10G/28G Chirp Managed 20 km Links based on Silicon Photonics Transceivers

A. Abbasi, B. Moeneclaey, X. Yin, J. Bauwelinck, G. Roelkens, G. Morthier

***Abstract*— High speed directly modulated single mode lasers are becoming important optical components for short reach communication. In order to cover a transmission distance that is required for PON and inter data-center applications, the chirp managed laser (CML) is an attractive transmitter technology. This technology enables to use a directly modulated laser (DML) for longer reach systems, resulting in a smaller footprint, low fabrication cost and lower power consumption. Error free 10 Gb/s non-return-to-zero-on-off-keying (NRZ-OOK) data transmission over 20 km standard single mode fiber (SMF) is demonstrated using a heterogeneously integrated III-V-on-Si distributed feedback laser in combination with a tunable optical filter as a transmitter and a Ge-on-Si waveguide-coupled Avalanche Photodiode (APD) with an integrated transimpedance amplifier (TIA) as a receiver. For inter-datacenter applications, by increasing the bias current of the laser (improving its modulation bandwidth and output power) and using a faster silicon-contacted germanium waveguide p-i-n photodetector with an integrated TIA, 28 Gb/s NRZ-OOK data transmission over 20 km standard single mode fiber is demonstrated..**

***Index Terms*— Chirp management, direct modulation, DFB lasers, avalanche photodiodes, Silicon photonics.**

I. Introduction

PASSIVE optical network (PON) technologies are being upgraded to meet the ever increasing bandwidth demand for the next generation of fiber access networks [1]. 10G-PON is already implemented for Fiber-to-the-Home (FTTH) application. Moreover, applications such as inter-datacenter interconnection and ultra-fast 25G-EPON require data transmission even at higher bit rate of 25 Gb/s over at least 20 km of standard single mode fiber in a cost effective way [2,3]. Transmission over such long distances has been done traditionally using externally modulated light sources rather than directly modulated devices in the C-band, because the chirp of directly modulated laser diodes gives rise to serious dispersion problems when using standard single mode fiber. However, direct modulation of laser diodes has several advantages over external modulation, such as a better power budget, lower complexity, a smaller footprint and cost effectiveness. Recently it has been demonstrated that even very high bitrate signals obtained using direct laser modulation can be transmitted over several tens of km of single mode fiber thanks to the technique of chirp management (CML) [4, 6]. In this approach, the transient chirp of the directly modulated laser diode is kept small by modulating the laser diode at high bias current with a small extinction ratio. Combination of the laser adiabatic chirp and an optical filter edge suppress the logical zero frequency which results in a higher extinction ratio, while creating a π phase shift between '1' bits which are separated by an odd number of '0' bits, thereby effectively creating an optical duobinary signal. This technique has been applied to demonstrate transmission of a 56 Gb/s signal over 10 km of standard single mode fiber using a commercially available monolithically integrated DFB laser [6].

In the past years, using silicon photonics for interconnects and PON applications got a lot of attention. Heterogeneously integrated III-V-on-silicon laser diodes have been shown capable of high-speed direct modulation up to 28 Gb/s [7,8]. As we mentioned earlier, the chirp of a directly modulated laser hinders its application for long distance communication. Applying the chirp management concept to the heterogeneously integrated transmitters will add new functionalities to this interesting III-V-on-Si platform. In [9], a ring resonator was used to shape the modulated signal spectrum and extend the link distance to 40 km at 20 Gb/s. However, in their measurement, a commercially available III-V receiver was used. In order to exploit the full functionality of Si photonics for high-speed transceivers we need high performance, low bias photodetectors (PD) integrated on a silicon photonic platform. Ge/Si waveguide PDs are becoming critical building blocks in silicon photonics optical interconnects and have been studied extensively. Optical receivers based on high modulation bandwidth, high responsivity and low dark current Ge PDs enhance the performance of Si-based optical interconnects [10,11]. Using these two silicon photonics technologies for the transmitter and the receiver enables to move towards high volume, low cost and integratable transceivers.

In this paper, first of all, we will present our recent 10G-PON CML results based on a silicon photonic transceiver. At the transmitter side, a heterogeneously integrated III-V-on-Si directly modulated DFB laser was used in combination with an optical filter with a 0.2 nm 3 dB bandwidth. The receiver was constructed using a low-voltage Ge waveguide APD wire-bonded to a 130 nm SiGe BiCMOS trans-impedance amplifier (TIA) [12]. In the second part of the paper, we will show 28 Gb/s NRZ-OOK data transmission using the same laser but biased at a higher current in order to enhance its modulation bandwidth and output power. At the receiver side, we have

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used a silicon-contacted Ge waveguide p-i-n PD with an integrated TIA with a combined 25 GHz modulation bandwidth [11, 13]. In both cases, the transmission link distance was 20 km of standard single mode fiber SMF-28, and the link was operated in the C-band.

II. TRANSMITTER

The transmitter is a heterogeneously integrated III-V-on-Si directly modulated DFB laser [7]. The DFB laser is fabricated using adhesive BCB bonding of the epitaxial structure, containing 8 InGaAlAs quantum wells as active region, to a silicon photonic integrated circuit. Ridge waveguides are defined on the bonded III-V material by contact lithography and both wet and dry etching. The final structure is metalized for both N and P contacts using evaporation/sputtering. The silicon photonic circuit consists of 400 nm thick silicon rib waveguides with a 180 nm deep UV etch depth. Underneath the III-V waveguide, a DFB grating (grating period 245 nm, grating duty cycle of 50%, 340 μm length with a quarter wave shift placed 35 μm away from the right edge of the grating) is etched in the silicon waveguide. The light is guided in a hybrid mode of the III-V/Si waveguide and is coupled from the III-V section to the passive Si waveguide by adiabatic tapering of both the III-V and Si waveguides, using 200 μm long taper structures. The tapering ensures maximum coupling and low reflection, which are essential for the fabrication of a high power and stable laser. The laser structure is similar to that reported in [7], except that the two 200 μm long InP tapers on either side of the DFB laser are electrically isolated and can be separately biased. This separation helped to suppress the strong low frequency response that was observed earlier in [14] and thereby flattened the small signal modulation response. The isolation was realized by etching a trench through the top InGaAs p-contact layer and part of the p-InP. The laser is connected on both ends to vertical grating couplers to couple the light to the SMF shown in Fig. 1 (a).

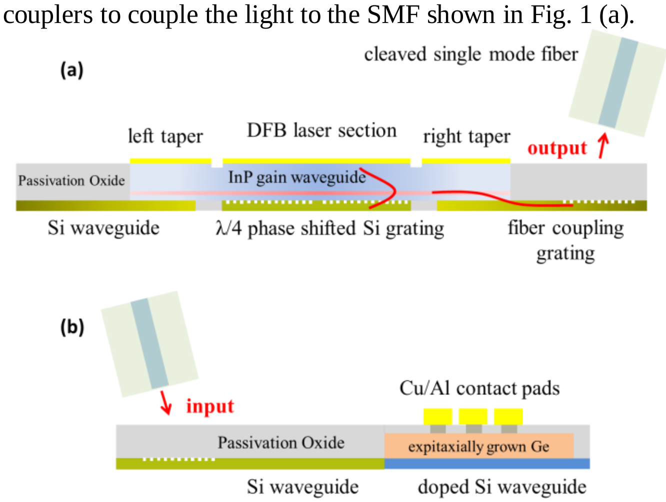

Fig. 1. (a) Schematic side view of the III-V-on-Si DFB laser. (b) Schematic of the waveguide-coupled Ge-on-Si APD. [15].

The static characterization of the DFB laser was first done on a temperature-controlled stage, with the laser contacted using electrical probe needles. The LIV curve and spectrum of the laser are shown in Fig. 2. As it is shown in Fig. 2, the laser shows excellent single mode behavior at 1570 nm with a side mode suppression of over 40 dB. The series resistance of the device is 7 Ω. The threshold current is 20 mA and the output power coupled to the silicon waveguide is approximately 3 mW for 100 mA laser bias current (with a taper bias of 10 mA). The isolation resistance between the DFB and the taper section was measured to be 3 kΩ. The coupling loss from the Si grating coupler into a cleaved single mode fiber was about 7 dB.

To determine the modulation bandwidth a small signal analysis of the laser was performed using a Keysight PNA-X 67 GHz network analyzer. The frequency response of the laser is shown for three different bias currents in Fig. 3. It is obvious that the modulation bandwidth of the laser increases with increasing bias current and that the response becomes flatter. A bandwidth above 14 GHz is obtained at a bias current of 100 mA.

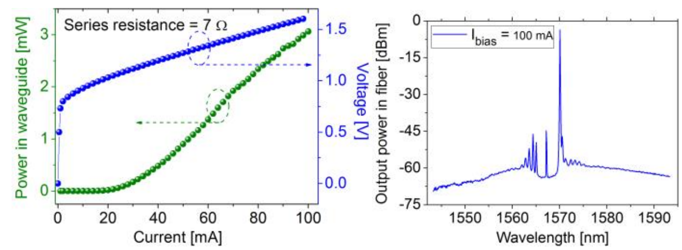

Fig. 2. Optical output power in the Si waveguide and the voltage over the laser diode as a function of the bias current , showing a series resistance of 7 Ω (left), the laser spectrum at 100 mA bias current, T = 20℃ (right).

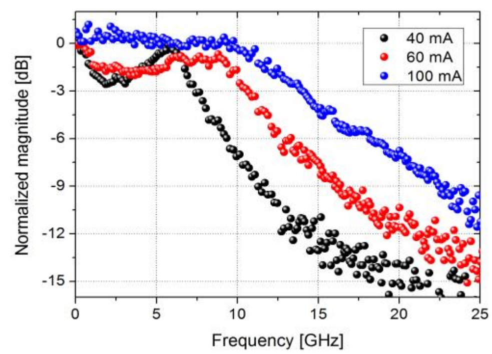

Fig. 3. Small signal response of the laser with isolated tapers at different bias currents to the laser, T = 20℃.

III. RECEIVER

For the full Si link experiment, we have used two different receivers for two different bit rates. For the lower bit rate of 10 Gb/s, and targeting PON applications, the receiver was a Ge-on-Si waveguide-coupled APD on a Si PIC co-integrated with a wire bonded burst mode TIA [10]. The burst-mode TIA was designed in 130 nm SiGe BiCMOS technology and has an input referred RMS noise current lower than 1.2 μA. The receiver electronics has multiple gain and bandwidth settings that can be optimized to the needs of the link [12]. For the 28 Gb/s experiment, a silicon-contacted Ge waveguide p-i-n PD integrated with a fast SiGe BiCMOS TIA was used [11,13]. The integrated receiver modulation bandwidth was 25 GHz (Fig. 4). A 3 V reverse bias is applied to the PD. The bandwidth and gain of the receiver was adjusted to optimize the transmitted signal quality. The TIA has an input referred (RMS) noise current of ~2 μA for 28 Gb/s settings.

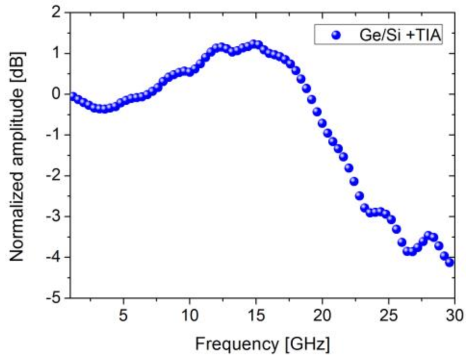

Fig. 4. Small signal response of the Ge waveguide p-i-n PD with integrated TIA.

IV. Link Demonstration

For the measurement at 10 Gb/s, the schematic of the measurement setup is shown in Fig. 5. The III-V-on-Silicon DML was mounted on a temperature-controlled stage and kept at a constant temperature of 20°C. The laser was contacted using a 40 GHz bandwidth Cascade RF probe. A Santec-350 optical filter that is tunable in wavelength and bandwidth is inserted after the laser diode. The laser was biased at 50 mA. The large signal measurement has been done in two configurations: for back-to-back and after transmission over a 20 km SMF-28. An RF signal of 0.6 V_{pp} from a SHF pulse pattern generator (PPG) was applied to the laser for the modulation. A 6 V reverse bias is applied to the APD.

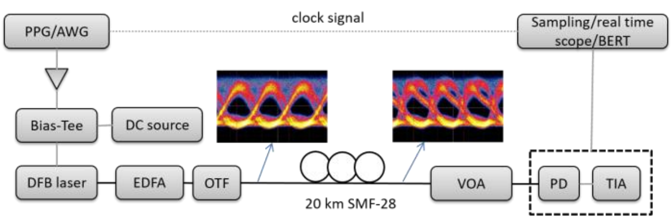

Fig. 5. Overview of the measurement set-up.

The bandwidth of the filter (0.2 nm) and its slope position were adjusted for the best performance after 20 km of SMF-28. The eye diagrams at 10 Gb/s are depicted in the insets of Fig. 5 for the back to back case and after transmission over 20 km of SMF-28. The extinction ratio of the signal was increased from 5.9 to 16.3 dB by the application of the optical filter. The position of the lasing wavelength with respect to the optical filter is depicted in Fig. 6, in which the red trace corresponds to the laser spectrum and the blue trace corresponds to the filter characteristic. The blue shifted '1' state will be transmitted while the '0' state will be suppressed at the edge of the filter (with a slope of 2.4 dB/GHz).

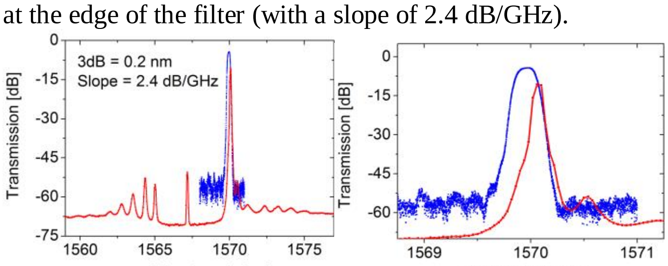

Fig. 6. Optical spectrum of the laser with respect to the filter transmission spectrum (left), zoom-in of both spectra (right).

The Bit Error Rate (BER) was measured using an SHF Error Detector (ED). The BER curves at 10 Gb/s are given in Fig. 7 for two PRBS pattern lengths of 2^7-1 and 2^{31}-1 with 1.5 dB power penalty for 20 km fiber transmission. The good sensitivity allows for a large splitting ratio in PON networks.

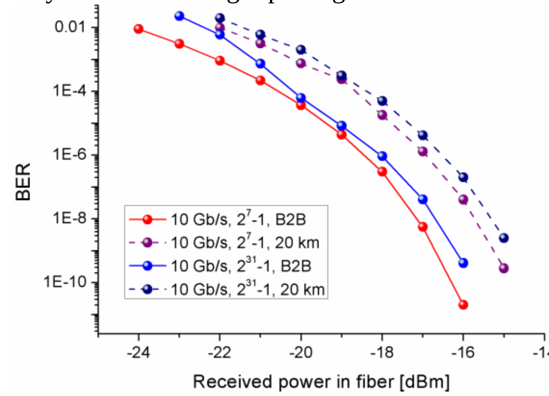

Fig. 7. BER vs received optical power at 10 Gb/s for two different PRBS patterns lengths and for a 50 mA bias current to the DFB laser, T = 20℃.

Stable single mode operation and alignment of the laser wavelength with the optical filter is critical for chirp managed links. For stability, one can use a PS in the middle of a DFB cavity or exploit a so-called distributed reflector (DR) laser approach [16] to satisfy these conditions. The alignment of laser wavelength and filter can be achieved by implementing a micro-heater on top of the silicon filter, to tune its wavelength of operation.

For the measurement at 28 Gb/s, the laser bias current was increased to 100 mA and a high bandwidth receiver (Ge on Si p-i-n photodetector + SiGe BiCMOS TIA) was used at 3 V reverse bias. A 1 V_{pp} drive signal was generated by a Keysight M8195A arbitrary waveform generator (AWG), which is used to drive the laser through a bias tee. Again the OTF filter was used after the EDFA for the chirp management and also for removing amplified spontaneous emission of the amplifier. The bandwidth of the filter (0.25 nm) and its slope position were adjusted for the best performance after 20 km of SMF-28. Fig. 8 shows the eye diagrams at 28 Gb/s for the back-to-back case and after transmission over 20 km of SMF-28. A data stream is stored using the real time oscilloscope and off-line BER analysis is performed using Matlab. The BER curves at 28 Gb/s are given in Fig. 9 for two different pattern lengths. At 28 Gb/s, the extinction ratio of the signal was increased from 1.6 to 4.8 dB by the application of the optical filter.

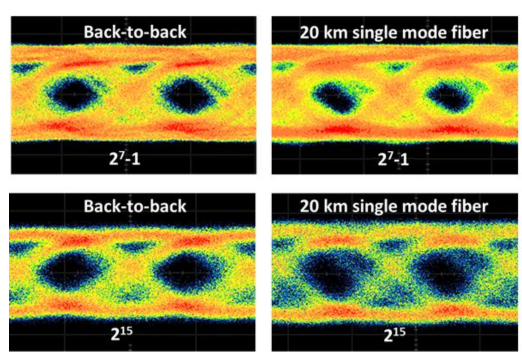

Fig. 8. Eye diagrams at 28 Gb/s for the back-to-back case (left) and after transmission over 20 km SMF-28 (right) for the pattern length of 2^7-1 (first row) and 2^{15} (second row) , T = 20℃.

In principle four different wavelengths in C-band from four directly modulated DFB laser diodes can be multiplexed in Course Wavelength Division Multiplexing (CWDM) format to increase the aggregate data rate to 100 Gb/s (4x25 Gb/s) for short and medium reach applications. Flat-top and low loss silicon-on-insulator four-channel MUX filters have already been demonstrated [17] and will be implemented with our heterogeneous integration platform in the near future.

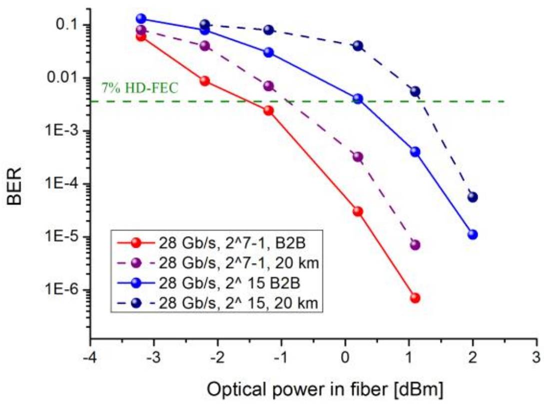

Fig. 9. BER vs received optical power at 28 Gb/s for two different PRBS patterns lengths. I_{bias} = 100 mA, T = 20℃.

V. Conclusion

In summary, we investigated 10 and 28 Gb/s chirp managed links using direct modulation of a heterogeneously integrated InP-on-Si DFB laser diode and a silicon photonic receiver. For the 10 Gb/s experiment, the laser is biased at much lower bias current than for the 28 Gb/s experiment and the APD +TIA receiver is used to meet the high sensitivity requirements of 10G-PON systems. At 28 Gb/s the laser bandwidth and output power is increased by increasing the bias current and a faster silicon photonics receiver is used. A chirp-managed silicon photonic transceiver is well suited for inter-datacenter and 25G-PON applications where small form factor pluggable transceivers are desirable. Although the filter was a commercial instrument, it can be replaced with a ring resonator with engineered spectrum similar to the work in [9, 18, 19]. The use of integrated DFB lasers creates a straightforward path to implement wavelength division multiplexing on the chip, allowing to increase the aggregate bitrate per transceiver chip.

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