WDM Transmission at 2µm over Low-Loss Hollow Core Photonic Bandgap Fiber

N. Mac Suibhne(1,a), Z. Li(2), B. Baeuerle(1), J. Zhao(1,b), J.P. Wooler(2), S.U. Alam(2), F. Poletti(2), M.N. Petrovich(2), A.M. Heidt(2), N.V. Wheeler(2), N.K. Baddela(2), E. Numkam(2), I.P. Giles(2,3), D.J.Giles(3), R. Phelan(4), J. O'Carroll(4), B. Kelly(4),D. Murphy(5), Brian Corbett (1)A.D. Ellis(6), D.J. Richardson(2), F.C. Garcia Gunning(1,b)

(1) Tyndall National Institute and (a) Department of Electronic Engineering and (b) Department of Physics, University College Cork, Ireland
(2) Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
(3) Phoenix Photonics Ltd., Sarre Business Centre, Birchington, Kent, UK
(4) Eblana Photonics Ltd., Dublin 2, Ireland
(5) Optics Research Group, CMP Dept., Waterford Institute of Technology, Ireland
(6) Aston Institute of Photonic Technology, Aston University, Birmingham B4 7ET, UK
naoise.macsuibhne@tyndall.ie

Abstract: World's first demonstration of WDM transmission in a HC-PBGF at the predicted low loss region of 2µm is presented. A total capacity of 16 Gbit/s is achieved using 1×8.5 Gbit/s and 3×2.5 Gbit/s channels modulated using NRZ OOK over 290 meters of hollow core fiber.

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1. Introduction

Ongoing efforts to meet the requirements of future fiber based optical communication systems have resulted in fundamentally new approaches to address the threat of a "capacity crunch". Traditionally, fiber systems have operated over standard single mode fiber (SMF) links with the majority of R&D and commercialization in recent years being focused on optimizing the transmitters and receivers positioned at either end of such a link. Properties such as nonlinearity and loss are a result of the physical structure of standard SMF and will fundamentally limit the total capacity [1]. This has led the community to sharply address new types of fibers that would overcome some of these limitations, allowing for fundamentally higher capacities.

Hollow Core Photonic Bandgap Fiber (HC-PBGF) is a very promising fiber due to its low nonlinearity and near vacuum latency. Substantial progress has been made in the design and fabrication of low-loss HC-PBGFs with wide transmission bandwidth [2]. Recently, HC-PBGF has been utilized in a system with a record transmission of 1.5 Tbit/s achieved over a 250 meter length at the standard operating window of 1.55 µm [3]. However, the ultimate goal is to have fibers with ultra-low loss [1], and HC-PBGF has the potential to reduce losses to about 0.1 dB/km, with a minimum around the 2 µm region [2]. Advantages of working at this wavelength range also include the availability of Thulium-doped fibre amplifiers (TDFA), and the possibility of integration using Silicon photonics [4].

This paper demonstrates, for the first time to our knowledge, WDM transmission over HC-PBGF at the low loss window of 2 µm. A move to the 2µm region involves the development of a vast array of optical components capable of operating at a telecommunications grade. Recently, we have demonstrated a WDM sub-system in the 2 µm region [5], through the development of various components; including a wide bandwidth TDFA, and DFB lasers. We have also demonstrated that a 290 m long HC-PBGF fiber is suitable for high data rate transmission at 2µm [6]. Here, we demonstrate the world's first WDM transmission over HC-PBGF, specifically three directly modulated channels using non return to zero on-off keying (NRZ-OOK) at 2.5Gbit/s and one externally modulated channel at a bit rate of 8.5Gbit/s, over 290 m of low loss HC-PBGF.

2. Experimental Setup

Figure 1 shows the experimental setup, where the transmitter consisted of three directly modulated (2002.21 nm) and one externally modulated (2004.79, 2004.27 and 1997.64 nm) channels. The lasers used were highly strained $In_{0.74}Ga_{0.26}As$ multiple quantum well, ridge waveguide laser diode structure grown on InP substrates and designed for single mode operation at 2µm [7].

Three lasers were directly modulated using NRZ OOK at 2.5Gbit/s using a standard bit error rate test-set (BERT) and a pseudo random bit sequence of length 2^7-1 bits. In order to generate three data streams, "data" and "data-bar" outputs from the BERT were used, and the "data" stream was amplified and passively split to generate two other streams. Variable delay lines ensured that the patterns were decorrelated. The RF power applied to each laser did not

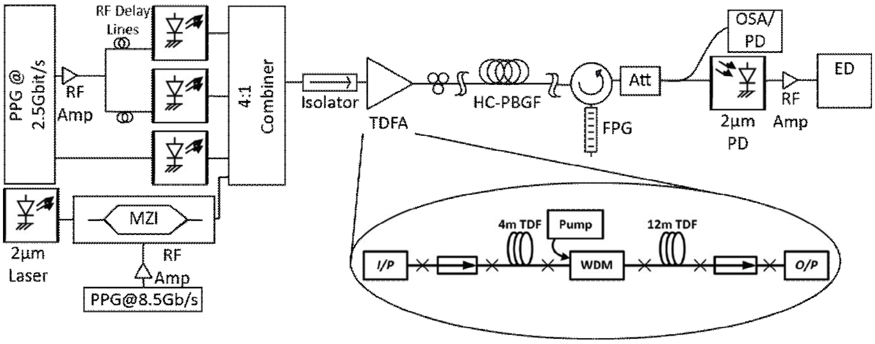

Figure. 1: Experimental Setup

exceed 1V. The bit rate here was fundamentally limited by the 3 dB bandwidth of the lasers of approximately 3GHz at 50mA.

The final WDM channel was externally modulated using a commercially available Mach Zender Lithium Niobate ($LiNbO_3$) intensity modulator (MZI) with a Vpi of 9.5 volts. The modulator was driven with a pseudo random bit sequence of length 2^7-1 bits at 8.5Gbit/s by using an independent BERT and a RF amplifier. The bit rate of the externally modulated channel was limited by the 3dB-bandwidth of the 2µm high speed detector, measured to be less than 9GHz.

All four channels where then combined with a 4:1 fiber-based combiner that was designed to have minimal PDL at 2µm, an excess loss of less than 1 dB, and an insertion loss between 6-9 dB per port [8]. This was followed by an isolator to prevent any unwanted reflections back to the lasers.

The optical amplifier was custom built for the purpose of data transmission at 2µm. A block diagram can be seen in the inset of Figure 1. It consisted of a pump operating at 1565nm that pumped 12 meters of commercially available Tm^{3+} doped fiber [9]. The amplifier also had a second stage of 4 meters of Tm^{3+} doped fiber that is backward-pumped with ASE in order to provide enhanced gain at longer wavelengths. The TDFA was capable of providing ~30 dB gain, with a noise figure of ~6 dB, and had a 3 dB gain bandwidth of ~80 nm. As can be seen from the ASE spectrum plotted in Figure 2, the TDFA has a wide operating bandwidth that is perfectly matched to the low loss window of the HC-PBGF.

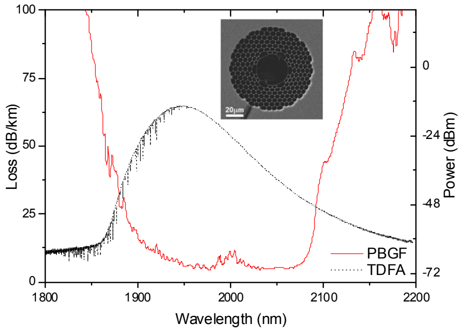

Figure. 2: Fiber loss window (red) and TDFA ASE spectrum indicating large usable bandwidth.

Table 1. Fiber Parameters

HC-PBGF Parameters	
Pitch (L)	5.5 µm
d/Λ	0.96
Core diameter	36 µm
Mode Field Diameter	~22 µm (estimated)
3 dB Bandwidth	152 nm
Minimum Loss	4.5 dB/km (at 1970 nm)
High Order Mode Suppression	~30 dB

A SEM image of the HC-PBGF can be seen in the inset of Figure 2. The fiber had a 19 cell core structure that was designed to have a minimal loss over a large window (see Figure 2) by reducing the number of supported surface modes [2]. The fiber's structural parameters can be found in Table 1 and are discussed further in [6]. Due to the hollow core nature of the fiber it contains atmospheric concentrations (395ppm) of Carbon dioxide (CO_2). Excess absorption around 2µm was avoided by the careful tuning of the laser diode to operate between the strong absorption lines. Previously we have demonstrated that it is possible to eliminate CO_2 through relatively minor changes to the fabrication procedure [10]. In order to avoid excitation of higher order modes supported by the fiber, strict control of the launch conditions was required. This was achieved by controlling the launch polarization at the input of the fiber before butt-coupling the HC-PBGF with standard SMF using optical translation stages at both the input and output of the fiber whilst at the same time controlling the launch polarization. Time of flight measurements were then taken in real time while the launch conditions and output coupling were adjusted in order to minimize higher order modes excitation. Once fixed, only the input polarization controller required regular readjustment to maintain optimum conditions.

The direct detection receiver consisted, primarily, of a filter and a high speed detector. The filter comprised of a circulator and three interchangeable Bragg gratings that provided an extinction ratio in excess of 20 dB. The Bragg gratings were designed to operate at 1997, 2002 and 2005 nm with a pass-band of ~0.4 nm. They were thermally tuned to select each of the four wavelengths in use.

The received power was then controlled with a tunable attenuator, and an optical tap was used to monitor the power levels and spectral data. The signal was then coupled to a commercially available high speed InGaAs PIN detector. Finally, the RF signal was amplified with an amplifier before being received by the error detector (ED).

3. Results

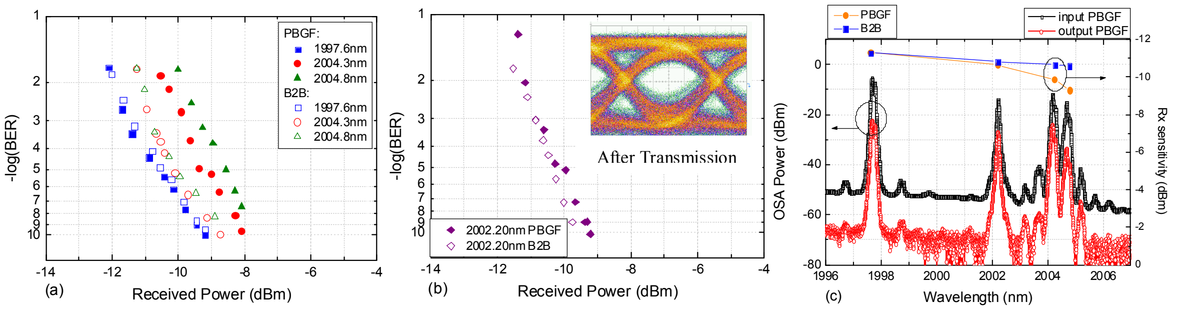

Figure 3: Results for directly modulated channels (a) and externally modulated channel with transmitted eye diagram (b) along with spectral data before and after transmission (c).

The performance of the system was analyzed by measuring bit error rates for both back-to-back and over 290 m of HC-PBGF. The results of these measurements can be viewed in Figure 3 for each of the four WDM channels. Error free transmission was achieved for all channels in both the direct and externally modulated cases. For the externally modulated channel (Figure 3b) there was a negligible transmission penalty when transmitting over fiber, with receiver sensitivity below -10.5 dBm at a BER of $1x10^{-3}$. The eye diagram after transmission indicated minimal distortion (see inset of Figure 3b). For the directly modulated channels receiver sensitivities of -9.3 dBm and below were achieved for each wavelength at a BER of $1x10^{-3}$. A maximum sensitivity penalty of 1.3 dB was observed when transmitting over fiber compared to back-to-back, and it is related to the drop of amplifier gain for these wavelengths, as evidenced by the spectrum in Figure 3c. The existence of a second peak, in wavelength, on each of the directly modulated channels is likely due to the lasers chirp and tends to be proportional to drive voltage.

4. Conclusions

We have presented, for the first time to our knowledge, WDM transmission measurements over HC-PBGF in the 2µm region with a total capacity of 16 Gbit/s using 1×8.5 Gbit/s externally modulated and 3×2.5 Gbit/s directly modulated channels. Our results show that such systems are enabled through key technologies such as TDFAs and 2µm lasers. We believe this work illustrates the potential and viability of technologies for future fiber based communication systems at 2 µm.

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