Demonstration of multi-channel 80 Gbit/s integrated transmitter and receiver for wavelength-division multiplexing passive optical network and fronthauling applications

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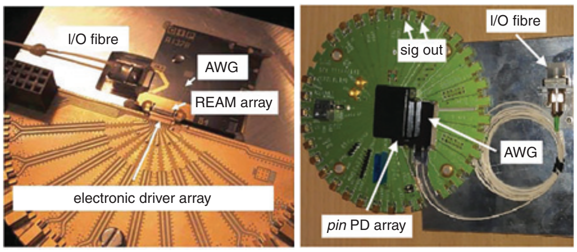
The performance evaluation of a multi-channel transmitter that employs an arrayed reflective electroabsorption modulator-based photonic integrated circuit and a low-power driver array in conjunction with a multi-channel receiver incorporating a *pin* photodiode array and integrated arrayed waveguide grating is reported. Due to their small footprint, low power consumption and potential low cost, these devices are attractive solutions for future mobile fronthaul and next generation optical access networks. A BER performance of $<10^{-9}$ at 10.3 Gbit/s per channel is achieved over 25 km of standard single mode fibre. The transmitter/receiver combination can achieve an aggregate bit rate of 82.4 Gbit/s when eight channels are active.

Introduction: Low-power multi-channel photonic integrated devices are promising candidates for addressing the rising energy and bandwidth demands faced by network operators and enable cost effective deployment of wavelength-division multiplexing (WDM) in next-generation passive optical networks (PONs) [1]. In addition, the WDM overlay specified in the upcoming NG-PON2 standard [2] could allow these multi-channel components to be utilised in next generation mobile fronthaul, as operators evolve towards 5G. The centralised radio access network (C-RAN) is a new architecture which will help to realise high-speed cell coordination in cellular networks [3]. In C-RAN, the link between base band units (BBUs) and the remote radio heads (RRHs) is called fronthaul. Where BBUs and RRHs would historically have been placed close together, they are now being placed much greater distances apart (up to 20 km) [4] by using fronthaul and the interfaces common public radio interface (CPRI) [4], open base station architecture initiative [4] and open radio equipment interface [4] between the BBU and RRH. CPRI data rates, for instance, are specified exceeding 10 Gbit/s [4], which demonstrates the necessity for technologies capable of meeting these requirements. The BBU equipment would generally support multiple RRH units and in the upcoming micro- and nano-cell multi-antenna 5G standards multiple RRHs can also be co-located. Compact, low power, integrated fronthaul transmitters and receivers would hence be advantageous for these applications. Here we demonstrate a 10-channel transmitter that employs an arrayed reflective electroabsorption modulator (REAM)-based photonic integrated circuit [5]. We also demonstrate a 10-channel receiver which operates in conjunction with the 10-channel transmitter providing an aggregate capacity of up to 100 Gbit/s in principle, although only 80 Gbit/s is demonstrated here due to equipment constraints. The results show that transmission over 25 km of standard single mode fibre (SSMF) (targeting typical maximum distances for WDM PON and fronthauling) with similar performance to back-to-back (B2B) and negligible inter-channel crosstalk penalty is achievable, suggesting that longer transmission distances could also be supported [5].

Multi-channel devices: The multi-channel transmitter assembly is composed of a single array of ten ridge structure-based InP REAMs hybrid integrated with an arrayed waveguide grating (AWG) multiplexer, and the 10 × 11.3 Gbit/s REAM driver array [6]. Several techniques are used in the design of the driver array to reduce power consumption while still maintaining sufficient voltage swing to the REAMs; further details on the driver array can be found in [6]. Fig. 1*a* shows a photograph of the main component blocks. The 10-channel AWG has 100 GHz spacing (1541.99–1549.18 nm) and is athermalised using polymer-filled slots to avoid wavelength drift with temperature. The REAM array is mounted on a silicon submount and aligned to the AWG silica planar motherboard. The integrated assembly features a single input/output (I/O) fibre such that the transmitter operates in reflective mode. The 10-channel optical receivers were developed using an off-the-shelf 12-channel 12.5 Gbit/s transimpedance amplifier (TIA) array. The board used was an IPTronics IPBTA12X12 populated and supplied by Mellanox Technologies. An array of 10 *pin* photodiodes (PDs) was mounted on a ceramic header with wrap around metallisation. The ceramic header containing the detectors was aligned to the pigtailed 10-channel 100 GHz athermal AWG with specifications matching the AWG in the TX and fixed in place. The optical assembly was then placed into a mechanical recess in the PCB and the electrical traces aligned to the appropriate TIA bond pads. The optical assembly was then wire-bonded to the TIA array. The receiver assembly and single input fibre are shown in Fig. 1*b*.



a *b*

Fig. 1 *Images of TX and RX arrays used in experimental setup*

a Multi-channel reflective TX
b Multi-channel RX array

Experimental setup: The experimental setup is shown in Fig. 2. Due to a limited number of pulse pattern generators (PPGs) and other equipment only eight channels were tested simultaneously. Eight C-band CW carriers (1541.99, 1542.75, 1545.18, 1545.98, 1546.78, 1547.54, 1548.37 and 1549.18 nm) aligned to the TX AWG channels were generated and passively combined using a 1 × 8 splitter/combiner. The eight carriers were then amplified by a semiconductor optical amplifier (SOA) and injected into the integrated reflective TX via a circulator (total $P_{in} \approx +13$ dBm). The REAMs were modulated with 10.3 Gbit/s non-return-to-zero $2^{31}–1$ pseudo random bit sequence (PRBS) drive signals from the PPGs, giving an aggregate bit rate of 82.4 Gbit/s. Each channel was differentially driven with 500 $mV_{Pk–Pk}$ AC coupled signals. The reflected modulated signals were then multiplexed by the integrated AWG and amplified by a second SOA. In this demonstration, the SOAs are required to amplify the input CW and output modulated signals of the TX due to the relatively high insertion loss of the device (∼25 dB per channel). However, it should be noted that the SOAs also have the potential to be integrated in the TX module [7] thus providing a fully integrated solution. The multiplexed modulated signals are then either detected by the pre-amplified receiver (RX) in the B2B case or launched into the transmission fibre (total launched power ≈ +3 dBm). The signals are then amplified by the SOA at the RX before being demultiplexed by the RX AWG and each channel is detected by its corresponding PD.

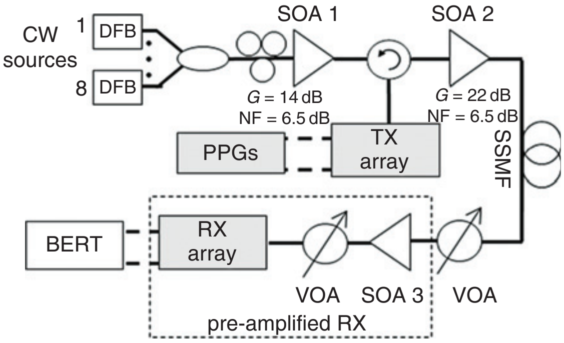


Fig. 2 *Experimental setup for evaluating multi-channel TX and RX*

VOA: variable optical attenuator, DFB: distributed feedback laser

The version of the RX used here required a relatively high overall input power to overcome insertion losses (input power greater than approximately −13 dBm required) hence the use of a pre-amplified receiver configuration. Similar to the TX, SOAs can be integrated with the RX or avalanche PDs can be used instead of *pin* PDs, removing the need for external amplification. A digital sampling oscilloscope was then used to capture eye diagrams and a BER tester (BERT) analysed the

BER of the multi-channel TX and RX combination in both B2B and over 25 km of SSMF.

Experimental results: Fig. 3 shows a set of eight representative eye diagrams captured using the experimental setup, showing a range of best- to worst-case performance. Figs. 3*a*–*d* show the optical eye diagrams after the SOA at the TX output for Chs1, 2, 4 and 5, whereas Figs. 3*e*–*h* show the electrical eye diagrams for the same channels at the output of the receiver after 25 km transmission. While the results for only four channels are shown here for practical reasons, eight channels were active in both the TX and RX while measurements were being obtained. Good eye opening can be seen in the optical eye diagrams, with Ch2 exhibiting slightly more noise, which can be attributed to a slightly higher optical loss and variations in the REAM performance. The received electrical eye diagrams also show good eye opening with Ch2 showing more jitter due to the slightly degraded optical signal.

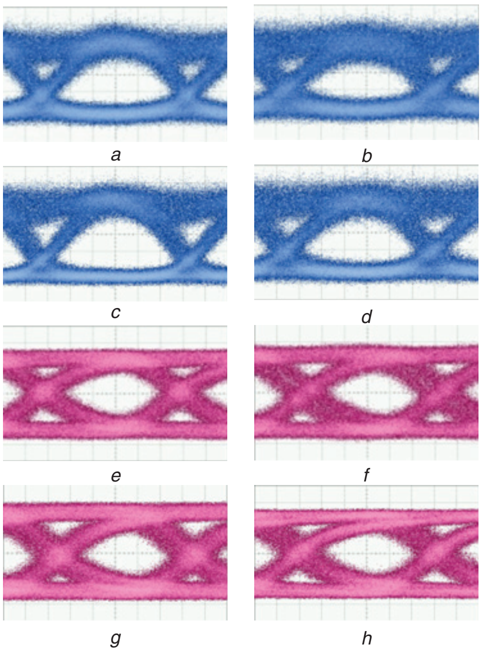


Fig. 3 *Optical eye diagrams at TX output and received electrical eye diagrams at RX after 25 km transmission*

a–*d* TX Ch1, Ch2, Ch4 and Ch5 output eye diagrams
e–*h* RX Ch1, Ch2, Ch4 and Ch5 received eye diagrams

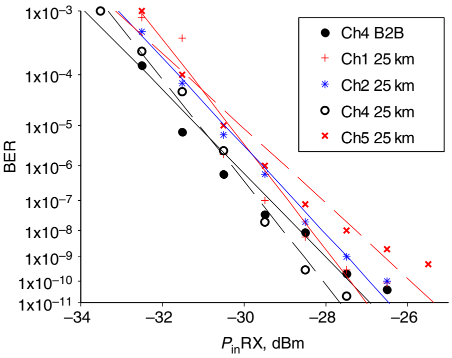


Fig. 4 *BER against received power for Ch4 in B2B and Chs 1, 2, 4 and 5 over 25 km of SSMF*

In Fig. 4, the BER curves measured at the RX output for one representative channel in B2B (Ch4) and four other channels over 25 km of transmission fibre (Chs1, 2, 4 and 5) are shown. Comparable performance can be seen between B2B and Chs 1, 2 and 4 over 25 km transmission with the BER of $<10^{-10}$ achieved on these channels. Channel 5 shows the possible onset of an error floor, however it still achieves a BER lower than 10^{-9} at 25 km with a penalty of approximately 1.5 dB compared to the other channels. This TX has also been previously demonstrated over transmission distances up to 96 km [5]. Both the TX and RX show good performance and no significant crosstalk issues were observed as previously demonstrated in [5, 6]. The variations in BER between the different channels over 25 km of transmission can be attributed to a number of factors such as small differences in the insertion loss of different channels in both the TX and RX along with variations in extinction ratio and jitter performance, as evident in Fig. 3. Future versions of both the TX and RX could be optimised to improve these issues, in particular a reduction in insertion loss and the addition of integrated SOAs.

Conclusion: We have demonstrated simultaneous operation of 8 × 10.3 Gbit/s channels of an integrated multi-channel transmitter that employs arrayed reflective EAMs and a low-power driver array in conjunction with a multi-channel receiver incorporating a *pin* PD array and integrated arrayed waveguide grating, giving an aggregate bit rate of 82.4 Gbit/s. The TX and RX combination achieves a BER performance of $<10^{-9}$ over 25 km of SSMF on all measured channels. This result demonstrates that such devices have the potential to be utilised in both next generation PONs and future fronthaul networks where they can meet the bit-rate and reach requirements between the BBU and RRH, while their low power consumption, small footprint and potential low cost offer advantages compared to competing solutions.

Acknowledgments: This work was supported by the European Commission through the C3PO project (contract 257377) under the FP7 ICT Programme. The Tyndall National Institute also acknowledges funding by Science Foundation Ireland (Grant 12/IA/1270).

Submitted: *21 December 2015* E-first: *11 March 2016*
doi: 10.1049/el.2015.4441
One or more of the Figures in this Letter are available in colour online.

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