Wavelength Division Multiplexing at 2μm

N. MacSuibhne(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), I.P. Giles(2,3), D.J.Giles(3), B. Pálsdóttir(4), L. Grüner-Nielsen(4), R. Phelan(5), J. O'Carroll(5), B. Kelly(5),D. Murphy(6), A.D. Ellis(1,b), 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) OFSDenmark, Priorparken 680, 2605 Brøndby, Denmark
(5) Eblana Photonics Ltd., Dublin 2, Ireland
(6) Optics Research Group, CMP Dept., Waterford Institute of Technology, Ireland
naoise.macsuibhne@tyndall.ie

Abstract *This paper shows, for the first time, the implementation of a WDM subsystem at the 2μm wavelength window with mixed formats. 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.*

Introduction

The ever increasing demand for high bandwidth Internet applications is inspiring the research community to develop systems capable of delivering higher capacities, but a fundamental limit is clearly on the horizon [1]. The use of multi-dimensional modulation schemes, such as amplitude, phase, polarization, frequency etc, has been widely demonstrated, pushing the available capacity very close to the nonlinear Shannon limit. Multi-mode (or few-mode) transmission has recently been investigated once again, together with coherent detection schemes and nonlinear compensation techniques, in order to push the available capacities even closer to the limits.

Hence, radical approaches become necessary to bypass the limited available transmission capacity at the well-known transmission windows [2]. Recent resurgent interest in the 2μm region [3, 4] is welcome, not only from the Silicon photonics view-point, but also given the emergence of radically new forms of fibres, such as hollow core photonic bandgap fibre (PBGF), that are predicted to have a minimum loss window around 2μm. Thulium doped fibre amplifiers (TDFAs) which cover an extended bandwidth spanning from ~1.85-2.05μm are also available in this waveband. However, shifting to this transmission window requires the development of a full suite of telecoms components [2], a move which is supported by a wealth of alternative (e.g. sensing and biomedical) applications, and offers exciting possibilities for Silicon photonics [5]. Previous reports of telecom operation beyond the U-Band (1660nm) have been restricted to the use of He-Ne lasers [3] and four wave mixing conversion from C-band sources [3,5].

In this paper we show the first direct implementation of a WDM subsystem at 2μm, using InGaAs/InP directly modulated lasers [6], $LiNbO_3$ external modulators, fibre couplers [7], Tm^{3+} doped optical fibre amplifiers, fibre Bragg gratings and high speed photodiodes. The complete functionality of the system is demonstrated through a mixed format transmission experiment, combining directly modulated BPSK Fast-OFDM [8] at 5Gbit/s (3 wavelengths), with externally modulated NRZ on-off keying (OOK) at 8.5Gbit/s. A total capacity in excess of 20 Gbit/s in the 2 μm window is achieved. The WDM signal was transmitted over 50m of commercially available solid core single mode optical fibre [9] with virtually no power penalty. These results indicate the potential for longer reaches using low loss hollow core PBGF.

Experimental Setup

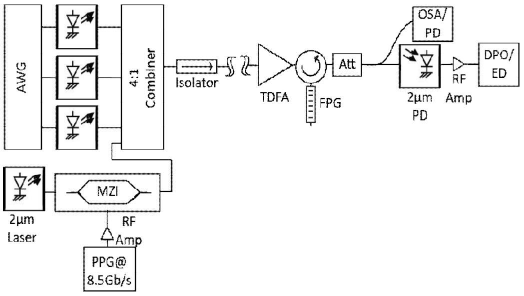

Fig. 1: 2μm Experimental Setup

Fig. 1 shows the experimental setup for the transmitter and receiver subsystems. The InGaAs/InP multiple quantum-well discrete-mode lasers [6] (at 1997.64, 2002.22, 2004.27 and 2004.80 nm) used had 3dB frequency responses of about 3GHz, as shown in Fig. 2 (black, squares.)

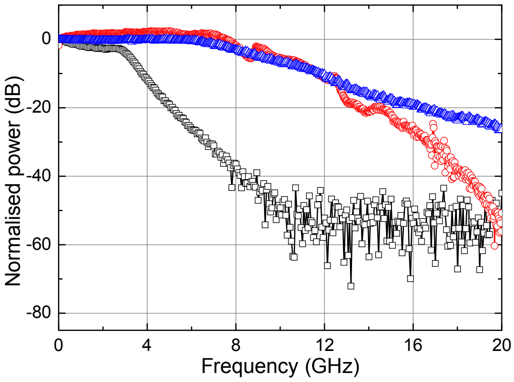

Fig. 2: S_{21} characterisation for: a typical directly modulated laser (black, squares), external modulator and 2μm detector at 1.5μm (blue, triangles) and at 2μm (red, circles).

The BPSK Fast-OFDM had 128 discrete-cosine transform point size, among which 106 subcarriers were used for data modulation. Direct modulation using BPSK Fast-OFDM on each of the 128 subcarriers increased the capacity of each directly modulated laser to 5 Gbit/s. Two independent outputs and one complimentary output of an Arbitrary Waveform Generator, operating at 12 GS/s, were used to repeatedly transmit 7 de-correlated frames, containing 100 data symbols, preceded by one training symbol for synchronization [8].

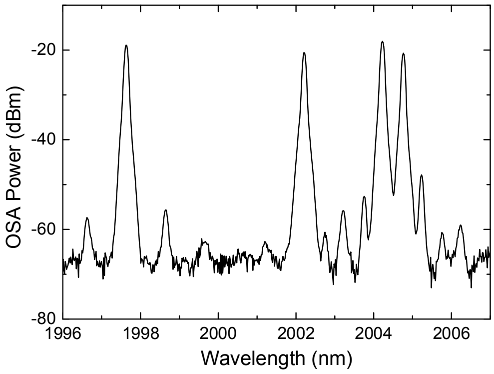

Fig. 3: Transmitter output spectrum.

The 8.5Gbit/s (2^{31}-1 pseudo random bit sequence) NRZ OOK channel (2002.22nm) was implemented using a commercially available $LiNbO_3$ Mach-Zehnder intensity modulator with a V_π of ~9.5V. The RF bandwidth of this channel was limited by the modulator and detector, with a combined 3dB frequency response of 8 GHz both at 1.5μm and 2μm (Fig. 2, blue triangles and red circles respectively), which allowed for a maximum operating data rate of 8.5 Gbit/s.

The WDM signals were then combined with a passive optical fibre based 4:1 combiner with an average excess loss of 1 dB, followed by an isolator, in order to avoid unwanted back reflections. Fig.3 shows the spectral output of the transmitter, with a 0.1nm resolution, showing that the side-mode suppression of the lasers were well below 30dB.

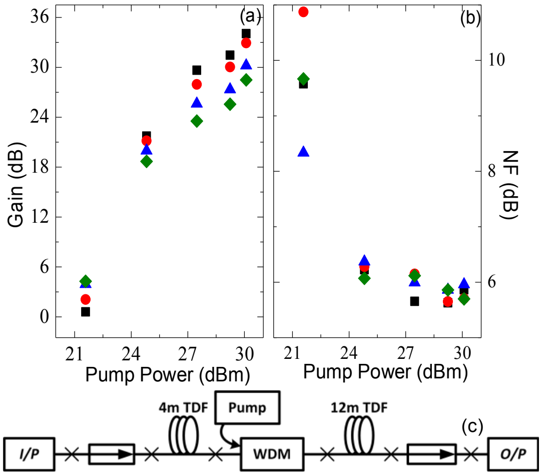

Fig. 4: (a) Gain and (b) noise figures (NF) of the TDFA used for input powers of -22dBm (squares), -26.5dBm (circles), -10dBm (triangles), and -7dBm (diamonds). (c) Schematic diagram of the TDFA.

A Tm^{3+}-doped optical fibre amplifier (TDFA) was developed for use at the receiver, and its schematic is shown in Fig. 4c. The amplifier was built with commercially available Tm^{3+}-doped fibre with mode field diameter of 5μm at 1700nm and absorption of 200dB/m at 790nm (TmDF200). The amplifier had two stages, which provided enhanced gain at wavelengths around 2μm. It consisted of two sections: firstly, a 4m long TDF section before the WDM coupler, followed by a second 12m long forward-pumped TDF section after this coupler. The second section was forward pumped by a 1565nm fibre Bragg grating (FBG) stabilized single mode laser. The first section was backward pumped by back-propagating ASE from the second stage which enhanced the long wavelength gain at 2μm by ~5dB. The amplifier gain and external noise figure (NF) are plotted in Fig. 4. The 3dB gain bandwidth of the amplifier was ~80nm, centered at 1960nm. A minimum NF of ~6dB was measured for practical input powers for the pump powers above 27.5dBm, 1dB of which was attributed to the losses of the first generation of passive components used in the input stage of the amplifier.

The filter comprised a circulator and a set of three thermally tuned FBGs, with an extinction ratio >20dB, a 3dB bandwidth of <0.5nm, and a (thermal) tuning range of >1nm. Each of the wavelength channels was selected by a combination of inserting the relevant FBG to the circulator and tuning their temperatures. This resulted in a maximum loss of 3.5dB, at the negligible expense of a slight increase in the out-of-band spontaneous emission. A tap monitor at the circulator output was inserted to monitor either the optical power for the bit error rate (BER) measurements or the filtered spectrum at the receiver. Finally, a high speed detector at 2µm was used, along with an RF amplifier, before either a 12GHz, 50GS/s DPO, or the PRBS error detector, depending on the particular format being measured.

WDM performance

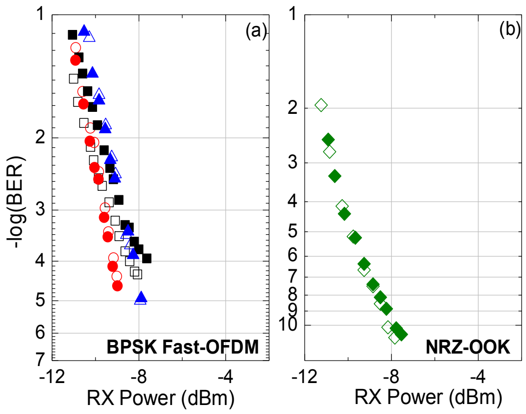

Fig. 5: BER performance against received power before the high speed detector for back-to-back (open symbols) and over 50m of solid core single mode fibre (closed symbols), for directly modulated channels at 1997.27nm (squares), 2004.8nm (triangles) and 2004.2nm (circles), and (b) externally modulated at 2002.2nm.

The 2µm WDM subsystem was analyzed in terms of its bit error rate (BER) performance either at back-to-back, or after 50m of a solid core single mode fibre with a total input power below 3dBm to avoid nonlinearities. The results in Fig. 5 show that the 5 Gbit/s directly modulated BPSK Fast-OFDM channels gave receiver sensitivities at $1\text{x}10^{-3}$ of -8.5dBm or below, with a spread of less than 1dB between channels at this BER. This difference is likely due to the coupling losses between ports from the 4:1 combiner, and the slight tilt on the amplifier gain over this wavelength region. For the NRZ-OOK channel, error-free performance was achieved, with a receiver sensitivity of -10.7dBm also at a BER of $1\text{x}10^{-3}$.

We observed less than 0.5 dB penalty after the 50m of fibre for all four channels, indicating that longer fibre lengths should be readily achieved. Fig. 6 shows open eye diagrams and clear constellations for two channels after 50 m of fibre, showing that no additional penalty is observed after fibre transmission.

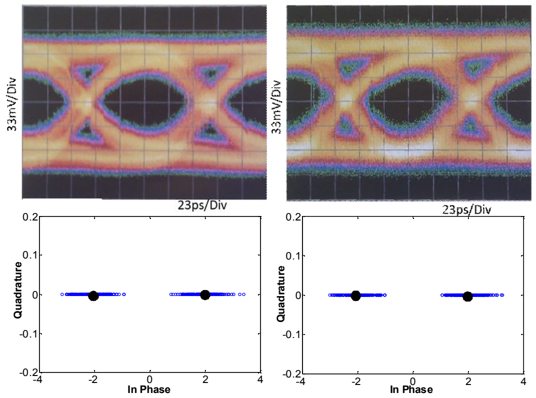

Fig. 6: (top) eye diagram of NRZ-OOK encoded channel and (bottom) constellation diagram of BPSK Fast-OFDM channel (2004.27 nm), both for back-to-back (left) and after fibre (right). Black dot on the constellations represents centre.

Conclusions

We have demonstrated the first direct implementation of a WDM subsystem at 2 µm, with a total capacity exceeding a record 20 Gbit/s. The WDM signal was transmitted over 50m of commercially available solid core 2 µm single mode optical fibre with virtually no power penalty. These results indicate the maturity of 2 µm technologies and the potential to develop long haul systems using low loss hollow core PBGF and highly spectrally efficient modulation formats. Furthermore, the increased bandwidth of the TDFA should allow additional capacity benefits at this new transmission window.

Acknowledgements

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