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Optical beam steering on distribution boards and its application for atom quantum experiments in space

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ABSTRACT

We present a novel optical beam steering technique (OBST) for fiber to free-space to fiber coupling schemes on optical breadboards, which uses glass wedge pairs and plates to correct for angular and translational misalignments respectively. This technique finds application in proposed missions for atom quantum experiments in space, e.g. where laser beams are used to cool and manipulate atomic clouds. The key advantage compared to the conventional beam steering is that OBST permits extremely fine adjustments whilst being far less sensitive to alignment errors and mechanical drifts. Beam steering resolutions of better than 5 µrad and 2 µm are achieved, resulting in a resolution in coupling efficiency (CE) of 0.1%. The inclusion of OBST on an optical breadboard reduces the requirements on the pointing and position precision adjustment of the fiber couplers, leading to a much-simplified design. The simpler construction of the couplers combined with the reduced sensitivity to drifts increases the stability-reliability of the breadboard and reduces the production duration and cost. We demonstrate CE of up to 90%, with a stability of 0.2% in a stable temperature environment and 2% over a temperature range from 10-40 degrees Celsius. We do not observe any change in the performance after large temperature changes.

Keywords: fiber optics, quantum technologies, ZERODUR, space instrumentation, optomechanics

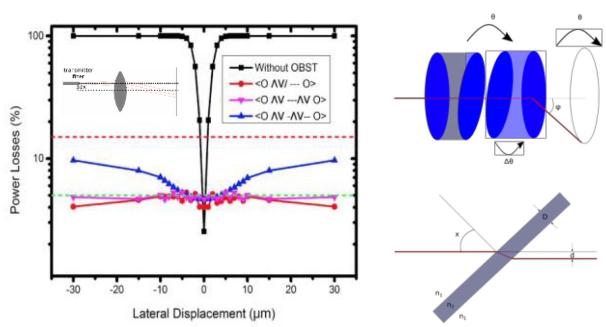
1. INTRODUCTION

Active optics play a rapidly increasing role in space, for example in satellite systems that have started to use LIDAR [1], optical communication [2], and laser ranging [3,4]. Space-based quantum technologies and atom clocks nearly always rely on an intricate manipulation of various on-board laser sources. This trend leads to an enormous increase in the optical complexity of space missions. In some cases, this can be handled by in-fiber devices. However, often the requirements exceed what can be achieved in single mode waveguide devices and optical benches handling fiber to free-space to fiber coupling are required. Examples are cases where frequency shifting (acousto-optic modulators) or very high extinction ratios are needed, such as proposals for cold atom experiments in space [5]. The single mode nature of the fibers results in very stringent requirements for the optical breadboard and its components. To meet these requirements, the PHARAO mission [6] was forced to use active stabilization of many optical components, whereas for the LISA Pathfinder [7] the optical components were attached to the breadboard using hydroxyl bonding.

In this paper, we report a novel scheme, that allows ultra-precise beam-steering for fiber-free space-fiber systems on a ZERODUR breadboard with the use of optical wedges and plates. The basic idea is to provide a robust beam steering element, which can adjust the beam's angle and position with extreme precision and stability but over a very narrow range. This then allows great simplification in the design of other elements such as fiber couplers and mirror mounts. The key advantage of OBST is that the wedge-angle and the plate thickness can be used to adjust the maximum possible deviation of the beam and thus allow for a very precise control of the beam alignment. Furthermore, the cost of the optical breadboards is reduced considerably by a) reducing the complexity of the sensitive components b) simplifying the alignment procedure c) moving to a more flexible UV adhesive system, compared to hydroxyl bonding used in similar applications. A relaxation of the manufacturing requirements of the mechanical components is achieved by separating the beam steering protocol into a coarse and a fine part, thus reducing the number of degrees of freedom required for the beam couplers, mirrors and beam splitters. This scheme yields highly robust, small optical breadboards for use in space missions, meeting very high stability requirements whilst reducing the complexity of the fiber couplers in terms of manufacturing and assembling the different parts that constitute them.

2. KEY FEATURES

A major challenge for a fiber- free space to fiber coupling scheme is to achieve high and stable coupling efficiencies, i,e the fraction of power which is actually transmitted through the fiber, while keeping the whole design simple to align and cost effective. Achieving CE above 85% sets a number of stringent tolerances for the fiber couplers which can be greatly relaxed with use of the corrective optics (wedges and plate). We performed numerical simulations of the sensitivity to misalignments of a simple fiber-free space -fiber configuration that consists of a transmitter single mode fiber, collimating optics, receiver optics and a receiver fiber to evaluate the tolerances the couplers must meet. The fiber used is a commercially available single mode fiber (Thorlabs PM780-HP, 5.3 µm mode field diameter) and the respective optics are molded aspheric lenses (Thorlabs 355230-B, 4.51mm focal length), which were chosen following an optimization process that will be described elsewhere. We compared the findings of this simple optical link with the ones we obtain for a number of different OBST configurations. Power losses for the common misalignment of the lateral displacement (dx) of the transmitter fiber with respect to the collimating lens are shown in Fig.1a. Without the use of corrective optics, displacements at the range of a few micrometers are enough to lead to a complete loss of signal. The operating principle of the alignment using corrective optics is illustrated in Fig.1b for the wedge pair and plate. A rotation of the prism pair by angle θ causes the direction of the beam to be rotated, while a relative angle Δθ of one wedge to each other adjusts the opening angle φ. A tilt of the glass plate by angle x can displace the beam by distance d yielding the other two degrees of freedom required for the alignment. The red line in Fig.1a corresponds to the performance of a pair of wedges (Thorlabs WW40530-B, 0.5 degree) and a glass plate (3mm thickness) at the transmitter side as corrective optics. The purple line corresponds to the performance of two pairs of wedges, one at the transmitter side one at the receiver side while the blue line is for two pair of wedges at the transmitter side. It can be seen that the use of corrective optics greatly relaxes the tolerances for the displacement of the fiber couplers to above 30 µm, simplifying that way the manufacturing process and reducing the total cost. Due to the ease of implementation and its performance we chose the configuration of a pair of wedges and a plate to be the best candidate for our system.



a) b)

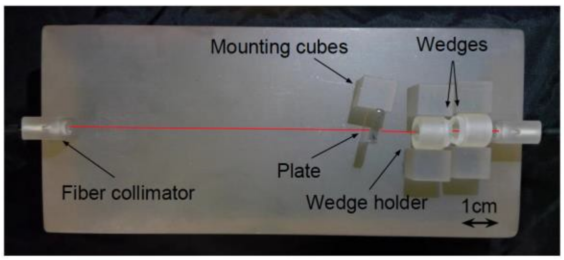
Figure 1. a) Typical values of power losses as a function of lateral displacement of the transmitter fiber for different system configurations (<O : fiber coupler, VΛ : wedge pair, / : glass plate, -- : free space propagation), b) operating principle of the corrective optics used in this work.

A key feature of a fiber-free space-fiber scheme in space applications is the high positioning and angular precision needed for the beam. Typically, the precision must be better than 100µm for positioning and 100µrad in angle, which is a big technical challenge to achieve. With the use of our corrective optics we can tackle this challenge and have high resolution in the CE. In addition to all these features, the breadboard must exhibit high stability in CE (fluctuations should be less than 5%) in the presence of long and short-term temperature fluctuations. In order to assess this behavior, we performed thermal cycling in a temperature range of 10-40 ^{o}C.

3. OPTOMECHANICAL DESIGN

The relaxed manufacturing tolerances enabled us to have a simple and robust mechanical design of the fiber couplers and the corresponding mounts of the corrective optics. All the components are made of ultra-low expansion (ULE) material ZERODUR class 1 which is appropriate for applications with large operation temperature range, due to its low thermal expansion coefficient 0 ± 0.050 ppm/K. The optomechanical design can be seen in Fig.2, where an integrated OBST breadboard with a total footprint of 20 x 10 x 5 cm is shown. The prototype OBST breadboard is composed of two ZERODUR couplers opposite to each other, two wedge holders, a glass plate and five ZERODUR mounting blocks to secure the position of the optical elements. The manufacturing process is relatively simple. ZERODUR plates are cut in slabs, polished at the required sides and then cut to produce the desired component. This parallel polishing scheme simplifies and speeds up the manufacturing procedure.

Figure 2. The integrated OBST prototype breadboard. The red line represents the optical path



The fiber coupler (seen in Fig.3a) is a nearly monolithic device (1.5 x 1 x 1.5 cm) without any moving parts and manufacturing tolerances that can be achieved with standard glass machining equipment. First, a hole is drilled for the placement of the lens and then a hole concentric to the first one is drilled for the placement of the ferrule. A ventilation hole is also drilled at the top side of the coupler so that gases produced during the curing process or in a high temperature environment can escape and not affect the performance of the system. The wedge holder (Fig.3b) is a cylindrical ZERODUR slab (1.5cm outer diameter, 1cm thick) with two concentric holes, one for the placement of the wedge and one for beam access. Lastly, we are using cubic supporting blocks of ZERODUR (1 cmx1 cmx1cm) in order to mount the components rigidly on the ZERODUR breadboard.

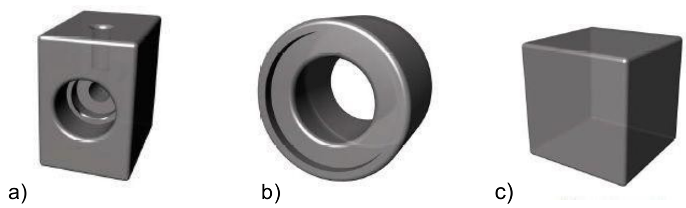


Figure 3. Drawing of a) the fiber coupler (without lens), b) the wedge holder (without wedge) and c) the mounting cube.

4. INTEGRATION

The integration of the breadboard is performed in two steps in order to decrease the degrees of freedom needed during the alignment phase. First, we collimate the fiber couplers off the breadboard and then we perform the alignment using the corrective optics on the breadboard.

During the first step, we apply a thin layer of UV curing glue (NOA61) at the hole of the fiber coupler which is intended for the lens. After placing the lens, the glue is cured using a UV LED (360 mW at recommended operation current). The next step is to fix the polarization and collimate the outgoing beam with the lens in place. The bare ferrule end of the polarization maintaining (PM) fiber is positioned using a 6 degree of freedom mount assembly. The mount assembly consists of a translation mount that gives the ability for xyz movement, a mirror mount with two degrees of freedom for aligning the ferrule with the coupler and a rotation mount for fixing the polarization. We use a polarizing beam splitter in order to align the polarization axis of the fiber to the input beam. When this is done, we remove the ferrule from the coupler in order to apply a layer of UV curing glue and proceed to the collimation. The optimal ferrule to lens distance is achieved by combining theoretical estimations and beam size measurements. A translation stage with 1μm resolution is used to position the ferrule, while a beam profiler, with a few micrometer resolutions, inspects the collimated beam during the collimation and curing phase. We can position the ferrule to the optimum position with an accuracy of 1-2μm which produces an error on the coupling efficiency of less than 1%. The theoretical prediction for 1μm longitudinal displacement of the ferrule is a loss of 0.87% which agrees with the experimental observations. In Fig.4 we show the diameter of the coupler's output beam while moving the ferrule around the position with the minimum diameter. We observe a reproducible dependence of the beam diameter on the fiber position. After achieving the optimal position, we cure the glue by UV radiation. During the curing process the diameter of the beam changes by less than 2%. The produced assembly has the beam quality and beam characteristics that were targeted. It is a robust monolithic device with a simple design that can be built efficiently and reproducibly, while errors are limited to the order of 1% in beam diameter.

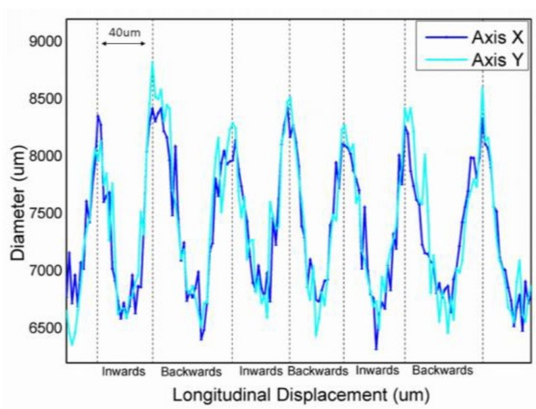


Figure 4. Beam diameter while scanning the ferrule back and forth around the position with the minimum diameter. Inwards and backwards refer to different directions in the movement of the micrometer positioner that determines the longitudinal displacement. X and Y axis refer to the beam size in the plane with (X) and perpendicular to (Y) the breadboard.

In the second step, we perform the alignment of the beam using the corrective optics. First, we align the two fiber couplers roughly by hand and then we fix them in place using UV curing glue. Next, the corrective optics are placed on the breadboard. The wedge holders are rolled using an extension rod which is attached to translation stages, while the plate is attached to a standard mirror mount. After positioning all the corrective optics on the breadboard, we use the translation stages and the mirror mount to maximize the CE, which is continuously monitored using a Si photodiode and an oscilloscope. Our precision of a few microrads and micrometers in tuning the beam angle and position respectively enables us to tune the CE with a precision of the order of 0.1%.

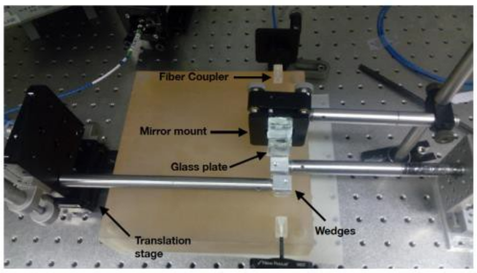


Figure 5. Setup during the alignment phase. The metallic arms attached to the translation stages are used to roll the pair of wedges and control the pointing of the beam. The glass plate is attached to a standard mirror mount to control the position of the beam.

After aligning, we fix the components in place using ZERODUR blocks. We apply thin layers of glue on the sides of the wedge holders and plate and we firmly bring them in contact with the blocks. After curing we remove the alignment equipment and we test the breadboard. During this process, we do not observe any significant loss in CE.

5. PERFORMANCE

In order to evaluate the performance of our breadboard in an environment where temperature changes, we set up a thermal enclosure that can cycle temperature from 10 ^{o}C to 40 ^{o}C. Temperature is measured at three different locations using three thermistors: in the air slightly above the breadboard surface (blue line), on the breadboard surface (green line) and on the surface of one wedge holder (purple line) in Fig.6. We measured the CE both under stable temperature conditions and during thermal cycling.

For the **stable** temperature measurements (25^{o}C with fluctuations approximately 0.1^{o}C over 15 hours), the CE has a mean value of **CE=89.8% and fluctuations less than 0.8% peak to peak and RMS=0.2%** over the same period. The performance of the breadboard during two **thermal cycles** can be seen in Fig.6. We observe a mean value of **CE=88% with an RMS value of fluctuation of 1.7%.**

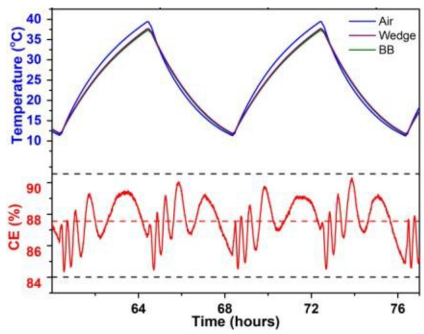


Figure 6. The CE (red curve) and temperature data from different points of the breadboard for two thermal cycles. Mean value of the CE is 88% and is represented by the dashed red line while the black dashed lines correspond to the extreme values.

An overview of the performance of our test system can be seen in Table.1.

Table 1. Achieved values of the OBST prototype board

Description	Unit	Values Achieved
Coupling efficiency	%	≥89%
Long & short-Term Fluctuations of CE	%	<2 %
Operating temperature range	℃	10-40
Positional alignment of optical components	µm	< 100 µm
Precision of the angular beam alignment	µrad	< 5
Precision of the lateral displacement of the beam	µm	< 5
Maximum temperature stability of the testing environment	K/Hz^{½}	< 6x10^{-4}

6. SUMMARY AND OUTLOOK

OBST is a novel beam steering technology for complex optical space applications where fiber -free space to fiber coupling is essential. It yields more versatile, compact and stable, optical benches. We presented the design, manufacturing, and assembly process of a ZERODUR prototype breadboard using OBST technology. This technology is directed towards future atom quantum experiments in space, but might be useful where highly efficient and stable fiber coupling is needed in complex optical setups. The performance of the breadboard has been assessed in the presence of temperature fluctuations and CE of up to 90% are achieved. Thermal cycling tests in a temperature range from 10-40°C show fluctuations of less than 2% RMS, while in stable temperature, fluctuations below 0.2% have been demonstrated over time scales of 15-30h. We did not observe any non-reversible changes due to the thermal cycling.

Beam steering with resolution at the micrometer and microrad regime has been demonstrated, enabling us to have a control of CE of 0.1%. OBST allows one to simplify the design of the optomechanical components and the assembly process, which can be performed in standard optical laboratories, resulting in large benefits in terms of speed of the assembly process and in terms of the cost of the final device.

Future works aims to assess the performance of the breadboard at the presence of vibrations and proceed to a full subsystem based on OBST that will include active optical elements such as acousto-optic modulators and beam shutters.

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