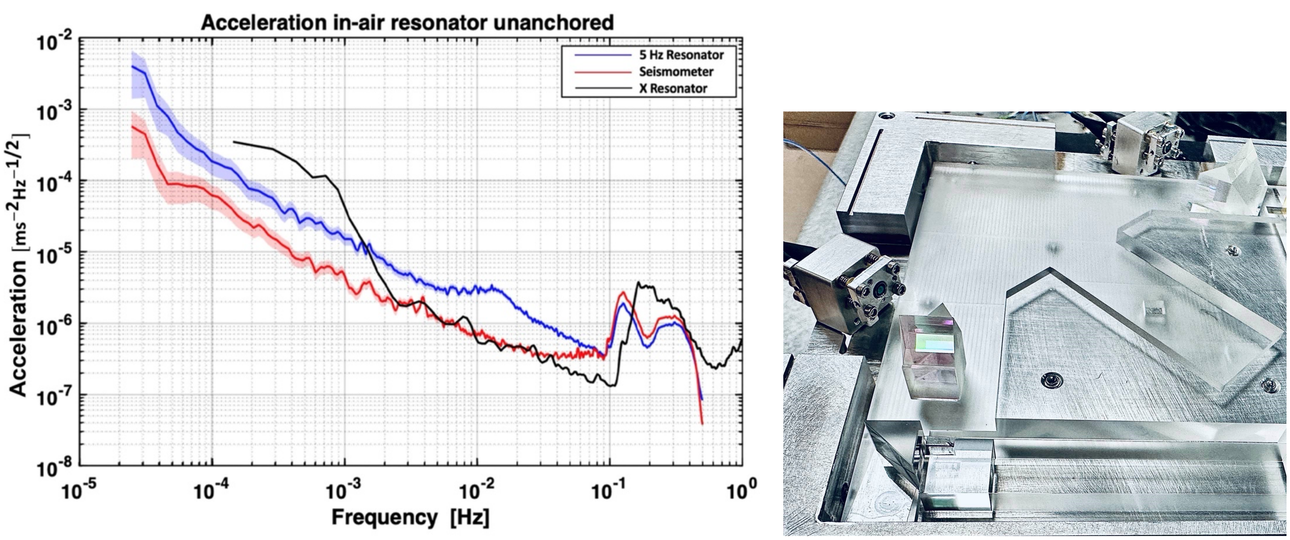

Figure 4. Acceleration measurements of a resonator plotted with those from a commercial seismometer. The blue 5Hz data was taken with an off the shelf setup, while the black X resonator data was taken with a fiber injector as shown on right.

Once assembled with the hardware and fiber collimators, the fiber injector integrates directly onto the mount that also holds the fused silica resonator and quasi-monolithic interferometer. The alignment process starts by securing the fiber injector directly onto an optical table or large breadboard. Then the polarization of the beams can be set using a polarimeter or a polarizing beam splitter by rotating the fibers within the adjuster tubes. Once secured, both adjuster tubes can be tilted using the adjuster screws until both beams are parallel to each other, 5 mm apart, and parallel to the surface of the table or breadboard. Then when integrating the injector onto the accelerometer mount, the entire mount block can be turned until the beams are entering the quasi-monolithic interferometer perpendicular to its entrance face and at the correct location. Further tweaking of the beams to maximize fringe visibility can be done within the available adjustment range. Once integrated and aligned, the optomechanical accelerometer can take measurements as it would with the off the shelf breadboard setup for the optical readout input.

5. FIBER INJECTOR STABILITY TESTING

A stability test was done to quantify the stability of the beam from the collimator mounted in the fiber injector over time. A 1064nm laser is split into two fibers with both secured in the fiber injector. The fiber injector was then mounted to a steel post and directed toward a beam profiler through a neutral density filter to lower the optical power. The beam profile used an auto calibration feature to tune the camera settings to maximize dynamic range without saturation and extracted beam parameters from each image such as the location, eccentricity, and radius. The data was collected for one beam at a time overnight and the position coordinates of the beam location were saved every few seconds.

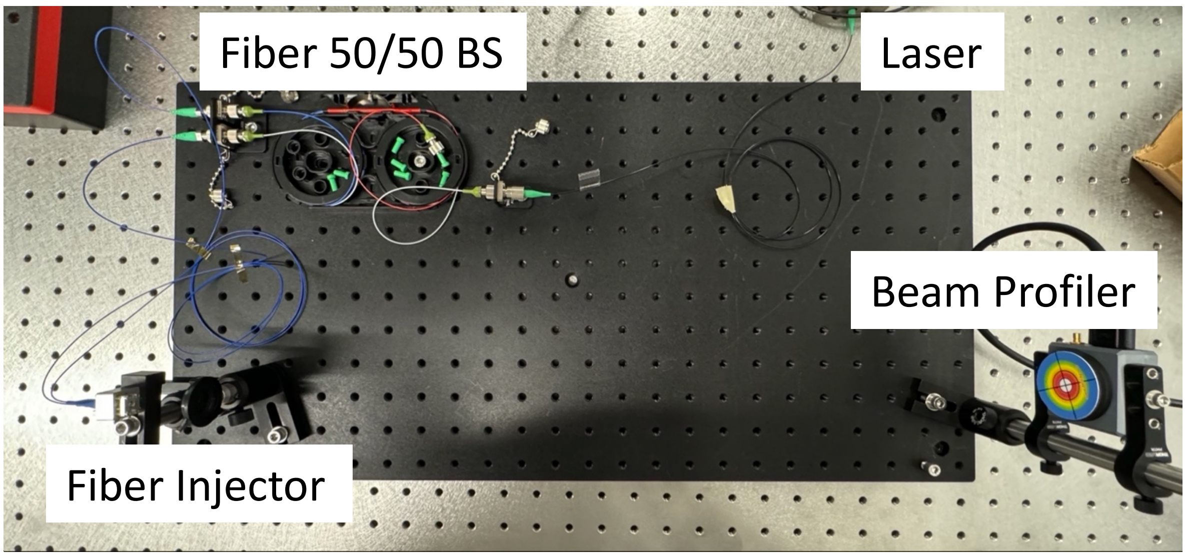

Figure 5. Stability test setup. Iris in front of fiber injector is to select beam to be tracked.

Another stability test was done to investigate the long-term drift of a beam mounted in a fiber injector using a similar setup without the beam profiler, by marking fiducials on a plate at the beam locations at the start and end of an 8-day period. This more rudimentary test showed both beams drifted together by 1 mm in the same direction 600 mm away from the injector, corresponding to an angular drift of 0.09 deg or 1.6 mrad.

The results of the beam profiler stability test are shown in figure 5. The raw position data for the X and Y coordinate of the beam as determined from the beam shape within the DataRay software are plotted over time along the positions averaged over a 2-minute period and over a 30-minute period for the top beam. The camera was 600 mm away from the fiber injector. In the bottom beam test the software crashed after tracking the beam position for a little over 2 hours. The final position of the beam ended up 0.35 mm away from the initial position, corresponding to an angular drift of 0.03 degrees or 0.6 mrad. In the top beam test the beam was tracked for 15 hours, and the final position of the beam was 0.67 mm from the initial position corresponding to an angular drift of 0.06 degrees or 1.1 mrad.

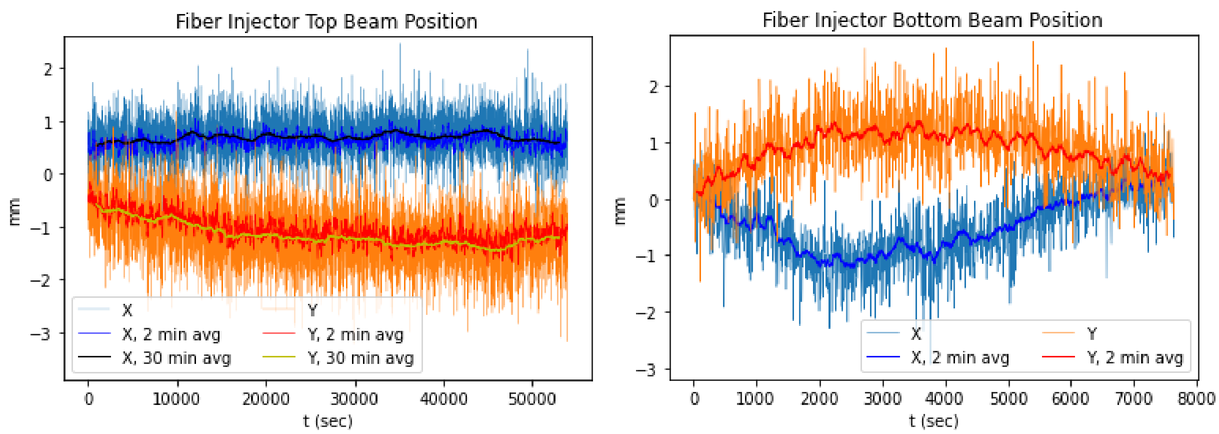

Figure 6. Position of a beam relative to starting point, as detected by a WinCamD CMOS beam profiler. Left: X and Y position of the top beam mounted in a fiber injector over a 15-hour period with data recorded every 10 seconds. Right: X and Y position of the bottom beam mounted in a fiber injector over a 2-hour period with data recorded every 5 seconds.

6. CONCLUSIONS

Our optomechanical accelerometers perform as well or better with fiber injector systems than with large off the shelf breadboard setups. The fiber injectors greatly reduce the footprint of the optical readout system while reducing the number of components and potential for noise to couple into the measurements. While the current iteration performs well enough, the stability testing shows some long-term drift that will degrade the optical readout system fringe visibility over time which could hurt the acceleration measurements. A new iteration of the design could improve the drifting stability, as could the use of an adhesive to fix the adjuster tubes in place in the fiber injector after optimal alignment is achieved. Future work will repeat stability testing on multiple fiber injector systems, investigate correlations of the beam drift with ambient temperature, and create an updated fiber injector design that increases stability, ease of alignment, and adjustment range.

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