III–V-on-Silicon C-Band High-Speed Electro-Absorption-Modulated DFB Laser

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Abstract—**Externally modulated lasers have proven to be key components for optical communication because of their compactness, low-power consumption, and speed. In this paper, we present unique heterogeneously integrated InP-on-Si electro-absorption-modulated DFB lasers, which were used to implement two optical modulation schemes. The first scheme uses a double-sided externally modulated DFB laser. Two taper sections on each side of the single DFB laser are fabricated with an identical epitaxial structure as the laser and perform two roles: coupling the light to the underlying Si waveguide and acting as modulators. These taper sections are electrically isolated from the DFB laser cavity. Each section can independently be driven with a 56-Gb/s non-return-to-zero (NRZ) on–off-keying signal resulting in 112–Gb/s aggregate data transmission from the device over 2-km non-zero dispersion-shifted single-mode fiber. The second scheme is an original method to generate an optical pulse amplitude modulation (PAM) signal using a similar device structure. By simultaneously directly modulating the DFB laser and one of the tapers (operating as an electro-absorption modulator) with two independent NRZ signals, we demonstrate the generation of a PAM-4 signal. In this way, the PAM-4 signal generation can be shifted from the electrical to the optical domain in a rather simple and power efficient way. We demonstrate the transmission of 25-Gbaud PAM-4 over 2-km non-zero dispersion-shifted single-mode fiber.**

Index Terms—**Distributed feedback lasers, electro-absorption modulation, hybrid integrated circuit fabrication, pulse amplitude modulation, silicon photonics.**

Manuscript received July 1, 2017; revised August 10, 2017; accepted August 16, 2017. Date of publication August 24, 2017; date of current version February 24, 2018. This work was supported in part by the UGent special research fund BOF and in part by the Belgian IAP network Photonics@be 14/GOA/034 and some of the high-speed equipment used in the work was supported by the Hercules Program of the Flemish Government. *(Corresponding author: Amin Abbasi).*

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I. Introduction

THE data traffi is exploding because of a worldwide spread of cloud computing and video streaming. This creates a huge demand for very high bitrate, low cost and compact optical interconnects, e.g., for intra-data-center and inter-data-center interconnects. There is a real need for optical components which would fi into a compact QSFP form factor and keep up with the fast increase in required data rates. The devices should be fast, compact, cost effective and suitable for large scale volume fabrication. In order to meet these requirements, high speed electro-absorption modulators (EAMs) based on the quantum confine Stark effect (QCSE) are being developed especially for short-reach applications.

For most proposed 400 GbE applications intensity modulation with direct detection is a promising approach [1]–[5]. Two modulation schemes have been considered for these 400 Gbps systems. NRZ-OOK is the simplest modulation format, providing a good trade-off between required modulation bandwidth and the complexity of the electronics. On the other hand, PAM-4, a four-level modulation format, is receiving a lot of attention because of a higher spectral efficien y compared to the OOK signal. With the same system bandwidth, one can double the signal bitrate at the cost of a higher complexity of the electronics and a lower optical modulation amplitude.

In the past years, most of the active photonic components were fabricated on a III-V monolithic integration platform. High performance lasers, modulators and photodiodes have been demonstrated using this technology. However, since some years silicon photonics is recognized as a potentially promising technology for optical interconnects due to the high refractive index contrast and its CMOS compatibility [6], [7]. This technology enables very dense optical integration as well as co-integration with the driver electronics. Due to the high index contrast of the silicon-on-insulator waveguide platform, it allows to fabricate all sorts of passive components (e.g., wavelength multiplexers and polarization control elements) with very small dimensions and low loss. The compatibility with CMOS fabrication tools also allows very large volume fabrication. The huge potential of both the III-V and the Si technology was a great motivation for the optical community to explore how to combine these leading technologies into one advanced platform with the best features

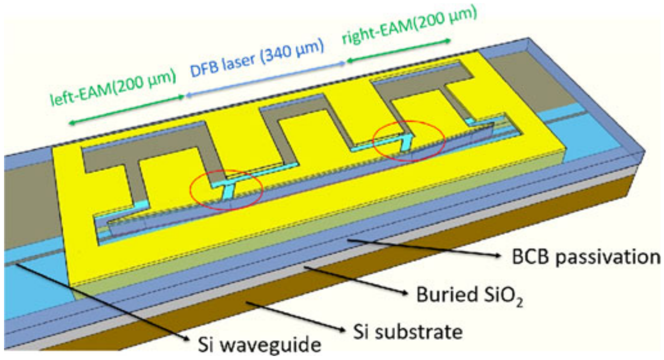
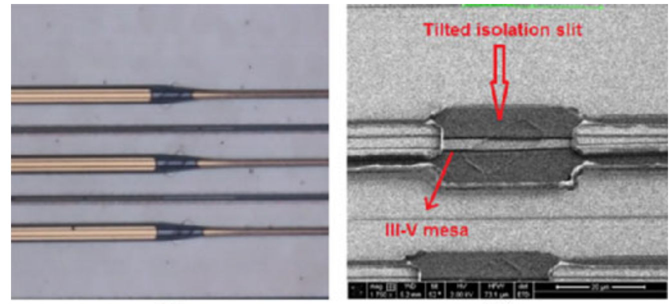


Fig. 1. Schematic of the III-V-on-silicon laser structure. The device consists of the central DFB section and two coupling tapers on each side. The tapers are electrically isolated by etching angled patterns into the p-InP (red circles).



(a) (b)

Fig. 2. Microscope image of the isolation area after the P-contact metallization (a), SEM image of the isolation area (a 45° angled rectangle is used to reduce optical back reflection (b).

of both. One approach is to directly mount pre-fabricated III-V active components such as lasers onto Si photonic circuits using flip-chi technology [8]. However this requires stringent alignment accuracy resulting in a high packaging cost especially when we consider scalability (i.e., integrating multiple lasers in a single transceiver). Considering these limitations, an interesting and fl xible heterogeneous integration technology has been developed [9]–[12]. Since then, there has been significan progress in III-V-on-silicon transceivers which consist of lasers, modulators and photodiodes, with the passive functionality implemented in silicon. Heterogeneously integrated tunable lasers [13], directly modulated lasers at 56 Gbps [14], high speed photodiodes [15] and electro-absorption modulators [16] have been reported based on InP-on-Si photonic integrated circuits.

In this paper, we present a heterogeneously integrated InP-on-Si double-sided electro-absorption-modulated DFB laser. This architecture is similar to an all-III-V version reported in [17]. EAMs are located on each side of the laser and can be independently modulated at 56 Gbps. The compact size of this device makes it an interesting solution for high-speed short-reach optical links. Using a similar DFB/EAM configuration we also demonstrate optical PAM-4 generation at 25 Gbaud by directly modulating the DFB laser and one of the EAMs with two uncorrelated independent NRZ signals at 25 Gbps. A similar optical digital-to-analog conversion has been demonstrated with a Multi-Electrode Mach–Zehnder Modulator (ME-MZM) [18] and Dual Parallel MZM (DP-MZM) [19], avoiding the need for a high-speed electronic digital-to-analog converter and resulting in lower power consumption and cost.

II. Fabrication and Static Measurement

The fabrication process for the EML transmitter starts by integrating the III-V multi quantum well epitaxial structure on top of the SOI waveguides using adhesive bonding and subsequent processing [20], [21]. The transmitter structure is similar to our previously reported heterogeneously integrated DFB laser [22]. A schematic of the device is depicted in Fig. 1. The laser section is 340 μm long and each taper is 200 μm long. The tapers have two functionalities. One role is to couple the light from the III-V waveguide to the underlying Si waveguide. At the same time, they act as electro-absorption modulators by reverse biasing. Optimized low reflectio coupling between the III-V waveguide and the 400 nm thick silicon waveguide is obtained by adiabatic tapering of both the InP mesa and the Si waveguide.

The InP epitaxial stack is the same for both the laser and the EAMs which eases the fabrication process. The active layer of the III-V stack consists of 6 InGaAsP quantum wells sandwiched between two 100 nm thick InGaAsP separate confinemen heterostructure (SCH) layers. A 200 nm thick doped n-InP provides a low sheet resistance underneath the bottom SCH layer. Using a single epitaxial layer structure for the laser and the EAM requires a careful design of the DFB grating period in order to avoid large insertion loss in the EAM section. The laser wavelength is pushed to the long-wavelength side as much as possible to minimize losses. The laser and EAMs are electrically isolated before P-contact metallization by forming 45 degree isolating rectangular patterns on the III-V waveguides using contact UV lithography followed by ICP dry etching through the InGaAs P++ contact layer (200 nm) and partially through the P-InP top cladding layer (300 nm) (see Fig. 2). By etching these isolation patterns which are 20 μm wide and 500 nm deep, a DC isolation resistance of 16 kΩ between both EAMs is achieved.

The threshold current of the laser at room temperature is 22 mA and the series resistance is 8 Ω. The output power of the device is collected by using two Si vertical grating couplers on the left and right hand side of the device. At 0 Volt EAM bias, the output power in the silicon waveguide is above 1 mW on each side at 50 mA bias current. As shown in Fig. 3, the laser spectrum is single mode at 1564 nm with more than 40 dB side mode suppression ratio. The output power from both grating couplers is nearly identical.

As we discussed before, using the same epitaxial structure for the laser and EAMs has a limitation on the lasing wavelength. In order to lower the insertion loss and increase the modulation efficien y, lasers with emission wavelength close to the bandgap were selected. The bias current to the DFB was fi ed to 50 mA. The normalized transmission of both EAMs is depicted in Fig. 4 versus the reverse bias voltage of the EAMs. A DC extinction ratio of $\sim$15 dB is obtained for a voltage swing of 1.5 Volt (between 0 V and -1.5 V) for both tapers.

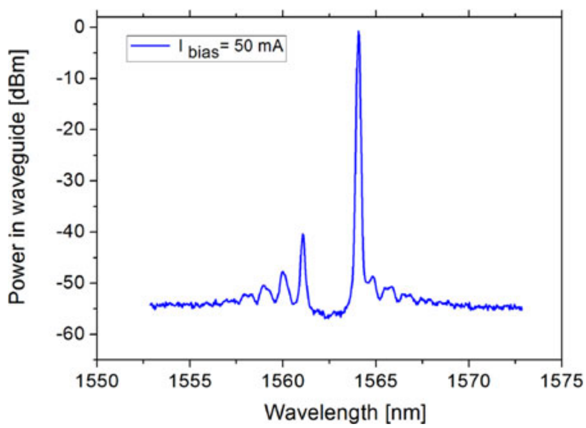


Fig. 3. The laser spectrum at 50 mA bias current and 0 Volt EAM bias voltage.

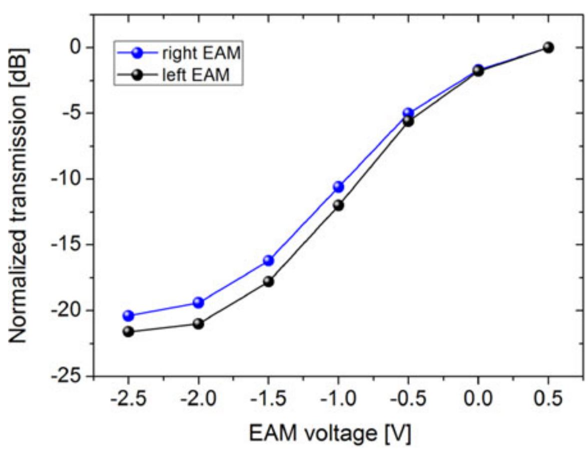


Fig. 4. Normalized transmission for both EAMs, $I_{DFB} = 50\,mA$, $T = 20\,°C$.

III. Double-sided Electro-Absorption Modulated DFB Laser: Dynamic Measurement

For the small signal characterization of the device, two identical 40 GHz GSG probes with 100 μm pitch are landed on the EAM pads while the DFB laser is DC biased at 50 mA. No matching resistor has been used during both the small signal and the large signal experiments. A Keysight PNA-X 67 GHz network analyzer is used to measure the electro-optical response. For this measurement, 0.7 Volt reverse bias was applied on each taper. The electro-optical response of the device is shown in Fig. 5. The 3 dB modulation bandwidth for both EAMs is about 20 GHz.

Since two EAMs are fabricated in one single structure, crosstalk between them can be an issue. In order to measure the crosstalk between EAMs, a sinusoidal tone with 1 Volt voltage swing is applied to one of the tapers while the optical signal was measured from the grating coupler at the other side. During measurement the bias conditions and temperature are kept the same as mentioned above. More than 50 dB RF isolation was measured in both directions up to 25 GHz. This amount of isolation should be enough to prevent the crosstalk from deteriorating the transmitted signals.

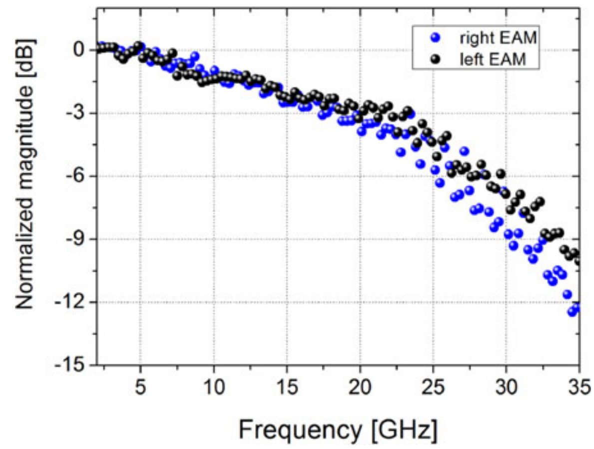


Fig. 5. Small-signal frequency response of each EAM at 0.7 V reverse bias voltage, $I_{DFB} = 50\,mA$, $T = 20\,°C$.

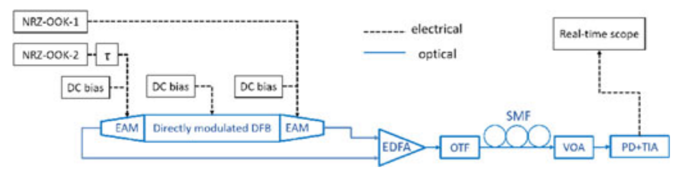


Fig. 6. Experimental setup. EDFA: erbium doped fibe amplifier OTF: Optical tunable filter VOA: variable optical attenuator; SMF: single mode fiber PD: photo-detector; TIA: trans-impedance amplifie .

For the large signal characterization, a Keysight M8195A AWG is used to generate NRZ-OOK PRBS sequences of 2^7-1 and 2^{15} with a voltage swing of 1.5 V_{pp}. A variable delay is applied to make two uncorrelated NRZ-OOK signals. The DFB laser and EAMs are biased at 50 mA and 0.7 Volt reverse voltage, respectively. In order to compensate the grating coupler loss and to boost the optical signal an Erbium Doped Fiber Amplifie (EDFA) is used (see Fig. 6). An optical filte (0.3 nm bandwidth) with 4 dB insertion loss is used to suppress the amplifie spontaneous emission of the EDFA. The signal is directly detected by a commercial photodiode and trans-impedance amplifie (TIA) with a bandwidth of 32 GHz (Discovery Semiconductor DSCR 409). The received electrical signal is captured by a real-time oscilloscope (Keysight DSA-Z63) with a sampling rate of 80 GS/s.

The measurement is performed for both the back-to-back case and after transmission over 2 km of non-zero dispersion shifted fibe (NZ-DSF) with a dispersion of 6 ps/nm·km at the laser wavelength. Eye diagrams are shown in Fig. 7 for both left and right EAMs at 56 Gbps. These eyes are captured while both EAMs were under 56 Gbps modulation simultaneously.

Data streams are stored using the real-time oscilloscope and off-line Bit Error Rate (BER) analysis is performed using Matlab. The results of the BER analysis are shown in Fig. 8. For all measurements, without any digital signal processing (DSP), BERs were below the 7% HD-FEC limit. The data for the right and left EAM are very similar. Each optically modulated signal was separately measured using a single receiver. This is similar to a multilane data communication link using two optical fibers However, by using a 2D grating coupler one could multiplex the

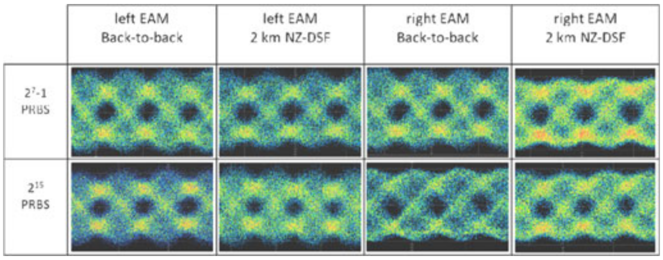


Fig. 7. Eye diagrams at 56 Gb/s NRZ-OOK with PRBS 2^7-1 pattern length (firs row); PRBS 2^{15} pattern length (second row); left EAM for both back-to-back and after 2 km NZ-DSF (two left columns); right EAM for both back-to-back and after 2 km NZ-DSF (two right columns). $I_{DFB} = 50\,mA$, $V_{EAM} = -0.7\,V$, $T = 20\,^\circ C$.

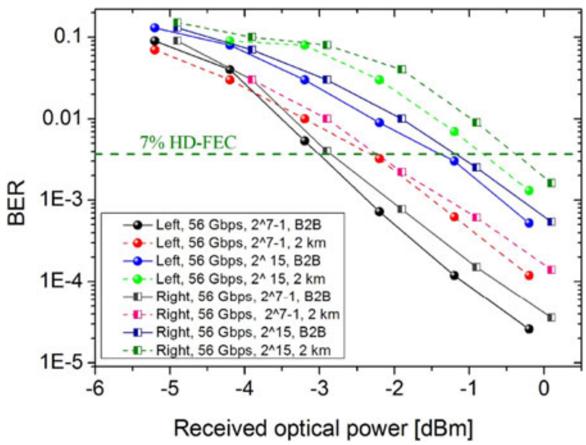


Fig. 8. BER vs received optical power at 56 Gbps for the back-to-back case and after transmission over 2 km of NZ-DSF fibe. Both EAMs are reverse biased at 0.7 Volt, $I_{DFB} = 50\,mA$, $T = 20\,^\circ C$.

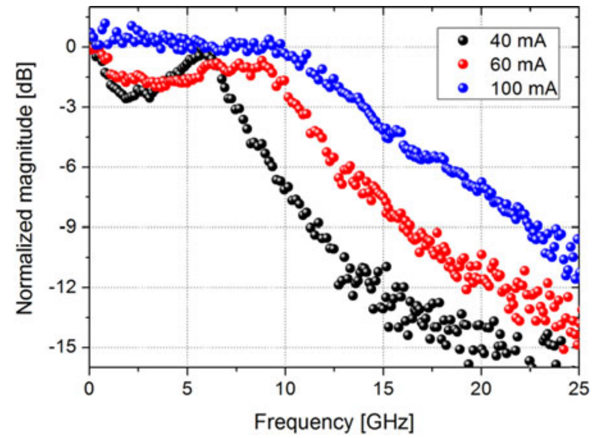


Fig. 9. Small-signal response of the laser with isolated tapers at different bias currents, $T = 20\,^\circ C$.

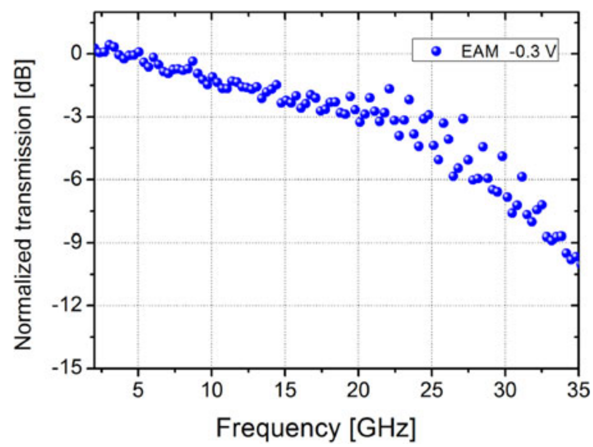


Fig. 10. Small-signal modulation characteristics of the EAM at 100 mA bias current to the DFB laser [14].

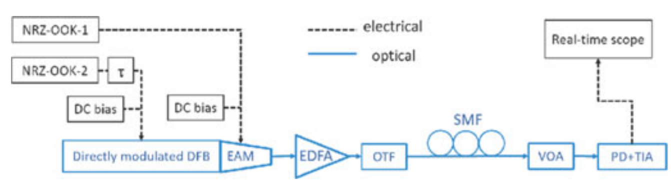


Fig. 11. Schematic of the experimental setup for the DFB/EAM PAM-4 measurement. Two NRZ-OOK signals are combined in the optical domain to generate an optical PAM-4 signal.

two outputs in polarization and use a single optical fibe for the transmission at an aggregate data rate of 112 Gbps.

IV. DFB/EAM PAM-4 Transmitter

In this experiment, the goal is to carry out direct intensity modulation of a laser and further modulate the optical signal using electro-absorption modulation using a single integrated DFB-EAM device. Simultaneously two NRZ-OOK signals are used to generate an optical PAM-4 signal. To do this, a DFB laser with a high modulation bandwidth is required. The direct modulation bandwidth of the InGaAsP based laser from the previous section was not high enough to achieve a high bit rate. For this experiment, we fabricated DFB-EAM devices using an epitaxial layer structure with 8 InGaAlAs quantum wells as the active region using the same bonding technique and device architecture (the same sample that was used in ref [14]). Threshold currents of 20 mA at room temperature, output powers in the silicon waveguide above 1.5 mW at 100 mA at 0 Volt bias of the EAM, and a series resistance of 7 Ω were measured for the laser. The lasing wavelength is located at 1570 nm with a wide stop band of 5 nm. The SMSR is larger than 40 dB.

The small-signal response of the laser is measured at different bias currents (see Fig. 9). It is obvious that the modulation bandwidth of the laser increases with increasing bias current and that the response becomes flatte. A bandwidth above 14 GHz is obtained at a bias current of 100 mA.

The static characterization of the EAM is done by reverse biasing it at 0.3 Volt. A DC extinction ratio of 15 dB is obtained for a voltage swing of 1.5 V on the EAM. The small-signal response of the EAM was measured at this bias point while the laser is biased at 100 mA (see Fig. 10). The electro-optical response of the EAM is very similar to the InGaAsP EAMs discussed in the previous section.

The PAM-4 experimental setup based on the DFB-EAM device is illustrated in Fig. 11. Two independent NRZ-OOK signals (1 and 2) are generated using the AWG with a maximum baud rate of 25 Gbaud. A tunable delay between these two RF signals is applied to accurately align the transitions of both bit

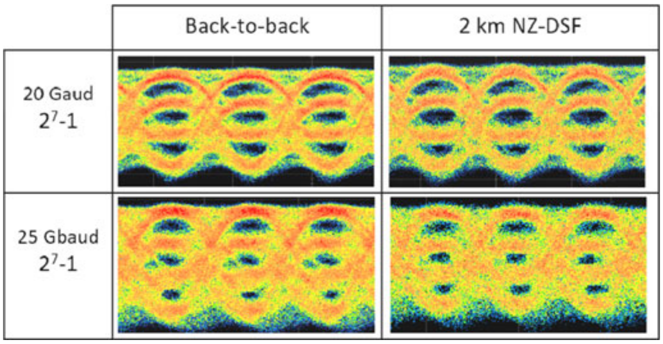


Fig. 12. Eye diagrams of 20 and 25 Gbaud optical PAM-4 signals with PRBS 2^7-1 pattern length for back-to-back and over 2 km NZ-DSF fibe . DFB current = 100 mA, EAM bias = –0.3 Volt, $V_{\rm pp}$ = 1 Volt for both DML and EML, T = 20 °C.

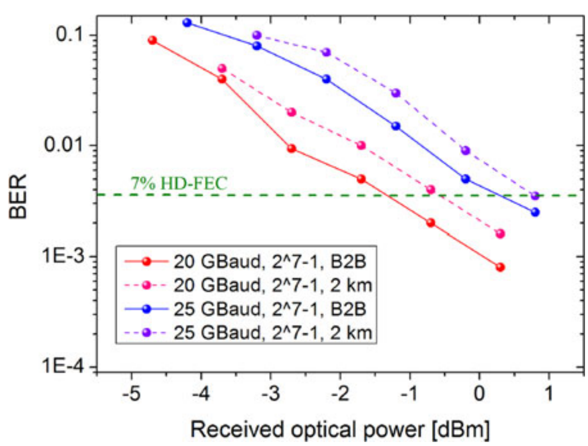


Fig. 13. BER vs received optical power at 20 and 25 GBaud PAM-4 transmission for the back-to-back case and after transmission over 2 km of NZ-DSF fibe .

streams. A 1 $V_{\rm pp}$ voltage swing NRZ-OOK-1 signal is applied to the DFB laser, together with a 100 mA DC bias current. Similarly, the EAM is biased at 0.3 Volt reverse bias and externally modulated by the 1 $V_{\rm pp}$ NRZ-OOK-2 signal. Since the laser is biased at a high DC current, the modulation bandwidth increases at the cost of a lower extinction ratio. A lower extinction ratio of the laser together with a higher ER from the EAM is desirable for a multi-level optical signal generation. The optical tunable filte and the laser bias point are adjusted to obtain an optimum transmission.

Transmission over 2 km of nonzero dispersion shifted fibe (NZ-DSF) was performed as well. Open eyes were obtained up to 25 Gbaud (50 Gbps), both for the back-to-back case and after transmission over 2 km NZ-DSF fibe . Fig. 12 shows the eye diagrams at 20 and 25 Gbaud (40 and 50 Gbps) for a pattern length of 2^7-1. Comparing the small-signal responses of the DFB and the EAM reveals that the modulation speed of the DFB laser is the limiting factor to go beyond 50 Gbps.

The BER results for optical PAM-4 at 20 and 25 GBaud are shown in Fig. 13. Operation below the 7% HD-FEC limit could be obtained in all cases.

As we mentioned earlier in this section, the modulation speed of the laser is not as high as that of the EAM. Hence, the primary results of the optical PAM-4 experiment are not superior to the individual EAM modulation. However, a PAM-4 signal at much higher baud rate is achievable by optimization of the laser design and leveraging the photon-photon resonance effect [23] to extend its bandwidth.

V. Conclusion

We demonstrate a 2 × 56 Gbps optical transmitter based on a single heterogeneously integrated III-V-on-silicon DFB laser, integrated with two electro-absorption modulators on both sides. The same epitaxial layer is used for the laser and the EAMs, which eases the fabrication process. The cross talk between EAMs is measured to be better than 50 dB. Also, an original method to generate an optical PAM-4 signal is demonstrated using a directly modulated DFB laser and an EAM using a single integrated device, not requiring a high-speed electronic digital-to-analog converter. We demonstrate the PAM-4 transmission over 2 km of non-zero dispersion shifted single mode fibe at 25 GBaud. The unwanted chirp of the EAMs was the limiting factor to transmit the data over a standard single mode fibe . The chirp characteristics are bias voltage dependent, therefore more precise and detailed experiments are planned to be done on these samples in the future. Recent advances in III-V-on-Si heterogeneous integration and demonstrations of high-performance optical devices open up new opportunities to implement these devices into optical communication networks, especially for inter- and intra-datacenter links.

Acknowledgment

The authors would like to thank the III–V Lab for supplying the III–V epitaxial wafer.

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