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Highly stable Zerodur based optical benches for microgravity applications and other adverse environments

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ABSTRACT

A number of cold atom experiments are restrained by the impeding effects of gravity. While efforts have been made to overcome these limitations in a gravitational environment, another approach is placing the experiment in a microgravity environment, as can be found aboard sounding rockets, satellites or a space station.

The cornerstone of such experiments is a robust laser system. The adverse conditions during a rocket launch impose stringent requirements on thermal stability and resilience against mechanical stress on this part of the experimental setup. Furthermore, the very limited space found on any of the aforementioned microgravity platforms necessitates maximal miniaturization.

In order to meet these requirements, we have developed a technology based on miniaturized free-space optics, mounted onto optical benches made from Zerodur, a glass-ceramic which exhibits a vanishing first order coefficient of thermal expansion. The technology has already been successfully implemented in the sounding rocket missions FOKUS, KALEXUS and MAIUS-1. It will also be used in the upcoming MAIUS-2/3 sounding rocket missions. To meet the even more restrictive size and mass constraints of the NASA-DLR Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) mission, a quantum optics multi-user facility aboard the International Space Station, we are currently investigating a new and improved design concept. While being motivated by these missions, our technology can be expanded to any other experimental field where a small and robust laser system is needed.

Keywords: Zerodur, optical bench, laser system, miniaturization, microgravity, quantum optics, atom interferometry

1. INTRODUCTION

One example that illustrates the benefits of microgravity are atom interferometers: Here, the sensitivity of the apparatus scales quadratically with the free evolution time. In ground-based atom interferometers, the interfering atoms are usually dropped from a confining potential, such that the free evolution time is limited by the size of the apparatus. A microgravity environment would void the apparatus of this constraint. Furthermore, microgravity allows for much shallower traps, which enables the creation of low-temperature and slowly expanding atomic gases.

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Microgravity environments can be found inside a drop tower capsule or aboard a parabolic flight. However, these platforms offer only very few and time-limited experimental cycles. Platforms such as satellites or a space station exhibit low residual gravitational effects and offer a great number of experimental cycles. As these platforms require a rocket launch, they impose stringent requirements on the mechanical and thermal stability of the experiment setup. Furthermore, the size aboard any spaceborne vehicle is usually very limited, such that the experimental setups must be very compact in size.

To accommodate these requirements, we have developed a toolkit based on Zerodur optical benches. Zerodur is a glass-ceramic which exhibits a thermal expansion coefficient of $\pm 0.007 \times 10^{-6}$ /K in a range of 0°C to 50°C [1]. Onto the benches we glue custom-made miniaturized optical components, especially designed to suit the aforementioned requirements. The feasibility of this technology has already been successfully demonstrated in the sounding rocket missions FOKUS [2], KALEXUS [3] and MAIUS-1 [4]. The next experimental milestone will be the launch of the payload for MAIUS-2/3 aboard a sounding rocket, for which the Zerodur optical benches have already been constructed and assembled. The experiments feature a dual-species rubidium-potassium atom interferometer. These missions will be followed by the NASA-DLR Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) mission, a multi-user experimental platform aboard the ISS that enables a great number of quantum optics experiments such as dual-species atom interferometry.

2. THE ZERODUR OPTICAL BENCH TOOLKIT

2.1 Jointing Technique

One commonly used technique for jointing two silica glass or glass ceramic composites is the hydroxide-catalysis bonding, developed and patented at Stanford University [5, 6]. However, the alignment must be finalized in 120 s, requires a surface flatness of $\lambda/10$ and curing to full bonding strength takes four weeks [7]. An alternative to this is adhesive bonding. Assemblies based on the two-component epoxy Hysol EA 9313 from Henkel are described in [8]. However, full bonding requires 5 days curing at room temperature.

The bonding scheme that we apply is based on three different adhesives with long processing and short curing times. This allows us to produce highly stable Zerodur modules in a short timeframe [9].

2.2 Optical Components

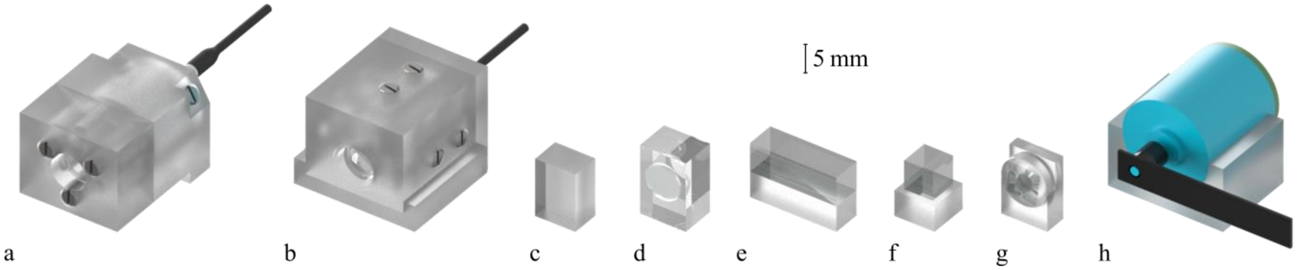

Figure 1. Renderings of Zerodur-based optical and opto-mechanical components including (a) fiber collimator, (b) fiber coupler, (c) fixed mirror, (d) adjustable mirror, (e) dichroic mirror, (f) polarization beam splitter, (g) waveplate holder, (h) holder for shutter.

We have developed a miniaturized version of many of the optical components that can be found in an optical laboratory (see Fig. 1) [9].

Efficient fiber coupling remains one of the major challenges when producing optical assemblies. Due to the small mode field diameter of the fibers we use, small displacements in the range of micrometers are detrimental to achieving a high

coupling efficiency. The optical components used for fiber coupling must thus be adjustable such that misalignments can be corrected:
Our custom fiber coupler (see Fig. 1b) allows for the correction of a lateral displacement by means of six invar screws. In conjunction with an adjustable mirror (see Fig. 1d), this allows us to compensate for misalignments caused by prior optics. To adjust the pointing of the beam coming from the collimator (see Fig. 1a), the fiber and collimating lens inside this component can be rotated around a pivot point by means of three invar screws. This is used to correctly align the beam. Furthermore, the free-space optics are glued sequentially onto the Zerodur optical bench in order of beam impingement. This allows us to correct misalignments caused by an optical component by its successor.

We also produce Zerodur holders for a great variety of active optical components such as shutters (see Fig. 1f) and photodiodes, and milling grooves of arbitrary shape and size can be created on the Zerodur board to accommodate components such as acousto-optic modulators (AOM) and optical isolators.

3. APPLICATION OF OUR TOOLKIT IN PAST AND FUTURE MISSIONS

In the scope of three sounding rocket missions, we have already successfully proven the capability of our Zerodur-based toolkit:
The FOKUS mission (first launched on the 23rd of April 2015) contained a module for the frequency stabilization of a distributed feedback laser onto the ^{87}Rb D2 transition, which remained locked during launch. It further featured a comparison of two frequency standards to test the local position invariance by creating a beat note with a frequency comb provided by Menlo Systems [2].
The KALEXUS mission (launched on the 23rd of January 2016) featured the first frequency modulation spectroscopy of the ^{39}K D2-line in space, using external cavity diode lasers to further decrease the linewidth [3]. The laser was locked in flight by using an autonomous frequency stabilization algorithm.
The latest achievement was the launch of MAIUS-1 (launched on 23rd of January 2017), where our Zerodur optical benches were used to enable switching and distribution of the light fields [10] to create the first Bose-Einstein condensate in space and to perform atom interferometry [4].

As a next major milestone, MAIUS-2/3 will build on this heritage by adding a dual-species atom-interferometer using rubidium and potassium. The Zerodur optical benches for the spectroscopy and switching, merging and separating of light at 780 nm and 767 nm needed for this mission have already been assembled [11]. The NASA Cold Atom Laboratory, developed by the NASA Jet Propulsion Laboratory, is a research facility aboard the International Space Station that enables the study of ultra-cold quantum gases in microgravity [12]. The experimental module was launched to the ISS on the 20th of May 2018. We are currently designing the optical benches for the NASA-DLR BECCAL mission, which will be the successor to CAL and incorporates the experimental heritage of the aforementioned sounding rocket missions. The BECCAL mission is a multi-user facility that will enable a wide variety of quantum optics experiments.

Considering the increased complexity of the setup when compared to previous sounding rocket missions, the space constraints in the foreseen experimental unit aboard the ISS are even tighter than on previous sounding rocket missions. We are currently in the process of testing a new design and mounting scheme that will enable further miniaturization.

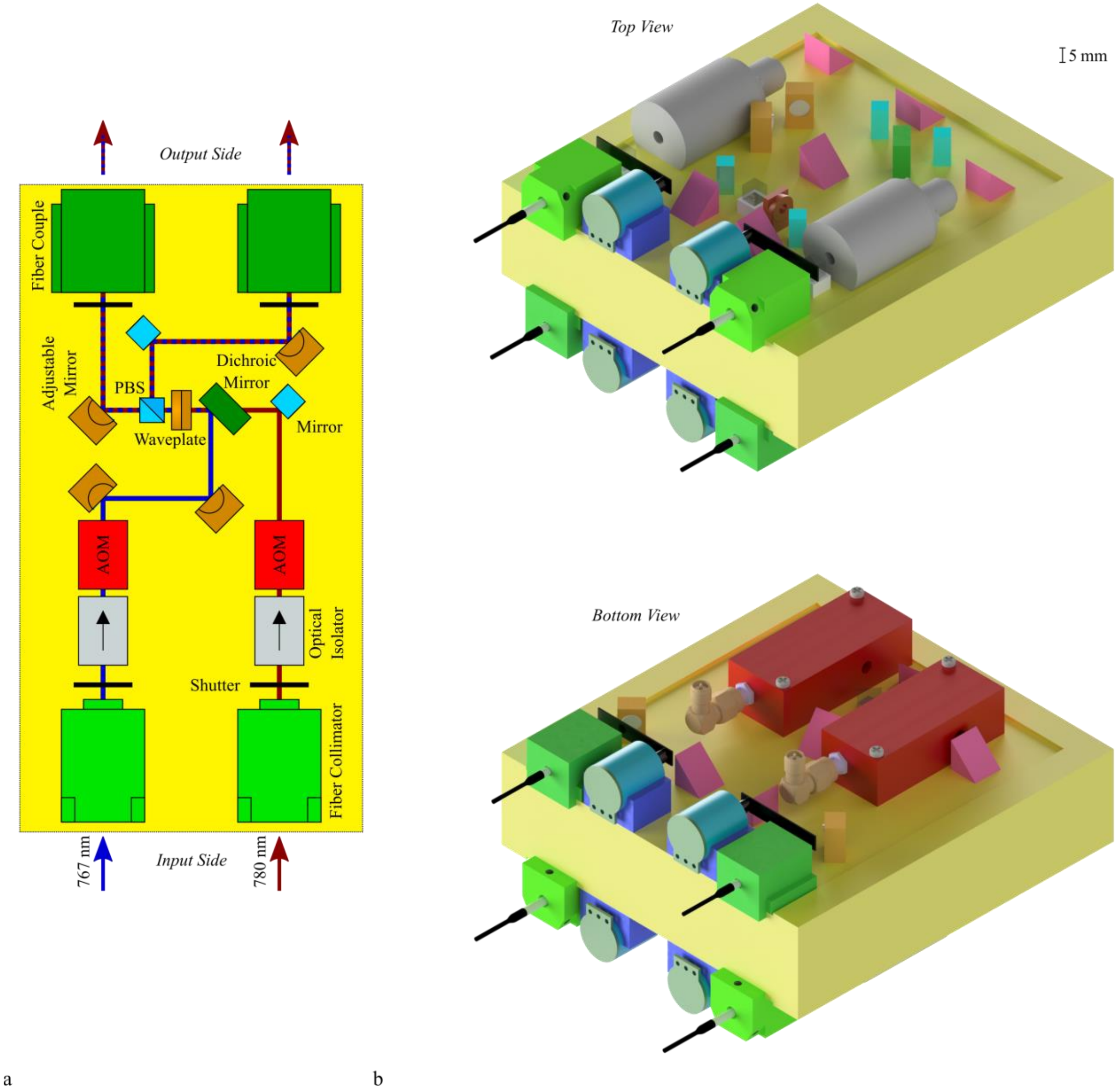

Figure 2. (a) Simplified schematic of the Merge-Split board used for merging and splitting two light sources of 767 nm and 780 nm. (b) Rendering of an early CAD concept drawing of the corresponding Zerodur bench.

Figure 2a shows a simplified schematic of one of our most complex Zerodur optical benches for use as part of the BECCAL payload, the Merge-Split board. Two collimators are used to collimate beams of wavelengths 780 nm and 767 nm, respectively. Both beams pass an AOM for fast light switching and a mechanical shutter to fully suppress the beams. The two beams are then joined by means of a dichroic mirror, two adjustable mirrors are included in the beam that is reflected off the dichroic mirror to achieve an optimal overlap of both beams. This resulting beam, which now contains light of both wavelengths, is then split into two separate parts by means of a waveplate and a polarization beam splitter (PBS). After passing an additional shutter, both beams are coupled into a fiber using an adjustable mirror and a fiber coupler.

The Merge-Split board can be used to illustrate the advantages of the new design concept. An early design of the corresponding Zerodur bench is depicted in Figure 2b. It has an active surface (surface on which components can be placed) of 100 mm × 115 mm, with an additional 10 mm overhead on three sides for the mounting structure. In contrast to our old design scheme, components are placed on both sides of the breadboard. Right angle prisms are used as 90° reflectors to guide beams through holes in the bench from one side of the breadboard to the other. By pacing components on both sides, we effectively double the active surface. This means that the effective volume of the Zerodur boards needed for this mission can be greatly reduced.

Another improvement is the position of the fiber couplers and collimators: When placing Zerodur boards next to an object in such a way that the side that faces the object contains at least one coupler or collimator, the distance between the two is limited by the bending radius of the corresponding fibers. In our new design scheme, all couplers and collimators are thus placed on one side, which, in conjunction with our new mounting concept, furthermore allows convenient guiding of the fibers.

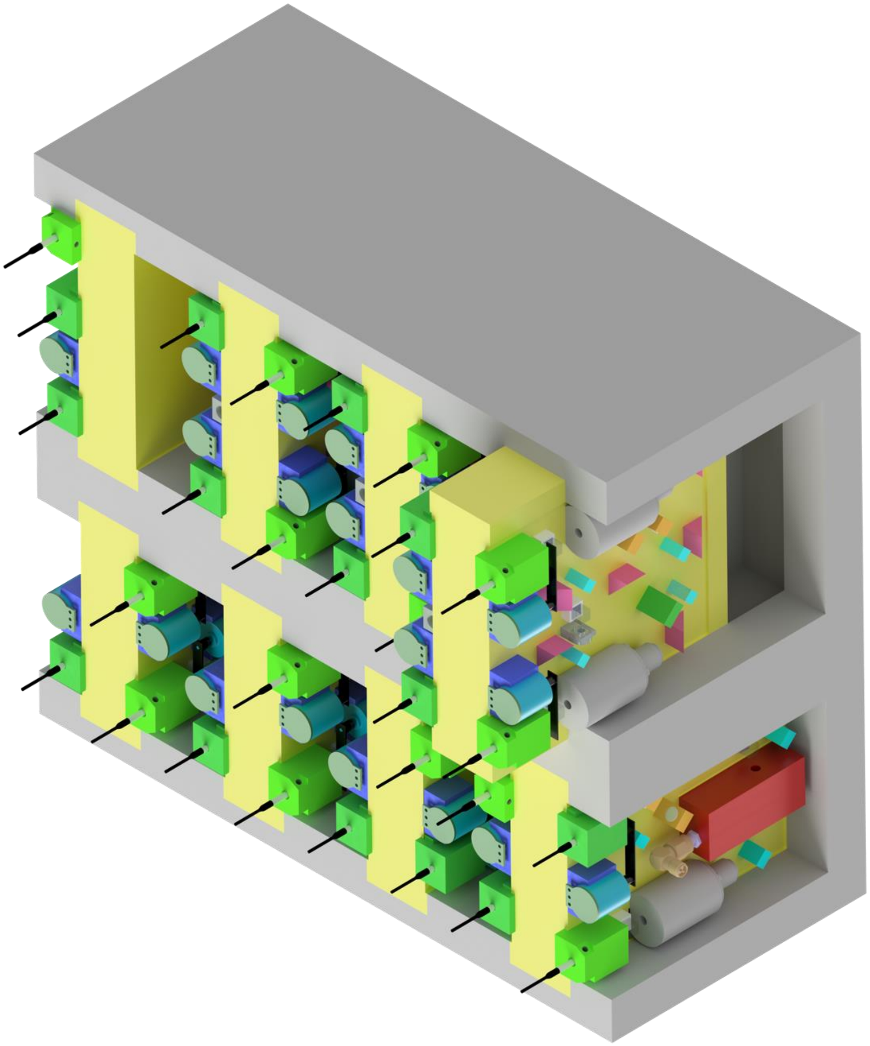

Figure 3. Renderings of an early CAD concept drawing of a new mounting system including Zerodur benches forseen to be used in BECCAL. The Zerodur benches (yellow) are inserted into a set of drawers (grey), the contact surfaces of Zerodur and mounting system are bridged by a layer of rubber. This facilitates mounting and unmounting of Zerodur benches and optimizes the distribution of force onto the Zerodur benches, as this can be detrimental to the coupling efficiency.

We are also investigating a novel mounting concept. It is based on placing the optical benches inside a set of drawers (see Figure 3). The contact surfaces will be cushioned by a layer of rubber. Previously, we used to screw the Zerodur benches onto a flat surface. This will be no longer possible as optics will be placed on both sides of the optical bench.
Furthermore, localized forces applied to the Zerodur bench can degrade the coupling efficiency, by adopting the new mounting system, the force that is exerted will be more evenly distributed. This concept also allows us to more easily mount and unmount the optical benches. We are currently finalizing the design of a demonstrator that will be used to assess the feasibility of this new technology.

4. CONCLUSION

In this paper, we have presented a toolkit based on Zerodur optical benches that can be used in any field where highly robust and thermally stable optical setups are needed. This technology has already successfully enabled a number of sounding rocket missions and is part of the upcoming MAIUS-2/3 missions.
We are currently expanding and adapting our toolkit by investigating new design and mounting concepts and adding compatibility to new wavelengths. This will help us enable future missions such as the NASA-DLR BECCAL mission.

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