WP4 Photonics Components for pre- and post- pulse conditioning

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 687880

Work Package 4 Overview

AIM: *Pulse compression & fibre beam-delivery*

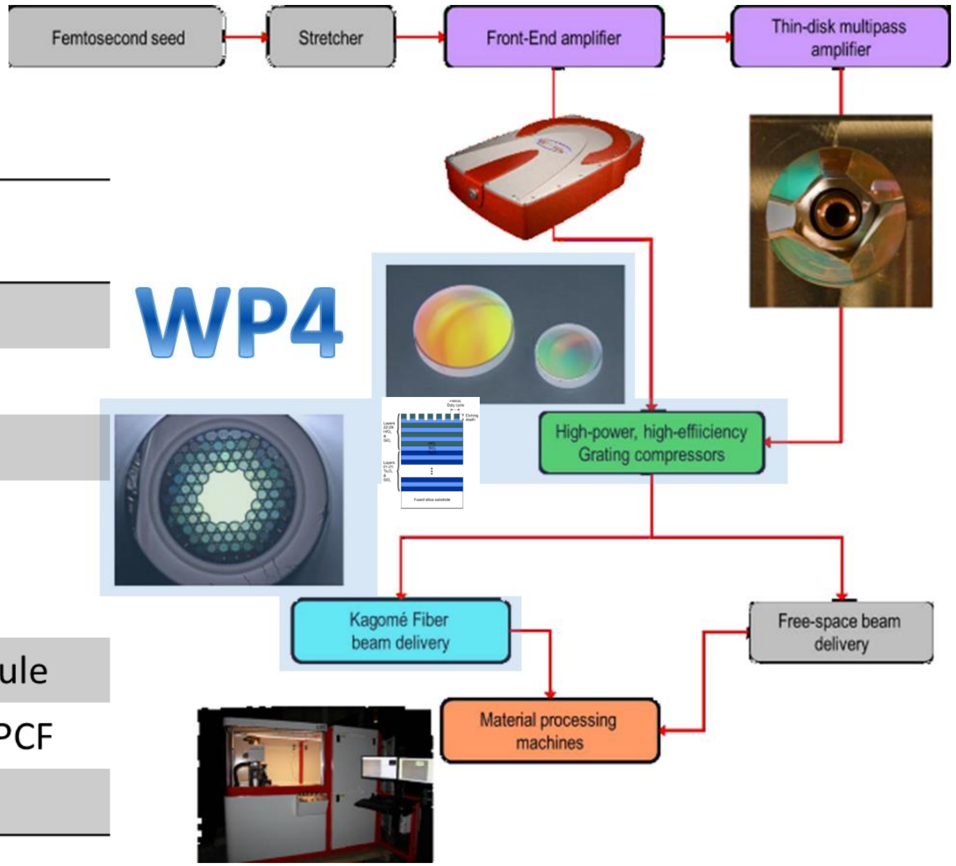
Partners & roles

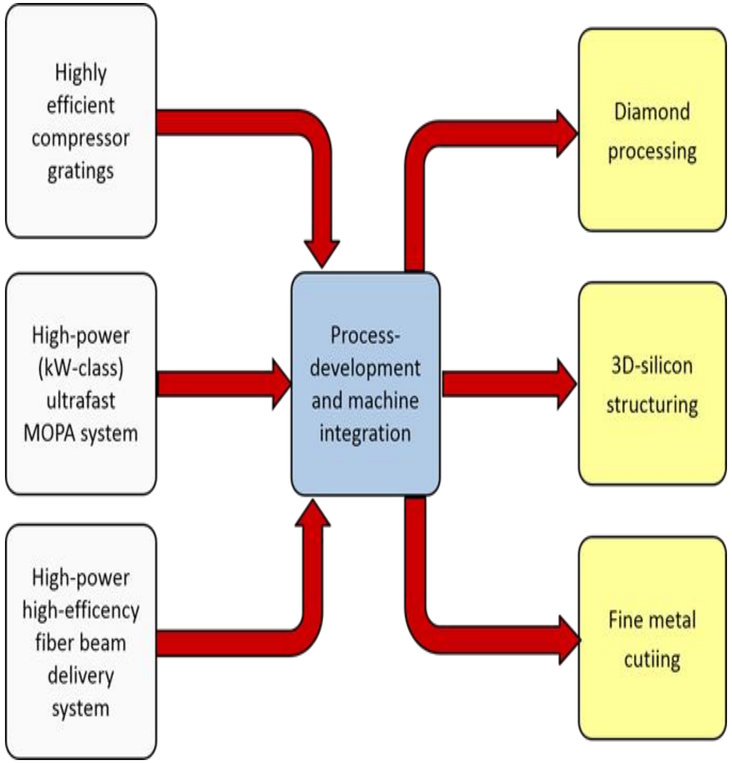
PULSE COMPRESSION
(Diffraction grating with high LIDT and high efficiency)

USTUTT	Design & qualification
AMO	Process development
AMP	Spec requirement

FIBRE BEAM DELIVERY
(HC-PCF design & fabrication)

GLO	Fabrication of HC-PCF and delivery module
XLIM	Design et development of high PER HC-PCF
AMP	Spec requirement & qualification





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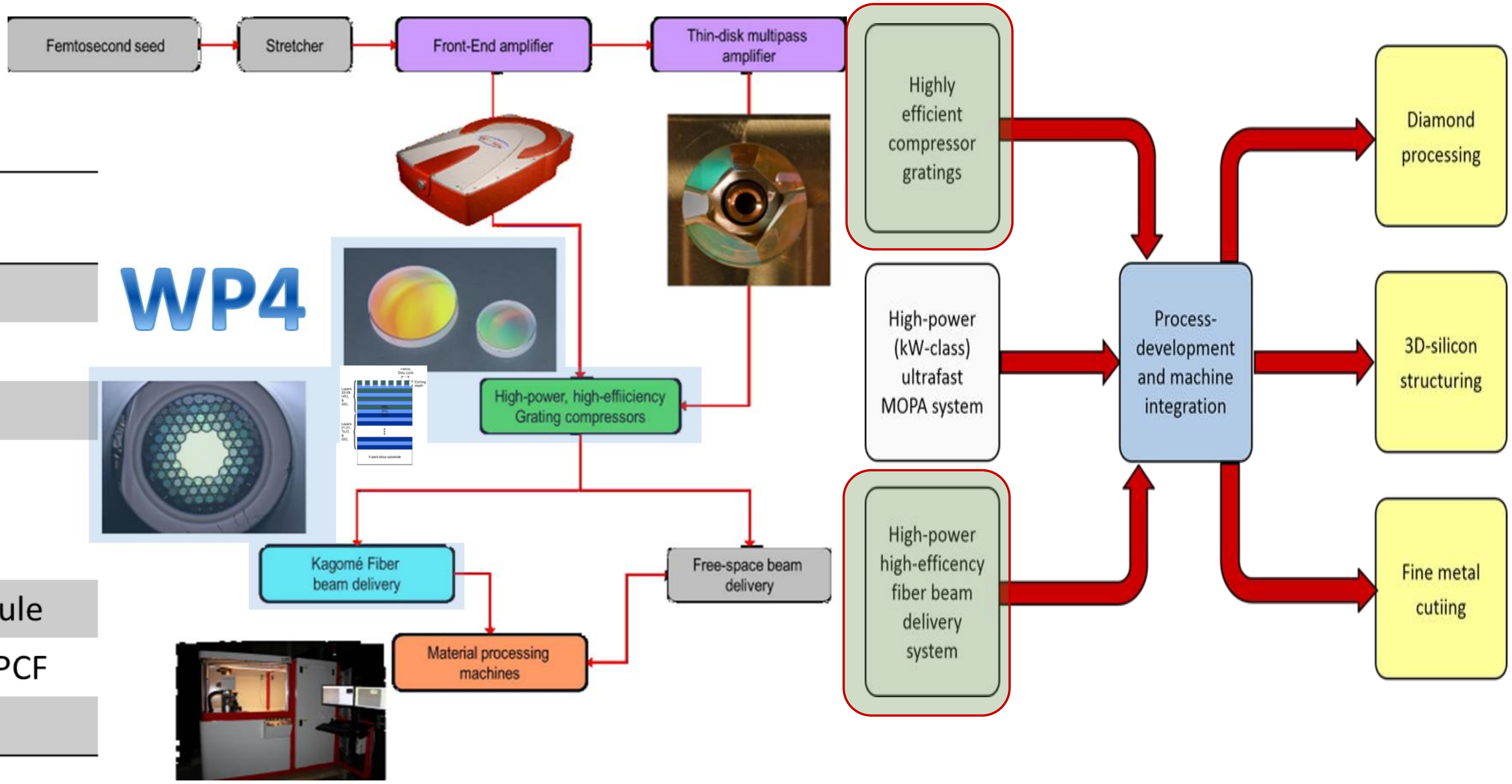

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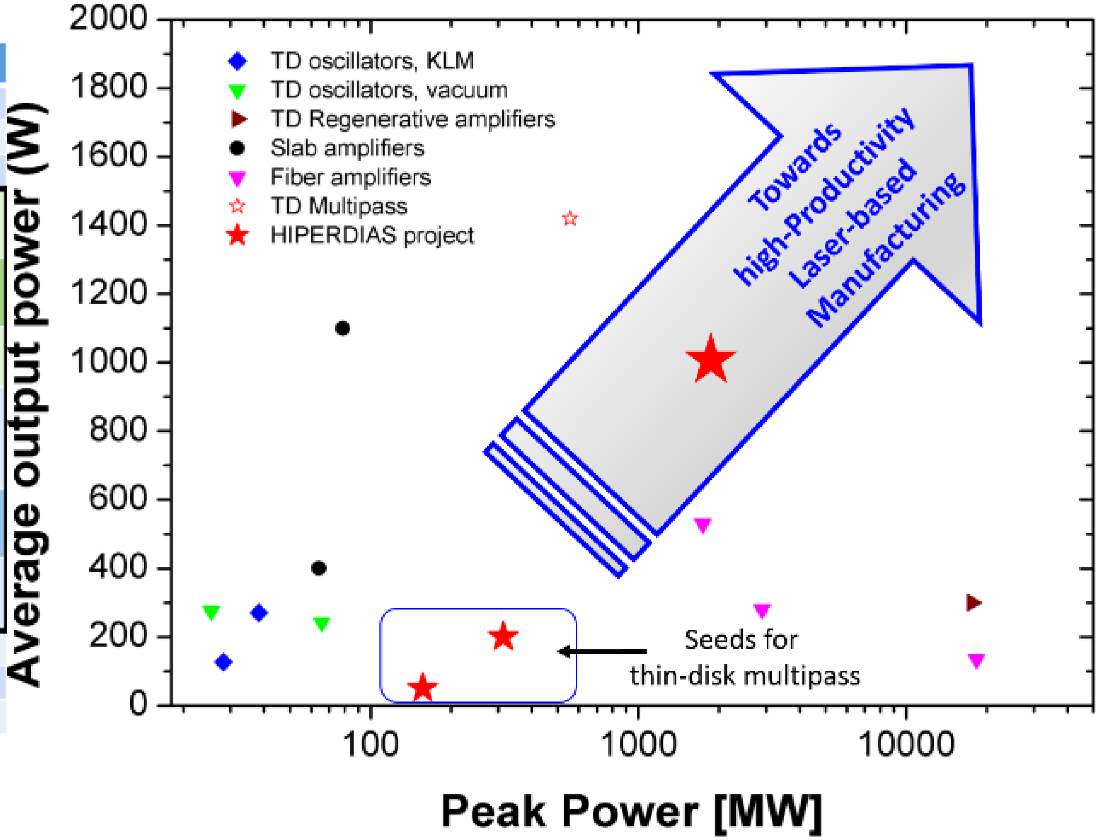
Work Package 4 Overview

AIM: *Pulse compression & fibre beam-delivery*

	Parameter	Current State-of-the-Art	HIPERDIAS Target
Laser system	Average power/peak power	1.4 kW (lab)/ 588 MW	1 kW / >1 GW
	Energy	4.7 mJ	1 mJ @ 1 MHz
	Pulse duration	8 ps	<1 ps
Grating compressors	Overall Efficiency (%)	80-85	> 96%
	Spectral bandwidth (nm)	~ 10	Several tens of nm (>99% efficiency)
	LIDT (@ 500 fs)	0.3 J/cm²	>0.3 J/cm² (up to 1J/cm²)
Beam delivery	Average power / Peak power	150W/2GW Note: peak power is not limiting factor in kagome fiber. Challenge is to handle larger avg power	>500W and up to 1kW />1 GW
	Propagation loss	20-50 dB/km (typical)	10-20 dB/km typical (down to 1 dB/km is aimed for
	PER	17 dB (typical in stationary configuration)	>20dB
Material processing	Fine metal cutting	mechanical	USP Laser
	3D silicon processing	mechanical	USP Laser
	Diamond ablation	mechanical	USP Laser



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Work Package 4 Overview

TASK BREAKDOWN

6 tasks, 14 Milestones & 7 delivrables

PULSE COMPRESSION
(Diffraction grating with high LIDT and high efficiency)

TASK /Leader	Description	Milestones	Deliverables
4.1 /USTUTT	Design of grating compressor • **Design** of the gratings • Parameter space review	M4.1 (M03)	D4.1(M04) D 4.2(M12)
4.2 /AMO	Development of optimized **lithography process** for the fabrication of pulse compression gratings		
4.3 /AMO	Development of optimized **etching process** for the fabrication of pulse compression gratings	M4.3(M08) M4.4(M12) M4.8(M18)	M05-M30 D 4.2

FIBRE BEAM DELIVERY
(HC-PCF design & fabrication)

TASK /Leader	Description	Milestones	Deliverables
4.4/ GLO	Fabrication & characterization of PMC module for USP fibre-delivery	M 4.1 (M06) M 4.5 (M12,18,28)	D4.4 (M24, M36) D4.7 (M30)
4.5/ GLO	Design and Fabrication of photonic microcell module with integrated coupling optics for fibre-delivery and interface with system integrator.	M4.7(M15) M4.9 (M18) M4.10(M24)	D4.6(M30)
4.6/ XLIM	Design and Fabrication of high PER HC-PCF for ultra-high energy pulse delivery	M 4.6 (M12) M4.11(M24)	D4.5 (M24)

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WP4 - Milestones

11 Milestones fulfilled as planed. 2 are ongoing

Milestone title	Task	Due date	Status
M4.1 First design, high efficient grating mirrors	T4.1	M03 – April 2016	Fulfilled
M4.2 PMC module for fiber beam delivery prototype #1	T4.4	M06 – July 2016	fulfilled
M4.3 1st generation grating mirror on large area, rectangular substrates fabricated	T 4.3	M08 – September 2016	fulfilled
M4.4 Fully optical characterization of grating mirror regarding diffraction efficiency and LIDT	T4.3	M12 – January 2017	Fulfilled LIDT: carried out
M4.5 PMC module for fiber beam delivery prototype #2 PMC module for fiber beam delivery prototype #3 PMC module for fiber beam delivery prototype #4	T4.5	M12 – January 2017 M18-July2017, M28-May 2018	Fulfilled. Ongoing qualification by AMP & USTUTT
M4.6 Design of HC-PCF with improved PER at 1µm (>20 dB)	T4.6	M12 – January 2017	Fulfilled with ongoing characterization and improvement
M4.7 End-capping definition and process design	T4.5	M15 – April 2017	Fulfilled
M4.8 Demonstration of optimized grating mirrors, 99% DE	T4.3	M18 – July 2017	Fulfilled
M4.9 End-capped output PMC module for beam delivery	T4.5	M18-July 2017	Fulfilled
M4.10 Qualification of end-capped output PMC module for beam delivery	T4.5	M24-January 2018	Partial fulfillment
M4.11 Fabrication of HC-PCF with improved PER at 1 um (>20 dB)	T4.6	M24-January 2018	Fulfilled
M4.12 End-capped input PMC module for beam delivery	T4.5	M26-March 2018	Fulfilled

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WP4 - Deliverables

6 Delivrables achieved. 1 deliverable is ongoing

Deliverable title	Due date	Status
D4.1 Report on simulation of pulse compression gratings with diffraction efficiency >=99% over large spectral bandwidth (5 – 10 nm) around 1030 nm	M04 – May 2016	Delivered
D4.2 Report on first fabrication of pulse compression grating with 98% diffraction energy on large area, rectangular substrate material	M12 – January 2017	delivered
D4.3 Report on fabrication and optical characterization of optimized gratings with single-pass diffraction efficiency >=99% over large spectral bandwidth (5 – 10 nm) around 1030 nm	M18 – July 2017	delivered
D4.4 (x2) Final version of PMC module for fiber beam delivery	M24-January 2018, M36-January 2019	Delivered
D4.5 End-capped PMC module for beam delivery	M24-January 2018	Delivered
D4.6 HC-PCF with improved PER at 1µm (>20 dB)	M30-July 2018	Delivered
D4.7 PMC module based on HC-PCF with improved PER at 1µm (>20 dB)	M30-July 2018	Partially delivered

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WP4 – Task 4.1: Design of grating compressors

Targeted specifications:

Grating period	610 nm (1640l/mm)
Angle of incidence	51.4°
Separation angle	13.7°
Diffraction efficiency at 1030 nm	99.5%
Spectral bandwidth at efficiency >99%	5-10 nm
LIDT in fs-ps operation	>0.3 J/cm²
Grating dimensions	75mmx50mm

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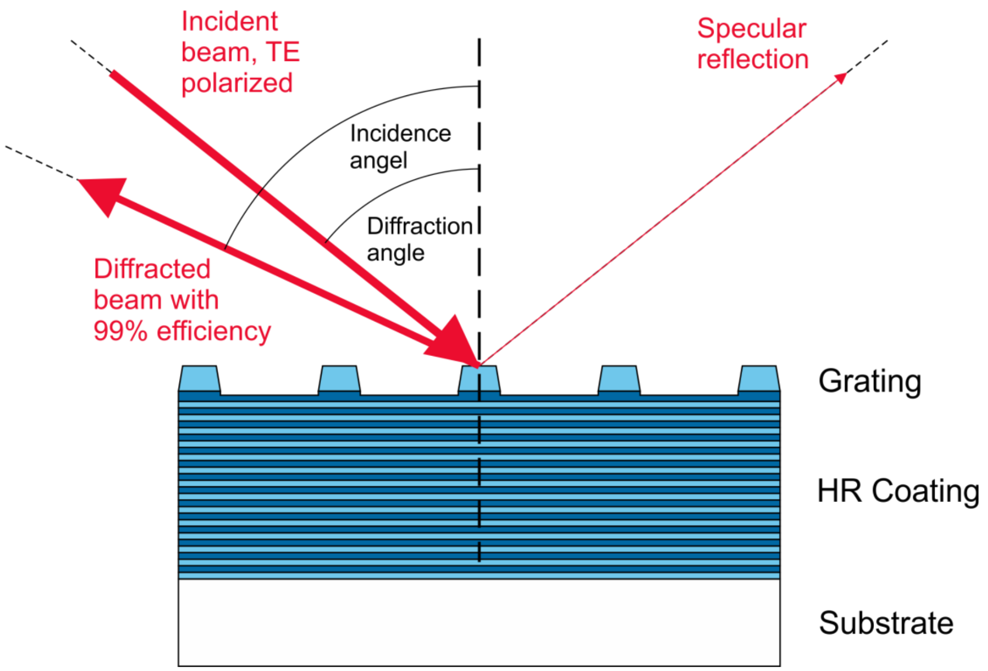
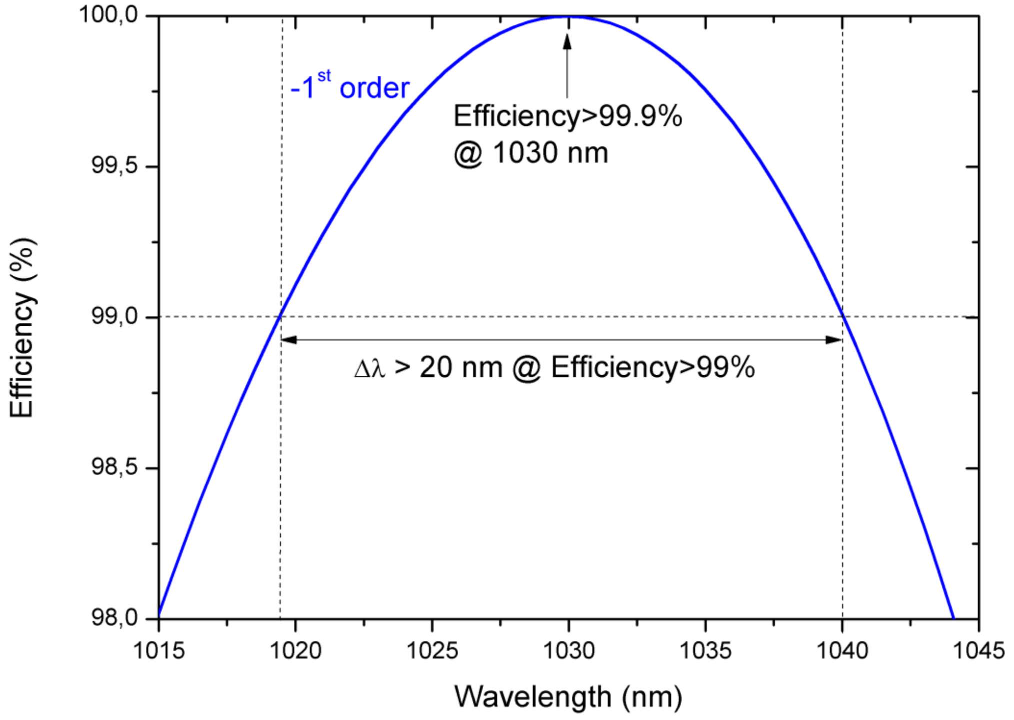
WP4 – Task 4.1: Design of grating compressors

Design results:





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WP4 – Task 4.1: Design of grating compressors

Design results:

	Targets	Obtained design results
Period	610 nm	610 nm
Angle of incidence	51.4°	51.4°
Separation angle	13.7°	13.7°
Diffraction efficiency at 1030 nm	99.5%	>99.9%
Spectral bandwidth at efficiency >99%	5-10 nm	>20 nm
LIDT in fs-ps operation	>0.3J/cm²	0.3 -0.5 J/cm²

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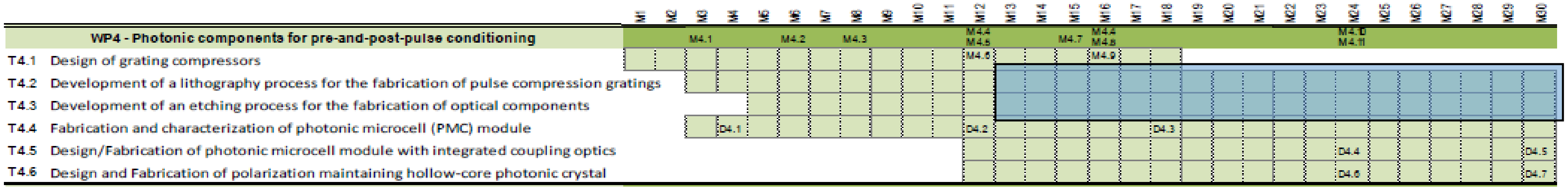
WP4 – Task 4.2 Development of an optimization of a lithography process for the fabrication of pulse compression gratings

WP4 – Task 4.3: Development and optimization of an etching process for the fabrication of optical components



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Overview: Main process steps in the fabrication sequence

1.) Large area resist coating

Goal: uniform large area resist coating
on 75mm x 50mm substrates

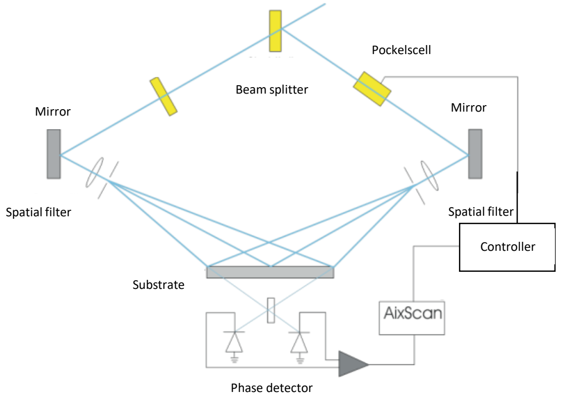
2.) Interference lithography

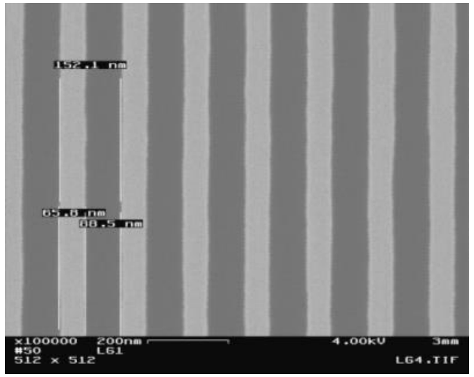
Benefit	Precise definition of large area periodic pattern
Parameter	Pitch: 610nm
Main challenges	Controll over DC

3.) Reactive Ion Etching (RIE)

Tool	Oxford Plasmalab 100 (ICP)
Chemistry	SF_6 / C_4F_8
Etching quality/ Target Specs	+ anisotropic etch profiles + smooth surfaces + 210nm etch depth

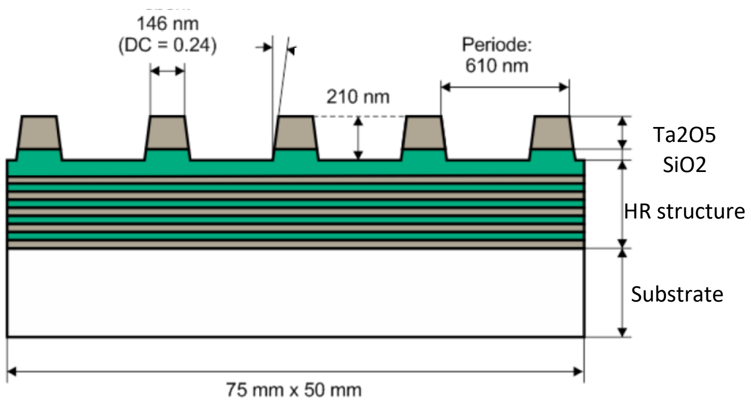
Interference lithography

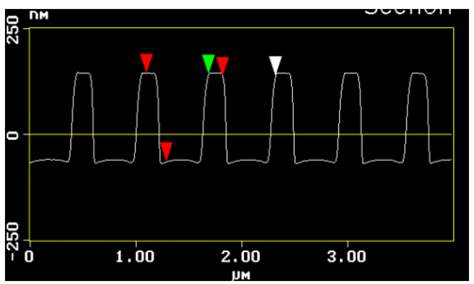




Grating pitch: $p = \frac{\lambda}{2\sin(\alpha)}$

Reactive Ion Etching (RIE)





AFM scan of etch grating

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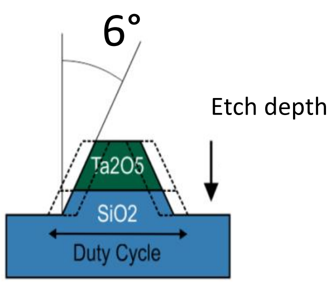
WP4 – Task 4.2 and Task 4.3

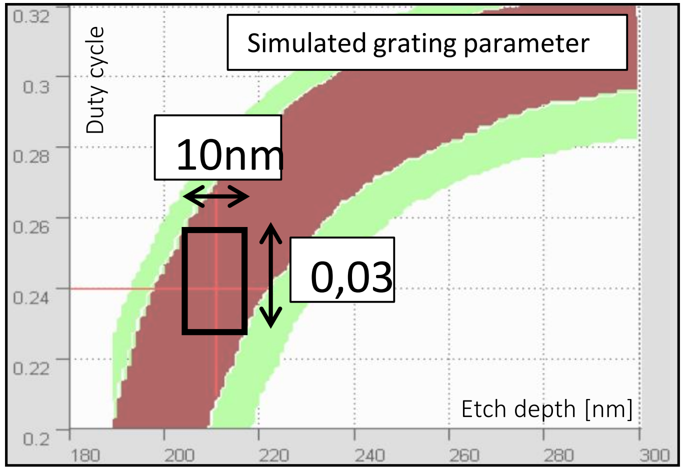
- Fabrication tolerances for the grating geometry according to task 4.1

- Target: Diffraction efficiency >= 99% over large spectral bandwidth
- Grating geometry:

Duty cycle : 0.24 **+/- 0.015** for the duty cycle
Etch dpeth: 210 nm **+/- 5 nm** for the etch depth

Diffraction efficiency at 1030nm
> 99% red
> 98% green

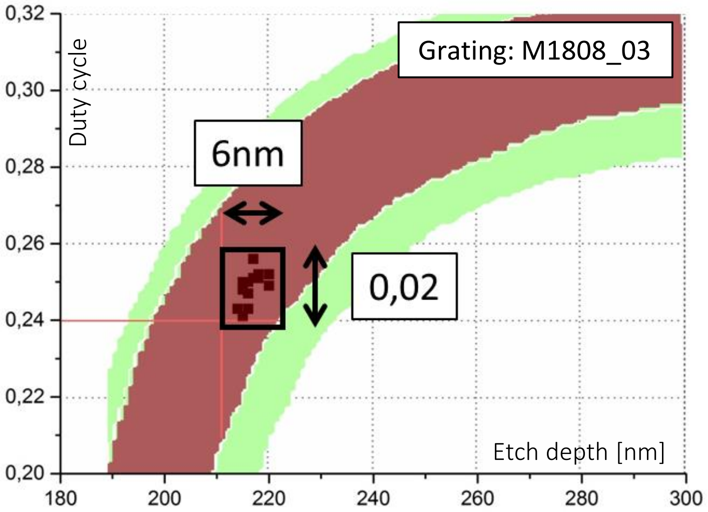




- Measured values for a single pulse compression grating

- Geometry measured with atomic force microscope and scanning electron beam microscope
- Measured at 15 points in a rectanglar with a size of 60 mm x 35 mm

-> Deviations: 0.02 for duty cycle and 6 nm for the etch depth



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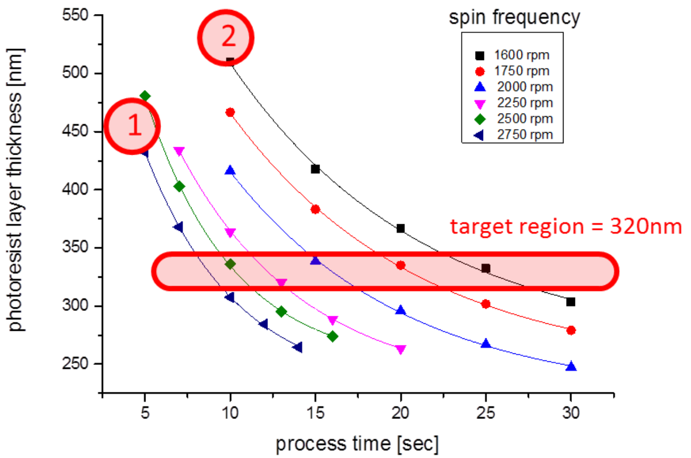
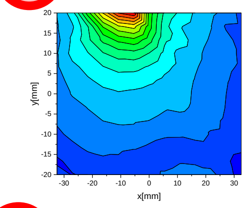
WP4 – Task 4.2 and 4.3

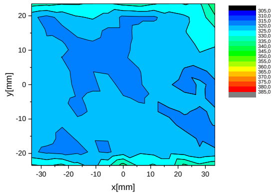
- Photoresist coating process development and optimization in terms of layer thickness and uniformity
- Post exposure bake (PEB) step, evaluation and modification of temperature and baking time
- Simulation of plasma energy distribution during RIE
- Compensation of the plasma edge-effect by adding dummies at the edges

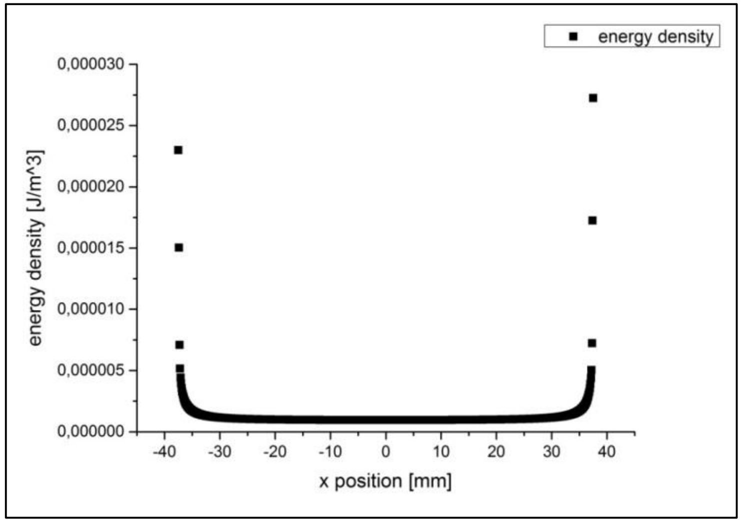


spin curve 1 / 9sec, 2750rpm



spin curve 2 / 25sec, 1600rpm





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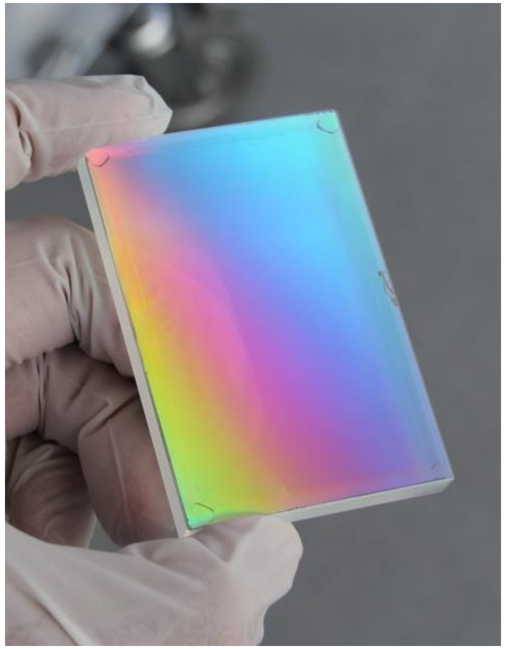
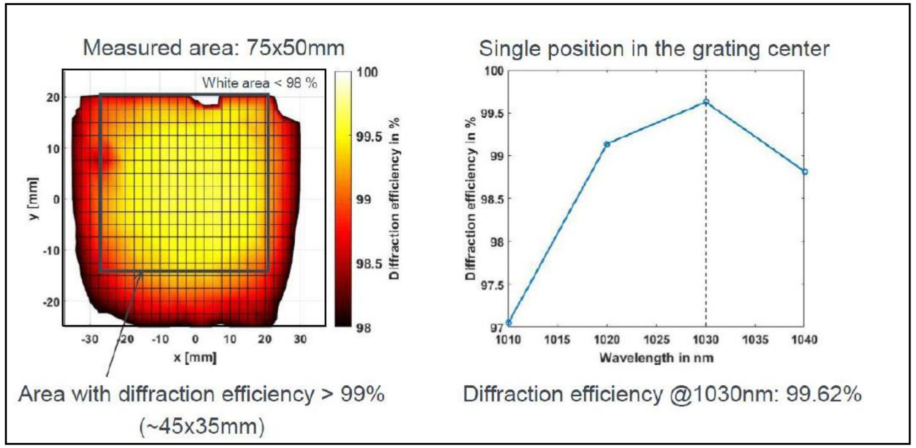
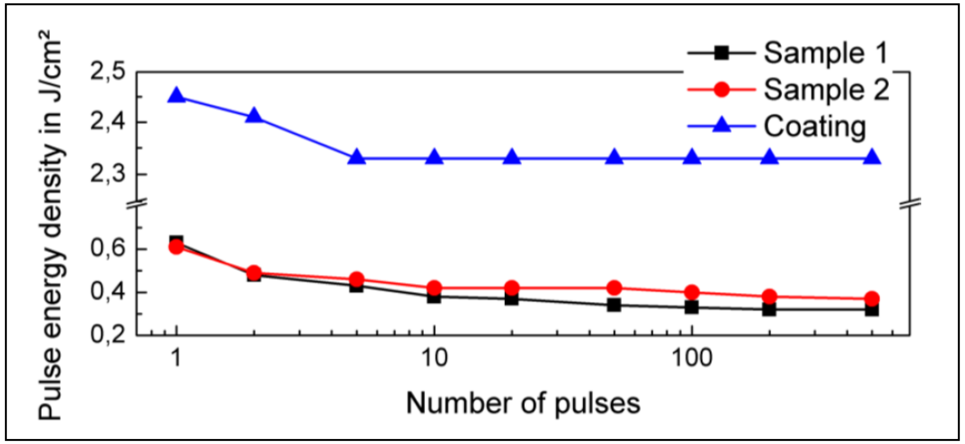
Results:



Pulse compression grating 75 mm x 50 mm

Spatial resolved diffraction efficiency measurement, done in Stuttgart at the IFSW





Laser Induce Damage Threshold (LIDT) measurements
Conducted at the Institute Fresnel in Collaboration with Dr. Gallais

-> „Hot spot" with DE > 99% achieved on an area of 45mm x 35mm
-> 0.32 J/cm^2 LIDT

D4.3 Report on fabrication and optical characterization of optimized gratings with single-pass diffraction efficiency >=99% over large spectral bandwidth (5-10 nm) around 1030 nm ✓ Submitted

MS20 Demonstration of optimized grating mirrors, 99% diffraction efficiency ✓ Fulfilled

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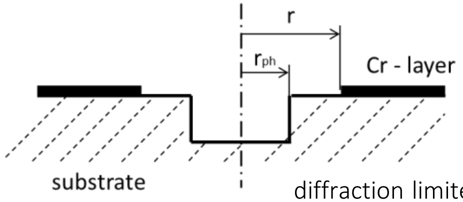
Outlook:

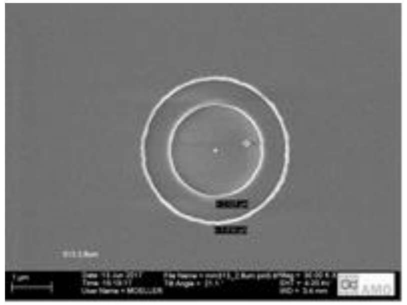


diffraction limited pinhole

<u>Potential for further improvement</u>

1) Increasing the area of high diffraction efficiency by flattening the exposure field of the Interference Lithography system

-> Development of a diffraction limited flat-top pinholes [1] enables better duty cycle uniformity


SEM picture diffraction limited pinhole

2) Improvement of the Laser Induce Damage Threshold (LIDT)

-> Replacement of tantalum pentoxide by hafnium dioxide

-> Extending the tasks 4.2 and 4.3 from WP4 beyond M30

[1] Modifed pinhole spatial filter producing a clean flat-topped beam, P. Hariharan, Andal Narayanan, Optics & Laser Technology 36 (2004) 151 – 153

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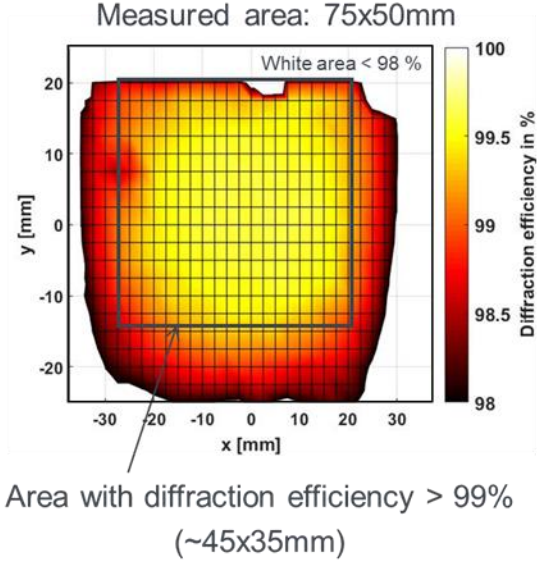
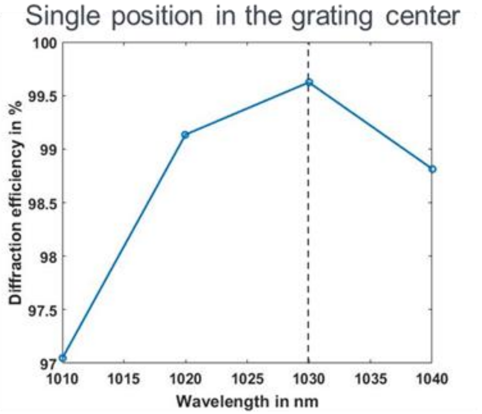
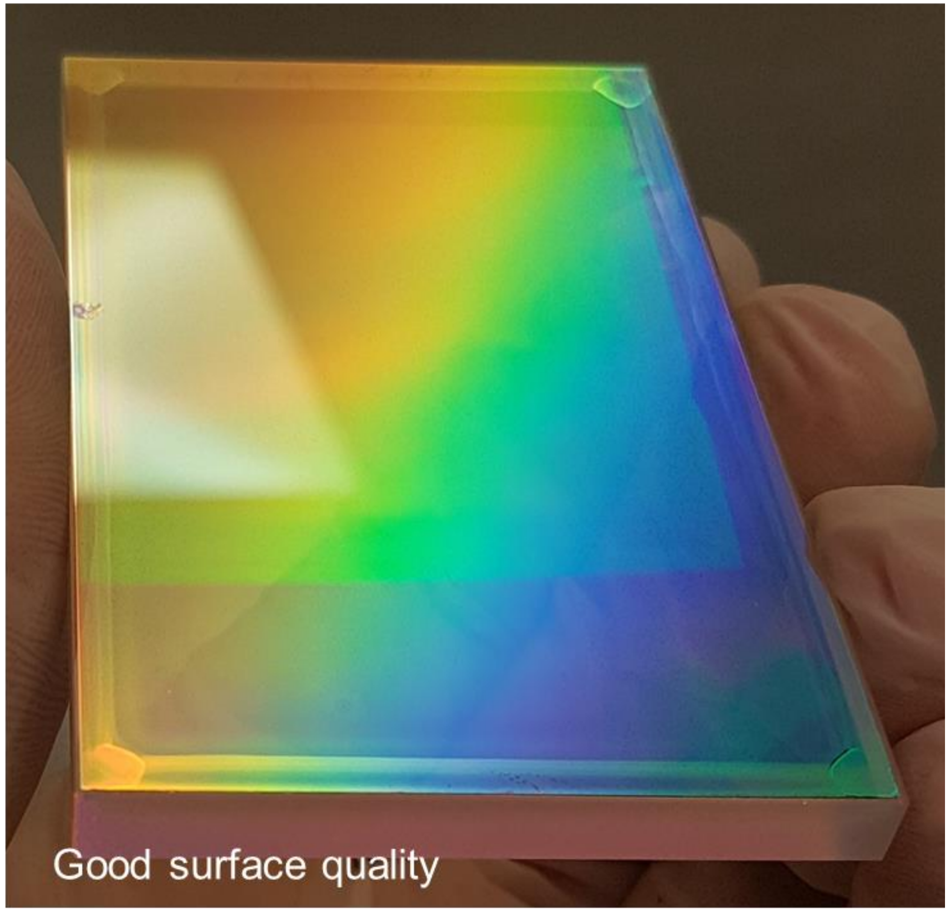




Diffraction efficiency @1030nm: 99.62%



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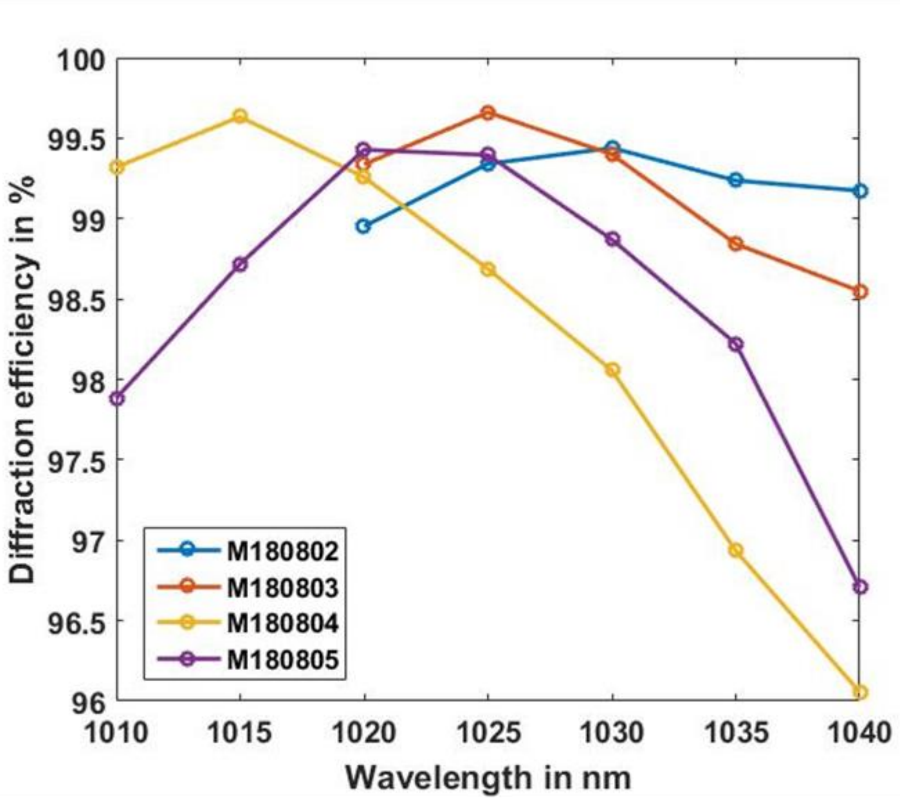
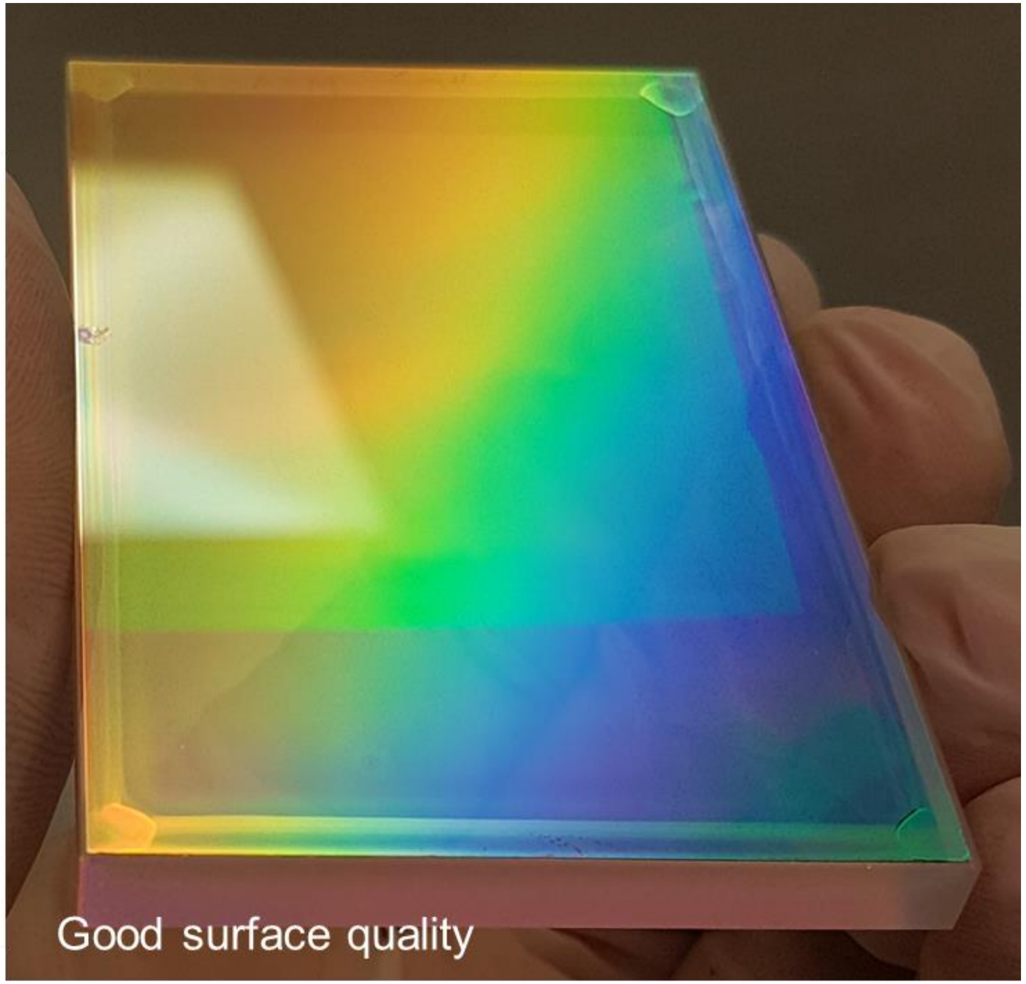
Second run of samples





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WP4 – Task 4.4: Fabrication and characterization of photonic microcell (PMC) module for fiber-delivery of ultra-short high power pulse

- Partners: GLO, XLIM, AMP

		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30
	WP4 - Photonic components for pre-and-post-pulse conditioning			M4.1			M4.2		M4.3				M4.4 M4.5			M4.7	M4.4 M4.8								M4.10 M4.11						
T4.1	Design of grating compressors												M4.6				M4.9														
T4.2	Development of a lithography process for the fabrication of pulse compression gratings																														
T4.3	Development of an etching process for the fabrication of optical components																														
T4.4	Fabrication and characterization of photonic microcell (PMC) module				D4.1								D4.2						D4.3												
T4.5	Design/Fabrication of photonic microcell module with integrated coupling optics																								D4.4						D4.5
T4.6	Design and Fabrication of polarization maintaining hollow-core photonic crystal																								D4.6						D4.7

- Design review undertaken
- Prototype of α-prototype made
- Initial Characterization (USP Energy/duration handling, modal content)
- Prototypes #2,3 been achieved and sent to partner AMP (Fab. 2017)
- Protoype #4 sent for test.

- Deviations and proposed corrective actions…
  - NA

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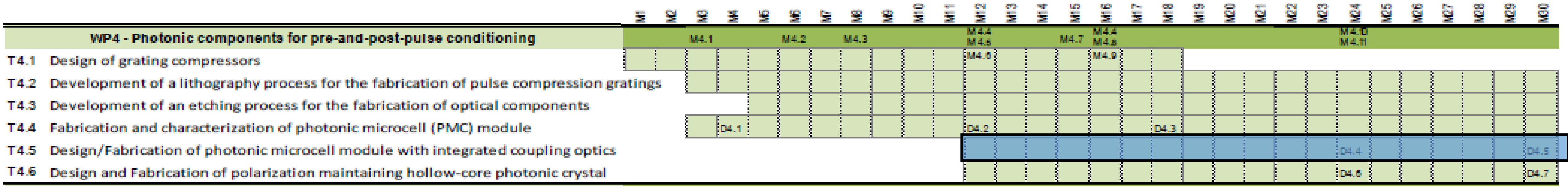
WP4 – Task 4.5: Design and fabrication of photonic microcell module with integrated coupling optics for fiber-delivery and interface with system integrator

- Partners: GLO, XLIM, AMP



- Achievements…
  - End-termination design undertaken
  - End-user requirement definition ongoing
- Deviations and proposed corrective actions…
  - NA

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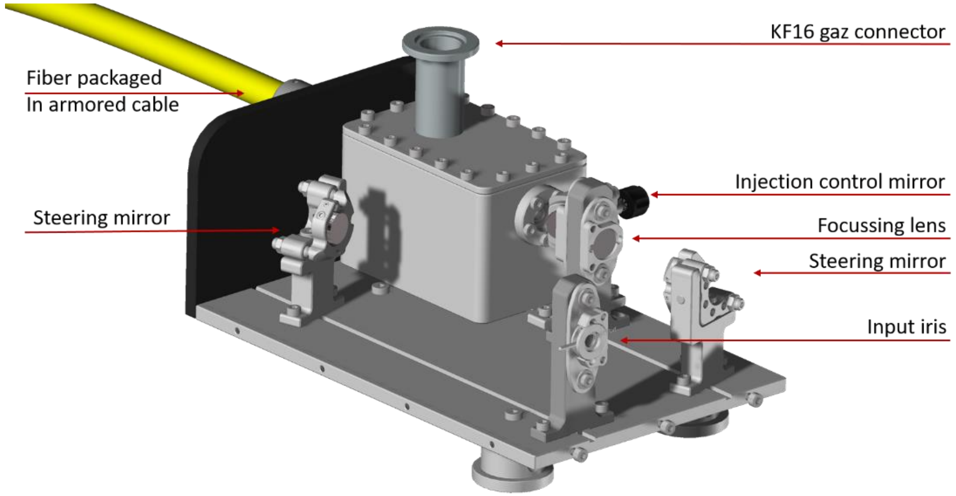
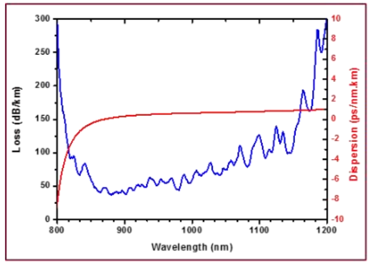
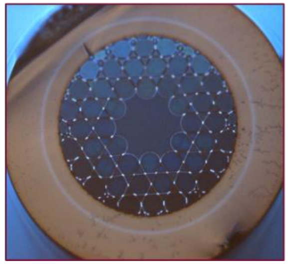
WP4 – Task 4.4: Fabrication and characterization of photonic microcell (PMC) module for fiber-delivery of ultra-short high power pulse

- Design and fabrication







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

3D design of the 2nd PMC beam delivery system incoupling module (left) and specification of the integrated fiber (center) and optical micrograph of the first assembled prototype (right).

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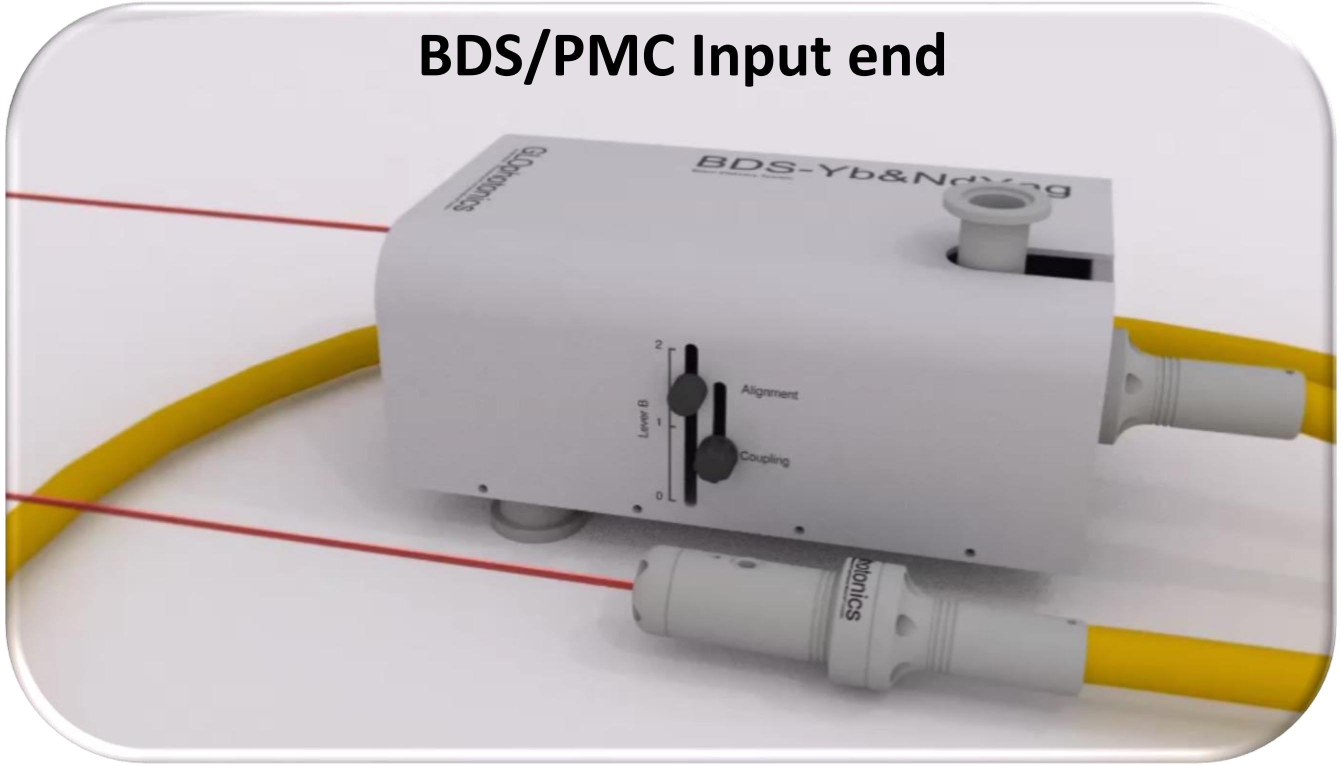
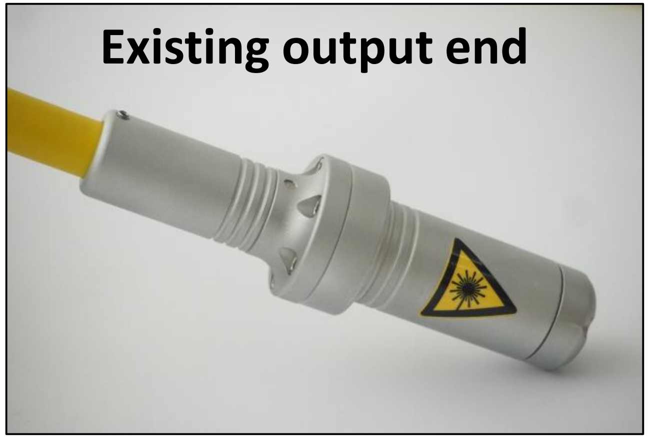
WP4 – Task 4.4/4.5: Fabrication and characterization of photonic microcell (PMC) module & coupling optics for fiber-delivery and interface with system integrator pulse

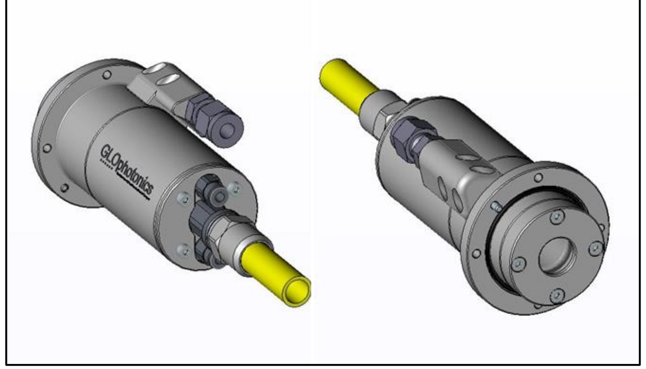
- Design and fabrication



BDS/PMC Input end



Existing output end



Cooled/vacuum output end

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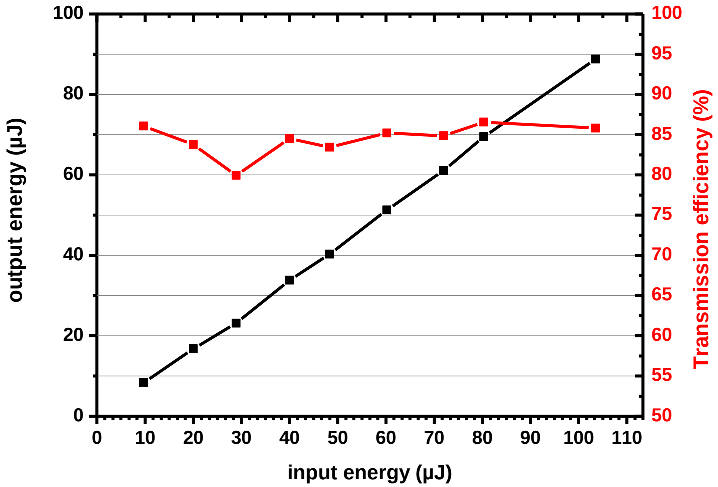
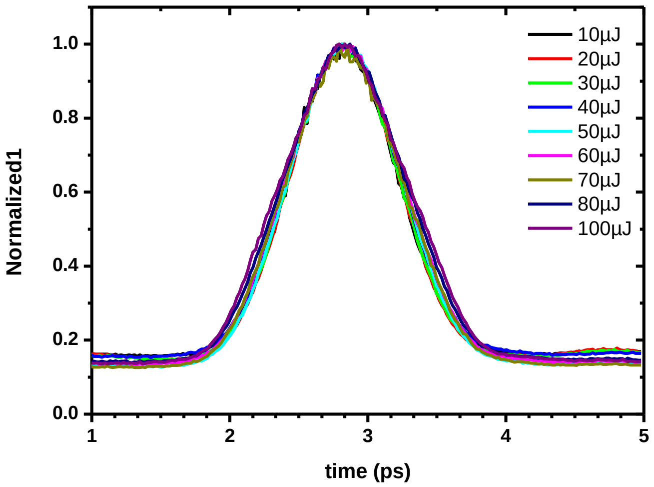
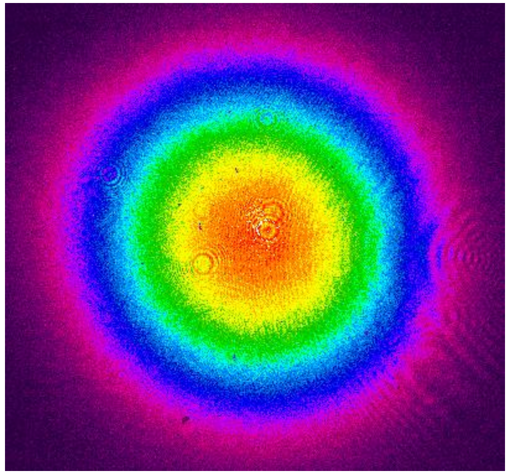
WP4 – Task 4.4: Fabrication and characterization of photonic microcell (PMC) module for fiber-delivery of ultra-short high power pulse

- Energy handling, pulse fidelity and beam quality







BDS transmission efficiency (Left), BDS output AC trace (middle), BDS output beam profil (right)

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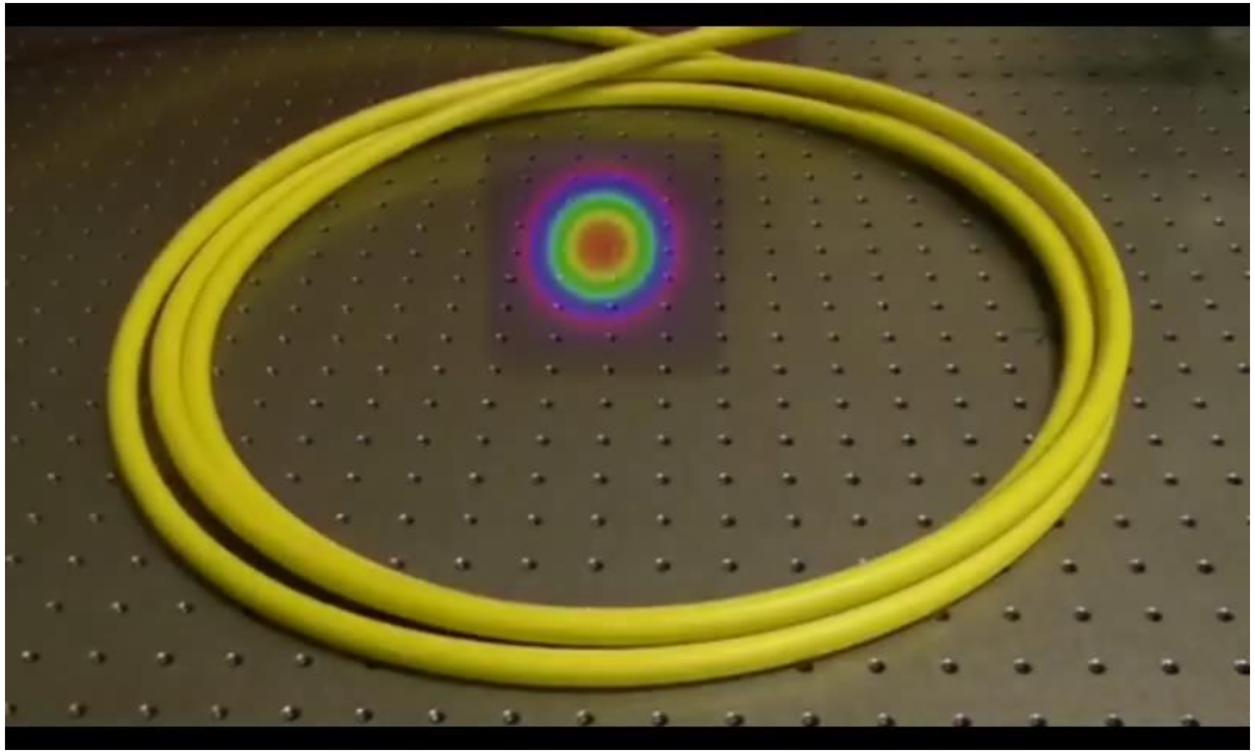
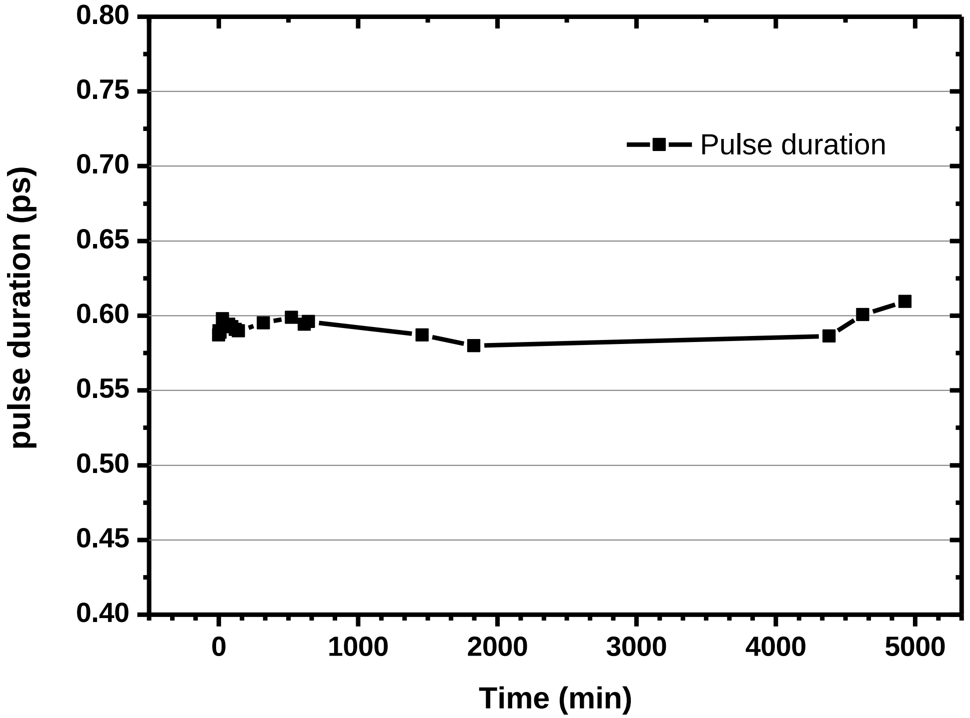
WP4 – Task 4.4: Fabrication and characterization of photonic microcell (PMC) module for fiber-delivery of ultra-short high power pulse

- Mode quality with movement, pulse stability with sealed BDS





Evolution of sealed (no pumping) BDS output pulse duration at 100µJ input energy with time

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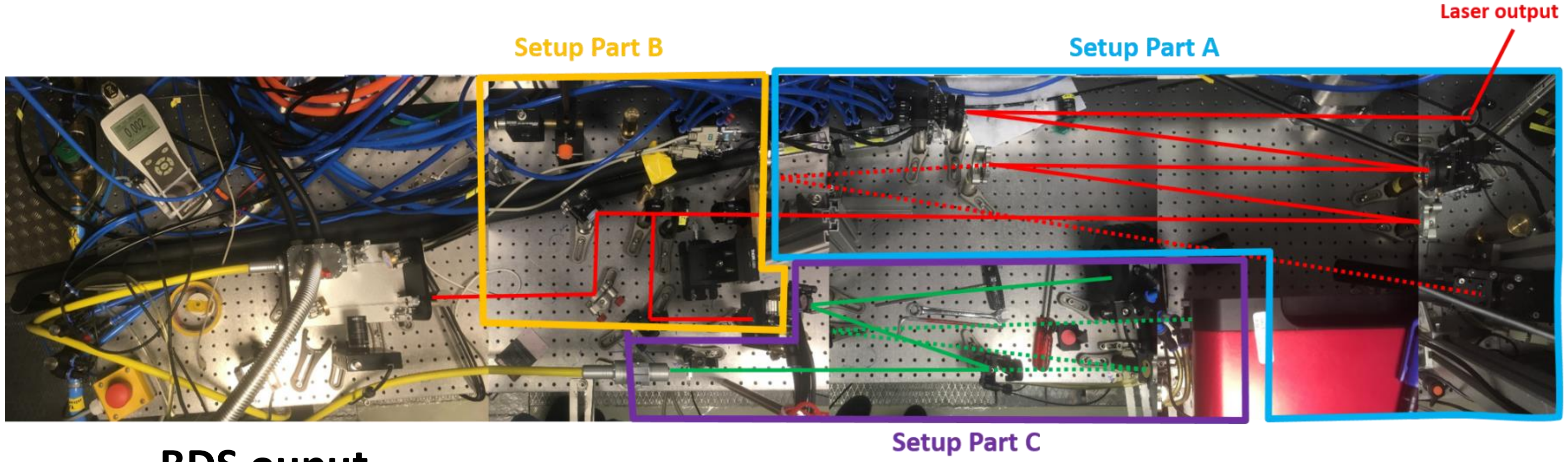
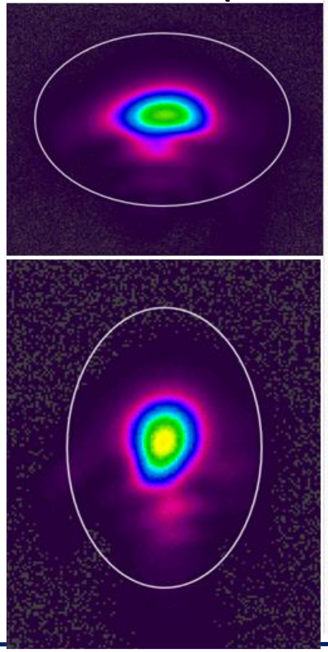
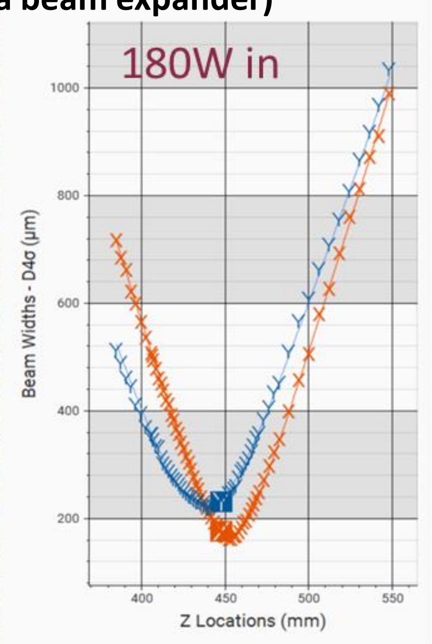
Test & qualification by partners

- AS tested BDS (non cooled version) with 100 W
- USTUT early test of water-cooled version of BDS

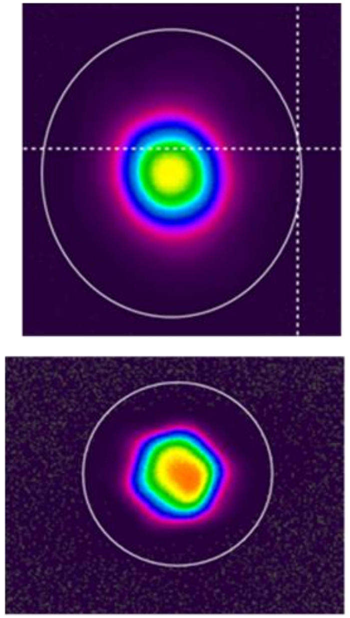


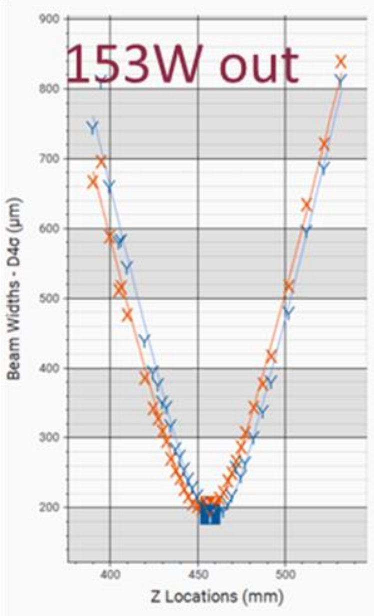
Laser input
(After a beam expander)



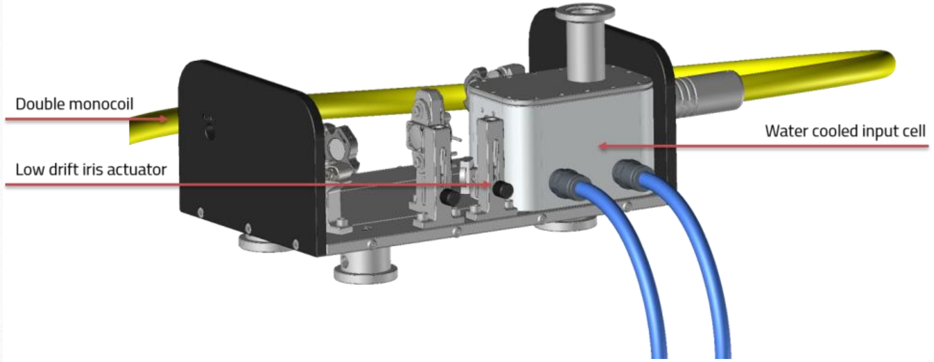


BDS ouput





BDS/PMC version #4



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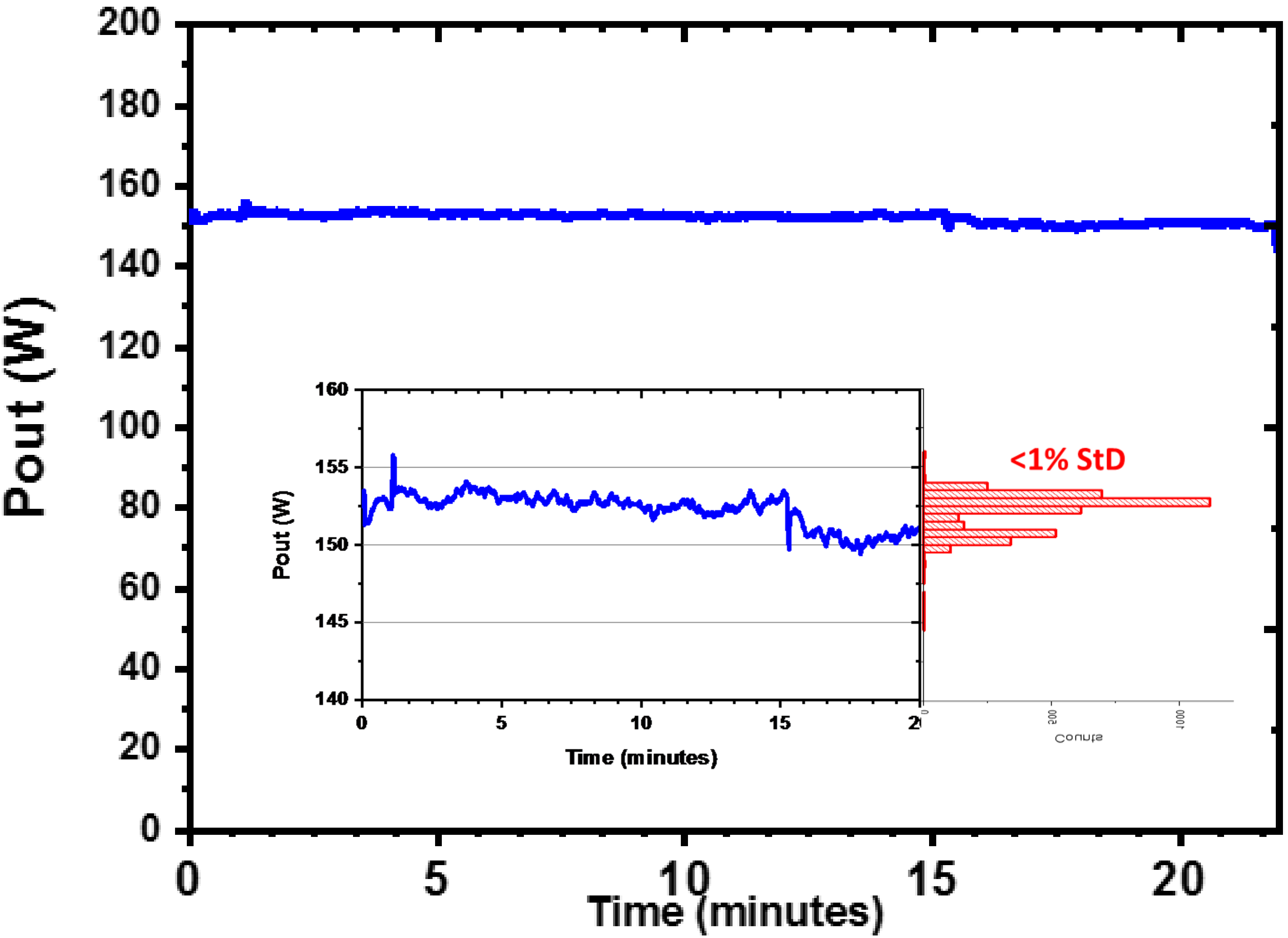

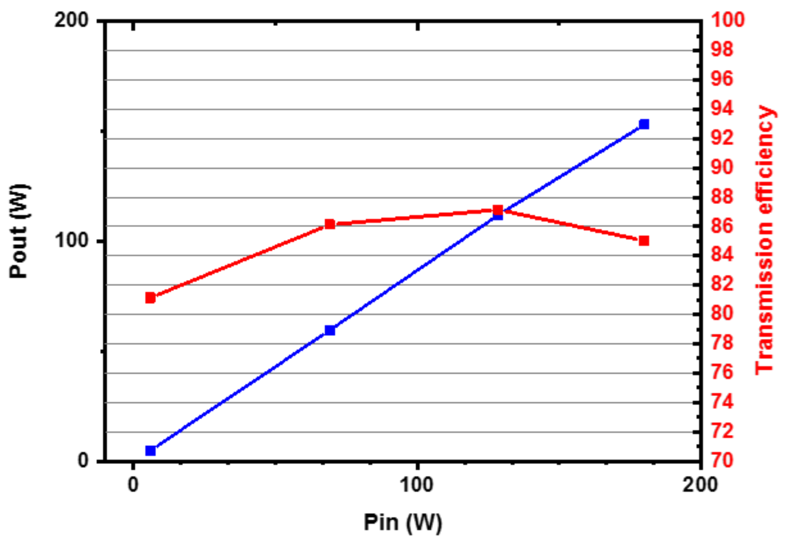

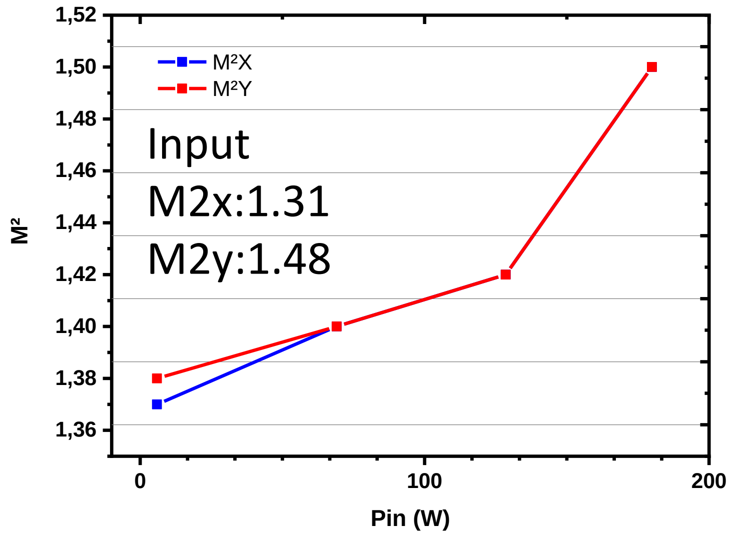

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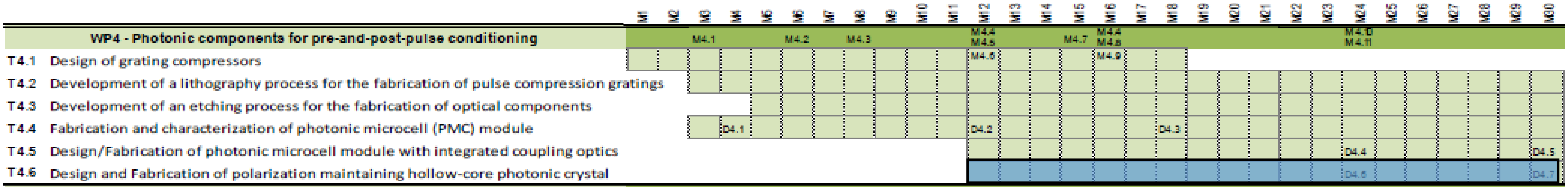
WP4 – Task 4.6: Design and fabrication of polarization maintaining hollow-core photonic crystal for ultra-high energy pulse delivery

- Overview, XLIM, GLO



- Achievements…
  - Two fiber designs explored (transmission loss: new records)
  - Kagome fiber parameters with PER=21 dB

- Deviations and proposed corrective actions…
  - NA

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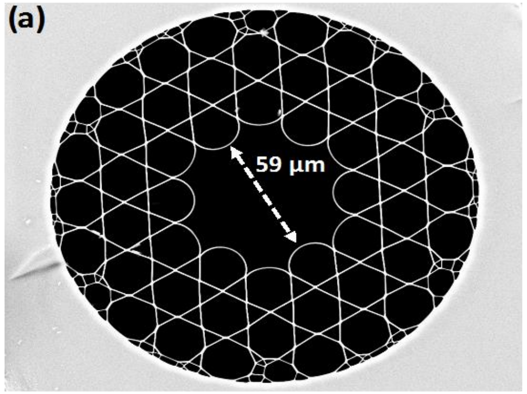
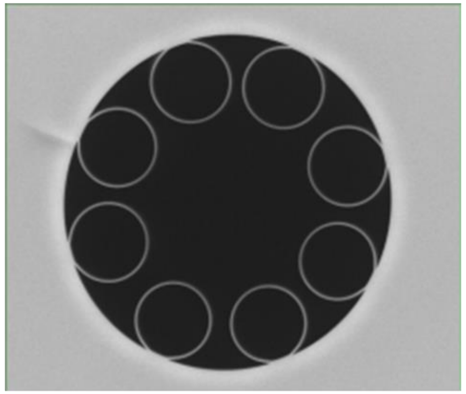
Fiber design identification

- Strategy taken

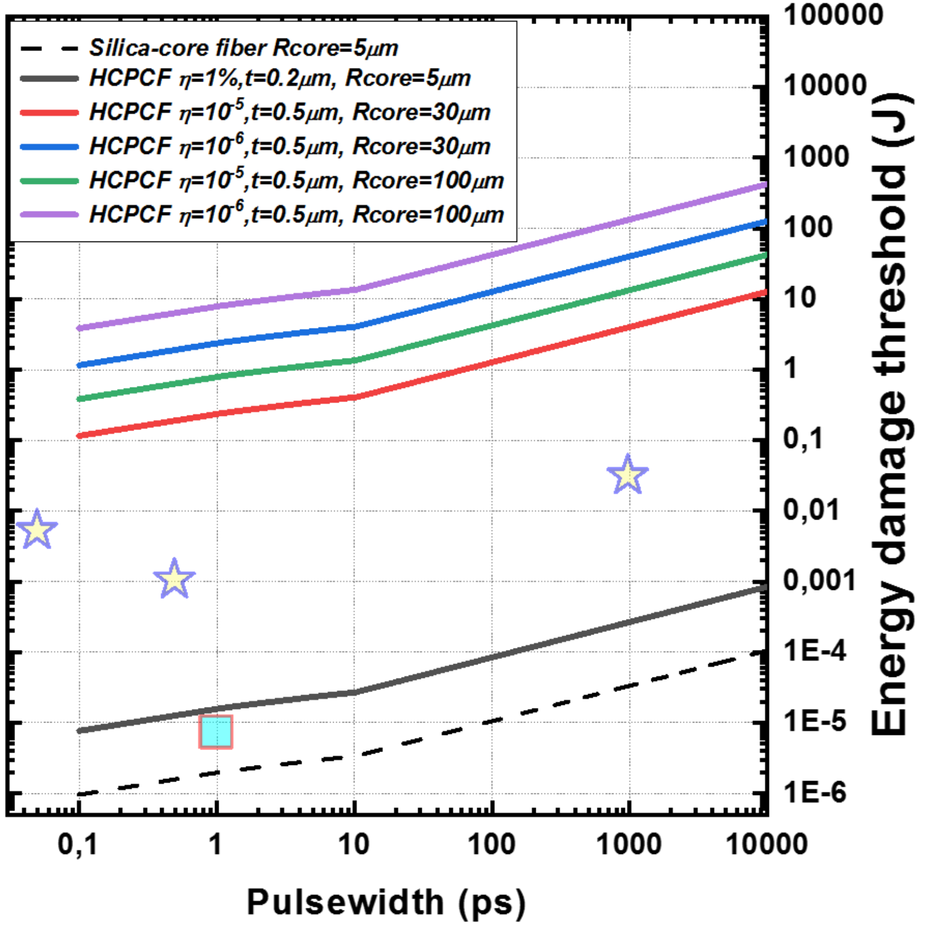
IC Kagome lattice



IC Tubular lattice



Fine tune the strcutural parameters of the fibre (strut thickness, contour curvature) to target high PER whilst keeping: ultra-low loss, ultra-low overlap with silica and close to single mode modal content



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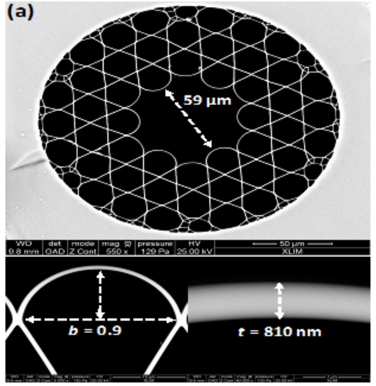
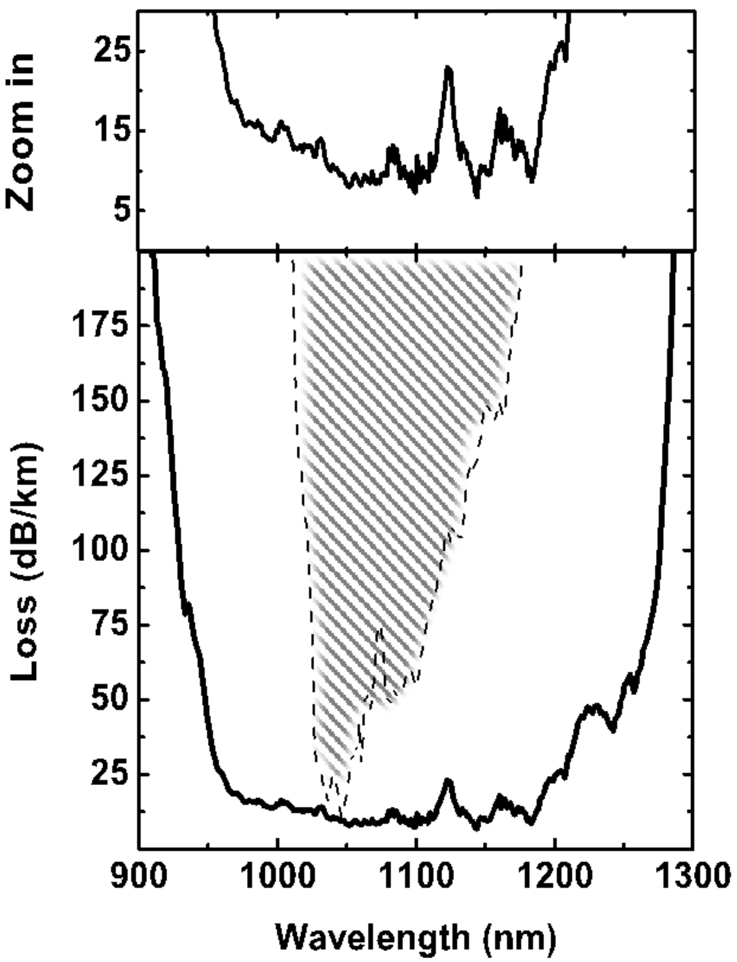
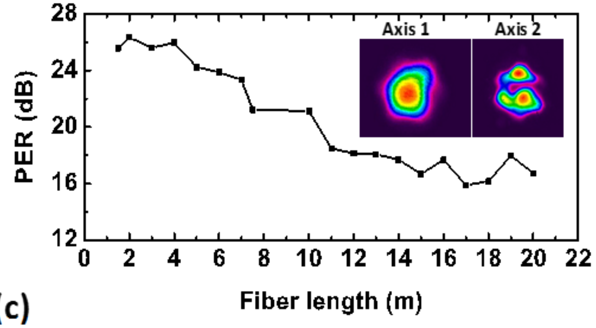
Loss:
~ 8 dB/km
(current world record)



(a)

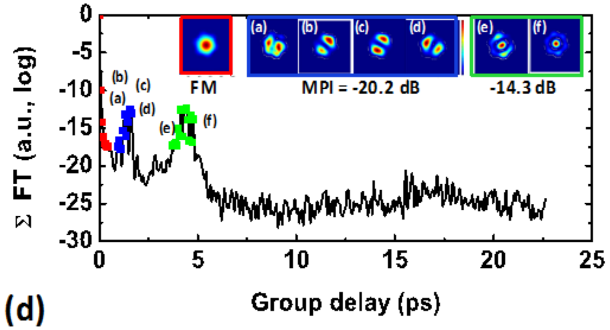


(b)



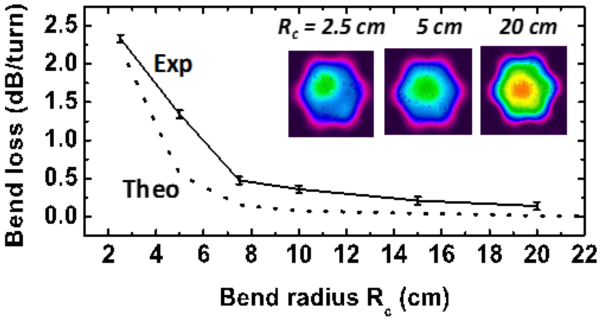
PER
up to 27dB
But
Dependence on coupling
Decrease with lengh

(c)



Modal content
20 dB extinction ratio
But
Dependence with length

(d)



bend loss of ~0.2dB/m
@ 15 cm radius,
But
Dependence on fibre motion

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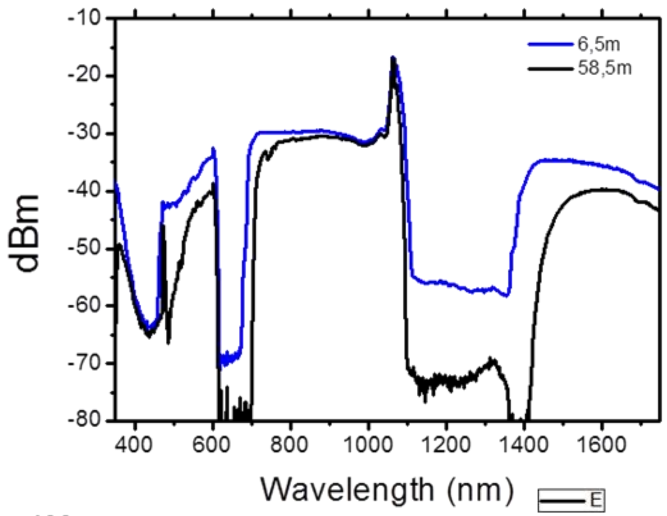
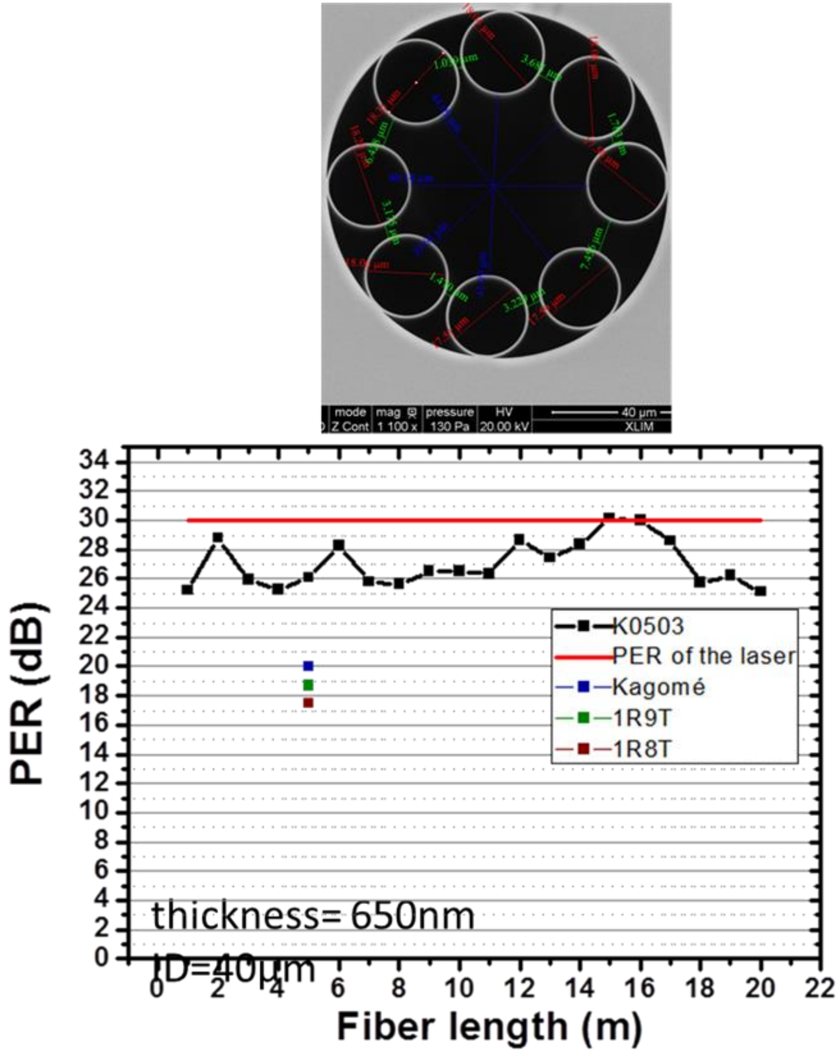
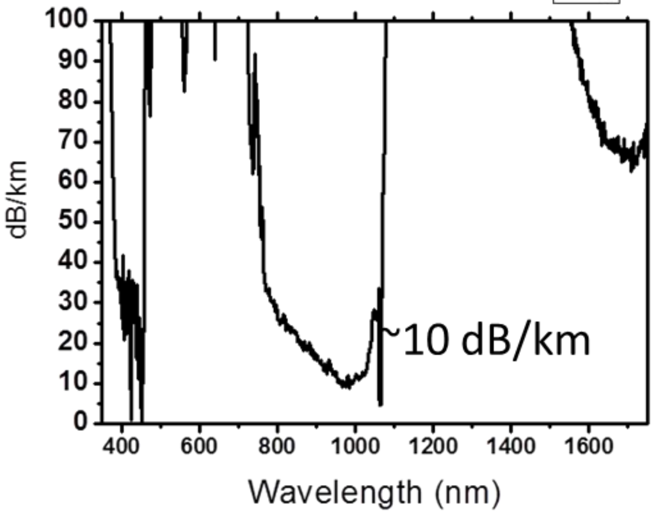
PER
up to 30dB
STABLE WITH LENGTH

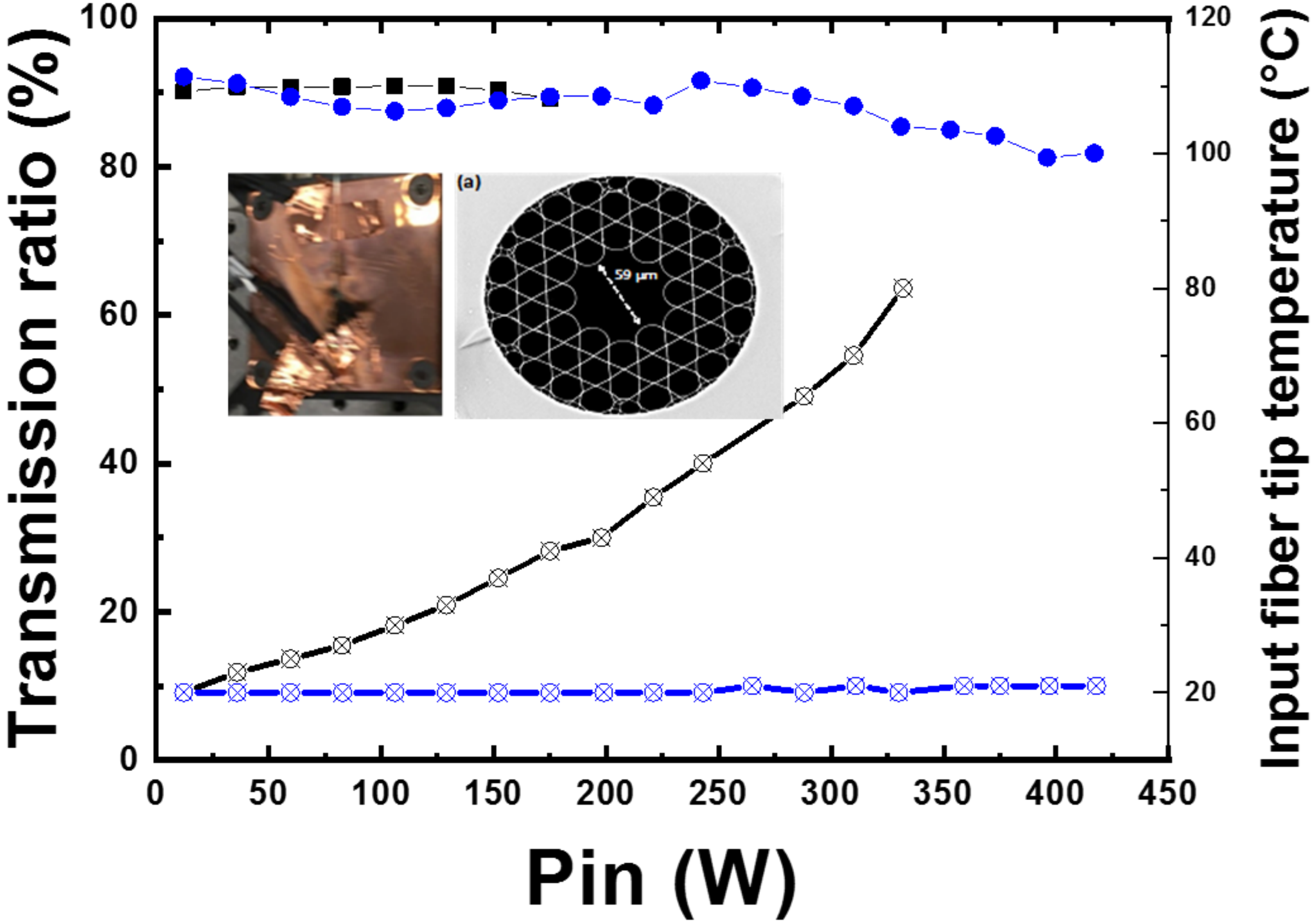




Loss
10 dB/km



Fiber Power handling preliminary test (lab conditions)



- Laser beam quality (M2 and jitter) dependent Performance
- Fiber Mounting dependent
- Guidance of 250-300 W range with no fiber cooling
- up to 400W (laser limit) demonstrated with water cooled fiber tip mount

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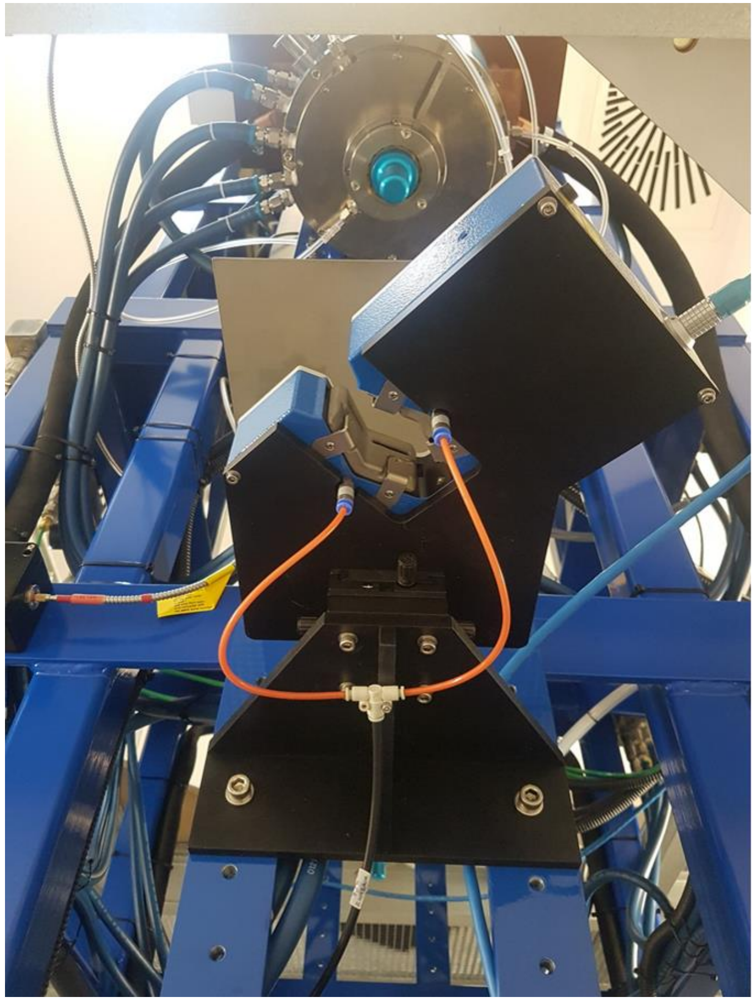
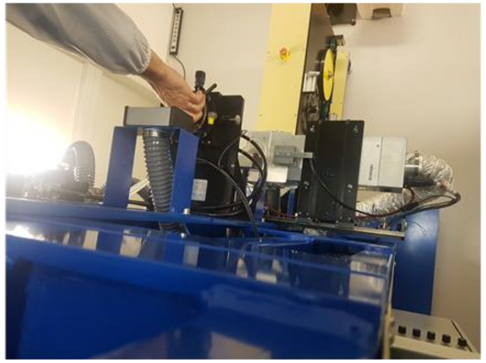
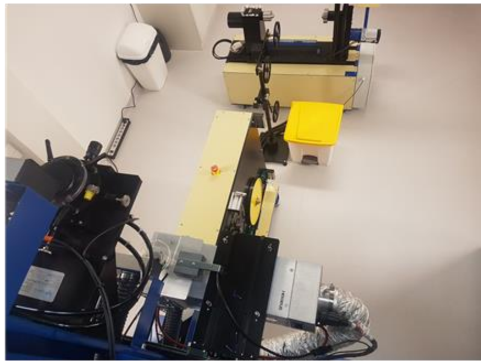


Installation of GLO new drawing facilities

- Prefrom drawing tower
- Fibre drawing tower
- Double layer coating capabilities
- Clean room and monitered ambient conditions





Stacking and fibre & preforms pre-processing

- Clean room (ISO7)
- Stacking rigs
- Stocking
- Annealing systems

First test runs & Tech transfer

- Cane draw tested/validated
- Std diameter fibre draw tested/validated
- Instrument calibration of IC HCPCF ongoing
- GPPMM fibres qualification to start on Sept. 2018

WP4 Photonics Components for pre- and post- pulse conditioning

THANK YOU

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