16 Gbps RoF Link at 20 GHz Carrier Frequency using a Silicon Photonics Transmitter and Receiver

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***Abstract*—In future radio access networks, radio-over-fiber links will be a key enabling technology. A link which is cost-effective in both deployment and operation will be of paramount importance to the development of such networks. Using silicon photonics for the transmitter and receiver is a cost-effective and high-performance solution. In this work we present a link which can transport up to 16 Gbps 16-QAM data on a 20 GHz carrier over 5 km of SMF. The transmitter is a III-V-on-Si directly modulated laser and the receiver is a Ge-on-Si photodetector on a silicon photonic integrated circuit, co-integrated with a SiGe BiCMOS TIA. This is to the best of our knowledge the first Si PIC based RoF link with a directly modulated laser.**

***Index Terms*—Silicon photonics; Microwave photonics; Quantum well lasers; Photodetectors; Optical receivers**

I. Introduction

To keep up with business and customer demand, operators are looking to roll out the next generation wireless network (5G) by 2020. This network will offer higher data rates to more simultaneous users, while reducing the latency and improving connectivity. To accomplish all these features, radio access networks with new architectures are needed. A first new element is the expansion of usable spectrum both below and above 6 GHz [1]. Below 6 GHz bands can be re-allocated, above 6 GHz no consensus has been reached but strong interest has been developed in the 20-30 GHz band and millimeter waves. A second important element is a smaller cell size. This will be necessary when higher frequency carriers are used, but it also enables greater spectrum re-use. To service an increased number of small cells, operation and deployment costs will need to be decreased. Radio-over-Fiber (RoF) can be a key-enabling technology in this scenario, offering the possibility to generate the radio signal at a central office and transporting it over optical fiber to a remote antenna station [2]. However, current RoF solutions are often based on discrete opto-electronic components, which implies a high cost and large footprint of the final transceiver. Using integrated optics can greatly reduce the cost per link, both in deployment and operation. The development of integrated analogue optical transceivers or integrated microwave photonics circuits is gaining a lot of interest and is essential to deliver scalable solutions. A key technology offering cost reduction and high volumes is silicon photonics, and is therefor a promising technology for RoF transceivers and integrated microwave photonics [3]. The hybrid III-V-on-Si platform also gained great interest for microwave photonics applications [4][5]. Many RoF links are based on the external modulation of a CW laser by a Mach-Zehnder Modulator (MZM), related to the linearity offered by external modulation. Eliminating the modulator would allow reducing the cost of the transceiver further. Also, the insertion loss of the modulator is removed, improving the link budget. Integrated directly modulated lasers, both in InP and hybrid III-V-on-Si platforms, have shown very promising results for digital baseband communication applications. III-V-on-Si directly modulated lasers (DMLs) with a small-signal bandwidth of 34 GHz have been used in 56 Gbps OOK transmission [6]. These type of DMLs rival the bandwidth of MZM at reduced cost and complexity. On the receiver side very high bandwidth photodiodes have been demonstrated in silicon photonic platforms such as the imec iSiPP50G platform. On this platform we demonstrated a 67 GHz bandwidth Ge-on-Si PD [7]. In this work we combine these silicon technologies to demonstrate a high carrier frequency, high bitrate RoF transceiver. To achieve a better link performance we co-integrated a BiCMOS transimpedance amplifier (TIA) with the silicon photonic receiver. A data rate of 16 Gbps on a 20 GHz carrier is transmitted over 5 km single mode fiber using these transceivers. The remainder of this work is split into four parts, the first part will discuss the design, fabrication and characterization of the III-V-on-Si DML. In the second part the receiver will be discussed. We then analyze the RoF link performance and finally present a conclusion.

II. RoF III-V-on-Si Transmitter

The III-V-on-Si DFB laser is fabricated by the heterogeneous integration of an epitaxially grown InP material stack, comprising an InGaAsP MQW active region operating in the C-band, on a Si photonic integrated circuit (PIC). The passive Si PIC contains a first order DFB grating, waveguides and vertical grating couplers, as shown in Fig. 1. The passive PIC is realized on a silicon-on-insulator wafer with a 400 nm Si device layer and a 2 μm buried oxide layer. The waveguides and grating were created by an 180 nm etch of the Si device layer. The first order DFB grating has a total length of 390 μm and a period of 245 nm with a 50 percent duty cycle. The epitaxial InP material was bonded on the PIC using adhesive

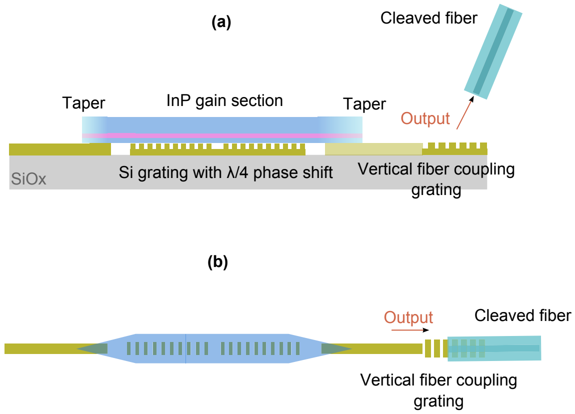


Fig. 1: (a) Side view of the III-V-on-Silicon DFB laser. (b) Top view of the same laser.

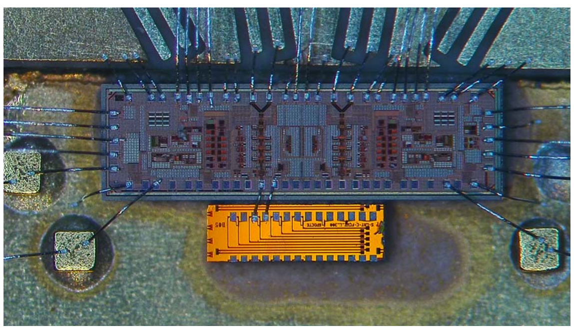


Fig. 2: A microscope image of the Silicon Photonic Receiver: the Ge-on-Si photodetector small die wirebonded to the SiGe BiCMOS TIA (large die).

wafer bonding with a 50 nm thick DVS-BCB bonding layer, after which a waveguide is defined in the InP layer stack using dry and wet etching and metal contacts are defined. A more detailed description of the fabrication of such devices can be found in [8]. For a bias current of 100 mA the output power of the laser was 4.5 mW, operating at a wavelength of 1570 nm. The linearity of the DML was determined to be 90 $\mathrm{dBHz}^{2/3}$.

III. RoF SiGe Receiver

As receiver, a waveguide-coupled Ge-on-Si p-i-n photodetector co-integrated with a BiCMOS TIA was used. The photodiode is fabricated in the imec iSiPP50G platform [7]. The photodiode is 14.2 $\mu\mathrm{m}$ long and 0.5 $\mu\mathrm{m}$ wide. It is coupled to a 0.22 $\mu\mathrm{m}$ thick and 0.45 $\mu\mathrm{m}$ wide Si waveguide using a Si and poly-Si taper. The responsivity for a bias voltage of -1 V and a wavelength of 1550 nm is 0.72 A/W. The device has a dark current of 2.4 nA. The small-signal bandwidth of the device exceeds 50 GHz. The TIA was fabricated using a 0.13 $\mu\mathrm{m}$ SiGe BiCMOS process. The TIA consumes approximately 180 mW and needs a 2.5 V supply. Wirebond-based co-integration was used. A microscope picture of the silicon photonic receiver co-integrated with the TIA on a high-speed printed circuit board is shown in Fig. 2. A more detailed

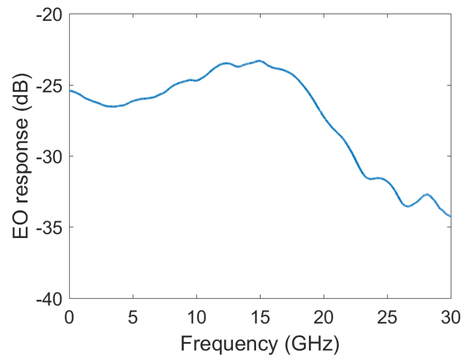


Fig. 3: Electro optical response of the receiver (Ge receiver and SiGe BiCMOS TIA on a high-speed printed circuit board).

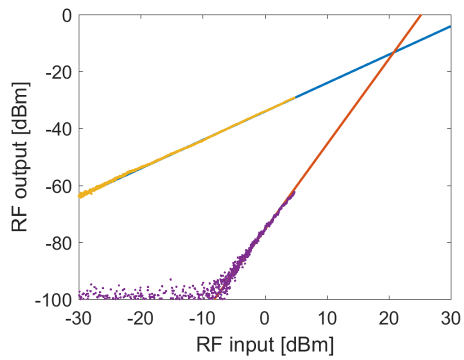
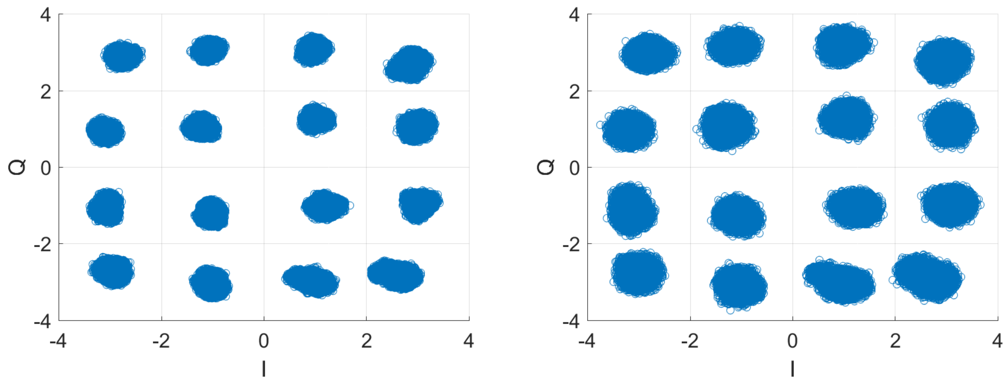


Fig. 4: IP3 measurement of the Ge-on-Si PD with TIA. The yellow and purple dots represent measured values, the blue and red line are the extrapolated values. The SFDR is 81 $\mathrm{dB{\cdot}Hz}^{2/3}$, for a photocurrent of 450 uA.

description of the TIA can be found in [9]. We measured the small-signal bandwidth of the receiver with a Santec TSL 510 laser, an Oclaro AM-40 Mach-Zehnder Modulator (MZM) and a Keysight PNA-X vector network analyzer. The photocurrent during the measurement was 0.45 mA corresponding to approximately - 2dBm of waveguide-coupled optical power. The small signal electro-optical response is shown in Fig. 3, from which we can deduce that the 3 dB bandwidth is 21 GHz for the detector/TIA combination. Clearly The TIA limits the bandwidth as the Ge-on-Si PD has a bandwidth exceeding 50 GHz. The linearity of the receiver was determined by an IP3 measurement using the PNA-X, a Santec TSL 510 laser and an Oclaro AM-40 MZM. The PNA-X generated two tones spaced 5 MHz at 20 GHz and the strength of the intermodulation distortion ($2f_1 - f_2$ tone) was measured. The result of the IP3 measurement is shown in Fig. 4. The SFDR is 81 $\mathrm{dB} \cdot \mathrm{Hz}^{2/3}$ and the IIP3 is 21 dBm, for a photocurrent of 450 uA.

IV. RoF Link demonstration

To demonstrate the use of these components for RoF links, 16-QAM signals on a 20 GHz carrier were generated by a Keysight M8195A Arbitrary Waveform Generator and amplified with a SHF RF amplifier. The laser PIC is placed on a



(a) 4 Gbps (b) 16 Gbps

Fig. 5: Constellation diagrams of 4 and 16 Gbps signals, using 16-QAM modulation, on a 20 GHz carrier transmitted over 5 km of SMF. The constellations were formed using 10^6 symbols and the BER was found to be error free and $3 \cdot 10^{-6}$, for the 4 Gbps and 16 Gbps transmission respectively.

temperature controlled stage and kept at a constant temperature of 20 °C. The laser is contacted using a Cascade RF probe and the optical output is collected, using a cleaved SMF, from the grating coupler. The output of the laser is amplified with an EDFA to compensate the chip-to-fiber coupling losses. A Santec Optical Tunable Filter (OTF-350) is used to filter excess noise from the EDFA. 5 km standard single mode fiber was used in the experiment, before coupling to the silicon photonic receiver. An overview of the measurement set-up is shown in Fig. 6.

A first transmission experiment was done with a 1 GBaud signal (4 Gbps) on a 20 GHz carrier using 16-QAM, using a $2^9 - 1$ symbols long pseudo random bit sequence (PRBS). The signal was captured by a 80 GSa/s real-time oscilloscope (Keysight DSAZ634A). The received signal was equalized online and found to have an error vector magnitude (EVM) of 5.7%. The EVM was also determined online, on the oscilloscope, using the native VSA software.

To determine the BER, the unequalized waveform was saved and loaded into Matlab. In Matlab the measured single carrier signal is directly down mixed to a baseband I/Q signal. To obtain the symbol sample time of the I/Q signal, the Gardner algorithm was used. A FIR equalizer was implemented to reduce the Inter Symbol Interference (ISI). A constellation of the equalized signal, based on 10^6 received symbols, is shown in Fig. 5a. The equalized transmission was found to be error free. When no equalization was used, a BER of $5 \cdot 10^{-5}$ was found. We then further investigated the evolution of the online determined EVM as a function of the symbol rate of the 16-QAM signal on a 20 GHz carrier. This is shown in Fig. 7. Because we are operating on the edge of the bandwidth of the TIA, we see a steady increase of the EVM as the symbol rate is increased. Offline analysis of the 16 Gbps transmission shows a BER of $3 \cdot 10^{-6}$. The constellation diagram for the 16 Gbps link is shown in Fig. 5b.

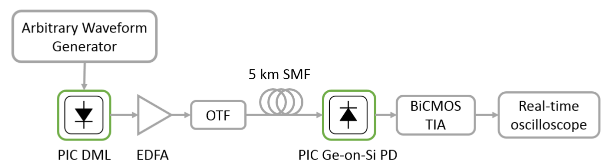


Fig. 6: Overview of the measurement set-up. PIC: Photonic Integrated Circuit, DML: Directly Modulated Laser, EDFA: Erbium Doped Fiber Amplifier, OTF: Optical Tunable Filter.

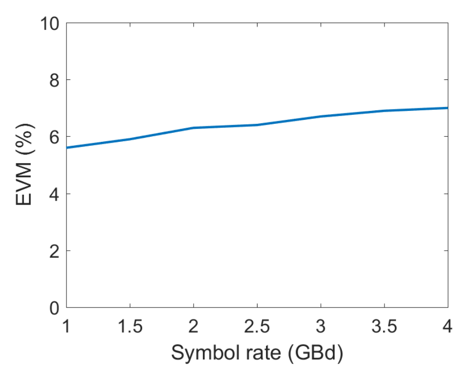


Fig. 7: The Error Vector Magnitude (EVM) as function of the symbol rate, for a 16-QAM signal on a 20 GHz carrier.

V. Conclusion

In this work we have demonstrated a Si photonic integrated circuit based RoF link which can transmit 16 Gbps of data on a 20 GHz carrier at a BER of $3 \cdot 10^{-6}$. This is to the best of our knowledge the first Si PIC based RoF link with a directly modulated laser. The use of distributed feedback lasers on a silicon photonic platform allows for wavelength division mulitplexing in future generation transceivers.

REFERENCES

[1] H. Tan, W. Li, T. Wang, J. Fang and Z. Feng, ”The analysis on the candidate frequency bands of future mobile communication systems,” China Communications, vol. 12, pp. 140-149, 2015.

[2] D C. Liu, J. Wang, L. Cheng, M. Zhu and G. K. Chang, Key Microwave-Photonics Technologies for Next-Generation Cloud-Based Radio Access Networks, Journal of Lightwave Technology, vol. 32, no. 20, pp. 3452-3460, 2014.

[3] W. Zhang and J. Yao, ”Silicon-Based Integrated Microwave Photonics,” in IEEE Journal of Quantum Electronics, vol. 52, no. 1, pp. 1-12, Jan. 2016.

[4] J. E. Bowers, T. Komljenovic, J. Hulme, M. Davenport and C. Zhang, ”Integrated photonics for MWP,” 2016 IEEE Photonics Conference (IPC), Waikoloa, HI, 2016, pp. 1-2.

[5] J. C. Hulme et al., ”Fully integrated heterodyne microwave generation on heterogeneous silicon-III/V,” 2016 IEEE International Topical Meeting on Microwave Photonics (MWP), Long Beach, CA, 2016, pp. 336-339.

[6] A. Abbasi; B. Moeneclaey; J. Verbist; X. Yin; J. Bauwelinck; G. H. Duan; G. Roelkens; G. Morthier, ”Direct and electro-absorption modulation of a III-V-on-silicon DFB laser at 56 Gbps,” in IEEE Journal of Selected Topics in Quantum Electronics , vol.PP, no.99, pp.1-1, doi: 10.1109/JSTQE.2017.2708606

[7] H. Chen, P. Verheyen, P. De Heyn, G. Lepage, J. De Coster, S. Balakrishnan, P. Absil, W. Yao, L. Shen, G. Roelkens, J. Van Campenhout,”-1 V bias 67 GHz bandwidth Si-contacted germanium waveguide pin photodetector for optical links at 56 Gbps and beyond,” Optics Express, 24(5), p.4622-4631 (2016)

[8] G. Roelkens et al., ”III-V-on-silicon photonic devices for optical communication and sensing,” Photonics (invited), 2(3), p.969-1004 (2015)

[9] B. Moeneclaey, J. Verbrugghe, E. Mentovich, P. Bakopoulos, J. Bauwelinck and X. Yin, ”A 64 Gb/s PAM-4 transimpedance amplifier for optical links,” 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, USA, 2017, pp. 1-3.