COSIGN

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COSIGN

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Deliverable D2.3 – Report on development of first generation Multi-Core Fibres and Photonic Bandgap Fibres

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CO	Confidential, only for members of the consortium (including the Commission Services)	

Executive Summary

In this deliverable we report on the development and supply of first generation SDM fibres to the COSIGN project by ORC and OFS. Firstly, we report the characterization and supply of initial 7-core multi-core fibre (and associated multiplexing devices) to DTU by OFS for data centre architecture studies. Secondly, we report on the characterization of few-mode fibres with a view to investigating their potential use in high spatial density interconnection. Thirdly, we report on the development and supply of both 4-core and 5-core multi-core fibres for multi-lane switching studies using the Polatis switch fabric, and the fabrication of multiple hollow-core fibre samples for a low-latency data centre architecture demonstrator experiment at the University of Bristol. Plans for the next project period are briefly mentioned.

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1 Introduction

In this deliverable we report on the development and supply of first generation Space Division Multiplexing (SDM) fibres to the COSIGN project by partners ORC and OFS. The specifications and priorities for the fibre development work undertaken within WP2 have evolved during the first year of the project as a result of ongoing dialogue between the project partners. This dialogue has been directed towards better understanding the performance benefits of particular data centre architecture approaches and establishing the best way of realizing and demonstrating these new architecture/performance benefits using the considerable array of fibre, switch and transceiver technologies available within the consortium.

Within the report we first describe the characterization and supply of initial samples of 7-core multi-core fibre (and associated multiplexing devices) to DTU by OFS for fundamental data centre architecture studies. Secondly, we report on the characterization of few-mode fibres with a view to investigating their potential use for high spatial density interconnection. Thirdly, we report on the development and supply of both 4-core and 5-core multi-core fibres for multi-lane switching studies using the Polatis switch fabric, and the fabrication and supply of multiple hollow-core fibre samples for a low-latency data centre architecture demonstrator experiment at the University of Bristol. Plans for the next project period are also briefly described throughout.

1.1 Reference Material

1.1.1 Reference Documents

[1]	COSIGN FP7 Collaborative Project Grant Agreement Annex I - "Description of Work"

1.1.2 Acronyms and Abbreviations

Most frequently used acronyms in the Deliverable are listed below. Additional acronyms may be defined and used throughout the text.

DoW	Description of Work
SDN	Software Defined Networks
MCF	Multi-Core Fibre
MMF	Multi-Mode Fibre
SDM	Space Division Multiplexing
HC-PBGF	Hollow-Core Photonic Bandgap Fibre
TMC	Tapered Multi-core Coupler
MIMO	Multiple Inputs - Multiple Output
DSP	Digital Signal Processing
OTDR	Optical Time-Domain Reflectometry
MFD	Mode Field Diameter
NZ-DSF	Non-zero Dispersion Shifted Fibre
FMF	Few-Mode Fibre

1.2 Document History

Version	Date	Authors	Comment
01	24/07/2015	See the list of authors	First draft
02	31/07/2015		Final version

2 Multi-Core Fibres for Use in COSIGN Test Rigs

Given the strong research interest in fibres enabling spatial division multiplexing (SDM) over the past five+ years, OFS had pre-existing activities in the development of multi-core fibres (MCFs) to bring into COSIGN. In particular, 7-core MCFs based on a triangular lattice geometry and associated fan-in/fan-out devices had been developed by OFS prior to the start of the COSIGN project [1]. After extensive discussions with the project partners, some of the existing fibre types developed by OFS were found to be suitable for the initial activities of COSIGN and were thus provided to DTU. These fibre samples are currently in use within the DTU COSIGN test bed and their performance in this context will be reported in future deliverables and reports.

The typical properties for the 7-core MFC supplied to DTU are summarized in Table 1.

Table 1: Properties of OFS existing multi-core fibre

Property	**unit**	**Value**
Core diameter	µm	9
Core pitch	µm	46.8
Cladding diameter	µm	186.5
Coating diameter	µm	315
Cut off wavelength	nm	1440
Mode field diameter @ 1550 nm	µm	9.6
Attenuation @ 1550 nm	dB/km	~0.26
Crosstalk 1525 – 1575 nm	dB/23.5 km	< -40

Here we present a selected set of characterization data for the 7-core MCF. The spectral attenuation (1250 to 1700 nm wavelength range) measured for each of the 7 cores is shown in Figure 1(a). The centre core has the lowest attenuation while the outer cores have slightly higher attenuation due to weak but non-negligible mode coupling to the coating layer.

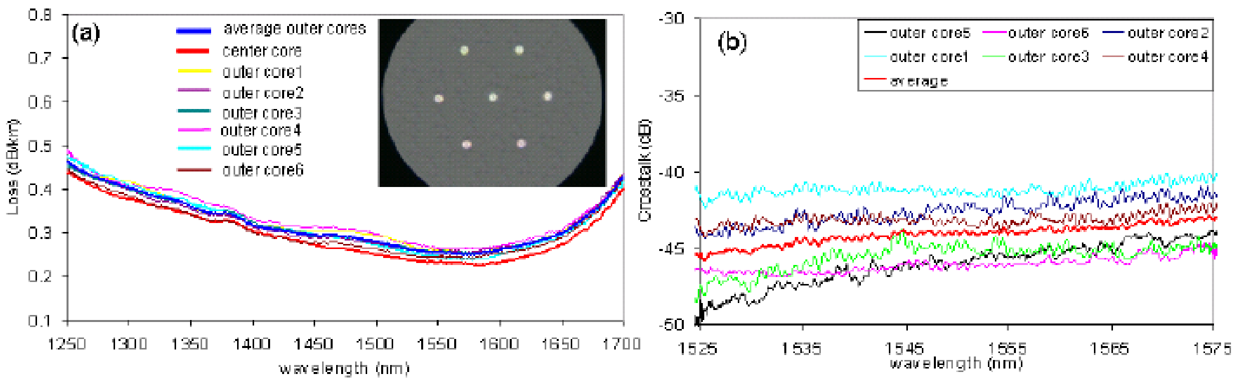

Figure 1: (a) Measured attenuation spectra of the 7-core MCF, Inset: cross-section optical microscope image of the MCF, (b) measured optical core-to-core crosstalk spectra of the MCF

The measured crosstalk from the centre core to the outer cores is shown in Figure 1(b). This is obtained by launching light in the central core and measuring any weak output in the six outer cores. The measurements were taken on a 23.5 km length of fibre spooled on to an 18 cm diameter bobbin.

To facilitate the light input/output coupling to the individual cores, a tapered multi-core coupler (TMC) fan-in/fan-out device previously developed by OFS was supplied to the project. In such a device, 7 single-mode pigtail fibres are tapered down together to match the core spacing of the multi-core fibre [1]. The principle as well as example of obtained insertion loss and crosstalk of the TMC is illustrated in Figure 2.

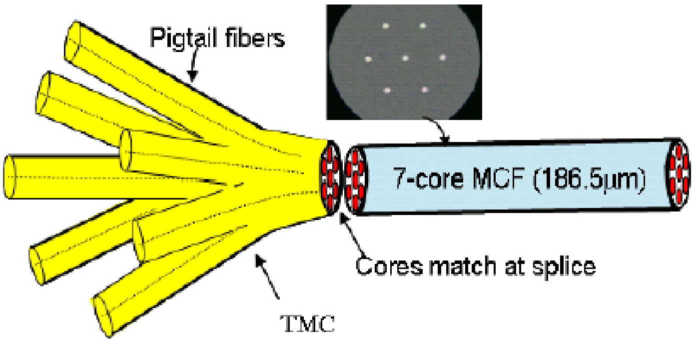

Table 1 insertion loss and crosstalk of TMCs

	TMC#1		TMC#2	
Core #	Loss (dB)	Crosstalk (dB)	Loss (dB)	Crosstalk (dB)
Center core	1.11		0.55	
Outer core1	0.75	-48.0	2.10	-49.0
Outer core2	2.77	-47.5	0.90	-46.5
Outer core3	1.95	-45.0	0.45	-46.0
Outer core4	0.98	-48.0	1.13	-47.0
Outer core5	1.42	-48.0	2.05	-48.5
Outer core6	1.37	-47.8	1.61	-45.5
average	1.48	-47.4	1.26	-47.1

Figure 2: Schematic diagram of tapered multi-core fibre connector

3 Characterization of Few-Mode Fibres

Few-mode fibres (FMFs) are emerging as an interesting alternative to multi-core fibres (MCFs) for SDM in data centres allowing for very high spatial channel densities. Compared to MCFs, FMFs have cylindrical symmetry and thus the advantage of having no requirement for precise rotational alignment during interconnection/interfacing/splicing. In this context FMFs are being assessed by OFS and DTU for applications within COSIGN.

In the second year of COSIGN, OFS has carried out a detailed characterization of four types of few-mode fibre that were developed by OFS over the course of a previous FP7 project ModeGap [2-4]. These fibres have recently been added to OFS' catalogue of commercial fibres [5]. This work has been carried out in collaboration between OFS and DTU. The new characterization work focused on measuring the characteristics of the individual modes and in particular the attenuation, group velocity dispersion, bend loss and intermodal crosstalk.

Predicted characteristics of the tested fibres are summarized in Table 2. The values are calculated from the index profile measured on the preform and scaled to fibre dimensions. The properties are found by solving the scalar wave equation with a finite element mode solver. The two step index designs are first generation fibres, while the graded-index designs have been further optimized, amongst other aspects towards targeting a low differential group delay between the modes, to make the fibres well suited for long haul SDM systems where crosstalk between the modes is mitigated by multiple-input-multiple outputs digital signal processing (MIMO-DSP).

Table 2: Predicted optical characteristics of tested few-mode fibres at 1550 nm (modelled using the measured refractive index profile)

	Two-Mode Graded index	**Two-Mode Step index**	**Four-Mode Graded index**	**Four- Mode Step index**
Differential group delay (ps/m)	-0.2 to +0.2	LP_{11}-LP_{01}:2.1	-0.4 to 0.4	LP_{11}-LP_{01}:2.0 LP_{21}-LP_{01}: 3.9 LP_{02}-LP_{01}: 3.0
Dispersion (ps/(nm·km))	LP_{01}: 19.9 LP_{11}: 20.0	LP_{01}: 21.1 LP_{11}:20.7	LP_{01}: 18.4 LP_{11}: 18.7 LP_{21}: 18.0 LP_{02}: 16.9	LP_{01}: 21.1 LP_{11}: 22.0 LP_{21}: 21.4 LP_{02}: 17.5
Dispersion slope (ps/(nm^2·km))	LP_{01}: 0.067 LP_{11}: 0.065	LP_{01}: 0.065 LP_{11}: 0.060	LP_{01}: 0.068 LP_{11}: 0.067 LP_{21}: 0.067 LP_{02}: 0.067	LP_{01}: 0.066 LP_{11}: 0.064 LP_{21}: 0.056 LP_{02}: 0.043
Mode field diameter (µm)	LP_{01}: 11.0 LP_{11}: 11.0	LP_{01}: 15.6 LP_{11}: 13.6	LP_{01}: 10.7 LP_{11}: 10.8 LP_{21}: 11.0 LP_{02}: 6.3	LP_{01}: 18.2 LP_{11}: 15.2 LP_{21}: 14.3 LP_{02}: 8.7
Effective area (µm^2)	LP_{01}: 96 LP_{11}: 128	LP_{01}: 215 LP_{11}: 210	LP_{01}: 90 LP_{11}: 122 LP_{21}: 166 LP_{02}: 184	LP_{01}: 312 LP_{11}: 280 LP_{21}: 315 LP_{02}: 295

For application in internal data centre networks, use of MIMO-DSP is unlikely to ever be a viable option as it would be too costly and it can also introduce unacceptable latency. For FMFs to be considered as a solution for this application space it is thus clear that the crosstalk levels must be as low as possible. We have therefore experimentally investigated the crosstalk between the modes due to distributed mode coupling in the fibres. We used spatially and spectrally resolved mode imaging (S^2 imaging) [6]. Launching of the individual modes has been accomplished by using splicing to a standard single-mode fibre for the LP_{01} mode and via use of mode-converter based suitable long

period gratings, for LP_{11} and LP_{21} modes. A mode converter for LP_{02} however was unfortunately not available at the time of measurements. The results are summarized in Table 3.

Table 3: Crosstalk of the four different FMFs measured @1550 nm

Fibre type	Input mode	Total crosstalk to other modes (dB)	Length (m)
Two-mode graded index	LP_{01}	-27	15000
	LP_{11}	-28	
Two-mode step index	LP_{01}	-18	1500
	LP_{11}	-19	
Four-mode graded index	LP_{01}	-25	8800
	LP_{11}	-18	
	LP_{21-02}		
Four-mode step index	LP_{01}	-23	150
	LP_{11}	-22	
	LP_{21}	Not currently measurable	
	LP_{02}	Not currently measurable	

Assuming that a crosstalk value below -15 to -20 dB is acceptable for transmission, it can be concluded that the two-mode graded index fibre can be used for transmission over several tens of km, while the two-mode step index fibre can be used for transmission over several km (at least). The four-mode graded index fibre is by design characterized by the LP_{21} and LP_{02} modes having an almost identical propagation constant and thus these two modes are more strongly coupled together, which makes this particular fibre less attractive for transmission without MIMO-DSP. The four-mode step index fibre seems to be able to support transmission over a few 100 metres, which is still an interesting distance within data centres.

The measured attenuations for the individual modes (at 1550nm wavelength) are summarized in Table 4. The attenuation was measured through two methods: cut back measurements using a 1550 nm laser and a power meter and optical time domain reflectometry (OTDR).

Table 4: Attenuation of FMFs measured @1550 nm

Fibre type	Mode	Attenuation cut back (dB/km)	Attenuation OTDR (dB/km)	Length used (m)
Two-mode graded index	LP_{01}	0.197	0.195	15000
	LP_{11}	0.183	0.187	
Two-mode step index	LP_{01}	0.178	0.184	9050
	LP_{11}	0.180	0.185	
Four-mode graded index	LP_{01}	0.224	0.224	8900
	LP_{11}	0.219	0.209	
	LP_{21-02}	0.215	0.205	

Reasonable agreement between the two measurement methods is observed and, more importantly, low attenuation was measured for all modes. Due to the strong mode coupling in the four-mode step index fibre it was only possible to measure lengths up to a few hundred metres which is too short to obtain reliable attenuation values. An OTDR measurement over 11 km of four mode step index fibre, where the modes must expect to be heavily mixed, showed an attenuation of 0.185 dB/km demonstrating that the average attenuation for the four modes is low.

Results for the dispersion measurements are summarized in Table 5. The dispersion is measured by measuring the change in group delay versus wavelength on an Agilent 86037C dispersion measurement station. A 5-term Sellmeier expression was then fitted to the group delay and differentiated to get the dispersion.

Table 5: Measured dispersion @1550 nm

Fibre type	Mode	Dispersion (ps/(nm·km))	Dispersion slope (ps/(nm^2·km))	Length used (m)
Two-mode graded index	LP_{01}	19.6	0.064	15000
	LP_{11}	19.5	0.061	
Two-mode step index	LP_{01}	21.0	0.063	9050
	LP_{11}	20.3	0.063	
Four-mode graded index	LP_{01}	18.4	0.066	8900
	LP_{11}	19.1	0.064	

It can be seen that the measured dispersion in Table 5 and the theoretical values in Table 2 are quite similar.

Finally, the bend loss performance of the individual modes was characterized again using S^2 imaging. For the two-mode graded index fibre for a bend radius of 5 mm bend loss bellow 0.5 dB/cm (below 1.5 dB/turn) for all modes was found. The graded index four-mode fibre had even lower bend loss. For more details please refer to [7].

During the next phase of the project work will continue at DTU/OFS focused on demonstrating use of FMFs in for specific Data Centre scenarios and for specific use cases. In addition, ORC and Polatis will explore the possibility of preserving mode extinction ratios during switching in the Polatis switch fabric.

4 Development of Multi-Core Fibres for Multi-Lane Switching

4.1 Rationale for this Activity

During the course of the first year of the COSIGN project and in the context of the definition of the main project drivers for its final demonstrators and activity within WP2, a strong requirement emerged for investigating the integration of the novel fibre types (multi-core fibres and low-latency fibres) with some of the other key components developed by the project, and in particular the high-port count fibre switches developed by Polatis.

The ORC was thus tasked with the design and fabrication of fibres suitably tailored for this activity (with support from OFS). The present document summarizes the properties of the first generation of special MCFs, designed in such a way that multiple spatial channels can be simultaneously switched between input and output switch ports (multi-lane switching) with the Polatis space switch. These first generation fibres comprise 4 cores located in a square array (i.e., 2x2 core array). The cores have properties very close to those of a standard single-mode fibre. The aim of this activity is to provide initial MCF samples to enable testing in a simplified but realistic configuration which mimics the operation of a Polatis switch. Further fibre development steps are envisaged in which the core count will be increased (likely to 3x3) through use of more complex refractive index profiles (e.g., trench design) and core material supplied by OFS.

The overall activity of development of MCFs for multi-lane switching, their characterization and integration with Polatis devices will be described in detail in a future deliverable (*D2.9 "Report on performance of MCF designed for multi-lane switching experiments*", month 24). Initial experiments though are underway and are yielding positive results.

4.2 Fibre Design and Fabrication

A detailed set of fibre requirements were identified jointly by the ORC and Polatis. For the purpose of the first demonstration the key requirements were:

- A square geometry (to better match the optics present within the Polatis switch).
- Multiple cores with properties as close as possible to those of conventional SMF.
- The cores should be located within a circular region of ~62.5μm in order to suit the field-of-view of the current multi-mode fibre Polatis device.
- The possibility of having a central core to facilitate alignment and connectorisation of these fibres by commercial contractors and thus a better packaged device solution in the future. (The additional core would is not intended for use under normal ongoing switch operation).

Note that at this stage the main goal is to enable simple fabrication and to obtain a meaningful demonstration of these fibres in a basic switching configuration. Minimisation of crosstalk which is clearly of great importance in real-world application with long fibre links was only considered of secondary importance for the purpose of this initial investigation with the target being to achieve <25 dB/km over 2 km length scales, rather than the absolute minimum value possible. Similarly, the issue of scaling up the number of cores to the maximum allowable for a given value of crosstalk will be addressed in due course. This will require the design and fabrication of special cores, likely with a trench design, which will be carried out in collaboration with OFS.

Based on the above points, a suitable fibre design was identified. This comprised four SMF28-like cores arranged in a square lattice such that their optical modes were fully contained in a circle of 62.5μm diameter. The dimension of the optical mode was assumed to coincide with its MFD (~11μm). This constraint results in a maximum separation of around 35μm for the four adjacent SMF cores.

The starting point for fibre fabrication is the preparation of a suitable preform, which was accomplished via a stacking procedure (see Figure 3(a)). We employed a commercial SMF preform and reduced its cladding layer via HF etching, so as to achieve a ratio of silica cladding to core diameter (~1:3.9) corresponding to a separation of 35μm in the final fibre. These core rods were

stacked inside a jacket tube and spaces filled with pure silica rods. Additionally, and at the request of Polatis, we investigated the possibility of placing a 5th ('shunt') core at the fibre centre to aid alignment during fibre end termination and device manufacture. Clearly the additional core reduces the minimum core-to-core spacing and thus is expected to adversely affect the crosstalk between the main cores. The numerical aperture and diameter of the shunt core was thus chosen to provide a large contrast in effective modal index as compared to the 4 transmission cores. The relative index difference of the shunt core material was chosen to be ~1%, i.e., significantly higher than that of a SMF (~0.35%). Figure 3(b) shows how the effective indices of the optical modes of the transmission and shunt cores as a function of the core diameter (model assumes a step index profile) at a wavelength of 1.55 μm. For a core radius >2.7 μm the shunt core is no longer single-mode and potential phase matching between the fundamental modes in the 4x transmission cores and the higher order modes in the shunt core is expected to increase crosstalk. To provide the maximum contrast in effective modal index whilst retaining single-mode guidance, the design diameter of the shunt core was chosen to be 5.7 μm. A single preform was stacked incorporating a section with a central shunt core and another section without. The fibre was then drawn to produce two different fibres. Optical Microscope images of the fibres are shown in Figure 4 and the relevant properties of the fibres are given in Table 6. The fibre performance in a basic switching setup is currently being characterized and the results will be reported in deliverable *D2.9 "Report on performance of MCF designed for multi-lane switching experiments"*.

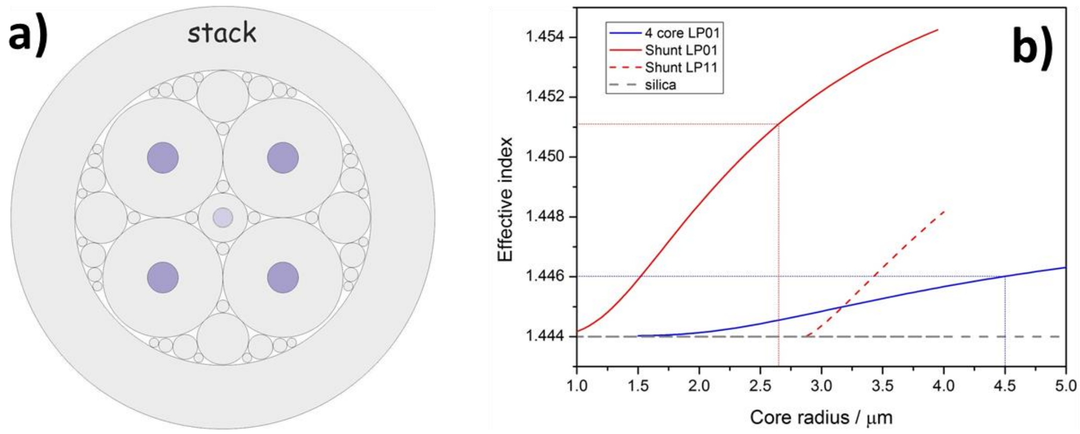

Figure 3: (a) Schematic of the stack plan for a MCF with 2x2 cores in a square array, showing the optional central "shunt" core; (b) Effective index of the fundamental mode of transmission cores (blue curve) and the modes of the "shunt" core (solid red) as a function of the core radii at a wavelength of 1.55 μm

Table 6: Properties of first-generation MCFs for multi-lane switching

	MCF w/o central "shunt" core	***MCF with central "shunt" core***
Fibre Diameter (μm)	125	125
No. Cores	4	4 (+1)
(main) Core NA	~0.11	~0.11
(main) Core diameter (μm)	9	9
(central) Core NA	-	~0.2
(central) Core diameter (μm)	-	5.7
Core spacing (μm) (centre to centre)	35.6±0.2	35.5±0.2
Max core positioning error (μm)	>0.5	>0.5
Diagonal core spacing (μm)	~50	~50
Length of fibre supplied to project (km)	0.32	~0.5

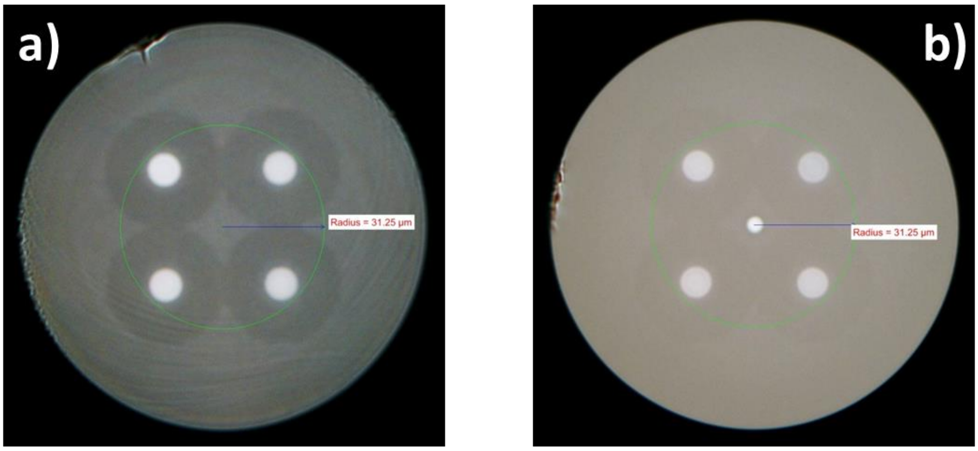

Figure 4: Optical microscope images of a 2x2 cores, square array MCF without (a) and with (b) central shunt core**.** Spacing between the main adjacent transmission cores is 35.5±0.5 μm. The main transmission cores lie within a circular region of approximately 62.5 μm diameter (green line).

4.3 Future Work

The MCFs fibres produced are currently being characterized, both in terms of their optical performance (i.e., loss, crosstalk, MFD, etc.) and also with respect to their performance in a basic switching rig setup at the ORC. We envisage that the results of these tests will feed back useful information for the design of a second generation of MCFs. In parallel, we are considering more complex core designs which will allow a reduction in crosstalk and possibly to increase the core count for a fibre with a manageable diameter. More detailed modelling of the crosstalk for different fibre designs will be carried out in the next period.

5 Development of Low-Latency Hollow-Core Photonic Bandgap Fibres

5.1 Rationale for this Activity

Hollow-core Photonic Bandgap Fibres (HC-PBGFs) enable light guidance in air (rather than glass) which offers a number of advantages as compared to conventional fibres. In terms of data transmission, possibly one of the most notable advantages is the very significant latency reduction (about ~33% or ~1.54µs/km) as compared to any type of standard solid fibre. This aspect has been investigated and demonstrated by the ORC [8]. Figure 5 illustrates this by showing a comparison of the transit time of a pulse down an identical length of HC-PBGF and non-zero dispersion-shifted (NZ-DSF) single-mode fibre.

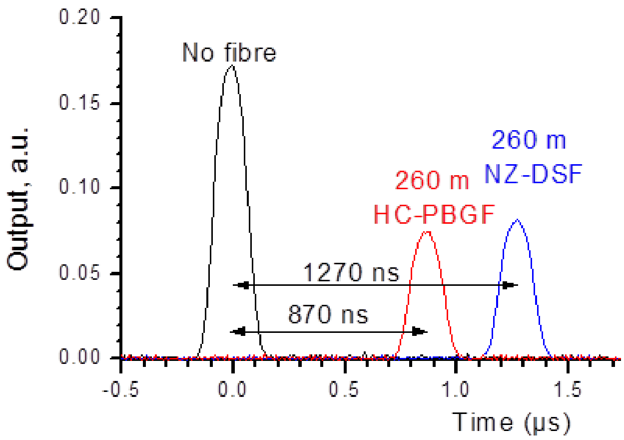

Figure 5: Latency reduction in a HC-PBGF as compared to a standard transmission fibre

The latency reduction is expected to bring about significant advantages in the context of data centres, particularly due to the progressive move to disaggregation of networks, which means that processors and memory are lumped together and require interconnections with as low as possible latency. In this context, the COSIGN project is investigating in detail the relative merits, and any possible drawbacks, associated with the replacing HC-PBGFs for standard solid fibres in such interconnections.

5.2 HC-PBGF Fabrication

The ORC has developed substantial know-how over the years and is currently one of the leading groups in the fabrication of these complex fibres. In the context of the COSIGN project, suitable fibres and fibre samples with spliced SMF-28 fibre FPC/APC connectors were prepared to support experiments carried out in a dedicated test bed at the University of Bristol. The fabrication of these fibres has already been reported in some detail in the milestone document M10.

HC-PBGFs are generally fabricated using a two-stage stack and draw technique. Firstly, a few hundred pure silica glass capillaries with thin walls and high geometrical consistency are assembled in an array with the required geometry. These are placed inside a glass jacketing tube, tightly packed and fused together by drawing them to “cane” in an intermediate stage. The cane material is then drawn into a final fibre via an involved fibre drawing procedure in which the pressure inside the various holes present in the structure is accurately controlled not just to prevent them from collapsing, but in fact to achieve the target structure. As the optical properties of HC-PBGF depend very strongly on the fibre structure, it is essential to achieve excellent longitudinal consistency of the fibre microstructure. This is a significant challenge given the fact that some of the features within a typical HC-PBGF are just a few hundred nm in size.

To date, the ORC has delivered one fibre sample to the project. The fibre, shown in Figure *6*(a), had a 19 cell core structure (i.e., core composed of 19 missing elements) and a six ring cladding structure and is obviously designed for operation in the standard telecommunication window at 1.55 μm. The key properties are summarized in Table 7. Figure *6*(b) shows the spectral loss measured on a 440 m long cutback using a broadband source.

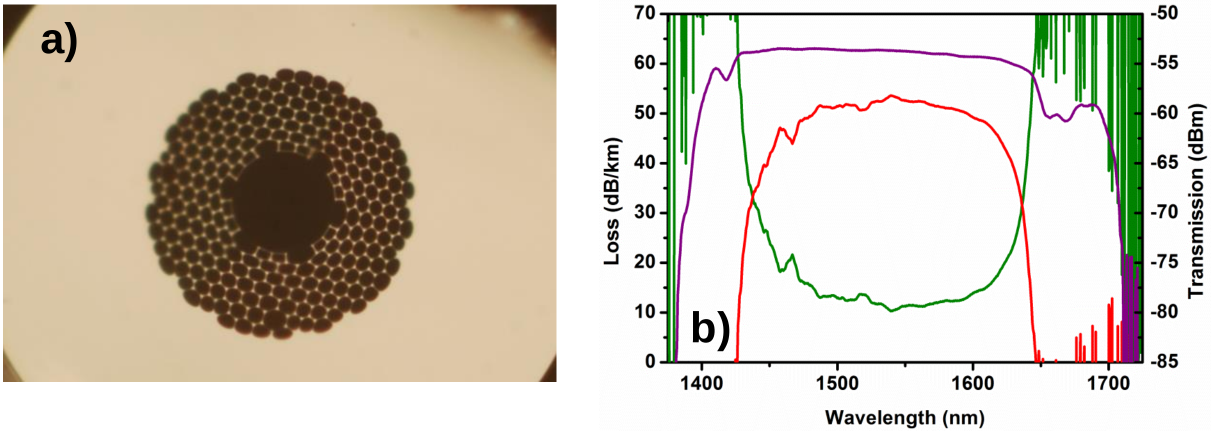

Figure 6: (a) Optical microscope image of the HC-PBGF, showing the hollow core located at the centre of a *micro structured* cladding with six rings of holes. (b) Spectral transmission of the HC-PBGF measured on a cutback length of approximately 440 m

Table 7: Characteristics of the low-latency HC-PBGF delivered to the project

Fibre Property	**Initial Design**
Operating wavelength	~1550 nm
Transmission Bandwidth	>150 nm
Core geometry	19 cell
Core OD	26.5 μm
MFD	≈16 μm (estimated)
Fibre OD	160 μm
Microstructure OD	72 μm
Background loss	≈10 dB/km (1545nm)
Latency improvement relative to an equivalent length of SMF28	1.54 μs/km
Modality	Few-moded. Can be operated as supporting SM transmission up to ~2km
Modal X-talk (1km) or mode purity under optimum launch conditions)	~20 dB
Sample Length	440 m

5.3 Demonstration of HC-PBGF in a Practical Transmission Test

The experiment designed by the group at the University of Bristol required multiple discrete samples of short (≈metre scale) and long (≈100-metre scale) length to mimic intra- and inter-rack fibre connections. The fibre sample described above was thus partitioned into 7x10 metre long samples and 3x100 metre samples. Each of these samples required to be connectorised for easy interfacing with standard single-mode fibre.

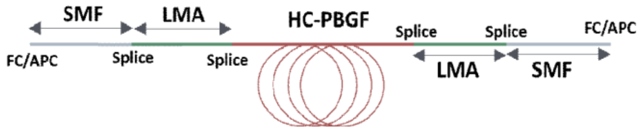

Figure 7: Schematic of connectorised samples of HC-PBGF

In general, interconnection of HC-PBGFs to conventional solid fibres requires addressing a number of challenges. Suitable splice recipes need to be identified in order to minimize distortion of the microstructure of the HC-PBGF, which unavoidably introduces undesirable loss. The microstructure within the HC-PBGF has very low thermal mass and thus as a consequence can easily be deformed (or even destroyed) if the amount of heat deposited by the splicer is not optimized. Furthermore, another challenge stems from the often substantial difference in MFD between HC-PBGFs and standard SMF. In order to address the latter problem, the approach we followed was to use a low numerical aperture, large mode field diameter (MFD) solid buffer fibre to aid the transition from the smaller MFD of the SMF to the larger MFD of the HC-PBGF. This approach allows decoupling of the MFD mismatch loss from the splice between the solid fibre and the HC-PBGF. A schematic of the interconnection approach using the buffer fibre is shown in Figure 7. The properties of the connectorised samples are shown in Table 8. The individual samples were characterized using Optical Time Domain Reflectometry (OTDR) to ensure that they have uniform loss along their length (Figure 8), and a basic transmission test using On-Off Keying (OOK) at 10Gb/s at a single wavelength (1550 nm) was also carried out (Figure 9).

Table 8: Properties of the connectorised HC-PBGF samples prepared for experiments at the University of Bristol

Sample Code	HC-PBGF Length (m)	Pigtail Length SMF/LMA (m)	Hollow to solid length (%)	Total Insertion Loss (dB)	Latency Reduction
1	100	1 / 0.5		4.1	
2	100	1 / 0.5	~97%	4.9	~154ns
3	100	1 / 0.5		4.5	
A	10	1 / 0.5		4.1	
B	10	1 / 0.5		3.9	
C	10	1 / 0.5	~70%	3.5	
D	10	1 / 0.5		4.2	~15.4ns
E	10	1 / 0.5		3.6	
F	10	1 / 0.5		3.7	
G	10	0.5/ 0.25	85%	3.8	

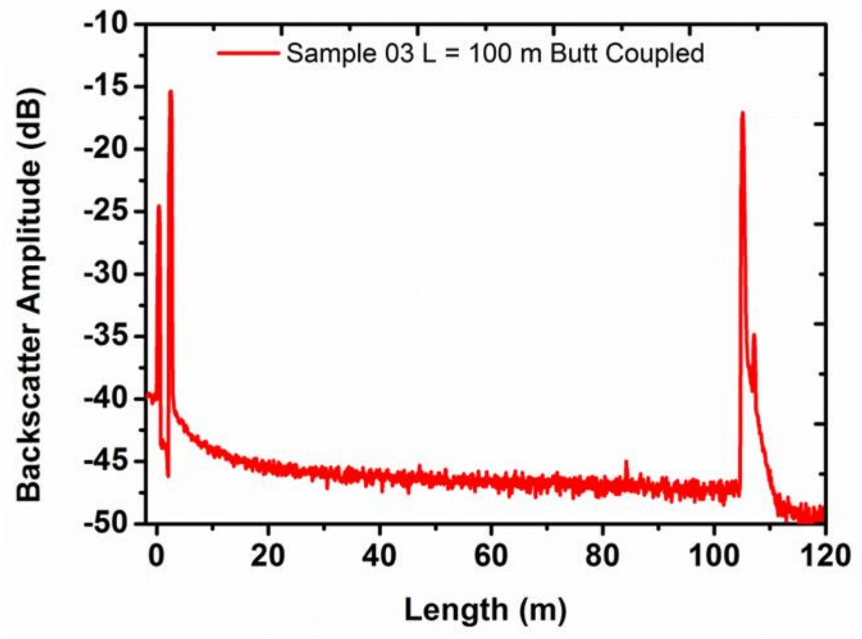

Figure 8: OTDR trace of HC-PBGF sample #3 (100 m long) showing uniform loss along the fibre length; peaks indicate reflections at the air/glass interfaces

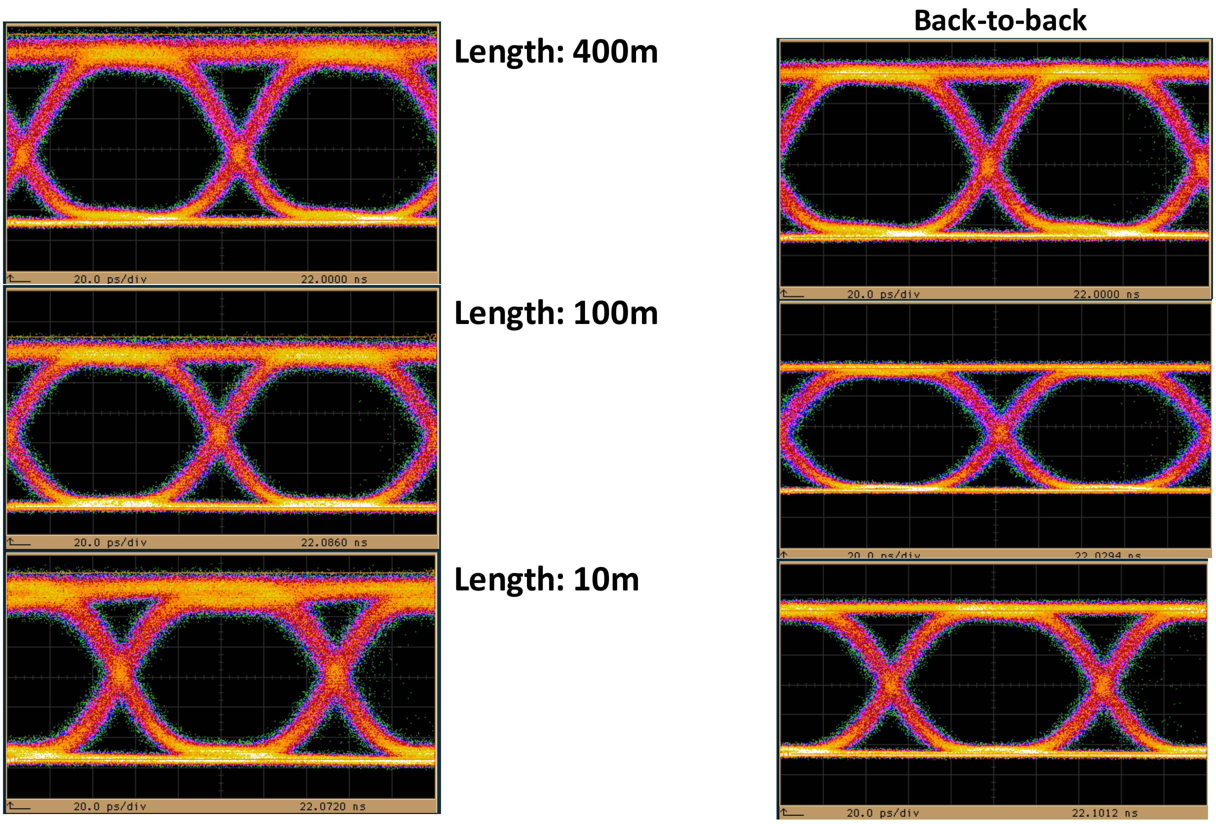

Figure 9: Eye diagrams from basic transmission tests over two samples (10 m and 100 m), as well as over the full undivided length of 440 m (before partitioning), carried out using OOK at 10 Gb/s at 1550 nm. The column on the right shows the relevant back-to-back traces

The connectorised fibre samples were successfully incorporated in the Data Centre test bed at the University of Bristol and facilitated experiments demonstrating a programmable and reconfigurable

disaggregated DCN architecture with low-latency fibre links mimicking inter- and intra-rack interconnections (see Figure 10). This work will be reported at the next ECOC 2015 conference [9].

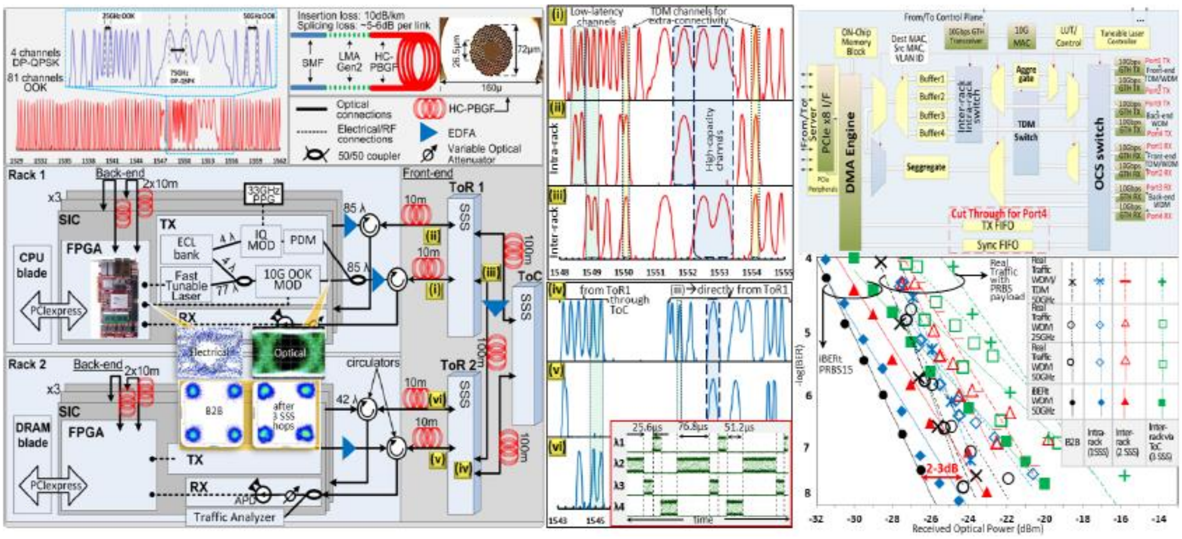

Figure 10: DCN test bed developed by the University of Bristol and incorporating HC-PBGF fibre links

6 Conclusion

In summary, we have reported on the fabrication and supply of first generation fibres to the consortium. Specifically, we have delivered 7-, 5- and 4-core multi-core fibres of different geometries and hollow-core photonic bandgap fibres in alignment with project needs and priorities. These fibres have been installed in partner test beds and are being used in ongoing experimental work within the project yielding novel and important results at the device and system levels.

Further refinements in these fibre types and the development of new fibres offering even higher density spatial interconnection will be undertaken in the next phase of the project. Particular focus will be directed towards supply of fibres for novel DC architectures and low latency links and fibres for simultaneous multi spatial channel switching.

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