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# HIGH REPRODUCIBLE $CO_2$ LASER SPLICED FIBER-COLLIMATOR FOR A SPACE BORNE LASER SYSTEM

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## I. INTRODUCTION

The Gravity Recovery and Climate Experiment Follow-On (GRACE FO) is a space borne mission to map variations in the earth's gravity field with an even greater accuracy than the first GRACE mission. GRACE FO is a collaborative project of NASA (USA) and GFZ (Germany) scheduled for launch in 2017. On GRACE the gravity field is reconstructed from a measurement of the distance variation between two satellites following each other in 200 km distance by use of a microwave ranging instrument. On GRACE FO a laser ranging interferometer (LRI) is added as a demonstrator in addition to the microwave. Moving from microwave range to optical wavelengths provides an improvement in distance measurement noise from some µm/√Hz to 80 nm/√Hz down to 0.01 Hz frequency. The criteria on the beam delivery system are demanding, in particular with respect to laser beam quality, wave front deviation and pointing as well as thermal and mechanical stability. Conventionally such a system can be manufactured with at least two special mounted lenses or an aspheric lens aligned with respect to the fiber end. However, the alignment of this optical system must be maintained throughout the mission, including the critical launch phase and a wide temperature range in orbit, leading to high alignment effort and athermal design requirements. The monolithic fiber-collimator presented here provides excellent optical and thermal and mechanical performance. It is a part of the LRI and located on the Optical Bench Assembly (OBA) which has already been described in [1, 3].

## II. MONOLITHIC FIBER-COLLIMATOR DESIGN

The approach of this design was to generate a monolithic assembly of the thin PM-fiber together with only one specially designed aspherical rod lens (Fig. 1). The PM-fiber connects the laser source via AVIM fiber connector.

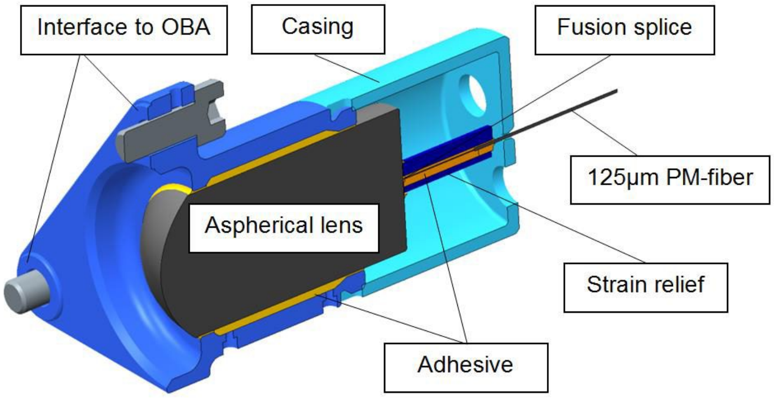


**Fig. 1.** Model of the monolithic fiber-collimator

A structural and thermal analysis of the designed fiber-collimator assembly fully complied with the permissible stress caused by the temperature range of 20°C to 60°C and a quasistatic design load of 100 g in all three principal axes. In accordance with OBA requirements and the finite element simulation, the casing was manufactured from titanium alloy. The splicing components fiber and aspherical rod lens are both typically made of fused silica. Space-approved adhesives have been applied for a stress free mounting of the lens in the titanium casing and to generate a necessary strain relief behind the splice.

That the diameter of the aspherical lens is 148 times that of the PM-fiber highlights the challenge of fusing both with an extraordinary beam quality for the guided laser light. The Fraunhofer IOF has been developing a fusion splicing process based on $CO_2$ laser as a heat source [2]. This process splices fused silica round blanks, called end caps, at optical fiber tips to reduce the optical power density in high power laser applications at the newly created glass-air interface. Very low splice losses, beam quality maintenance, high splice reproducibility, the inherent process cleanliness, as well as mechanical stability, are essential to apply this laser based splicing process. A further advantage is that the end cap surface can be functionalized as: AR coated, shaped as a wedge or spherical/aspherical surface. Only the current dimensions of the gripper sizes and their arrangements in the whole splicing device define some restrictions of the splicing process (Fig. 2) whereas the end cap thickness does not normally have an influence.

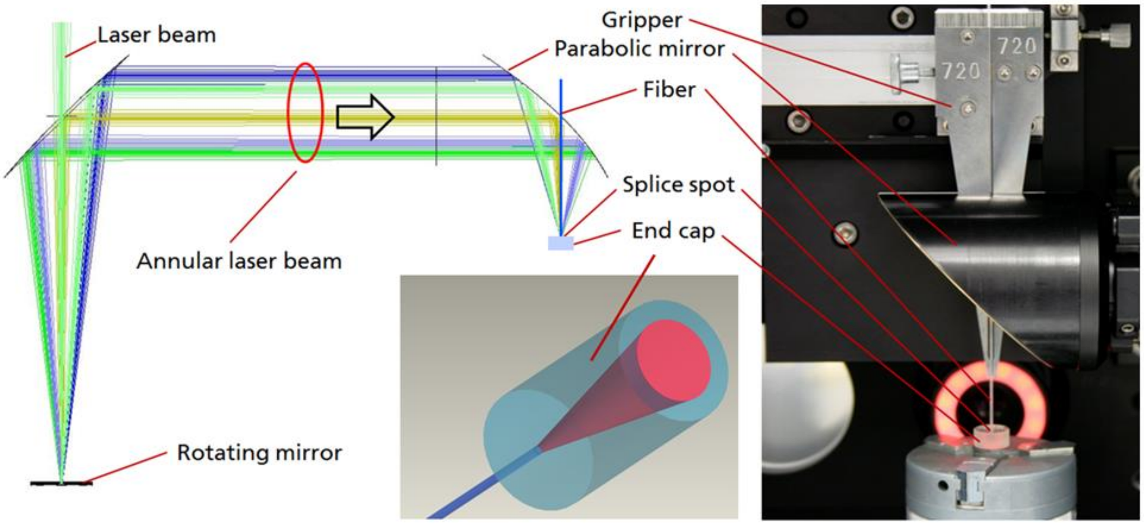


**Fig. 2.** Optical design of the $CO_2$ laser-splicing device with grippers for fiber and end cap

## III. CRITICAL SPECIFICATIONS OF THE MONOLITHIC FIBER-COLLIMATOR ASSEMBLY

The following table 1 lists the critical specifications of the assembled fiber-collimator.

**Table 1.** Fiber-collimator requirements

| Specification | Requirement |
|---|---|
| Wave front deviation | $\leq \lambda/15$ (at 1064 nm) |
| Beam quality factor $M^2$ | $\leq 1.2$ |
| Collimated beam diameter | $\geq 5$ mm |
| Angular optical axis error | $\leq 0.2$ mrad |

## IV. MEASUREMENTS

The critical specifications required additional measurement equipment for assembling the fiber-collimator. All tests applied a 1064 nm single mode laser module with PM-fiber pigtail. The wave front deviation was a significant challenge throughout the assembly process of the monolithic fiber-collimator. An active alignment procedure between fiber and the already mounted aspherical rod lens was used to minimize the wave front deviation. The integration of a Shack-Hartmann wave front sensor SHSCam HR-150-FWB (Optocraft) into the laser splicing device improved the flexibility and enabled a fast wave front measurement.

The beam quality factor $M^2$ could only be measured after completion of the assembly process with a $M^2$-200 from Spiricon. All other specifications listed in table 1 were also measured after the final assembling.

There was, therefore, a real risk of additional work and material in the event that the splicing process would not provide the desired results especially for the wave front deviation. The limited budget and limited number of expensive aspherical rod lenses available necessitated feasibility tests. Further splicing tests performed with a substitute fiber collimator confirmed the high quality $CO_2$ laser based splice.

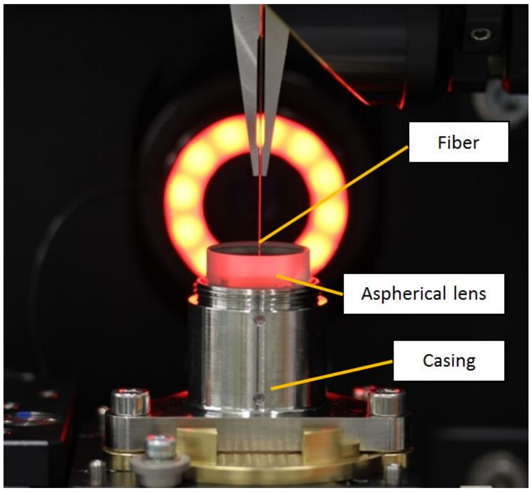


**Fig. 3.** Fiber with collimator (aspherical lens) in the $CO_2$ laser splicing device

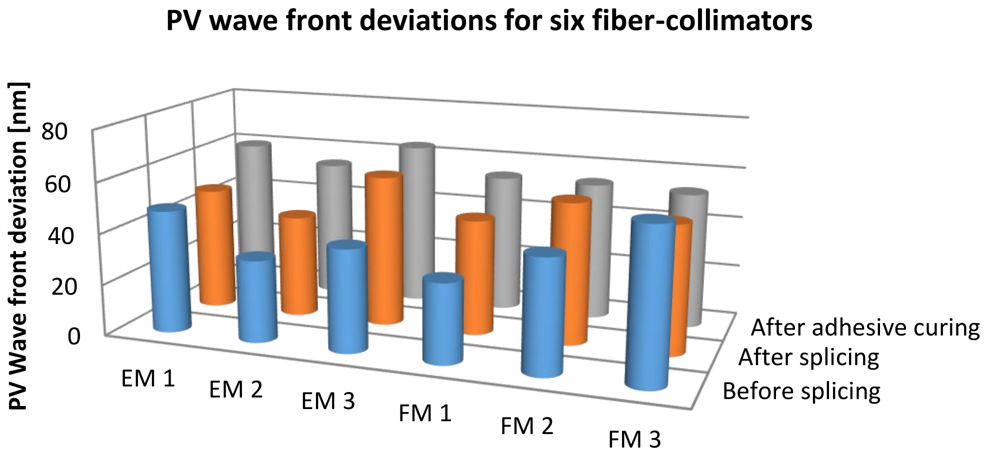
## V. ASSEMBLY PROCESSES

The laser splicing process needs a very similar preparation of the joining parts, PM-fiber and aspherical rod lens just like a conventional fusion splice. Cleanliness and well-prepared surfaces decide about a high quality splicing process. The cleaved fiber tip deviation generates small but different angular optical axis errors for each spliced and assembled model. This required an additional milling process of the OBA interface with reference to the emitted laser beam to obtain an angular optical axis error of less than 0,2 mrad.

## VI. RESULTS

Three evaluation models (EM) and the same numbers of flight models (FM) have been manufactured during the project. The optical quality of the assembled models was substantially influenced by the precision manufactured aspherical rod lenses as described in [1]. The following figure 4 shows the remarkable small changes of the wave front measurements before and after splicing and later after adhesive curing of the fiber strain relief. The difference between the fiber NA and the $1/e^2$ definition for the collimated beam led to a measured beam diameter of only 4,3 mm for the EM assemblies. A lens design modification rectified the beam diameter to the desired value of 5 mm for the FM. All six assemblies obtained the desired low wave front deviation of better than 70 nm at 1064 nm measurements wavelength.

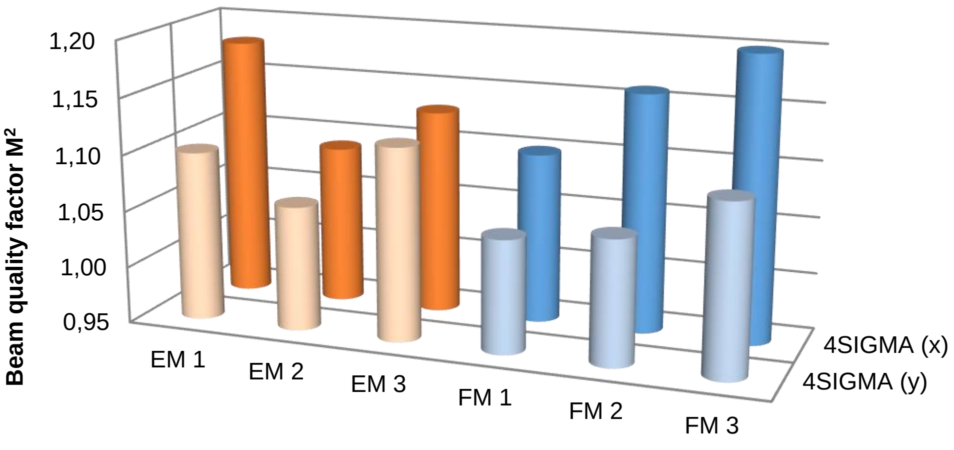
The opposite side of the fiber-collimator was already equipped with an AVIM connector, which connected the test single mode laser module as well as the laser source at the OBA.



| | EM 1 | EM 2 | EM 3 | FM 1 | FM 2 | FM 3 |
|---|---|---|---|---|---|---|
| 🟦 Before splicing | 48 | 32 | 40 | 31 | 44 | 59 |
| 🟧 After splicing | 48 | 40 | 59 | 45 | 55 | 50 |
| ◼ After adhesive curing | 60 | 54 | 64 | 54 | 54 | 53 |

**Fig. 4.** PV wave front deviations in nm at different process steps (λ: 1064nm)

The D4σ - beam width measurement has been applied to measure the beam quality factor M² after the wave front measurements. Due to the finished splice process, no changes were possible to improve the beam quality of the fiber-collimators. As showed in figure 5, all assembled fiber-collimator confirmed the requirement specification for M². Nonetheless, the remaining deviation in M² is higher than expected. A valid explanation of these deviations with the given low assembly numbers could not been found. All Collimators have been accepted for EM and FM application respectively.



| | EM 1 | EM 2 | EM 3 | FM 1 | FM 2 | FM 3 |
|---|---|---|---|---|---|---|
| 4SIGMA (y) | 1,10 | 1,06 | 1,12 | 1,05 | 1,06 | 1,10 |
| 4SIGMA (x) | 1,18 | 1,09 | 1,13 | 1,10 | 1,16 | 1,20 |

**Fig. 5.** Beam quality factor M² for all six monolithic fiber-collimator assemblies

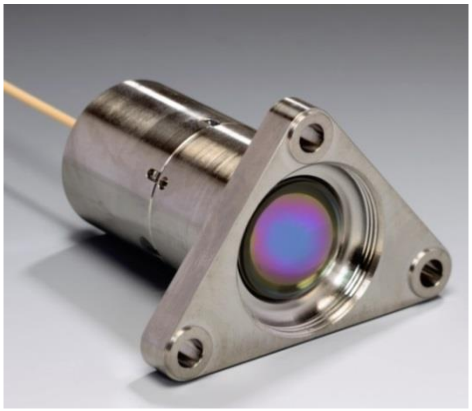


**Fig. 6.** Manufactured monolithic fiber-collimator

## VII. SUMMARY

The $CO_2$ laser spliced fiber-collimators show the innovative potential of these design approach especially for space application with extreme requirements. The wave front sensor is a suitable measurements tool to align fiber and collimator before and after the splicing process. Additional investigations with more probes and a cheaper fiber-collimator substitution should explain the differences in the obtained beam quality. The design approach is easily adaptable to other fused silica lenses, optical fibers with other NA, beam diameters and wavelengths. The fiber-collimators have been fully qualified for the GRACE-FO mission, integrated into the optical benches and the flight hardware has been delivered and integrated into the satellites. The launch is scheduled for 2017.

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