First Demonstration of 2μm Data Transmission in a Low-Loss Hollow Core Photonic Bandgap Fiber

M. N. Petrovich(1), F. Poletti(1), J. P. Wooler(1), A. M. Heidt(1), N. K. Baddela(1), Z. Li(1), D. R. Gray(1), R. Slavík(1), F. Parmigiani(1), N. V. Wheeler(1), J. R. Hayes(1), E. Numkam(1), L. Grűner-Nielsen(2), B. Pálsdóttir(2), R. Phelan(3), B. Kelly(3), M. Becker(4), N. MacSuibhne(5), J. Zhao(5), F.C. Garcia Gunning(5), A. D. Ellis(5), P. Petropoulos(1), S. U. Alam(1) and D. J. Richardson(1)

(1) Optoelectronics Research Centre, University of Southampton, UK
(2) OFS Denmark, Priorparken 680, 2605 Brøndby, Denmark
(3) Eblana Photonics Ltd., Dublin 2, Ireland
(4) Institute of Photonic Technology, IPHT, Jena, Germany
(5) Tyndall National Institute, Cork, Ireland

Abstract *The first demonstration of a hollow core photonic bandgap fiber suitable for high-rate data transmission at 2μm is presented. Using a custom built Thulium doped fiber amplifier, error-free 8Gbit/s transmission in an optically amplified data channel at 2008nm is reported for the first time.*

Introduction

Over the last 30 years, research and development in long-haul telecoms optical fibers has focused on the 1.55μm wavelength region. More recently, however, the quest for radical solutions to increase transmission capacity, decrease fiber loss and nonlinearity and reduce signal latency has stimulated interest in novel and more exotic fiber types, which may eventually justify a shift away from the traditional operating wavelengths. Hollow core-photonic bandgap fibers (HC-PBGFs) hold great promise as a transmission medium due to their ultra-low nonlinearity and faster transmission speed as compared to conventional solid fibres.

Still a maturing technology, HC-PBGFs cannot as of yet rival the loss levels of standard silica single mode fiber. However, steady and substantial progress has been made recently in understanding and engineering the transmission properties of these complex fibres. For instance, a tenfold increase in the transmission bandwidth of ultra-low loss HC-PBGFs has recently been reported[1]. This was achieved by combining a 19-cell core design, offering low scattering loss[2], with a thin wall surround[3], enabling a wide surface mode-free transmission region. Whilst low-loss HC-PBGFs are inherently multimoded, it was shown that through a combination of optimized fiber structure and selective input and output coupling, that these fibres can be operated as quasi-single mode to the level that meets the strict requirements for error-free transmission. Recently, a record 1.5Tbit/s transmission (37x40 Gbit/s on-off keyed DWDM channels on a 100-GHz ITU grid) was demonstrated over 250m of a HC-PBGF[4].

However, if HC-PBGFs are to ever outperform conventional SMFs, loss reduction is paramount. Whilst it is still unclear if a lower loss than SMF is feasible in HC-PBGFs, theoretical models[5] and a recent experiment[6] clearly predict that the minimum loss would be shifted to longer wavelengths at around 2μm. Moreover, this operating window coincides with that of Thulium doped fiber amplifiers (TDFAs) which offer the widest gain band (1750-2050nm) amongst all rare earth doped fibre amplifiers, providing further potential advantage to expand the overall fiber capacity. It is thus important to demonstrate the viability of data transmission in this as of yet unexplored wavelength region.

In this work we fabricate and characterize a wide bandwidth (152nm), record-low loss (4.5 dB/km) HC-PBGF for operation at 2μm. We then assess its data transmission capabilities using a combination of state-of-the-art commercially available 2μm transmitter and receiver components and a custom built TDFA. We transmit, for the first time to our knowledge, an optically amplified data channel at 8Gbit/s at 2008nm over 290m of a HC-PBGF. These results represent a stepping stone in the assessment of such a radically new solution for next generation transmission systems.

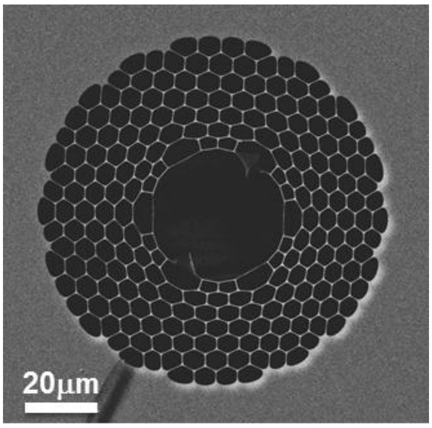

Fig.1 SEM micrograph of the 2.0μm HC-PBGF

Fiber fabrication and characterization

The HC-PBGF utilized in the present study had a 19 cell core structure and was fabricated via a two-step stack and draw method. A SEM image of the fiber is shown in Fig.1. The cladding is composed of 6½ rings of holes with an average spacing of ~5.5μm and relative hole size of ~0.96. The hollow core, 36μm in diameter, has a thin surround and an expansion ratio relative to the cladding engineered to minimize the number of surface modes and thus to obtain low-loss guidance over a broad wavelength interval[1]. The fiber's spectral attenuation, measured via a cutback from 300 to 5m, is shown in Fig.2. The minimum loss value of 4.5dB/km at 1980nm is the lowest reported to date for a PBGF operating in the 2μm wavelength region. Additionally, the fiber was observed to contain CO_2 at atmospheric concentration levels which produced absorption lines at wavelengths around 2.002μm. While recent works indicate that these undesirable spectral features may be eliminated with improved fabrication processes[7], here we demonstrate that error-free transmission can be achieved even at those wavelengths by tuning the signal to fit between absorption bands. The 3dB transmission window of the PBGF is approximately 150nm wide which is very well matched to the very wide TDFA gain bandwidth (Fig.2).

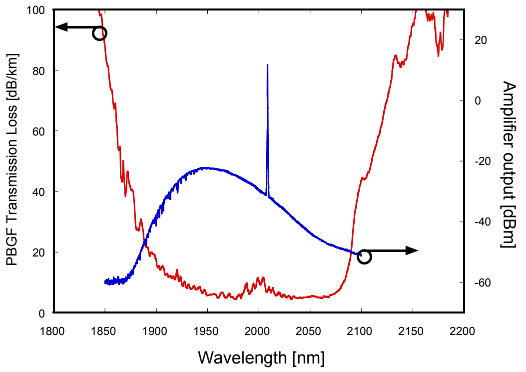

Fig.2 Transmission loss of the HC-PBGF with the amplifier output superimposed to illustrate location of signal channel and extent of ASE as an indicator of the amplifier bandwidth.

To estimate potential intermodal cross-coupling effects and evaluate the prospects for operating the HC-PBGF in a single-mode regime we used a time-of-flight (ToF) method. For this, a mode-locked fiber laser (1ps pulses at 25MHz repetition rate, from AdValue Photonics), an 8GHz bandwidth photodetector and a fast sampling oscilloscope were used. Both ends of the HC-PBGF were butt-coupled to SMF-28, providing selective input and output coupling into the fundamental LP_{01}-like mode. Fig. 3 shows the results for a 290m long HC-PBGF sample at a central wavelength of 1940nm under optimum input and output coupling conditions. The photodiode exhibited some ringing in the 0 – 1.5ns range which has been corrected for in Fig. 3, but results in a slightly elevated residual noise floor. The expected positions and intensity profiles of the higher order modes were determined via a separate S^2 measurement. Despite the large mode mismatch between solid and hollow fibre, we achieved a very encouraging 33dB suppression of the LP_{11} mode and any contributions of higher order modes fell below the noise floor of 37dB. The peak marked 'X' in Fig. 3, which appears with about 1ns delay and 28dB below the fundamental mode, could not be clearly attributed to a specific mode so far and remains the subject of continuing investigation.

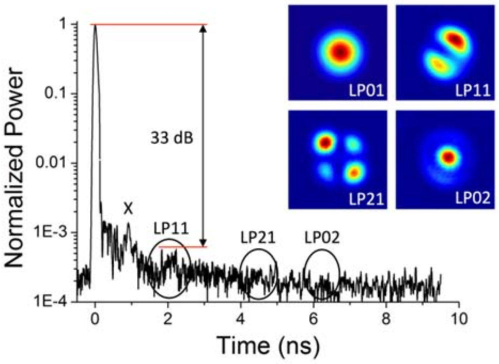

Fig.3 Time-of-flight measurement results. The positions and intensity profiles of the higher order modes were retrieved in a separate S^2 experiment.

Experimental set-up

The experimental set-up is shown in Fig.4. A 6 dBm discrete-mode continuous-wave laser (Eblana Photonics) at 2008nm was intensity modulated by a 2^{31}-1 pseudorandom bit sequence (PRBS) using an external lithium niobate Mach-Zehnder modulator (Photline Technologies) at 8 Gbit/s with overall loss of 8dB. The laser wavelength was chosen to ensure that it lay between the CO_2 absorption lines. The generated non-return-to-zero on-off keyed (NRZ-OOK) signal was then amplified using a TDFA, a schematic of which is also shown in Fig. 4. The amplifier was built with a commercially available Tm^{3+}-doped fiber (OFS TmDF200) having a mode field diameter of 5μm at 1700nm and a core absorption of 200dB/m at 790nm. A fiber Bragg grating stabilized single mode 1565nm Er/Yb fiber laser was used as the pump source and was optimized to provide enhanced gain at extended wavelengths around 2000nm. The TDFA consisted of two sections, 4 and 12m long, only the second of which was directly pumped in order to enhance gain at 2008nm. Fig. 5 shows the gain and external noise figure (NF) as a function of pump power for different input signal powers. The amplifier is capable of providing a maximum gain of 34dB for a signal input power of -22dBm and a saturated output power of 22dBm. Its NF decreases with increase in pump power or amplifier gain. A minimum NF of ~6dB was measured for input powers ranging from -22dBm to -7dBm when the pump power exceeds 27dBm. The internal NF was measured to be less than 5dB. The TDFA output was then filtered by a fiber Bragg grating (FBG) with 2nm reflection bandwidth centered around the signal wavelength, to suppress amplified spontaneous emission from the amplifier and increase the optical signal-to-noise ratio to > 50dB.

The signal was then butt-coupled into and out of the PBGF via SMF28 pigtails with particular care taken to ensure reliable excitation of the fundamental mode (see Fig.3). The total insertion loss through the fiber was 10dB, mostly attributed to coupling losses. The resulting signal was then filtered using a narrow band (~1.5nm) fibre Bragg grating centred at 2008nm and then detected using an extended InGaAs PIN detector (EOT, ET-5010F) before electronic amplification. The performance of the system both before and after transmission through the fiber was then assessed in terms of eye diagrams and bit error ratio (BER).

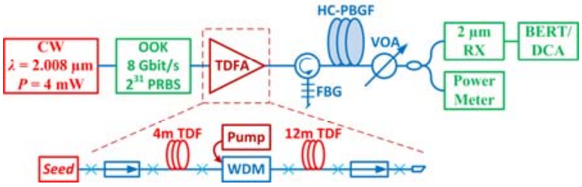

Fig.4: Experimental set-up and zoomed-in scheme of the custom-built TDFA.

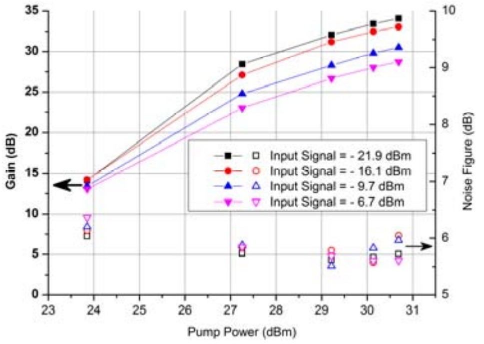

Fig. 5 Gain and NF of the TDFA operating at a wavelength of 2008nm.

Transmission results

Fig. 6 shows eye diagrams and BER curves with (PBGF-290m) and without (back-to-back, B-2-B) the HC-PBGF. Good open eyes were observed at the output of the fiber with negligible degradation compared to the B-2-B performance confirming negligible modal cross talk effects. This was also quantified by the corresponding BER measurements. The power penalty was negligible at a BER of 10^{-3} and increased up to 1.2dB at 10^{-9}. No BER floor was observed when measuring BER down to the 10^{-11} level. Note that the choice of data rate was limited only by the bandwidth of the amplitude modulator and photoreceiver used in the experiment and it is worth noting that 20GHz bandwidth and the first generation WDM components are already beginning to appear on the market.

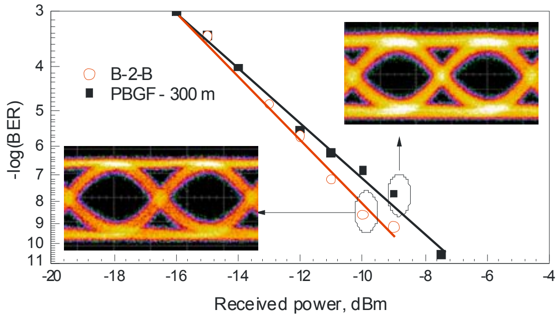

Fig.6 BER characteristics at 8 Gbit/s and selected eye diagrams.

Conclusions

We have presented the first demonstration of a HC-PBGF suitable for high data rate single mode transmission at 2µm and highlighted the suitability of TDFA technology for broadband amplification in the anticipated minimum loss window for this emerging fiber type. Our fiber exhibits a record low transmission loss of 4.5 dB/km for a PBGF operating at 2µm, a wide bandwidth (150nm) and very low modal crosstalk (< -33dB) between fundamental and higher order modes. Although clearly much further work is required, on further loss reduction and the production of longer fiber lengths in the first instance, we consider our results to illustrate the potential and technological viability of using HC-PBGFs operating at wavelengths around 2µm (in conjunction with TDFAs) as the basis for future generation high-performance optical communication systems.

Acknowledgements

This work was supported by the European Community under grant agreement 258033 (MODE-GAP) and by the UK EPSRC through grant EP/I01196X/1 (HYPERHIGHWAY).

References

[1] N. Wheeler et al, Proc OFC12, PDP5A.2.
[2] B. J. Mangan, et al. Proc OFC04, PDP24
[3] R. Amezcua, et al., Opt. Express **15**, 17577 (2007).
[4] R. Slavík et al., Proc ECOC12, Mo.2.F.2
[5] J. K. Lyngsø, Opt. Express **17**, 23468 (1007)
[6] Roberts et al. Opt. Express **13**, 236 (2005)
[7] Wheeler et al. Proc CLEO12, CM3N.5