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An optical distribution board for atom quantum experiments in space (a numerical analysis)

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ABSTRACT

We present the theoretical analysis of a novel optical beam steering technique (OBST) for fiber to free-space to fiber coupling schemes on optical breadboards. This technique uses glass wedges and plates to correct misalignments in the position and angle of beams on the breadboard. It can be used in any application where stable and robust coupling of light from an input to an output fiber is required, such as laser distribution boards for cold atom experiments in space. We examine the optical performance in terms of coupling efficiency (CE) for a number of different OBST systems and compare the results. Coupling efficiencies above 95% and positional and angular resolution of smaller than 5 μm and 5 μrad can be achieved using this technology.

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

1. INTRODUCTION

A major challenge for optical systems used in space applications is the stability, robustness and efficiency of the optical benches in harsh environments. Temperature fluctuations, vibrations during launch and in flight and radiation conditions set a number of requirements that need to be fulfilled. This is further complicated by the ever-increasing complexity of the benches in the context of the more recent developments of space bourn Lidar technologies, optical communications, laser ranging and most importantly quantum technologies. Several applications, such as quantum experiments in space require high extinction ratios, fast amplitude control and accurate frequency shifting [1]. For this reason, in-fiber solutions are often not available and the free-space propagation of an input beam from a single mode fiber through optical elements and coupling back to single mode fibers is needed. Some approaches, e.g. PHARAO [2], use active stabilization of optical components while others (LISA Pathfinder [3]) use hydroxide catalysis bonding. These approaches are mechanically very complex and/or make the construction of the breadboard extremely challenging.

In this paper, we report the theoretical analysis of a novel optical beam steering scheme, that allows precise beam-steering for fiber-free space-fiber systems with the use of optical wedges and plates [4]. We study the effect of potential misalignments on the performance of the systems in terms of Coupling Efficiency (CE), i.e. the fraction of power that is transmitted from the transmitter fiber to the receiver fiber. The key feature is that we use a steering element, which when moved over a large distance change the beam by a very small amount. This guarantees that one can adjust the beam's angle and position with extreme precision and stability. The steering optics can be easily tailored to the resolution and correction range required and precisely control the CE. By combing wedges and plates, we have the required degrees of freedom to perform the alignment of the beam on the breadboard. This allowed us to simplify the optomechanical design of sensitive components on optical breadboards, such as fiber couplers and mirror mounts, thus reducing significantly the tolerances they must comply to. The total cost and manufacturing time of the breadboard is thus much reduced. The high precision achieved simplifies the manufacturing and assembling procedure making the process cost effective and efficient.

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2. NUMERICAL ANALYSIS

We performed in terms of coupling efficiency a detailed analysis of the performance of an optical breadboard in the presence of various misalignments for a number of different optical beam delivery system configurations. We used both analytical descriptions and numerical simulations obtained using the ZEMAX optical analysis software. Here, we present the result of the numerical simulation for one of the most critical misalignments, which is the lateral displacement of the transmitter fiber with respect to the optical axis. The complete analysis including the analytical predictions for the system's behavior will be presented elsewhere.

The main optical components used throughout our analysis are summarized in Table 1. Note that all components are assumed to have an antireflection coating at the design wavelength (780 nm). Depending on the optical element we used broadband antireflective (BBAR) or narrow range (V) coating. For BBAR the reflectance for each surface is smaller than 0.5%, with a typical value of 0.3%, while for V-coating, reflectance per surface is smaller than 0.25% as quoted by the manufacturer.

Table 1. Overview of main optical components used in our analysis

Type	Product ID	Specifications	Supplier
Aspheric Lens	355230-B	Ø=6.33 mm, f = 4.51mm, NA = 0.55, material: DZLaF52LA	THORLAB S
Wedge Prism	WW40530	Ø=12.7 mm, thickness=3 mm, surface flatness=λ/20 @633nm (central surface), material: UVFS	THORLAB S
Flat Plate	225-0123	thickness=3 mm, surface flatness=λ/10@633nm, material: BK7	EKSMA
Optical fiber	PMC780	mode field diameter (MFD)=4.7-6.0 µm	Schäfter+ Kirchhoff

2.1 Simple transmitter-receiver link

We examine the behavior of a simple transmitter-receiver system to potential misalignments, in order to evaluate its performance without the implementation of OBST. It consists of a transmitter fiber, collimating optics, receiver optics and receiver fiber as shown in Fig. 1. For practical reasons, the system has a fixed 250 mm distance between the lenses. Our numerical model takes into account the optical material, surface losses and aberrations. For the simulation, we set at ZEMAX the fiber type to Gaussian waist (waist x= 2.5µm, waist y =2.5 µm) and fiber position at surface vertex. We have a maximum achievable CE of 98.1% for this setup.

Figure 1. Schematic of a simple transmitter - receiver link optical interface.

We study how this simple system behaves after inducing various misalignments either on the fibers or the optics. Concerning the fibers, our analysis indicates that the most critical misalignment is a lateral displacement with respect to the optical axis. Figure 2 shows the dependency of CE on such a lateral displacement. A displacement of only 1 μm can result in 20% loss of CE. This sensitivity is expected since the displacement, although small compared to typical specifications of optomechanical components, is ~18% of the input filed mode diameter.

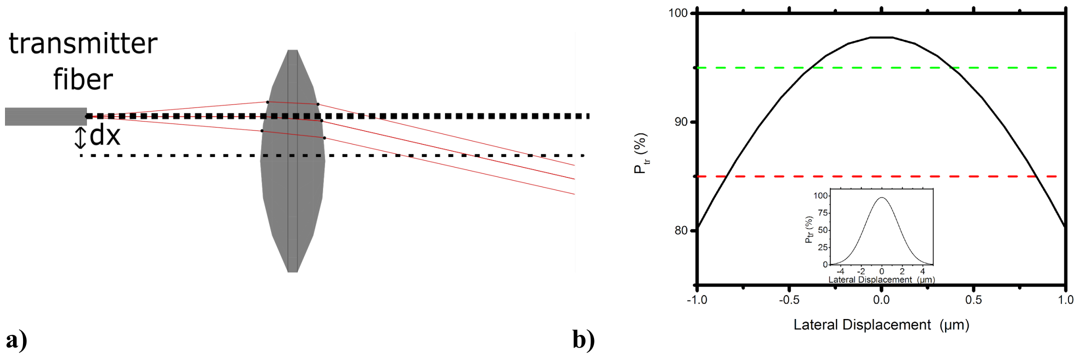


Figure 2. a) Schematic of the optical layout of the fiber's lateral displacement and b) Numerical simulation results of the coupling efficiency as a function of lateral displacement of the transmitter fiber. Dashed lines: green 95%, red 85% (inset shows a larger displacement range).

2.2 The OBST beams steering technique

I in order to retain high coupling efficiencies, the tolerances that a typical fiber coupler must comply to are extremely tight. The alignment requires up to five degrees of freedom of the alignment, which is why typical fiber couplers are quite complex mechanical devices in terms of manufacturing and assembling the different parts that they consist of [5]. An important advantage of our proposed OBST technology [4] is the relaxation of these tight tolerances while improving the stability and robustness of the system overall. The use of corrective optics (plates and wedges) provides us with the required degrees of freedom to perform a precise alignment. The operating principle is simple and can be seen in Fig. 3(a) for the wedges and Fig. 3(b) for the plate. By rotating the prism pair by angle θ we rotate the beam, while a relative angle Δθ of one wedge to each other can adjust the opening angle φ. For the glass plate, a tilt by angle x can displace the beam by distance d. Using the optical elements described in Table 1 we can achieve positional and angular resolution of better than 5 μm and 5 μrad. A detailed analysis of our technique and it's implementation is presented in [4].

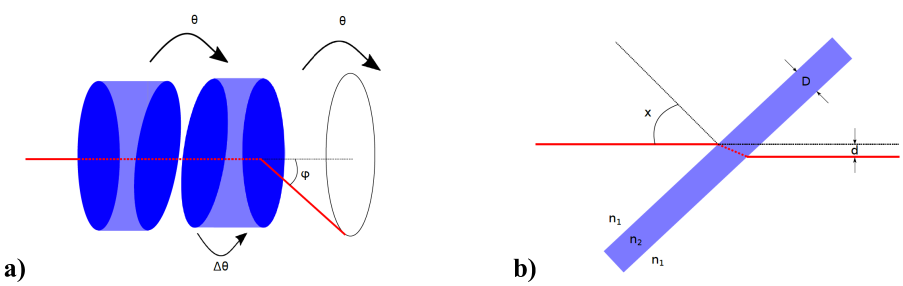


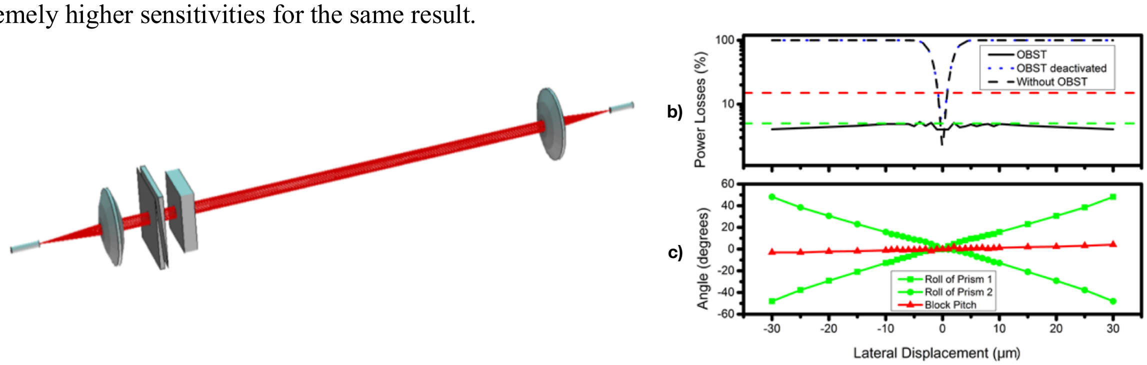
Figure 3. Schematic of the OBST operating principle. a) a Wedge pair is used to rotate the beam by θ on a cone of angle ϕ around the optical axis and b) a tilted flat plate to displace the beam by d.

The proposed technology can make use of various combinations of wedges and flat plates to control the beam direction and position. In the following we will present numerical simulation results, for various configurations, on the ability of the OBST technology to effectively correct misalignments induced in a simple transmitter – receiver system (shown in Fig. 1) after a transmitter fiber displacement as shown in Fig. 2.

OBST configuration 1: Two wedges combined with flat a plate

Configuration 1 consists of a wedge pair followed by a glass plate as shown in Fig. 4(a). In this configuration the wedge pair, positioned 20 mm away from the transmitter lens, corrects misalignments regarding the direction of the beam. The glass plate, following at a 25 mm distance, corrects misalignments regarding the beam displacement.

In Fig. 4(b) we can see the numerical simulation results of correction achieved by configuration 1 in the presence of a lateral displacement of the fiber. The top plot shows the transmissivity power losses for a number of different cases, which can be without OBST (for a system shown in Fig. 1), with OBST deactivated (system including OBST optics in place but not tuned to correct the misalignment), or with OBST correction (sub-components optimized). The red dotted line represents 15% power losses which is close to the limit of unacceptable losses in space applications, while the green dotted lines represents 5% losses which is the goal for optimum operation. Without any correction optics, even a 1 μm displacement causes unacceptable losses more than 15%. If we use configuration 1, but without optimizing it (correction deactivated) we obtain the blue dotted curve that depicts slightly larger losses due to the reflectance and material absorption induced by the optical surfaces of the sub-components added to the system. As we can see, the black solid line shows that configuration 1 can successfully correct lateral displacements in the range of ±30 μm, retaining the system losses below 5%. The simulations show that for 50 μm displacement we obtain 7% losses. The lateral displacement of the fiber causes a tilt to the collimated beam with respect to the optical axis. Our results confirm that this tilt can be well compensated by the symmetrical rotation of the two prisms around the optical axis. Note that as we can see at the lower diagram, a 30 μm displacement can be corrected by θ = 50 degrees and -50 degrees roll of the first and second prism respectively. This result is indicative of the coarse sensitivity required to control the wedge rotation, and obvious advantage of the OBST technology compared to other alignment methods that would require extremely higher sensitivities for the same result.

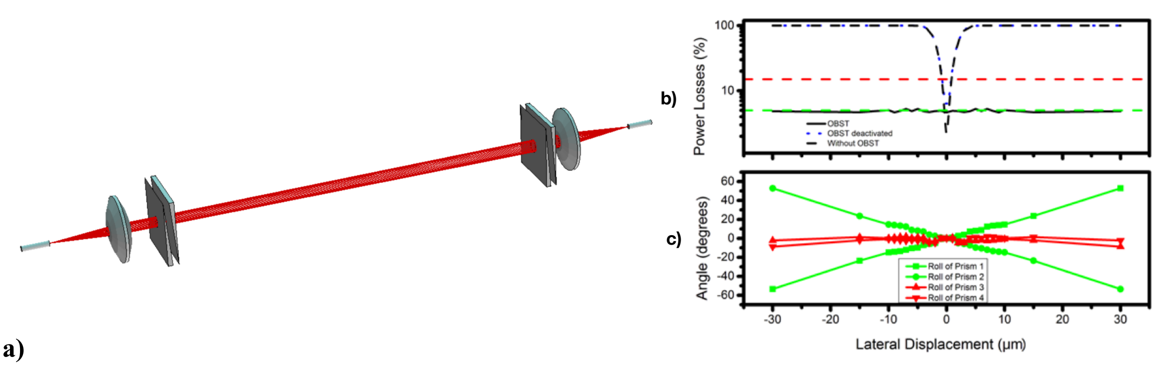


a)

Figure 4. a) Schematic of the OBST configuration 1, two wedges and a plate are inserted after the transmission lens in the simple transmitter - receiver link optical interface (see Fig. 1) and b) Power losses: dashed black line for a system shown in Fig. 1, dashed blue line for a system including OBST optics in place but not tuned to correct the misalignment, black line for sub-components optimized, red and green dotted lines represent the 85% and 95% CE respectively, c) required adjustment of the corrective optics for compensation.

Configuration 2; Variation 1 (2.1): Two wedge pairs positioned at the transmitter and the receiver side

Configuration 2; variation 1 consists of one wedge pair at the transmitter side and one wedge pair at the receiver side in order to correct the misalignment induced by the perturbations as shown in Fig. 5(a).



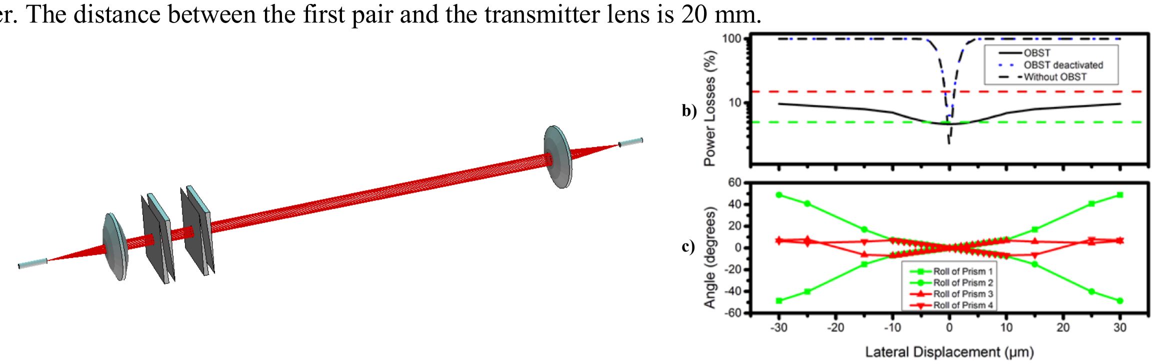
a)

Figure 5. a) Configuration 2; variation 1: Two wedge pairs positioned at the transmitter and the receiver side and b) Power losses: dashed black line for a system shown in Fig. 1, dashed blue line for a system including OBST optics in place but not tuned to correct the misalignment, black line for sub-components optimized, red and green dotted lines represent the 85% and 95% CE respectively, c) required adjustment of the corrective optics for compensation.

As we can see in Fig. 5(b) this system can also compensate lateral displacements of the fiber in the range of ±30 μm. This compensation is achieved by the symmetric roll of each prism of every pair to different directions.

Configuration 2; Variation 2 (2.2): Two wedge pairs on the transmitter side

In this variation of the configuration 2 we are again using 2 wedge prisms pairs but now the second pair lies on the transmitter side, close to the first one, as shown in Fig. 5(a). Each wedge prism pair is 30 mm away from the other. The distance between the first pair and the transmitter lens is 20 mm.



a)

Figure 6. a) Setup 2 variation 2: Two wedge pairs transmitter side and b) Power losses: dashed black line for a system shown in Fig. 1, dashed blue line for a system including OBST optics in place but not tuned to correct the misalignment, black line for sub-components optimized, red and green dotted lines represent the 85% and 95% CE respectively, c) required adjustment of the corrective optics for compensation.

Results presented in Fig. 6(b) show that this system is not as effective as the two previously presented at correcting the lateral displacement of the fiber. For a lateral displacement above 10μm losses reach a value of 10%, remaining nonetheless below the limit of 85%.

2.3 Comparison of different OBST setups

In the previous section, we have shown through numerical simulations the amount of correction that different OBST configurations can achieve to compensate lateral displacements of the transmitter fiber. This misalignment is one of the most critical and imposes technical difficulties in the construction of optical distribution boards. Here, we summarize the results and compare between the proposed configurations. In Fig. 7 we represent configuration 1 as <OΛV/ --- O>, 2.1 as <O ΛV --- ΛV O> and 2.2 as <O ΛV- ΛV – O>. In this textual representation "<O" denotes the transmitter coupler, "ΛV" the two wedge system, "/" the glass plate, "O>" the receiver coupler and " ---" the free space propagation of the collimated beam.

The comparative results on the correction achieved for a lateral displacement of the fiber from the optical axis, for all 3 different configurations can be seen in Fig. 7. We note that configurations 1 and 2.1 can well compensate displacements at the range of ±30 μm, retaining the overall power transmission losses below 5%. We also notice that configuration 2.2 displays slightly higher losses that reach ~10% for displacements of 30 μm. Configurations 1 and 2.1 are more promising for correcting this particular kind of misalignment. Similar results (not presented here) are obtained from numerical simulations for other potential misalignments, such as tilt of the transmitter fiber and tilt of the transmitter lens. Configuration 1 shows slightly better performance when there's a tilt of the transmitter fiber, while config. 2.1 is slightly better when there's a tilt of the transmitter lens. The differences are minor, and do not favor any system. Thus, the decisive criterion for the final choice of the compensating configuration lies in the manufacturing and assembling aspects and not in the optical performance of different setups [4].

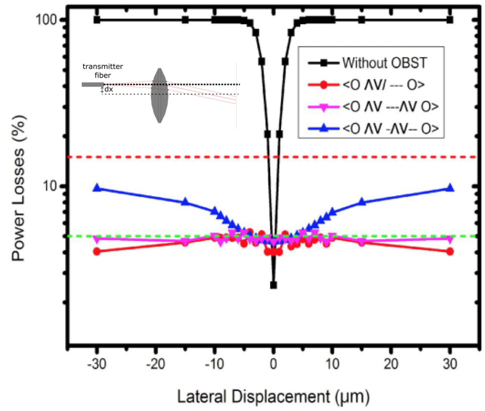


Figure 7. Typical values of power losses as a function of lateral displacement of the transmitter fiber for different system configurations (<O : fiber coupler, VΛ : wedge pair, / : glass plate, -- : free space propagation)

3. SUMMARY AND OUTLOOK

OBST is a novel technique that allows precise beam steering in optical breadboards where high and durable CE is essential. Numerical simulation results, performed using optical analysis software ZEMAX, on the ability of various OBST configurations to correct transmitter fiber displacement misalignments have been presented. The results show that all proposed OBST configurations can effectively correct the misalignments and achieve high CE, above 95%. Furthermore, although the wedge and flat plate OBST sub-components are rotated with a rather coarse accuracy of a few millirad, a positional and angular resolution of better than 5 μm and 5 μrad is achieved. Using OBST technology the fiber coupler's mechanical design is simplified thus reducing the production cost and time. The high resolution simplifies the assembly procedure by allowing the use of standard laboratory equipment.

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