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D2.5 – Report on Development of Optimised Second Generation Fibres

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

Executive Summary

In this deliverable we report the fabrication of a second generation Multi-Core Fibre (MCF) for incorporation in a multi-lane switching device under development within the project. The MCF provides extremely low crosstalk (XT) levels due to the use of a trench-assisted core design. Modelling was performed to identify the maximum number of cores (based on the available trench design) compatible with a nominal crosstalk level of −25 dB/km. Fibres with a geometry and refractive index profile closely matching the optimised 4-core design were fabricated in sufficient length to support low power characterisation, small scale switching tests as well as larger scale experiments that are planned with partners at University of Bristol and DTU. The fabricated 2nd generation MCF has a very low XT level of −55 dB/km, which is several orders of magnitude better compared to the 1st generation MCFs.

This document also details the properties of the second generation of low-latency Hollow-Core Photonic Bandgap Fibres (HC-PBGFs), which were delivered to the COSIGN project. Improved fibres were developed and fabricated by the University of Southampton. Main improvement areas concern fibre loss, consistency and fibre yield. The obtained loss is ~4 dB/km and the fibre yield is more than 2 km, which is significantly better compared to the ~10 dB/km loss and few hundred meter yield of the HC-PBGFs previously reported in this project. Separately, we have also investigated issues concerning the practical use of these fibres, such as connectorisation and cabling.

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1 Introduction

The ORC (UNISOUTH) was tasked with the design and fabrication of Multi-Core Fibres (MCFs) tailored for integration with the high-port count fibre switches developed by Polatis. Milestone MS11 reported the fabrication of a first generation MCF [2]. The fibre had 4 identical cores, located in a 2x2 square array, each one with a refractive index profile and properties close to the one of standard single-mode fibre, and designed in such a way that light can be easily switched between different cores (multi-lane switching) when incorporated in a Polatis device. The fibre described in MS11 was successfully utilised for an initial demonstration of multi-lane switching where a simplified but realistic configuration reproduced the operations of a Polatis switch (Deliverable *D2.9 "Report on Performance of MCF Designed for Multi-Lane Switching Experiments"*). Subsequently, the fibre was also incorporated into a suitable collimator assembly in order to facilitate more advanced tests involving an actual commercial Polatis switch. Whilst this has allowed for successful testing of the switch itself, it was not possible to utilize this fibre in realistic-scale data transmission trials (e.g., using multi-hundred meters fibre lengths) due to the high crosstalk of this particular MCF, which had not been optimized to operate over such long distances.

This deliverable reports the fabrication of a second generation improved MCF, based on the use of trench design core material supplied by OFS, which provides extremely low crosstalk levels. Modelling was performed to identify the maximum number of cores (based on the available trench design) compatible with a nominal crosstalk level of –25 dB/km. Fibres with a geometry and refractive index profile closely matching the optimised design were fabricated in sufficient length to support low power characterisation, small scale switching tests as well as larger scale experiments that are planned with partners at University of Bristol and DTU.

This document also details the properties of the second generation of low-latency hollow-core fibre, which were delivered to the COSIGN project. Improved fibres were developed and fabricated by the ORC. Main improvement areas concern fibre loss, consistency and fibre yield. Separately, we have also investigated issues concerning the practical use of these fibres, such as connectorisation and cabling.

1.1 Reference Material

1.1.1 Reference Documents

[1]	COSIGN FP7 Collaborative Project Grant Agreement Annex I - "Description of Work"
[2]	M11 - Delivery of First Generation Multi-Core Fibres for Multi-Lane Switching
[3]	M12 - Delivery of Second Generation Low Latency Fibres and Multi-Core Fibres for Multi-lane Switching
[4]	D2.9 - Report on performance of MCF designed for multi-lane switching experiments
[5]	T. Mizuno, K. Shibahara, H. Ono, Y. Abe, Y. Miyamoto, F. Ye, T. Morioka, Y. Sasaki, Y. Amma, K. Takenaga, S. Matsuo, K. Aikawa, K. Saitoh, Y. Jung, D. J. Richardson, K. Pulverer, M. Bohn, and M. Yamada, "32-core Dense SDM Unidirectional Transmission of PDM-16QAM Signals Over 1600 km Using Crosstalk-managed Single-mode Heterogeneous Multicore Transmission Line," in Optical Fiber Communication Conference Postdeadline Papers, OSA Technical Digest (online) (Optical Society of America, 2016), paper Th5C.3.
[6]	M10 - Delivery of first generation ultralow latency fibres and multi-core fibres (MCF)

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
HC-PBGF	Hollow-Core Photonic Bandgap Fibre
OTDR	Optical Time-Domain Reflectometry
MFD	Mode Field Diameter
XT	Crosstalk

1.2 Document History

Version	Date	Authors	Comment
01	26 June 2016	See the list of authors	First draft
02	5 July 2016		Final version

2 Second Generation Multi-Core Fibres Suitable for Realistic-Scale Multi-Lane Switching Experiments

2.1 Fibre Requirements and Design

In order to reduce the crosstalk between the four cores in our first generation MCF, which used a standard single-mode fibre (SMF 28) core design, it is necessary to introduce cores with a more complex refractive index profile. Specifically, it is necessary to use cores with a depressed index trench around the core. The presence of the trench restricts the tails of the modes extending far into the surrounding cladding greatly reducing the potential for inter-core crosstalk. Our goal in producing these fibres was a crosstalk level < −25 dB/km as opposed to the −12 dB/km or so in our first generation fibres, sufficient to allow reliable transmission over distances of 1-2 km.

OFS provided the core glass material (one preform with proprietary trench-assisted refractive index core design) and associated characterisation data (preform geometry and refractive index profile). Using the refractive index data, UNISOUTH performed simulations to generate a fibre design that can provide suitable transmission properties and in particular the required low level of crosstalk. The results are summarized in Table 1. The modelling performed demonstrated that a higher core count (e.g., 3x3 square, or 7 close packed triangular arrangement) would not be compatible with the target crosstalk of <−25 dB/km. This could be achieved at a later stage, e.g., utilizing two or more sets of slightly different core designs, similar to what has been demonstrated in MCFs with much higher core count by various groups [5]. For the same reason the central on-axis relatively high numerical aperture "shunt" core, included in the 1st generation MCF in order to facilitate alignment during connectorisation/collimation, was also removed so as to reduce the potential for it inducing crosstalk between the four primary data carrying cores. This is not considered likely to impact fibre post-processing significantly in the longer term, as alternative solutions for centring of MCFs could easily be identified.

As mentioned above, the refractive index profile included a trench, i.e., a region of depressed refractive index, to provide better mode confinement for each core, thereby reducing crosstalk compared to the less sophisticated step-index profile employed in the first generation MCF. The crosstalk was predicted to be as low as −40 dB after 10 km. This 2nd generation MCF is intended for transmission purposes over multi-km distance scales. As the core MFD (11 µm) and geometry of the core distribution is very closely matched to the one of the 1st generation MCF, the new and 1st generation MCF can be directly spliced to each other with low loss. Consequently the multi-lane switch prototype can be directly connected to the new fibre. Use of the 1st generation MCF for coupling to the multi-lane switch is preferable for the purpose of the planned project tests and experiments due to the presence of the shunt core, which makes connectorisation/collimation much easier in the shorter term (see MS11).

Table 1: Set of initial fibre requirements

No. Cores	4
Core arrangement	2x2 Square Lattice
Target core diameter	~10.8 µm
Target core distance (centre to centre)	~36 µm
Calculated MFD	11 µm
Calculated Crosstalk	–40 dB after 10km
Refractive index profile	Trench assisted, OFS proprietary
Additional requirements	Addition of a marker feature (low index element which shows as a dark spot) to provide core identification

2.2 Fabricated Fibres

Core material provided by OFS was used by UNISOUTH in order to produce multiple fibre samples. MCF preforms were produced with the stack and draw technique, where the OFS core material was first thinned down in diameter by etching (using a specialist external glass processing company) and then composed in an array of the required geometry, and placed within a jacketing tube made of high purity silica glass. The preform obtained in this way was then fused together and drawn into fibre in a single step. Particular care was devoted to ensuring that minimal modifications of the fibre geometry took place during the drawing step. Thus an appropriate temperature was chosen, e.g., to avoid changes in the refractive index profile due to dopant diffusion, and suitable preform preparation and draw conditions were chosen to minimize any deformation of the geometry of the stacked array due to the drawing process itself.

Three individual fibres were delivered to the Project – their characteristics are summarized in Table 2. An optical microscope image of the cross section of Fibre Y is shown in Figure 1. As can be seen, all the fibres have minimal differences between each other, and are very close to the target design. Their high consistency was determined by checking the geometry at both ends. The combination Fibres X and Y will provide a ~10 km length for transmission experiments. A third fibre (Fibre Z) is recommended for building initial devices or carrying out preliminary tests.

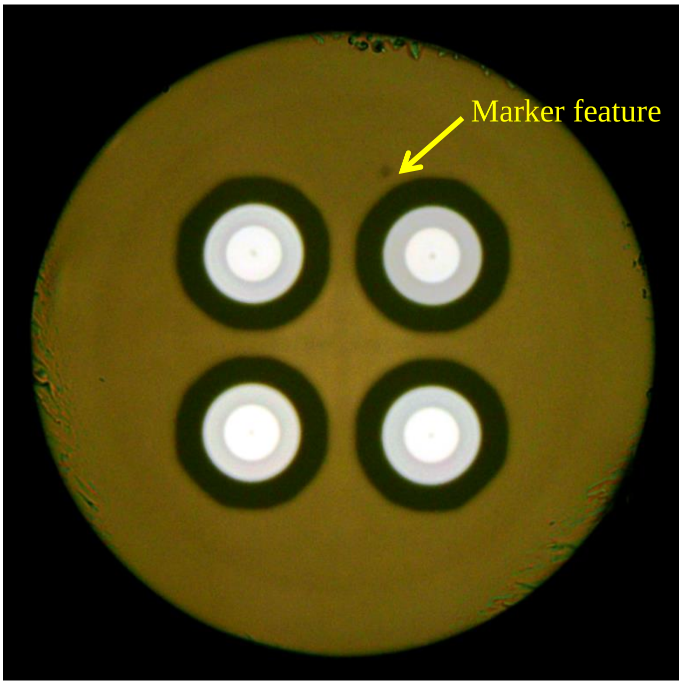

Figure 1: Second generation 2x2 core square lattice MCF for multi-lane switching

Table 2: Properties of Fabricated Multi-Core Fibres

Fibre Code		**Length (m)**	**Pitch (μm)**			**Notes**
			Ave.	**Min.**	**Max.**	
Fibre X	End #1 (Sop)	1004	36.3	36.0	36.6	
	End #2 (Eop)		36.1	36.2	36.3	
Fibre Y	End #1 (Sop)	9084	36.2	36.1	36.3	
	End #2 (Eop)		35.9	35.9	36.0	
Fibre Z	End #1 (Sop)	1001	36.0	35.9	36.0	
	End #2 (Eop)		34.9	34.7	35.0	slight non-circularity of trench
Sop = fibre end nearest Start of pull Eop = fibre end nearest End of pull						

2.3 Characterisations of the Fabricated MCF

In the following, we report the characterisations performed on the fabricated MCF. The characterisations include the propagation loss of the four individual cores based on Optical Time-Domain Reflectometry (OTDR) and the core-to-core crosstalk (XT).

2.3.1 Propagation Loss

The propagation losses of the four cores are evaluated by OTDR. These measurements were performed on Fibre Z which has a length of 9084m, cf. Table 2. The individual cores of the MCF are excited at End #1 by butt coupling with a standard single-mode fibre (SMF). The results are shown in Figure 2.

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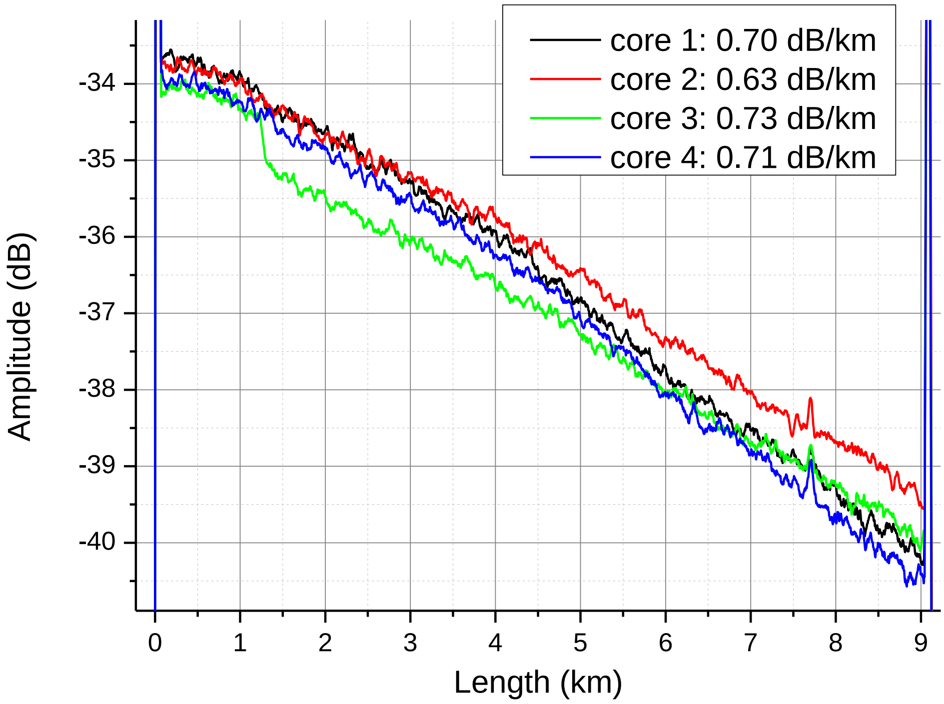

Figure 2: OTDR measurements on the 4 cores of Fibre Z (length 9804 m), measured at 1550 nm

The OTDR measurements show that the propagation losses range from 0.63 dB/km to 0.73 dB/km for the individual cores. These values are obtained from a linear fit to the OTDR trace over the entire length of the fibre (excluding the reflections at the input and output ends). The values for each core are shown in Figure 2. Note that core no. 3 has a defect at 1.3 km from the input end, where a ~0.5 dB drop can be observed. If the propagation loss of core no. 3 is estimated from the trace after the defect point, a value of 0.60 dB/km is obtained. Note also that all traces indicate a small defect in the fibre at 7.7 km.

If the above defects are to be excluded, a usable length of about 6.4 km could be cut out between the 1.3-km and 7.7-km points in Figure 2. However, we believe that the full length of fibre Z can be used in transmission experiments, since the observed defects do not result in any excessive losses nor significant crosstalk (cf. next section). The difference in propagation losses between the cores is not significant for the relatively low transmission distances within a data centre. For example, the total propagation loss in Fibre Z of length 9 km varies only between 5.7 dB (core no. 2) to 6.6 dB (core no. 3). In a transmission scenario, the total loss must include the input and output coupling loss to, e.g., a fan-out device or a multi-lane switch. The fan-out devices for the 2nd generation MCF were not available for these measurements, but coupling losses below 1 dB are expected.

2.3.2 Crosstalk

The core-to-core crosstalk measurements were performed on Fibre Z of length 9084 m. A single core was excited at the fibre input (End #1) by butt coupling with a standard SMF. At the fibre output (End #2), the power in all the individual cores is measured by using a scanning technique to obtain a power profile across the entire end facet of the fibre. This is achieved by moving the fibre end using a motorised stage, and measuring the local power across the facet using a single-lens magnification system followed by a pin-hole and a power meter (similar to the setup in D2.9, Figure 6). Figure 3 shows the four scanning profiles obtained when each individual core is excited.

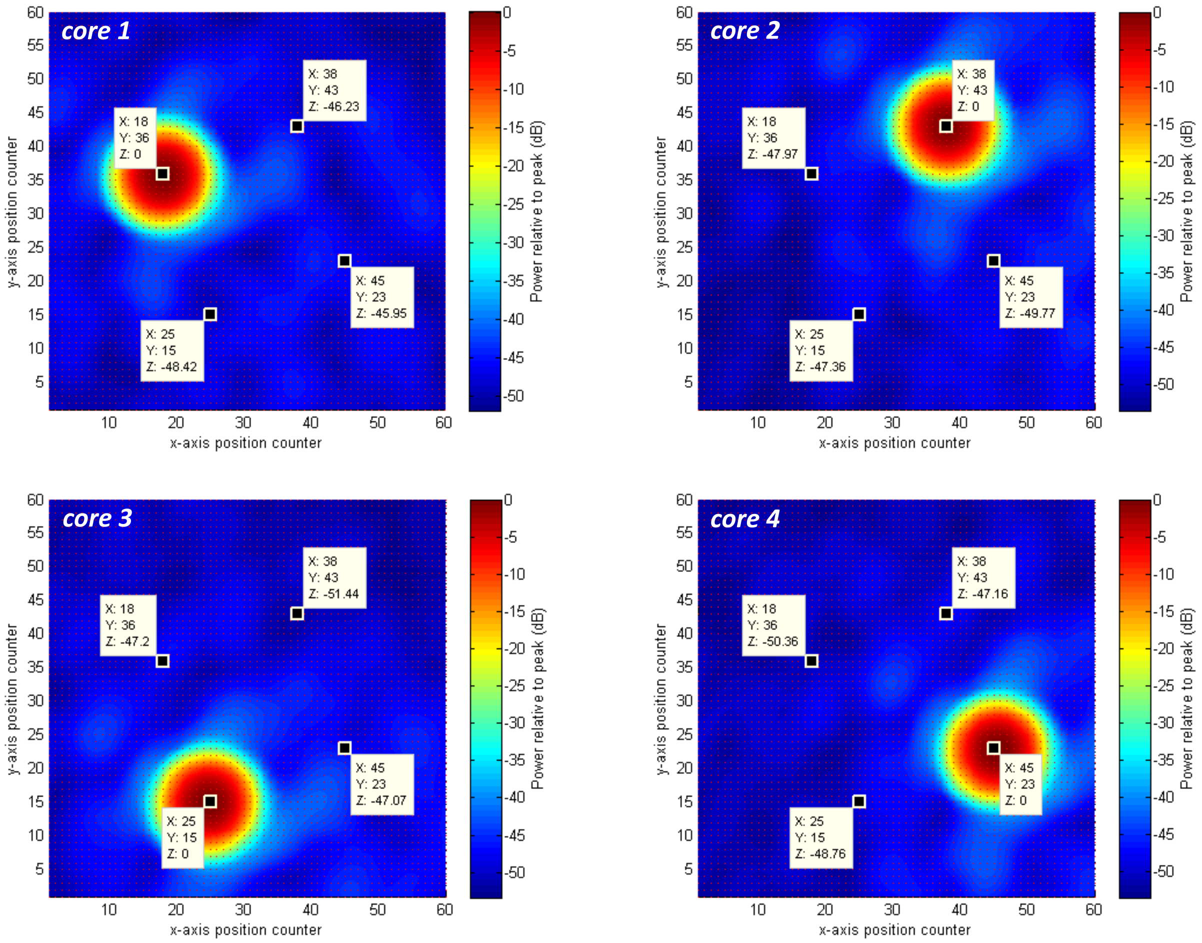

Figure 3: Crosstalk measurements on the MCF (Fibre Z, length 9084 m), measured at 1550 nm

In Figure 3 each plot shows the power profile across the end-facet of the MCF output, when either core no. 1, 2, 3, or 4 is excited at the MCF input. The power is plotted relative to the peak value of the excited core. Data markers show the detected power level at the centre position of each core.

In all four cases, the detected power levels at the positions of the neighbouring cores are more than −45 dB below the peak power level of the excited core. The mode profiles of the neighbour cores are hardly visible since the corresponding power levels are close to the sensitivity level of the power meter used, and the observable features should therefore be attributed primarily to background light and/or noise. In any case, these measurements indicate that the core-to-core crosstalk level is below −54.6 dB/km.

To obtain a more accurate estimate of the crosstalk level, a different method was used. Firstly, a target core was excited, and the pinhole size was adjusted to detect the full power within this core, while at the same time providing the highest possible suppression of light emanating from the neighbour cores. Subsequently, each of the three neighbour cores was excited and the power passing though the pinhole was detected. The results are shown in Table 3.

Table 3: Crosstalk levels obtained in a specific target core

Core excited	Nearest core 1	Nearest core 2	Diagonal core
Power in excited core (dBm)	0.5	1.1	0.4
Power in target core (dBm)	−44.0	−44.5	−51.0
Crosstalk level (dB)	−44.5	−45.6	−51.5
Crosstalk level (dB/km)	−54.1	−55.2	−61.0

In this case, the detected power levels are well above the background noise level of ~−55 dBm. Furthermore, it was verified that the detected power is from the target core and not due to background noise. This was achieved by slightly shifting the x- and y-position of the pinhole, and observing the expected drop in the detected power level. The crosstalk levels obtained from this measurement are −54.1 dB/km and −55.2 dB/km from the nearest neighbours, and −61.0 dB/km from the most distant core (diagonal core). Note that the latter value might be uncertain since the corresponding power level is closer to the background noise level. We expect that similar crosstalk levels will be obtained if this measurement is repeated for the other three cores (considering that Figure 3 did not indicate any difference in crosstalk performance).

Overall, these experimental results confirm the crosstalk value predicted by simulations, which was better than −40 dB over 10 km, corresponding to −50 dB/km. The results show that the trench assisted index profile successfully results in significantly lower crosstalk. Thus, the crosstalk levels of the fabricated 2nd generation MCF are several orders of magnitude better compared to the 1st generation MCFs, which had crosstalk values in the range −10 to −20 dB/km (cf. deliverable D2.9).

3 Second Generation Low Latency Fibres

3.1 Description of Fibre Properties

The advantages of Hollow-Core Photonic Bandgap Fibres (HC-PBGFs) over conventional fibre technology for data centre applications were established in the early stages of the project and have been summarized in Milestone MS10 [6]. HC-PBGFs have ~1.54 μs/km lower signal latency and ~30 dB lower nonlinearity, as well as the ability to be designed for operation at both 1.55 μm and 1.3 μm wavelengths.

In MS10 we reported fibres with ~10dB/km loss, wide operation bandwidth centred at about 1550nm in lengths of a few hundred meters. As a part of other development programs, the ORC have achieved a substantial increase in the typical fibre yields that can be achieved in a single fibre draw (current state of the art is 11km). Multi-km lengths are routinely obtained at the ORC. In this deliverable we report a HC-PBGF with substantially lower transmission loss (4.2dB/km) than the fibre reported previously. Furthermore, the length originally manufactured was in excess of 2000 m. Fibres were prepared using a standard two-stage stack and draw technique (see MS10 for a brief description). A summary of the fibre properties is given in Table 4 and a cross-sectional optical microscope image of the fibre showing the microstructure is shown in Figure 4.

Table 4: ***Properties of Fabricated Hollo- Core Fibre***

Fibre Property	**Length (m)**
Operating wavelength	1550 nm
Geometry	19-cell core, 6-ring cladding
Core OD	35 μm
MFD	≈22 μm (estimated)
Fibre OD	172 μm
Microstructure OD	87 μm
Background loss	≈4 dB/km (1595 nm)
Modality	Few moded. Can be operated as supporting SM transmission up to ~2 km
Mode purity for optimum launch conditions (1 km)	<20 dB

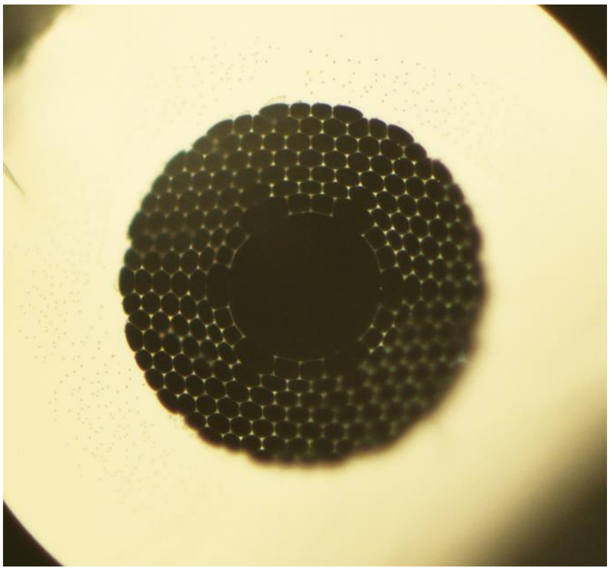

Figure 4: Second generation Hollow-Core Photonic Bandgap Fibre (cross-sectional optical microscope image). Core OD is 35 μm

Figure 5(a) shows the spectral loss measured on a 2000 m long cutback using a broadband source. Figure 5(b) shows the result of an Optical Time-Domain Reflectometry (OTDR) measurement, demonstrating that the loss is uniform along the fibre length and the fibre is completely free of discrete defects.

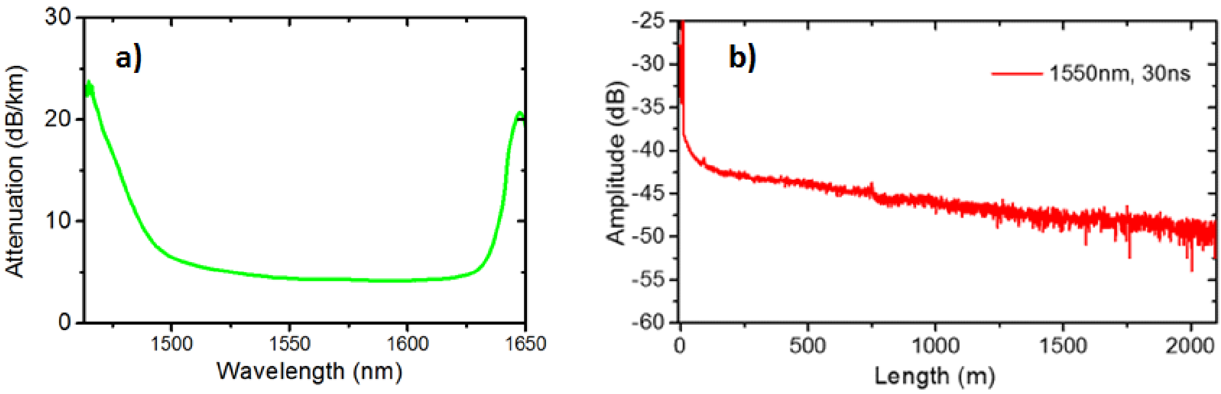

Figure 5: (a) Spectral Transmission loss of HC-PBGF measured via cutback (cutback length ~2000m) demonstrating a minimum loss of ~4dB/km at 1595nm and transmission centred in the telecom C-band. (b) OTDR trace of the same fibre, demonstrating uniform loss along

In parallel to fibre fabrication work, UNISOUTH have also investigated the issue of making HC-PBGFs more practically useable. For instance, HC-PBGF with some simple cabling was produced, e.g., 900 µm fibre samples with tight buffering (via a commercial supplier), demonstrating that the processes used for conventional fibres are also suitable for these fibres. Likewise, we have developed improved custom ways to interface HC-PBGFs to conventional single-mode fibres with substantially lower insertion loss (<1 dB) as compared to the higher values reported in MS10.

4 Summary

This deliverable reports on the fabrication of second-generation Multi-Core Fibres (MCFs) and low-latency Hollow-Core Photonic Bandgap Fibres (HC-PBGFs) with improved properties and performance. In the case of MCFs, a 2x2 square lattice fibre was demonstrated, with a Mode Field Diameter compatible with conventional single-mode fibres and extremely low inter-core crosstalk. The crosstalk was improved from −10 to −20 dB/km for the 1st generation fibre to approx. −55 dB/km. In the case of HC-PBGF, a fibre with loss ~4 dB/km was achieved and tight buffered fibre samples were obtained as well as improvements in the connectorisation and interfacing with conventional single-mode fibres.