3.1 Publishable summary

3.1.1 Project description and objectives

"The project goal is to develop the disruptive technology and concepts needed to enhance our communications infrastructure 100-fold to meet future needs, avert network gridlock and reduce energy consumption."

Driven by the exponentially growing demand for capacity, it is apparent that the next generation of telecommunication networks will be radically different from previous implementations, coherent detection and multi-carrier techniques, along with powerful digital signal processing will be deployed to maximise the available capacity of each fibre strand within the network. However, whilst welcome, such developments will only delay the inevitable single mode fibre capacity crunch. Put simply, once these developments are deployed, it will only be possible to increase network capacity by lighting additional fibres, with a cost linearly increasing with capacity. With a per annum growth rate of over 40%, this only delays a total capacity exhaust by a few years before new cable deployments are required.

The imminence of new and extensive deployment of new fibre cables in the next decade (2020-30) provides a unique opportunity to re-examine our choice transmission medium in order to have a dramatic impact on the exploitable network capacity increase which would accompany such a deployment. MODE-GAP is exploiting this opportunity by developing two complementary technologies, both of which would individually offer sufficient benefit, but which combined offer extraordinary potential increases in available network capacity.

The concept of the project is to address the future needs by optical Multiple Input Multiple Output (MIMO) through longhaul Mode Division Multiplexing (MDM) over multimode fibre. The Project objective is to demonstrate increased transmission capacity potential byapplying MIMO techniques to multimode optical fibre and gaining the benefits of utilising PBG fibre in the 2μm region. A three strand approach has been adopted

i. MDM techniques in solid core multimode fibre transmission in C-band
ii. Transmission in PBG fibre in C-band
iii. Transmission in PBG fibre at 2um

To meet the overall objective there are component and system challenges to be met:

- **MM-PBGF -** Develop ultra-low loss multi-mode photonic band gap transmission fibre (MM-PBGF).
- **Rare earth doped optical amplifiers -** Develop novel rare earth doped optical amplifiers for the new transmission windows necessary for the achievement of the lowest loss.
- **Sources and detectors** - Develop sources and detectors operable in to the 1.8 to 2.1 um region.
- **Multimode fibre MIMO coupling -** Develop multiplexing and demultiplexing components for operation in C-band and 2μm window
- **MIMO Processing -** Develop MIMO and dispersion compensation signal processing algorithms applicable to both conventional solid core fibres and MM-PBGF.
- **Long Haul WDM transmission-** Demonstrate the concept on a longhaul WDM transmission testbed

3.1.2 Description of work and key results

System trials
The past project year saw some very key experiments on the system level. First coherent transmission using mode-division multiplexing with coherent reception was demonstrated over 80km of few mode fiber (FMF) with true inline multi-mode amplification. As an initial verification of the components used (such as (de-)multiplexer, fiber, amplification, and digital signal processing) experiments were performed with 112Gb/s dual polarization quadrature phase shift keying (DP-QPSK) per mode in a single channel environment. This contribution was presented at ECOC 2012 and was nominated for the best student paper award. This work was followed up by a record breaking experiment presented at the ECOC 2012 Postdeadline session. Here, 96 C-band channels were transmitted over the three spatial modes of the few mode fiber used with a gross bit rate of 256Gb/s per mode over 119km with inline multi-mode amplification. The total gross rate was 96x3x256Gb/s = 73.7Tb/s with dual polarization 16-ary quadrature amplitude modulation (QAM) as the underlying format. This rate more than doubled the previous record over multi-mode fiber set by NEC and was the first ever experiment using mode-division multiplexing that used a higher order modulation. It was also the first amplified DWDM transmission experiment using an in-line EDFA.

In addition to the transmission over solid core fiber, major progress has been achieved in transmission over hollow core photonic band gap fibers (PBGF). Using a 19-cell multi-mode PBGF, single mode transmission with 37 WDM channels was achieved for 40Gb/s on-off-keying modulation giving a total capacity of 1.45Tb/s over 250m of fiber in the 1.5μm transmission window. These initial results are very promising for subsequently planned high bit rate coherent trials using first one then several modes.

At the ECOC 2012 Postdeadline session two initial contributions were presented in the 2μm window. Three wavelength channels were directly modulated with BPSK Fast-OFDM at 5Gbit/s per channel, with a fourth channel NRZ-OOK externally modulated at 8.5Gbit/s giving a total capacity in excess of 20 Gbit/s. The signal was transmitted over 50m of single mode fiber demonstrating the feasibility of crucial 2micron components, such as lasers, modulators, fiber couplers, optical fiber amplifiers, as well as photodiodes. A second experiment demonstrated the feasibility of data transmission over PBGFs in the 2micron window (current minimum loss of 4.5dB/km). Using a 290m long sample, 8Gbit/s data was transmitted in a PBGF for the first time in this window highlighting the potential for a substantially lower loss than current C+L band applications.

Components
In support of the systems trials the project has researched into a range of new components to realise the necessary transmitter and receiver functionality in the 1.55μm and 2μm wavelength ranges.

Fibres
Conventional solid fibres supporting either two or four LP modes with a low differential group delay (DGD) have been designed and fabricated. The fibres have an index profile with a parabolic shaped core and a surrounding trench. The two mode fibre has been shown to have an attenuation below 0.20 dB/km, DGD below 0.1 ps/m, distributed mode coupling below -25 dB for a 30km length, and good splice performance to itself for both modes. By combining fibres with positive and negative DGD low total DGD has been achieved. Almost 300 km has been delivered to the partners for transmission experiments and for the implementation of multimode devices. This work was reported in the OFC 2012 Postdeadline session.

An improved understanding of the relationship between surface roughness in hollow core photonic band gap fibres (HC-PBGF) and scattering loss has been obtained through the development of a suitable model. A paper on this was presented at OFC 2012 and won the Corning Best Student Paper Award. In parallel, a novel method for the measurement of physical roughness based on oil immersion high resolution optical interferometry has been developed and proven. Our HC-PBGF development work has produced new fibre designs affording an unprecedented combination of ultralow loss (few dB/km) and very wide (>150nm) transmission bandwidth. Key to this result was the ability to engineer the position of surface modes in 19 cell PBGF structures. Fibres designed for operation at both 1.55 and 2.0μm, and lengths up to 2km in a single draw have been obtained. Fig.1a shows a HC-PBGF with minimum loss of 3.5dB/km loss and 3dB bandwidth of ~160nm. These results were reported at the OFC 2012 Postdeadline session.

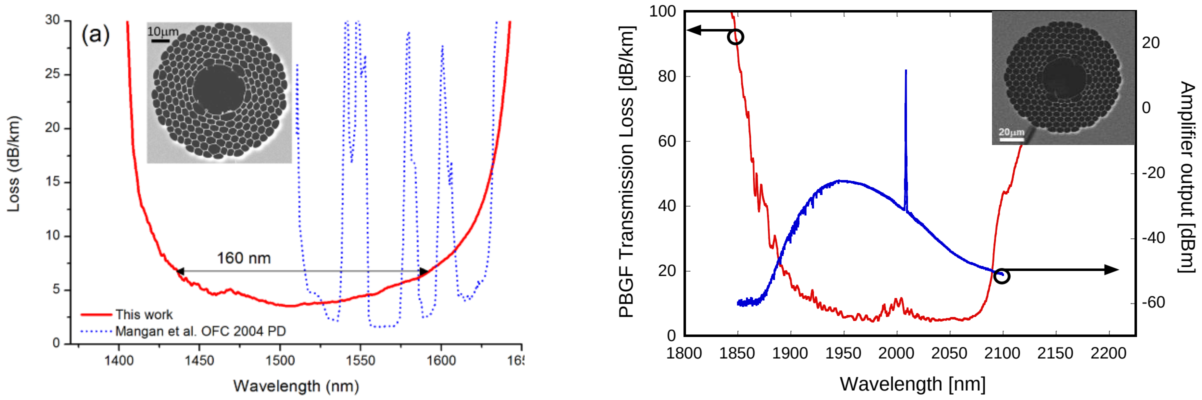

Fig.1. (a) Low loss, wide bandwidth HC-PBGF designed for operation at 1.5μm (work presented at the OFC 2012 Postdeadline session (b) HC-PBGF with 4.5dB/km minimum loss around 2μm and transmission bandwidth matched to TDFA gain bandwidth (work presented at the ECOC 2012 Postdeadline session).

HC-PBGFs with a transmission window well matched to the TDFA gain bandwidth around 2μm were also obtained (Fig.1b). As a part of fibre development, we analysed the presence of gas species in HC-PBGFs with absorptions at 2μm and identified the presence of HCl, H_2O, and CO_2. The origin of CO_2 in our fibres was established along with methods for its removal during fabrication.

Fibre characterisation tools to investigate the modal and transmission properties of the fabricated fibres were implemented. In particular, we applied a combination of S^2 imaging and time-of-flight in order to identify guided modes, measure their DGD and to investigate coupling issues.

Fibre Amplifiers

Optimized Er-doped fibres supporting two LP modes matched to those of the low-DGD transmission fibres developed within the project have been made and low mode-dependent gain achieved (<1dB for 20dB LP_{01}/LP_{11} gain). Portable lab units have been constructed and used in partner transmission tests. We have also investigated inter-modal cross gain and associated transient effects. Our results indicate that all modes experience roughly similar responses under a range of different add/drop conditions, although some evidence of mode dependent sensitivity was observed in experiments operating at higher levels of amplifier saturation.

We have also developed low loss Tm-doped fibres for single-mode/multimode amplifiers operating at 2 μm and constructed portable devices using commercial OFS fibers for use in the partner transmission experiments described above. Small signal gains of ~30dB and NFs <6dB have been achieved over > 100nm bandwidths.

Transmitters& receivers

Single frequency laser diode transmitters, used in the direct modulation experiments, operating at wavelengths across the 1.85 - 2.05 µm range were developed (Fig. 2). Full static and dynamic characterisation was carried out using both automated and manual bar testers. A pigtailed coupler for laser chip launch into single-mode fibre was developed at a supplier site, modelled directly on an Eblana 2 µm laser diode. This allowed chip to fibre coupling efficiencies of up to 25% to be achieved. High speed waveguide photodiodes and the associated high speed packaging technology for the 2 µm range were developed using materials with quantum well active regions. Bandwidths in excess of 10 GHz were achieved at 2 µm. New designs for high responsivity photodiodes are being implemented using a metamorphic buffer layer crystal growth technique for the high indium containing structures. A number of options on the spatial multiplexing of signals into Few Moded Fibre were investigated including phase plates and multiple spot launch with an InP mux. Phase plates were fabricated for 980, 1.55 µm and 2 µm using dry etching and moulding techniques and were used in the systems experiments.

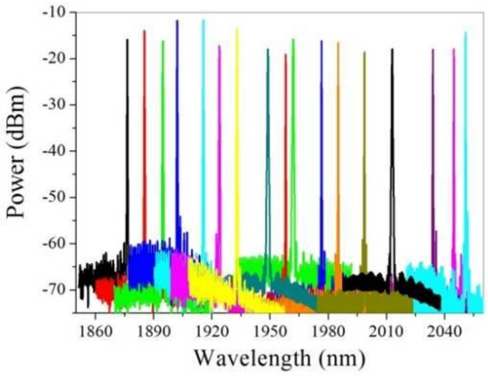

Fig. 2: Single mode spectra of a batch of laser diode transmitters developed under the project. Wavelength range from 1870nm to 2050nm with a SMSR >40dB.

Work on coherent components for spatial multiplexing has commenced this year starting with high speed modulator designs. These designs have been implemented in quantum well epitaxial structures and are being processed as arrays of Mach Zehnder IQ modulators at 1.55 µm. A strategy for direct integration of lasers and modulators at 2 µm has been designed and will be implemented next year.

3.1.3 Expected final results and impact

The project has progressed well during the first two years and the objectives remain the same to demonstrate the potential of 100-fold enhancement of transmission capacity. The plan has been to develop the necessary components to undertake systems evaluation and those components have been delivered to schedule enabling progression of the project. Successful achievement of the anticipated results will have major implications for future transmission systems enabling the development of future networks capable of substantially higher information carrying capacity than achievable with single mode fibre solutions. This will have obvious benefits in terms of cost and ability to supply society’s constantly increasing demand for information capacity.

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