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Optical Bench Interferometer - From LISA Pathfinder to NGO/eLISA

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Abstract. We present a short summary of some optical bench construction and alignment developments that build on experience gained during the LISA Pathfinder optical bench assembly. These include evolved fibre injectors, a new beam vector measurement system, and thermally stable mounting hardware. The beam vector measurement techniques allow the alignment of beams to targets with absolute accuracy of a few microns and 20 microradians. We also describe a newly designed ultra-low-return beam dump that is expected to be a crucial element in the control of ghost beams on the optical benches.

1. Introduction

Space-borne gravitational wave detectors would detect gravitational waves by monitoring the relative motions of drag free test masses located in separate distant spacecraft using optical metrology. For LISA-type missions (e.g. LISA/NGO/eLISA), the frequency range of operation is between 0.1 mHz and 1 Hz, complementing that of the ground-based detectors (ref. Pitkin et al. (2011)). Implementing the optical metrology requires complex optical benches on each spacecraft. These optical benches will be constructed using hydroxy-catalysis bonding (ref. Elliffe et al. (2005); Killow (2012)) of fused silica components to a baseplate made of material with a low coefficient of thermal expansion, typically Zerodur®. The general approach is based on that adopted for the optical bench at the heart of the LISA Technology Package (LTP) (ref. Racca & McNamara (2010)). However the more complex eLISA-type metrology schemes have driven the development and evolution of a number of optical bench subsystems that will be mounted, together with other directly bonded components, to assemble complete benches. Within many of these subsystems, and also for the directly bonded components, the need for stability, accurate alignment and the careful control of stray light all play important roles.

Current work on an eLISA-style optical bench has centred around the development of an Elegant Breadboard (EBB) of the bench planned for the original LISA concept. As the mission concept has evolved to eLISA, this focus on the EBB has proved to be a highly valuable technology development approach, since the EBB design involves many of the subsystem challenges that feature in the reduced-size optical benches envisaged for eLISA.

2. Optical bench

The EBB optical bench (figure 1) contains four principal interferometric readouts: a reference interferometer, the PAAM (Point Ahead Angle Mechanism) metrology, the test mass readout and the science interferometer. Differences from the LTP optical bench include dual fibre injector assemblies for redundancy, greater number of optical components, beam dumps, precision aperture stops and optics to focus or resize beams. A further difference is that beams must also be aligned in the out-of-plane direction, to and from the telescope and the proof mass.

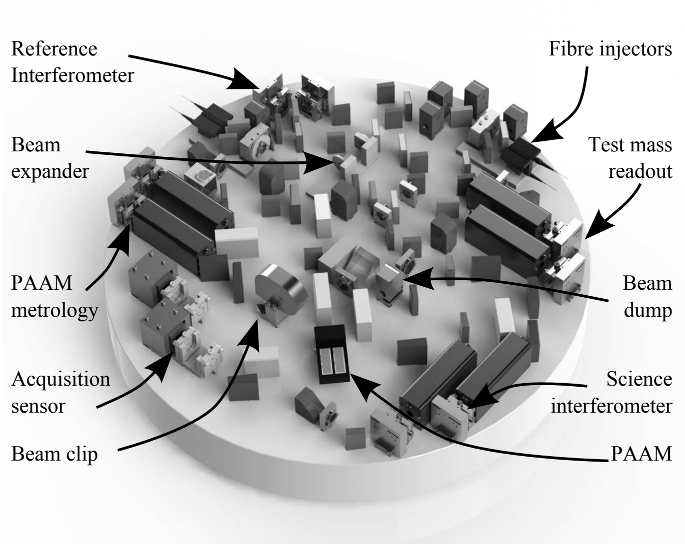

Figure 1. This picture shows the optical bench design for the EBB. Key components are labeled. These include the fibre injectors, beam dumps and mountings for the photodiodes and other mechanical hardware.

3. Fibre injectors

Fibre injector optical subassembly (FIOS) were developed for use in LISA Pathfinder. The requirements were to provide precisely defined and stable beams on the optical bench. Commercial injectors with metal mounts did not meet the thermal stability goals and so a design was developed in which the fibre end was glued into a silica ferrule that was, in turn, glued into a hole through a silica block. The face of this block was then polished to form a “Fibre Mounted Assembly” (FMA) which was then attached to a small baseplate by hydroxide-catalysis bonding. A collimating lens mounted in a fused silica u-groove was then bonded to the same baseplate at a precisely adjusted distance from the fibre end to produce a collimated beam. This small baseplate provided the interface between the FIOS sub-system and a post bonded to the optical bench. The two bonds - baseplate to post and post to bench - provided alignment control of the injected beam (ref. Fitzsimons (2010)).

The LTP FIOS design has been upgraded to a quasi-monolithic design (see figure 2) in which the fibre end is no longer exposed to free space. This avoids the risk of particulate contamination at a point of very small beam size and high power density. In the new quasi-monolithic design the lens is bonded to the FMA via a precision length fused silica spacer through which the beam propagates. The principal thermal sensitivity of the design is to first order a change in the optical path length between the fibre end and the lens output face. Over the expected operating temperature range of 20 $\pm$ 10°C the optical path length has been modeled to change by $\pm 1.2\,\mu$m. This is well below the tolerance on the focus of $10\,\mu$m and leads to only slight changes in the collimation of the output beam. The design also provides improved thermal stability of beam pointing.

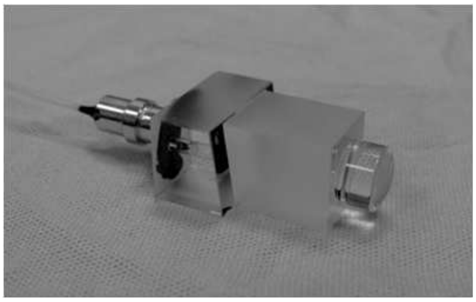

Figure 2. This picture shows the first completed quasi-monolithic FIOS. The output of the FIOS is a collimated 0.8 mm radius beam.

4. Component alignment

Some of the beam alignment requirements that have to be achieved on the optical bench are extremely challenging. Some critical beams have to be positioned and aligned to an absolute accuracy with respect to masses, photodiodes and other beams. Examples are the position of the beam onto the test mass face of around $\pm 20\,\mu$m, or the overlap of beams at a combination beamsplitter of less than $\pm 10\,\mu$m and $\pm 30\,\mu$rad. A technique that actively reads out a beam vector through the use of a pair of quadrant photodiodes with known position in the reference frame of the optical bench has been developed. The pair of photodiodes are on a separate optical bench and form a device called a CQP (Calibrated Quadrant photodiode Pair) (ref. Fitzsimons et al. (2012)). The location of the CQP with respect to that of the optical bench is measured using a coordinate measuring machine (CMM) with an accuracy of a few microns. This system of CQP and CMM can be used both as a beam measuring device and as a target. In its measurement role it allows the build up of a complete as-built optical model of the bench. In the latter, target, role its output is used to provide the information during alignment and bonding of a component from which the measured beam is reflected.

The most recent version of CQP uses large 11 mm diameter photodiodes mounted to low CTE glass blocks catalysis bonded to a Zerodur® base plate. The dimensions of the new design are optimised to benefit fully from the available CMM measurement accuracy and the materials used provide improved immunity to thermal fluctuations.

5. Beam dumps

On an LISA-type optical bench there is a large disparity in power levels among many of the optical beams. The main outgoing light to the far spacecraft has a power level of $\sim$ 1 W whereas the received power from the far spacecraft is around 200 pW. The control of scattered light and the absorption of stray beams are therefore significant challenges.

Commercial beam dumps are very effective absorbers, but often use a black powder coating to absorb the unwanted light. Typically these coatings are not suitable for use on spacecraft. For the EBB there is an additional requirement for thermal stability of potential residual backscatter, driving the adoption of titanium as the best non-magnetic material available that is easily machined.

The adopted approach was to design a beam dump through optical modeling in Zemax. The result was a spiral design to channel the light. The beam dump is formed from two halves that are bolted and glued together. The design is such that any input beam must undergo at least eight reflections before re-emerging onto the optical bench (figure 3). Experimental verification of this design has been carried out with an uncoated, machine finished prototype. Using a heterodyne readout system the experiment showed that less than 10^{-8} of the input power was reflected by the beam dump. This measurement was, however, limited by the noise floor of the readout.

A space-qualified dielectric coating produced by CILAS has 98% absorption at 1064 nm. Application of which would further enhance the performance of the beam dump.

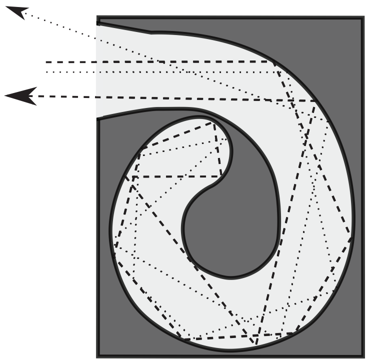

Figure 3. This plot shows a cross-section of the beam dump, illustrating the internal spiral design. Paths for two rays are shown; one is on the nominal design axis (dashed line) and the other is laterally displaced by one beam radius from the beam centre (dotted line). The multiple reflections encountered by these trace rays indicate that the design is tolerant to input beam displacement.

6. Precision mechanical mounting techniques

Thermally stable mechanical structures have been designed to provide mounting of opto-mechanical and opto-electronic components to the optical bench. Titanium and thermally compensated aluminium-titanium constructions have been used throughout for the mounting of photodiodes, acquisition sensor cameras, beam clips and some optics, achieving thermal stability for all critical items of better than $\pm 3\,\mu$m over the design temperature range. Minimisation of stress on the optical bench at metal/Zerodur® interfaces has been achieved by the use of thin flexure feet at the gluing points (ref. Smith & Chetwynd. (1992)).

Photodiode mounts are based on an adjustable X-Y flexure mount. This type of flexure mechanism has been shown to be repeatable in alignment to a micron over a range of around $\pm 100\,\mu$m. The thermally compensated design has a modelled photodiode displacement of less than one micron over a 20°C temperature change.

7. Conclusions

Most of the technologies needed to build an optical bench for a future gravitational waves mission are now under development. The FIOS, CQP and photodiode mounts have functioning prototypes. These provide the stable beams and ability to measure and align the beams for an eLISA optical beam. The photodiode mountings aid in the alignment by allowing for careful adjustment in position of photodiodes in a controlled manner. Some of the photodiode mounting parts have been assembled and testing will continue once appropriate photodiodes are available. The beam dumps have been prototyped and measurements of their performance are on going.

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