Deliverable 4.4: Final version of PMC module for fiber beam delivery (1)

Dissemination Level: Public

Owner

Name: Benoît Beaudou

Lead Beneficiary: GLO

Phone: +33587506724

E-mail: benoitbeaudou@glophotonics.fr

Context

Author(s): Benoît Beaudou

Work Package: WP 4

Task: T4.4 ; T4.5

Document Status

Version: 1.0

Last modified: 24/07/2018

Status: Final

Approved by: Dr Marwan Abdou-Ahmed

Date Approved: 26/07/2018

Declaration: Any work or result described therein is genuinely a result of the Hiperdias project. Any other source will be properly referenced where and when relevant

Contents

1 Scope and objectives

The goal of WP4.4 is to fabricate and characterize a Photonic microcell (PMC) module for fiber delivery of femtosecond high energy and high average power laser.
The task objective is for GLO to provide the project partners with a modular PMC based ultra-short high power pulse delivery. The module entails the fabrication of hollow-core photonic crystal fiber (HC-PCF) from GLO standardized HC-PCF and assembly of the PMC. The PMC process consists of HC-PCF housed with a cable (such as metallic monocoil) and whose tips are attached to mechanical gas cells. The final beam delivery PMC module will results through several iterations between GLO, the laser manufacturer and the end user. During this iteration process the full specifications of the module will be defined and optimized for the laser characteristics and to the requirements of the end-user. The specifications comprise the final HC-PCF design, its diameter and length. The specifications include also the requirements in gas definition and management for both power handling and dispersion compensation. Finally, the specifications include the final packaging form for optimum integration with the laser on the up-stream of the beam delivery chain and to the work peace via integration to the system integrator on the chain down-stream. Six modules are planned to be fabricated during the tenure of the project in a sequential fashion and at a rate of 1 module per six months with the aim having the final module fully compliant with the laser and system integrator requirements. The optical fiber developed is a Kagome HC-PCF fiber. This type of fiber guides the beam in the hollow core via a mechanism called “Inhibited Coupling” (IC), which allows record optical power guidance (transmission for commercial fibers = 50 dB/km at 1 um).
The physical specs are the following:
1. Fiber OD is in the range of 250 to 350um. The typical one (GLO standard) =320 um +/-10%
2. Fiber OD with coating (The fiber is coated with acrylic for flexibility and protection) ranges between 450-800 um
3. Core diameter: The core contour is hypocycloidal with two defining diameters. Inner diameter set the mode field diameter of the core. Typical range of the inner diameter is: 40-60 um. The mode field diameter can be deducted from the inner diameter. It is 70% of the inner diameter.
4. Jacketing/tubing: In PMC form the fiber is provided by GLO with monocoil tubing for further protection and work in harsh environment.
5. Fiber ends: In PMC form the fiber is attached to mechanical housing with optical windows for light coupling and output and with gas connections for the gas filling or evacuation.

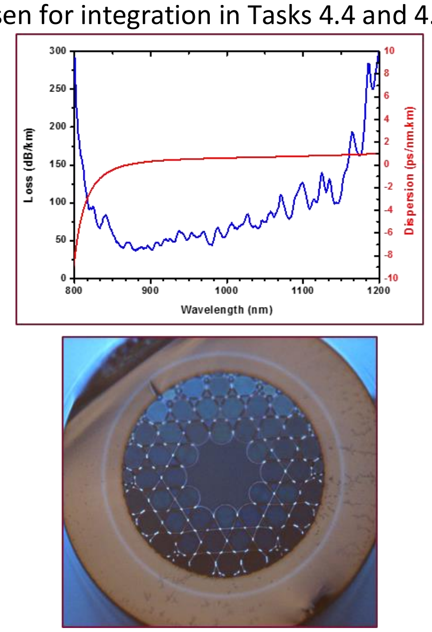
AMP will provide GLO with the necessary feedback for redefining the module specifications for optimum performance and ease-of-use. XLIM will provide the necessary scientific and technical skills in designing and characterizing the HC-PCF and its dispersion properties for distortion free pulse delivery.

All tasks and milestones reported in this document are summarized in the following table.

TASK	TASK DESCRIPTION	MILESTONE	MILESTONE TITLE	DUE DATE
T4.4	Fabrication and characterization of photonic microcell (PMC) module for fibre-delivery of ultra-short high power pulse	MS19	PMC module for fiber beam delivery prototype #3	18
		MS35	PMC module for fiber beam delivery prototype #4	28
T4.5	Design and Fabrication of photonic microcell module with integrated coupling optics for fibre-delivery and interface with system integrator	MS18	End-capping definition and process design	15
		MS21	End-capped output PMC module for beam deliver	18
		MS28	Qualification of end-capped output PMC module for beam delivery	24
		MS33	End-capped input PMC module for beam delivery	26

2 Fibre High power/energy handling ability

As the core component and technological enabler of the beam delivery system GLO standard fiber (PMC-C-Yb-7C) has to be qualified for high power and high energy operation. AS described in first periodic report the fiber chosen for integration in Tasks 4.4 and 4.5 has the specifications presented below



Optical Properties	
Center Wavelength	1030 nm
Attenuation @ 1030 nm	50 dB/km ± 5
Dispersion @1030 nm	1 ps/nm/km ± 0.5
Transmission band** **Attenuation lower than 100 dB/km for the 900-1100nm	>300nm
Mode Field Diameter (1/e²)	39 µm ± 1
3 dB bend loss radius @1030 nm	5 cm ± 2

Physical Properties	
Core contour	Hypocycloid with negative curvature parameter *b=1***
Inner Core Diameter	57 µm ± 1
Outer Fiber Diameter	320 µm ± 1
Fiber Coating Layer	Primary polymer coating

Figure 2.1 : Specifications of the fiber integrated into Beam delivery System

2.1 State of the art

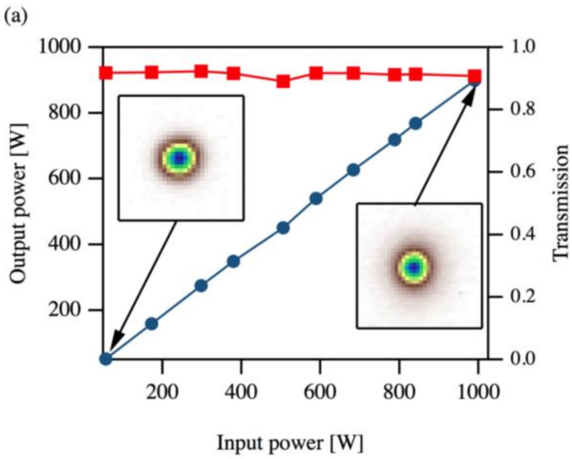


Figure 2.2 :Transmission efficiency and output mode profile of PMC-C-Yb-7C GLOphotonics fibre at 1kW CW regime [1]

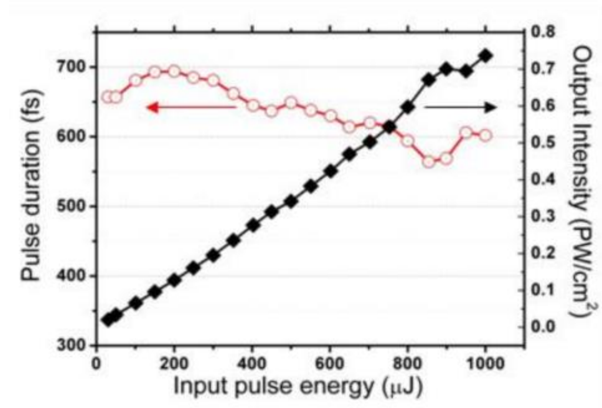


Figure 2.3 :Transmission efficiency of PMC-C-Yb-7C GLOphotonics fibre in fs regime [2]

First if we look at the literature one can find work published by GLO customer. First, [1] demonstrates kW Continuous Wave (CW) operation up to 1kW with 90% transmission and no deterioration of mode quality. Second [2] shows operation up to 1mJ with 600 fs pulses. On can notice transmission efficiency is lower at high energy because of nonlinearities experienced by pulses travelling into the Helium filled fiber core. This unwanted behavior is tackled through the gas management of the BDS described lower in the document.

[1] S. HÄDRICH ET. AL., "TESTING HOLLOW WAVEGUIDES FOR NONLINEAR PULSE COMPRESSION IN KILOWATT AVERAGE POWER OPERATION," IN 2015 EUROPEAN CONFERENCE ON LASERS AND ELECTRO-OPTICS - EUROPEAN QUANTUM ELECTRONICS CONFERENCE, (OPTICAL SOCIETY OF AMERICA, 2015), PAPER CJ_8_2
[2] C. FOURCADE-DUTIN ET. AL., "MILLI-JOULE FEMTOSECOND LASER-PULSE DELIVERY AND COMPRESSION IN HYPOCYCLOID CORE KAGOME HC-PCF," IN CLEO: 2013 POSTDEADLINE, OSA POSTDEADLINE PAPER DIGEST (ONLINE) (OPTICAL SOCIETY OF AMERICA, 2013), PAPER CTH5C.7.

2.2 In-house fiber testing

In spite of the reported knowledge on the power handling capability of GLO fiber, we have repeated high power experiment in-house. We did perform the experiment using a 400W CW Ytterbium fiber laser, a couple of mirrors, a single plano-convex lens and the fiber simply copper taped to a water cooled copper V- groove (fig.2.3). We also used thermocouple to measure temperature of the different components (different position of the fiber were also probed) on the setup while transmitting high power through the fiber.

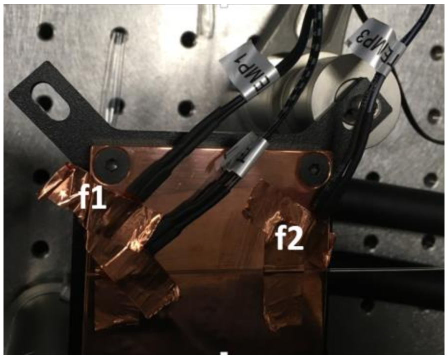


Figure 2.4: Micrograph of V- groove mounted fire with indication of measurement of temperature.

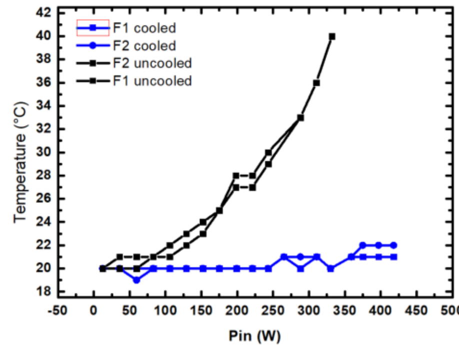


Figure 2.5 : temperature measurement on fiber tip and fiber at the end of the V-groove for uncooled V-groove (black) and cooled V-groove (blue)

First is to notice the water cooled setup allow to reach 400W (maximum laser power) transmission through the fiber with more than 90% efficiency and stable operation during 30min. Figure 2.5 illustrates the impact of insufficient temperature management causing misalignment finally leading to fiber input facet destruction at 320W (uncooled V-groove).

3 Beam Delivery System (BDS) design and test for high average power and high energy femtosecond pulses beam delivery

3.1 BDS#3 design and testing (MS19, MS18, MS21)

3.1.1 BDS#3 Design and fabrication

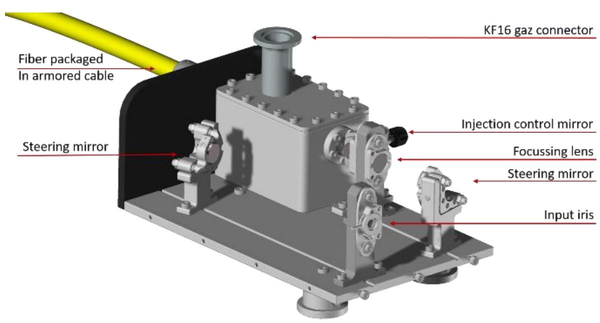


Figure 3.1 : Schematic of the BDS#3 design

Figure 3.2 : Design of end-capped fiber output (MS18)

Figure 3.3 micrograph of fabricated BDS (MS19 , MS21)

First month of the project has been used to design the in coupling module (3D + drawings) shown in Fig. 3.1. This design accommodates 3mm 1/e² collimated input beam @1030nm and includes features for vacuum management (KF16 connection) and alignment (iris & injection control mirror). At the same time GLO design the output cell (Fig. 3.2) and share technical drawing with the system integrators (C4L, Lasea) and laser manufacturer Amplitude Systèmes (AS). Based on this design and exchanges with consortium members BDS prototype#3 has been produced with 5 meters long fiber (Fig. 3.3)

3.1.2 BDS#3 qualification and testing

As part of the qualification process evaluation of BDS#3 has been tested with USP laser both internally and at AS place.

3.1.2.1 BDS#3 in-house testing

Prior to send the BDS#3 to AS, GLO perform tests with USP laser (S-pulse, 750fs, 1 KHz, 1mJ)

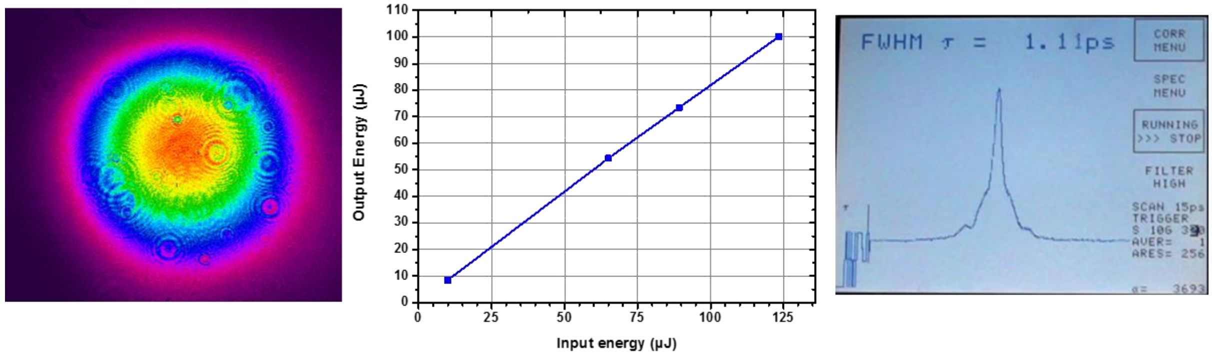


Figure : 3.3 False color output far field beam profile (left), transmission efficiency (middle), Autocorrelation trace @125µJ input power (right)

The characterization of the first prototype shows an excellent output beam quality, a transmission efficiency greater than 80% over a wide input energy range. The autocorrelation trace shows no change in pulse duration. PER in static (20cm diameter coil) has been measured at 14dB.
The prototype has been delivered to AS for evaluation at M11.

3.1.2.2 BDS#3 review of test in AS

AS made comments (M15) on several points to be corrected :

- Armored cable stiffness has to be adapted.
- Vacuum tightness seems deficient (only low energy few µJ operation).
- Iris mechanic actuation is not accurate enough.
- Iris alignment procedure allows fiber coupling but not at maximal efficiency.
- Only 80% transmission efficiency was measured at AS.

GLO took into account AS remarks for design of BDS#4 with the action described below:

- Fiber is now protected with 2 monocoils.
- Vacuum tightness is now measured and quoted.
- Iris mechanism has been updated to limit position drift due to their actuation.
- Due to the accuracy (both position and angle) needed to have an optimal coupling into the fiber no cost effective mechanical means have sufficient precision to reach perfect coupling without fine tuning. Nevertheless in coupling procedure has been reviewed to minimize disparity between iris alignment and optimal coupling positions.
- BDS#3 has been again tested in-house and 87% transmission efficiency has been recorded with proper matching of incoming beam size. Pulse energy up to 130µJ has been transmitted without noticeable pulse duration change.

A second set of tests has been performed (M22) at AS on a Tangor laser system (370fs / 15µJ / 90W) in view to evaluate BDS#3 handling of medium average power. BDS#3 was equipped with thermocouple to probe the temperature of the different optical and mechanical components.

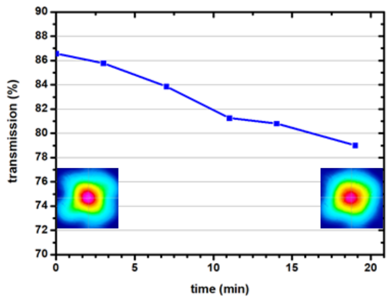


Fig3.4a: Transmission efficiency at 90W input power versus time. BDS#3 output far field at t=0min (left inset) and t= 20min (right inset)

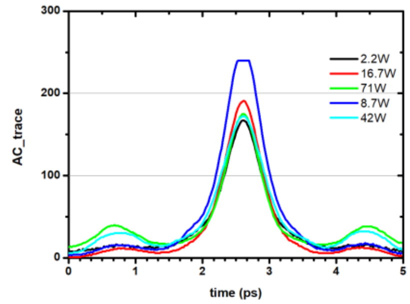


Fig3.4b: Evolution of BDS#3 output autocorrelation trace versus input power.

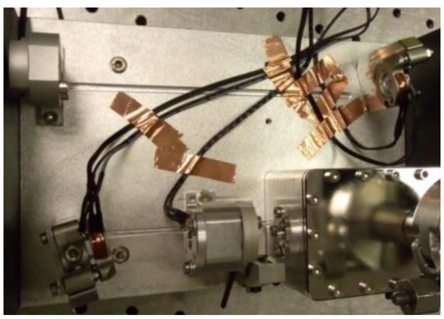


Fig3.4c: micrograph of BDS#3 with thermocouple in test at AS

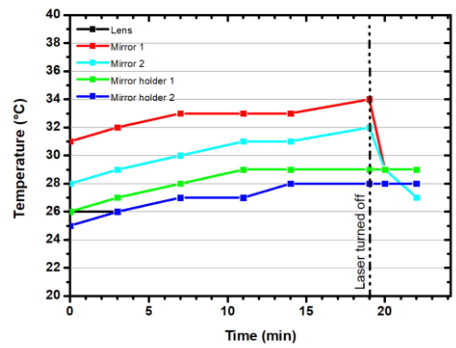


Fig3.4d : Temperature of different component of BDS#3 versus time when operating at 90W input power

Two noticeable informations are highlighted by this test. First, vacuum and transmission efficiency issues seen during first test have been tackled as more than 85% transmission efficiency is achieved (Fig. 3.4a) and no pulse broadening (Fig. &3.4b) is seen. Secondly, decrease of transmission efficiency and beam quality over time (Fig. 3.4a) and heating of mirror holders (Fig. 3.4d) indicate thermal management in BDS#3 is not sufficient to accommodate high average power laser system.

3.2 BDS#4 for high average power (MS28, MS33, MS35)

Taking into account remarks from consortium members and experience acquired during the project BDS#4 has been designed and fabricated. The 3D view of the BDS below (Fig.3.4) highlight the major mechanical evolutions : an updated monocoil and iris actuator as suggested by AS comments and a water cooled input cell to manage thermal load induced by high average power laser systems.
Optics have also been upgraded to high reflection mirrors (>99.95%) and low absorption transmissive optics to limit thermal load.

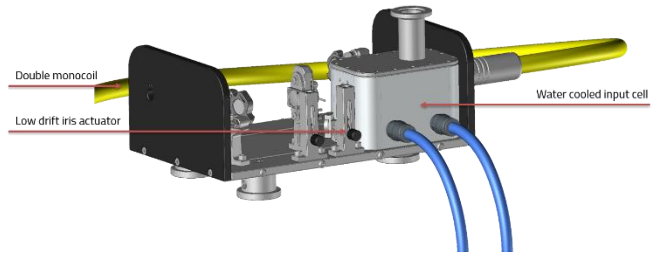


Figure 3.4 :Schematic of BDS#4

3.3 BDS#4 testing

In view of segregating the design problematics of high energy and high power we did measurements and tests on two different lasers exhibiting, for the first one high energy and low average power (1mJ ; 1W) and, for the second one, low energy (CW laser) and high average power (400W).

3.3.1 High pulse energy BDS#4 testing report

The laser used for this test is an S-pulse (450fs, 1mJ, 1W). The test consists of coupling the laser into the BDS and record transmission efficiency, pulse duration and modal profile at the output of the BDS at different input pulse energy.

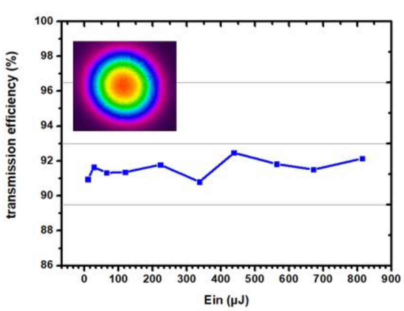


Figure 3.5 : BDS transmission efficiency Versus input pulse energy

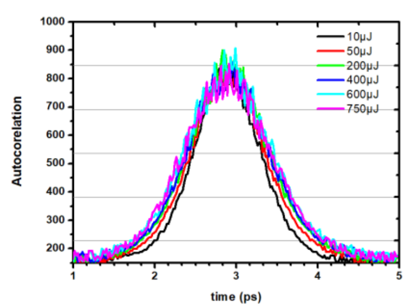


Figure 3.6 : Autocorrelation trace measured at the output of the BDS for different output energy

One can conclude seeing no change on transmission efficiency, output mode quality (Fig.3.5) and autocorrelation trace (Fig.3.6) of the output pulse while ranging input pulse energy from 10µJ to 800µJ than BDS#4 is suitable for high pulse energy delivery.

3.3.2 High average power BDS#4 test report

On top of a careful choice of optic and cooling at input fiber facet, there are other challenges to be addressed for high average power laser handling. The small portion of light (few %) coupled into the cladding of the fiber need to be coupled out of the fiber jacket to prevent fiber heating up. If mode stripping is well known for solid fibers, it needs to be adapted for HC-PCF technology (fiber design, vacuum compatibility…). Furthermore the thermal contact between the fiber and the cooling plate has also to be HC-PCF and vacuum compatible. These two aspects are gathered into the denomination of sealing process (SP) for high average power. We report test on three different SP suitable for high average power USP fiber delivery.

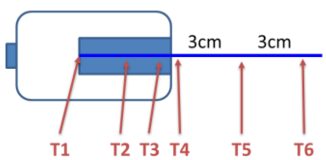


Figure 3.7 : BDS#4 input cell schematic with temperature sampling location

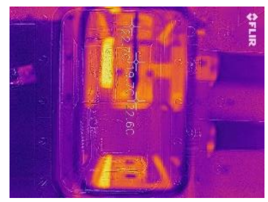


Figure 3.8 : BDS#4 input cell thermal imaging

Test is performed by coupling a 400W CW laser into the BDS while measuring transmission efficiency, output modal content and temperature at different fiber location via thermal imaging.

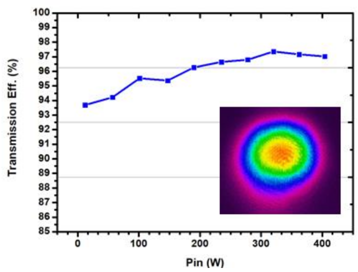


Figure 3.9a : BDS#4 with SP1 transmission efficiency versus input power and output beam quality (inset)

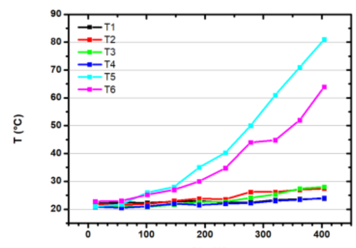


Figure 3.9b BDS#4 with SP1 temperature versus input power

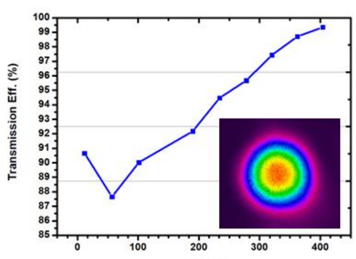


Figure 3.9c : BDS#4 with SP2 transmission efficiency versus input power and output beam quality (inset)

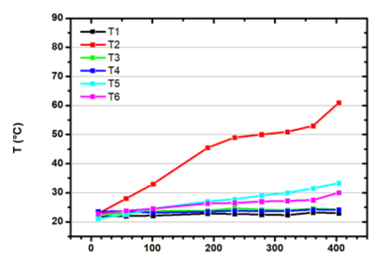


Figure 3.9d BDS#4 with SP2 temperature versus input power

To illustrate both mode stripping and thermal contact we report two investigated SP. Both of them allowed operation at 400W with more than 90% transmission efficiency but one can notice unwanted temperature behavior indicating they are not suitable for long term use. BDS#4 with SP1 exhibits an increase of temperature on the first tens of centimeters of fiber outside the input cell while other measured point remained at room temperature; signature of cladding light insufficiently evacuated. For BDS#4 with SP2, hot spot is located at the middle of the cell/fiber sealed portion, indicating too low heat removal.

Remembering optimization of SP for high average power is an ongoing work we evaluate middle term stability of a third SP by recording transmission efficiency and temperature at 400W input power during 15min.

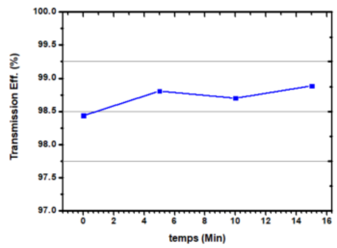


Figure 3.10a : BDS#4 SP3 transmission efficiency at 400W input power versus time

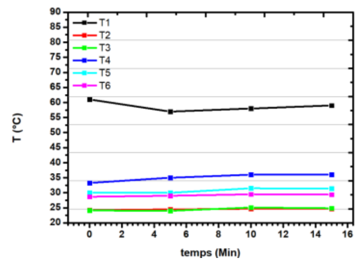
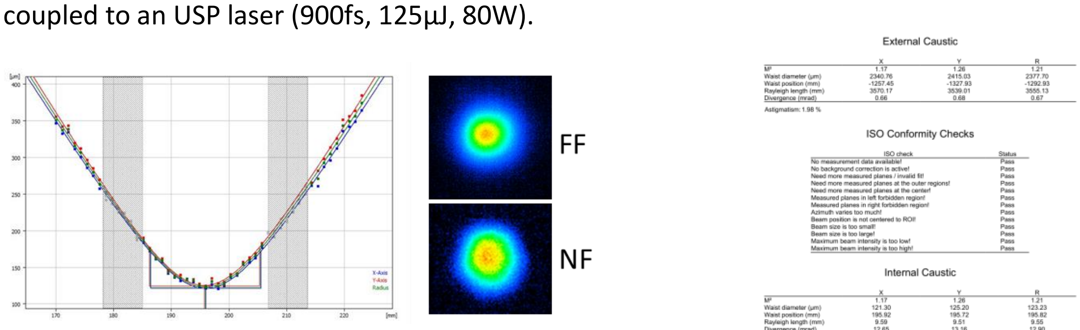


Figure 3.10b : BDS#4 SP3 temperature at 400W input power versus time

The SP3 gives stable transmission efficiency and temperature over 15 minutes and would be the first candidate to be tested on 500W USTUTT laser.

To further characterize this BDS#4 we performed an ISO-11146 compliant M² measurement whilst the BDS is coupled to an USP laser (900fs, 125µJ, 80W).



External Caustic

	X	Y	R
M²	1.17	1.26	1.21
Waist diameter (µm)	2340.76	2415.03	2377.70
Waist position (mm)	-1257.45	-1327.93	-1292.93
Rayleigh length (mm)	3570.17	3539.01	3555.13
Divergence (mrad)	0.66	0.68	0.67

Astigmatism: 1.98 %

ISO Conformity Checks

ISO check	Status
No measurement data available!	Pass
No background correction is active!	Pass
Need more measured planes / invalid fit!	Pass
Need more measured planes at the outer regions!	Pass
Need more measured planes at the center!	Pass
Measured planes in left forbidden region!	Pass
Measured planes in right forbidden region!	Pass
Azimuth varies too much!	Pass
Beam position is not centered to ROI!	Pass
Beam size is too small!	Pass
Beam size is too large!	Pass
Maximum beam intensity is too low!	Pass
Maximum beam intensity is too high!	Pass

Internal Caustic

	X	Y	R
M²	1.17	1.26	1.21
Waist diameter (µm)	121.30	125.20	123.23
Waist position (mm)	195.92	195.72	195.82
Rayleigh length (mm)	9.59	9.51	9.55
Divergence (mrad)	12.65	13.16	12.90

Figure 3.11 : BDS#4 M² measurement caustic and report while operating at 80W

This measurement displays no perturbation of the beam quality at 80W (M²<1.3)

4 Conclusions

A second version BDS system has been designed, fabricated and tested by one the project consortium member. A newer version of the BDS has been designed and fabricated. This version has bespoke terminations at both fiber end for easy coupling and power handling. The latter is ensured by water cooling system integrated to the fiber input cell. This version is assembled, tested and ready for field and demonstrator evaluation and feedback by relevant consortium members. The next actions for

GLOphotonics is to qualify the high PER fiber developed by GPPMM/XLIM for industrial production and then to integrate into the BDS.