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Repeater-less Data Transmission at 1310 nm using Silicon Photonic Integrated Circuit

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ABSTRACT

NRZ data with PRBS length $2^{31} - 1$, was propagated over 25 km of standard single mode fibre at a rate of 10 Gbit/s and 12.5 Gbit/s in a repeater-less transmission system. Results show that, for a received optical power of -13.2 dBm, the BER were 2.7×10^{-6} and 3.3×10^{-4} respectively, with sufficient margin below the FEC limit of 1×10^{-3}. The packaged transmitter comprised an integrated DFB laser, electro-absorption modulator and semiconductor optical amplifier hybrid integrated on silicon wafer.

Keywords: photonic integrated circuits, silicon photonics, 1310 nm, packaging, fiber optic communications, photonic characterisation, semiconductor lasers, electroabsorption modulators

1. INTRODUCTION

Increasing demand for internet based data services is driving the development of optical interconnect technology being deployed in data centres across the globe.[1] Key to future development of this field will be high performance flexible optical components that can be manufactured at low cost. Photonic integrated circuits (PICs) enable multiple photonic devices to be fabricated on a single substrate. PICs have enhanced functionality, low insertion loss, low manufacturing cost and low operating cost.[2] The advantages of PICs are most clearly realised when active III-V semiconductor devices are combined with passive silicon (Si) devices to make silicon PICs (Si-PICs). The hybrid III-V on Si integration approach has been pursued for a number of years[3,4] and has demonstrated the ability to produce multi-channel, high data capacity Si-PICs.[5]

In this paper we present results on the performance of a new Si-based optical transmitter, hybrid integrated with InP active materials and packaged for quick deployment in an access network or data centre setting. An InP-PIC comprising DFB laser, electroabsorption modulator (EAM) and semiconductor optical amplifier (SOA) was fabricated from InAlGaAs-based multiple quantum well (MQW) epitaxial structure on 50 mm InP substrate. The InP-PIC was hybrid integrated using wafer bonding on 200 mm silicon-on-insulator (SOI) wafer. Optical coupling between the InP chip and the SOI wafer was maximised using tapered InP waveguides. This technology approach has been used to successfully demonstrate a hybrid III-V on Si laser,[6] a directly modulated C-band tunable laser,[7] an electro-absorption modulated tunable laser[8] and a directly modulated DFB laser integrated with SOA.[9] The Si-PIC was packaged with temperature control element and optical fibre.

In this work, we demonstrate, for the first time, repeaterless NRZ data transmission over 20 km and 25 km of standard single mode fibre (SMF) at data rates of 10 Gbit/s and 12.5 Gbit/s with bit error rates (BER) below the 1×10^{-3} limit for forward error correction (FEC) using a packaged Si-PIC comprising DFB laser, EAM and SOA. Previous work has used a pre-amplified receiver in order to obtain the same transmission distance.[10]

A description of the device fabrication and packaging technology is given in section 2. Results from the characterisation of the transmitter are described in section 3. Finally, section 4 describes the repeaterless transmission experiment used to validate the dynamic performance of the packaged Si-PIC.

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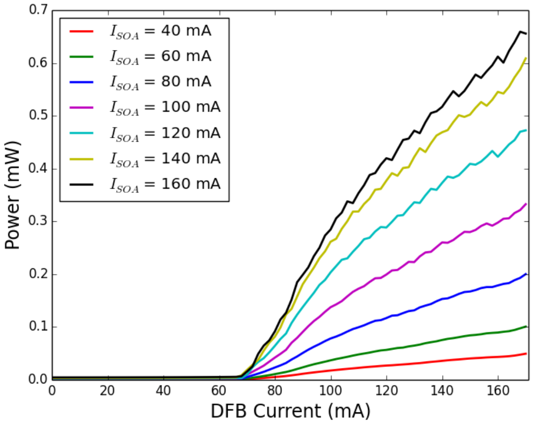

Figure 1. Measured optical output power from Si-PIC as current in SOA is varied and EAM is maintained at 0 V. Temperature of packaged chipset is $20\,^{\circ}C$.

2. DEVICE FABRICATION AND PACKAGING

Fabrication of the device follows steps described in previously published work.[11] Processing of this device starts from a 200 mm silicon on insulator wafer (SOI), which contains a 440 nm thick silicon waveguide layer upon a 2.0 µm buried oxide layer. An epitaxial structure comprising 10 InAlGaAs-based MQW is grown over 50 mm InP substrate. Deep UV 193 nm lithography and HBr etching of 220 nm silicon enables fabrication of rib waveguides in which the laser cavity is defined. These waveguides are tapered in order to obtain the best optical power coupling between silicon layer and III-V gain material. Si wafer includes grating coupler through which light is coupled to optical fibre. The whole wafer is then transferred upon a silicon wafer using molecular bonding.

Packaging process proceeded by bonding of Si-PIC to a ceramic sub-mount; bonding was accomplished by application of an approximately 30 µm layer of thermally and electrically conductive silver epoxy which was cured for 30 min. at $120\,^{\circ}C$. Chip and sub-mount were further bonded to an aluminium heat spreader and mounted on a temperature control (TEC) unit by same process. Temperature sensing component in the package is a 10 kΩ thermistor mounted beside Si-PIC. Chip, sub-mount and TEC were secured in a kovar butterfly package. Gold (Au) wire-bonds were used to make electrical connections between DC and RF bond-pads on butterfly package and Si-PIC. Ultrasonic vibration was used to ensure wire-bonds were held in place. A Fibre-to-PIC active alignment process, using an angle polished single mode fibre, was used to achieve optimal coupling at a grating coupler on the surface of Si-PIC. Further details of packaging technology used can be found in.[12] Advantages of hybrid integration approach include the fact that there is no IL between DFB, EAM and SOA sections and 66% operating cost savings, since only one packaged device has to be maintained at fixed temperature.

3. TRANSMITTER CHARACTERISATION

Isolated characterisation of each element of the integrated device is not easy. Compromises take place, in order to estimate the individual performances. The characterisation of the DFB section of the Si-PIC, for example, took place by keeping the EAM bias constant at 0 V and the SOA current at a fixed value, while keeping the package temperature at $20\,^{\circ}C$. The observed output power of the Si-PIC, see Fig. 1, for DFB bias 170 mA, varied from 0.05 mW to 0.66 mW, when the SOA current was varied from 40 mA to 160 mA respectively. Threshold current of DFB section was measured to be 68 mA at $20\,^{\circ}C$, similar to previously reported results for this technology.[6] The optical output power decreased as temperature of device increased according to the rate $\Delta P_{out}/\Delta T = -0.04\,\mathrm{mW/K}$ when biasing DFB at 170 mA, SOA at 160 mA and keeping EAM at 0 V.

Operating wavelength of the DFB laser at $20\,^{\circ}C$ was found to be 1321.94 nm with DFB biased at 172 mA. Fig. 2 shows the Si-PIC optical spectral density when biasing the DFB, EAM and SOA at 172mA, 0 V and 170mA respectively. The laser is clearly single-mode, with side mode suppression ratio (SMSR) greater than

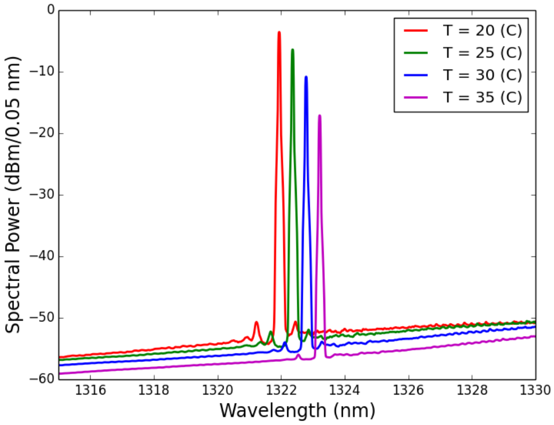

Figure 2. Measured optical spectral density of DFB section as temperature of packaged Si-PIC is varied. DFB operates in single mode with SMSR $>$ 47dB. Current across DFB and SOA sections are 172mA, 170mA respectively, EAM section is biased at 0 V.

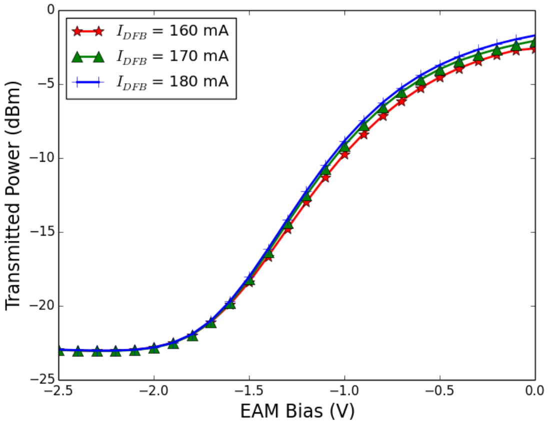

Figure 3. Measured optical power transmitted through EAM as reverse bias is varied for different values of current in DFB section. Current across SOA is fixed at 170mA.

47 dB between 20 °C and 35 °C, the ratio of wavelength tuneability to temperature is measured to be $\Delta\lambda/\Delta T = 0.08\,\mathrm{nm/K}$.

The EAM section was characterised by measuring the Si-PIC output power while varying the EAM DC bias as current in DFB and SOA sections was fixed with device was maintained at constant temperature. The DC extinction ratio of the EAM is 22 dB for EAM reverse bias between -2 V and 0 V, see Fig. 3. Fig. 3 also shows the EAM response against different input powers, which is emulated by increasing the DFB current from 160 mA to 180 mA. The result shows that there's very little variation or dependence on DFB operating parameters; while EAM is biased at -1 V the change in transmitted power with respect to current in DFB section is $\Delta P_t/\Delta I_{DFB} = 1.2\,\mu\mathrm{W/mA}$.

The small signal frequency response of EAM section was measured using an Agilent E83642 network analyser and a Newport 1544-B Photoreceiver, which has a responsivity of approximately 0.8 (A/W) at 1300 nm and a bandwidth of 12 GHz. Measured S_{21} data shows that EAM has 3dB bandwidth of $f_{3dB} = 5.6$ GHz when operating at 20 °C with EAM bias of -0.5 V while current in DFB and SOA sections was fixed at 160 mA and 167 mA respectively. Optical output power from the Si-PIC in this configuration was -4.2 dBm. The frequency response obtained indicates that EAM is capable of modulating at data rates in excess of 10 Gbit/s.

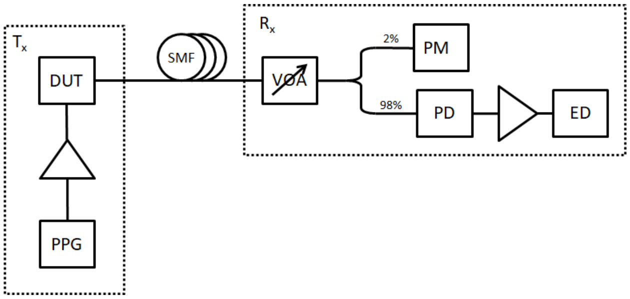

Figure 4. Set up of repeaterless system used to measure BER of Si-PIC. PPG: Pulse Pattern Generator, SMF: Single Mode Fiber, VOA: Variable Optical Attenuator, PM: Power Meter, PD: Photodetector, ED: Error Detector.

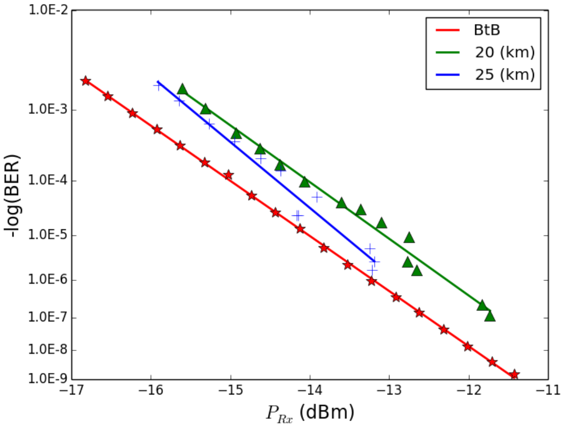

Figure 5. Measured BER of Si-PIC at data rate 10 Gbit/s. BER after 20 km is 1.2×10^{-7} with $P_{Rx} = -11.7$ dBm. BER after 25 km is 2.7×10^{-6} with $P_{Rx} = -13.2$ dBm.

4. DYNAMIC PERFORMANCE CHARACTERISATION

Dynamic performance of the Si-PIC was characterised by modulating the EAM with NRZ signal and a PRBS sequence of length $2^{31} - 1$, and measuring bit error rate (BER) of transmitted data back-to-back (BtB), after transmission through standard single mode fibre (SMF) with lengths of 20 km and 25 km and also at two data rates of 10 Gbit/s and 12.5 Gbit/s. In each of the transmission experiments Si-PIC temperature was maintained at $20\,^{\circ}C$, current in DFB and SOA sections was 172 mA, 170 mA respectively, EAM section was reverse biased to -0.75 V. The optical output power of the device in this configuration is -5 dBm.

The set-up used to perform BER characterisation is shown in Fig. 4. It is a repeaterless system configuration, as there is no source of optical amplification, apart from the Si-PIC. Data was generated using SHF 12100A pulse-pattern generator (PPG) and an RF amplifier with peak-to-peak voltage set to $V_{pp} = 1.35$ V in order to exploit the EAM full ER of 14 dB. The RF signal was fed to the EAM section using a bias-tee, enabling DC biasing and RF modulation simultaneously. Data was fed to EAM section of Si-PIC and transmitted over the optical fibre link.

The transmitted optical signal was connected to a variable optical attenuator (VOA) with intrinsic insertion loss of 0.5 dB and subsequently split with ratio 98:2; 2% arm was connected to a power meter to enable power at the receiver (P_{Rx}) to be recorded; 98% arm was connected to a Newport 1544-B photoreceiver. Power at the receiver is limited by available transmitter power, since the link is non-amplified, and optical fibre loss of 0.3 dB/km. An RF amplifier was added after the photoreceiver to ensure a good signal to noise ratio and also to match the dynamic range to the error detector (ED) $V_{pp} = 1$ V. BER was measured using SHF 11100A error detector (ED). No clock recovery was used, and both the sampling oscilloscope and ED were triggered by the same clock used by the PPG from the RF Synthetiser, Rohde and Schwarz SMF100A.

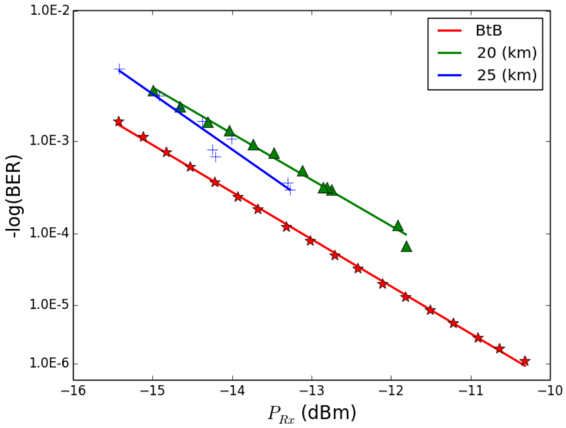

Figure 6. Measured BER of Si-PIC at data rate 12.5 Gbit/s. BER after 20 km is 7×10^{-5} with $P_{Rx} = -11.8\,\text{dBm}$. BER after 25 km is 3.3×10^{-4} with $P_{Rx} = -13.3\,\text{dBm}$.

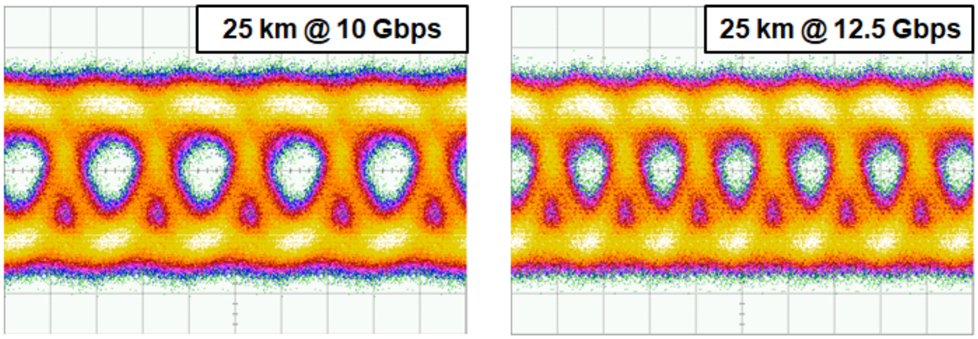

Figure 7. Open eyes after transmission over 25 km at 10 Gbit/s (left) and 12.5 Gbit/s (right). Eye height after 25 km at 10 Gbit/s is 198 mV. Eye height after 25 km at 12.5 Gbit/s is 148 mV. Time scale is 50 ps/div, volt scale is 100 mV/div.

In the first experiment the PPG was set to output data at rate 10 Gbit/s. The BER against received power (P_{Rx}) is shown in Fig. 5 for BtB (red stars), after SMF transmission over 20km (green triangles) and 25 km (blue crosses). BER after 20 km is 1.2×10^{-7} with $P_{Rx} = -11.7\,\text{dBm}$. BER after 25 km is 3.3×10^{-4} with $P_{Rx} = -13.3\,\text{dBm}$. Received power is limited by optical fibre loss of 0.3 dB/km. BtB receiver sensitivity at BER $= 1 \times 10^{-3}$ level is $P_{Rx} = -16.3\,\text{dBm}$, optical power penalty after transmission over 20 km and 25 km of SMF is 1 dB. BER measurements show that Si-PIC developed here is capable of transmitting data at 10 Gbit/s over 25 km without external optical amplification with BER performance below FEC limit. The received 10 Gbit/s eye diagram after propagation over 25 km is shown in Fig. 7, the eye-diagram is still very opened, eye height after 25 km at 10 Gbit/s is 198 mV.

For the second experiment the PPG was set to output data at rate 12.5 Gbit/s. The measured BER at this data rate is displayed in Fig. 6 for BtB configuration (red stars) and after 20 km (green triangles) and 25 km (blue crosses) of SMF. BER after 20 km is 7×10^{-5} with $P_{Rx} = -11.8\,\text{dBm}$. BER after 25 km is 3.3×10^{-4} with $P_{Rx} = -13.3\,\text{dBm}$. BtB receiver sensitivity at BER $= 1 \times 10^{-3}$ level is $P_{Rx} = -15\,\text{dBm}$. The increase in required power for the 12.5 Gbit/s case indicates a limitation of the frequency response of the overall system, the photoreceiver has bandwidth of 12 GHz. The power penalty after 20 km and 25 km of SMF is 1.2 dB, similar to the 10 Gbit/s case. BER measurements show that Si-PIC developed here is capable of transmitting data at 12.5 Gbit/s over 25 km without external optical amplification with BER performance below FEC limit. The received 12.5 Gbit/s eye diagram after propagation over 25 km, shown in Fig. 7, is open with eye height after 25 km at 12.5 Gbit/s being 148 mV.

5. CONCLUSION

We have shown the DC characterisation and systems-level performance of a Si-PIC comprised of a DFB laser, EAM modulator and an SOA. NRZ data, with PRBS length $2^{31}-1$, was transmitted over 25 km of standard single mode fibre at data rates of 10 Gbit/s and 12.5 Gbit/s with BER performance below the 1×10^{-3} FEC limit. Data transmission was accomplished without the use of external optical amplification in a system with optical fibre loss of 0.3 dB/km, a bandwidth limited photoreceiver and no clock recovery. These results demonstrate the potential of this technology approach, InP PIC hybrid integrated on SOI, for deployment in access and data centre communication networks.

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REFERENCES

[1] C. Kachris, K. Kanonakis, and I. Tomkos, "Optical interconnection networks in data centers: Recent trends and future challenges," *IEEE Comms. Mag.* **51 (9)**, pp. 39–45, 2013.

[2] M. Smit, X. Leijtens, H. Ambrosius, E. Bente, J. Van der Tol, B. Smalbrugge, T. De Vries, E.-J. Geluk, J. Bolk, R. Van Veldhoven, *et al.*, "An introduction to InP-based generic integration technology," *Semiconductor Science and Technology* **29**(8), p. 083001, 2014.

[3] M. J. Heck, J. F. Bauters, M. L. Davenport, J. K. Doylend, S. Jain, G. Kurczveil, S. Srinivasan, Y. Tang, and J. E. Bowers, "Hybrid silicon photonic integrated circuit technology," *IEEE Selected Topics in Quant. Electron.* **19 (4)**, pp. 6100117–6100117, 2013.

[4] G.-H. Duan, C. Jany, A. Le Liepvre, A. Accard, M. Lamponi, D. Make, P. Kaspar, G. Levaufre, N. Girard, F. Lelarge, *et al.*, "Hybrid III–V on silicon lasers for photonic integrated circuits on silicon," *IEEE Selected Topics in Quant. Electron.* **20 (4)**, pp. 158–170, 2014.

[5] G. de Valicourt, C.-M. Chang, S. Chandrasekhar, Y.-K. Chen, A. Maho, R. Brenot, and P. Dong, "Integrated 5-channel WDM hybrid III-V/Si transmitter enabling 100Gb/s and beyond," in *OFC 2017*, pp. 1–3, 2017.

[6] G.-H. Duan, S. Olivier, C. Jany, S. Malhouitre, A. Le Liepvre, A. Shen, X. Pommarede, G. Levaufre, N. Girard, D. Make, *et al.*, "Hybrid III-V silicon photonic integrated circuits for optical communication applications," *IEEE Selected Topics in Quant. Electron.* **22 (6)**, pp. 379–389, 2016.

[7] A. Shen, G. Levaufre, A. Accard, J. Decobert, N. Lagay, J.-G. Provost, D. Make, G.-H. Duan, S. Olivier, S. Malhouitre, *et al.*, "50km error free transmission of fully integrated chirp-managed 10 Gb/s directly modulated C-band tunable III-V/SOI hybrid lasers," in *OFC 2016*, pp. 1–3, 2016.

[8] X. Pommarede, N. Girard, S. Olivier, S. Malhouitre, A. Accard, G. Levaufre, A. Shen, D. Make, R. Brenot, F. Lelarge, *et al.*, "Transmission over 50km at 10 Gbs/s with a hybrid III-V on silicon integrated tunable laser and electro-absorption modulator," in *OFC 2016*, pp. 1–3, 2016.

[9] R. Sheehan, C. Eason, L. Carroll, P. O'Brien, F. Gunning, A. Gallet, I. Ghorbel, A. Shen, and G. Duan, "1310 nm data transmission using silicon photonic integrated circuit comprising directly modulated DFB laser and SOA," in *SBMO/IEEE MTT-S IMOC 2017*, pp. 1–4, 2017.

[10] I. Ghorbel, A. Gallet, A. Shen, D. Carrara, D. Make, G. Levaufre, G. H. Duan, S. Olivier, C. Jany, S. Malhouitre, C. Kopp, C. Eason, and P. O'Brien, "25 Gb/s error-free transmission with a packaged chipset integrating a III-V/SOI DFB laser an electro-absorption modulator and a semiconductor optical amplifier," in *GFP 2017*, pp. 99–100, 2017.

[11] G. Levaufre, A. Le Liepvre, C. Jany, A. Accard, P. Kaspar, R. Brenot, D. Make, F. Lelarge, S. Olivier, S. Malhouitre, *et al.*, "Hybrid III-V/silicon tunable laser directly modulated at 10 Gbit/s for short reach/access networks," in *ECOC 2014*, pp. 1–3, 2014.

[12] L. Carroll, J.-S. Lee, C. Scarcella, K. Gradkowski, M. Duperron, H. Lu, Y. Zhao, C. Eason, P. Morrissey, M. Rensing, *et al.*, "Photonic packaging: Transforming silicon photonic integrated circuits into photonic devices," *Appl. Sci.* **6 (12)**, p. 426, 2016.