Direct and Electroabsorption Modulation of a III–V-on-Silicon DFB Laser at 56 Gb/s

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***Abstract*—In order tocope with the ever-growing Internet traffic, high-speed optical interconnects are becoming indispensable. Silicon photonicsis emerging as a key technology for such interconnects. In this paper, we demonstrate 56 Gb/s nonreturn to zeroon–off keying (NRZ-OOK) direct modulation based on a high bandwidth heterogeneously integrated III–V-on-silicon distributed feedback laser, as well as transmission over 2 km single mode fiber. Using a very similar device, but with electrically isolated and reversely biased tapers, we obtain compact electroabsorption modulation at 56 Gb/s NRZ-OOK as well.**

***Index Terms*—Distributed feedback laser, electroabsorption modulator, heterogeneous integration, silicon photonics.**

I. Introduction

As CLOUD services and video streaming are becoming popular worldwide, the amount of data traffic is exploding especially inside and between datacenters. Therefore, there is a need for high-speed optical interconnects for such inter- and intra-data center communication. In response to this need, IEEE is working on a 400-gigabit Ethernet (400GbE) standard for this application [1], using an $8\lambda \times 50$-Gbit/s/λ configuration for 2-km and 10-km single-mode-fiber (SMF) transmission. Discrete optical transmitters have been reported recently that meet these requirements. However, integration of such devices will be key to decrease the footprint of these components to scale down the final package size, power consumption and cost of the transceiver. In order to reach the 50 Gbit/s/λ one can chose between an advanced modulation format such as PAM-4 or NRZ-OOK. While NRZ-OOK puts more stringent requirements on the transmitter bandwidth, it is more relaxed in terms of required signal to noise ratio and reduces the amount of digital signal processing.

In response to this need, >50 Gbit/s directly modulated C-band VCSELs have been developed recently [2], [3]. But it is not easy to integrate such lasers in Wavelength Division Multiplexing (WDM) transceivers in a low-cost wafer-scale approach. In addition, VCSELs normally provide limited output power, limiting the reach of the link, which could be several 10s of km for inter-datacenter optical interconnects. Another alternative can be the use of integrated modulators such as Si Mach-Zehnder modulators (MZM) [4]. However, the use of a MZM increases the circuits' footprint and cost and introduces extra insertion loss. The first issue can be dealt with by using SiGe electro-absorption modulators (EAMs) [5]. However, such modulators require an additional epitaxial growth step, which again increases cost.

In this paper, we demonstrate two different transmitters operating at 56 Gbps based on the heterogeneous integration of InP-based epitaxial material on a silicon photonic waveguide circuit: one based on direct modulation of a III-V-on-Si distributed feedback laser (DFB) and one based on external electro-absorption modulation (EAM) of a similar III-V-on-silicon source. The direct modulation using a heterogeneously integrated III-V-on-Si laser, with output coupled to a Si waveguide has been studied previously [6], [7]. In [6], a hybrid DFB laser was directly modulated at 12.5 Gbps with an extinction ratio of 2.8 dB for a 1.5 V voltage swing. In [7], a much higher bitrate of 21.4 Gbps is demonstrated using a heterogeneously integrated tunable laser, using an external cavity resonance (photon-photon resonance). Electro-absorption modulation in the same platform has been reported in [8], [9]. The uncooled lumped III-V-on-Si EAM was demonstrated at 40 Gbps with a 1 V_{pp} and low power consumption [8]. Based on the same technology, 100 Gbps 5 channels multiplexed electro-absorption modulation with an individual device with a 3-dB E/O bandwidth of 17 GHz was demonstrated in [9].

First of all, the technology for the fabrication of an InP-on-Si DFB laser with ultra-high modulation bandwidth is briefly described. A DFB laser with 34 GHz modulation bandwidth is then used to demonstrate 56 Gbps NRZ-OOK direct modulation, as well as errorless transmission using 7%-overhead hard decision forward error correction (HD-FEC) over a 2 km Non-Zero

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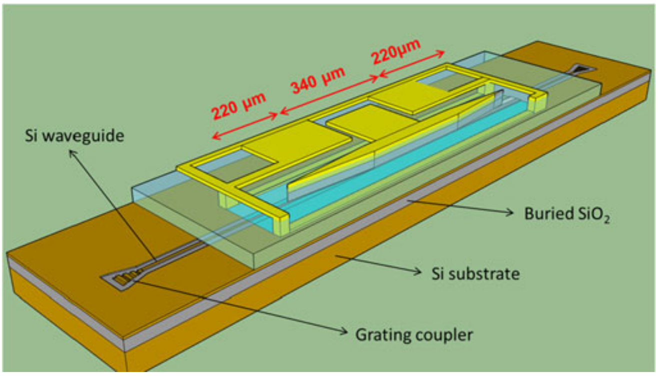

Fig. 1. Schematic of the III-V-on-silicon laser structure. The device consists of the central DFB section and two coupling tapers on each side to couple the light from the III-V waveguide to the Si waveguide.

Dispersion Shifted Fiber (NZ-DSF) without any equalization. The DFB laser has taper sections at each end to couple the light between the InP device layer and the Si waveguide layer. By electrically isolating the tapers and applying a reverse bias of 0.3 V on the taper a strong electro-absorption effect was observed. The low RC time constant of the taper section again enables 56 Gbps NRZ-OOK modulation with 0.8 V_{pp}, as well as errorless transmission using 7%-overhead HD-FEC over a 2 km NZ-DSF.

II. Heterogeneous Integration

The III-V-on-silicon DFB laser structure is schematically shown in Fig. 1. There are three sections which are highlighted in the figure. The middle section is the DFB laser with a grating on the Si waveguide underneath and the III-V waveguide on the top which provides the optical gain. This waveguide section is 340 μm long and 3.4 μm wide. The DFB grating period is 245 nm, etched 180 nm deep and has 50% physical length duty cycle. The active layer consists of 8 pairs of an InAlGaAs Strained Layer Multiple Quantum Well (SL-MQW) structure. The active region is separated by a 200 nm thick n-InP contact layer from the silicon grating. On either side of the DFB laser, a III-V-to-Si coupling taper is defined, by tapering down the III-V waveguide as well as tapering the 400 nm Si rib waveguides underneath. The Si waveguides and grating are fabricated in a CMOS pilot line by a 180 nm dry etch, after which the waveguide structures are planarized. The III-V taper is a piecewise linear taper that quickly tapers from a 3.4 μm mesa width to a 0.9 μm waveguide width after which a slower adiabatic taper is implemented by tapering both the III-V and silicon waveguide structure [10].

The fabrication process begins with adhesive bonding of unprocessed III-V epi on the SOI circuit using divinyl-bis-benzocyclobutene (DVS-BCB). In this method the surface-quality requirements on the III-V and silicon surfaces are relaxed, compared to molecular bonding. This results in a high bonding yield, while very thin bonding layers are still feasible. The bonding process is described in detail in [11]. The bonding layer thickness and InP mesa structure are designed such that the mode has a good overlap with both the active layer and the grating. Fig. 2 shows a SEM picture of the device cross-section. Very thin bonding layers (as thin as 10 nm) are realized by over etching the top planarization SiO_2 (Fig. 2(b)). These thin bonding layers (and thin n-contact) allow obtaining a large coupling coefficient ($\sim$200 cm^{-1} in this case). The large coupling coefficient gives a small cavity loss, which together with the large confinement factor of the laser mode in the active layer ($\sim$10%) results in a low threshold gain and a large differential gain. These are the essential requirements to obtain a high relaxation oscillation frequency.

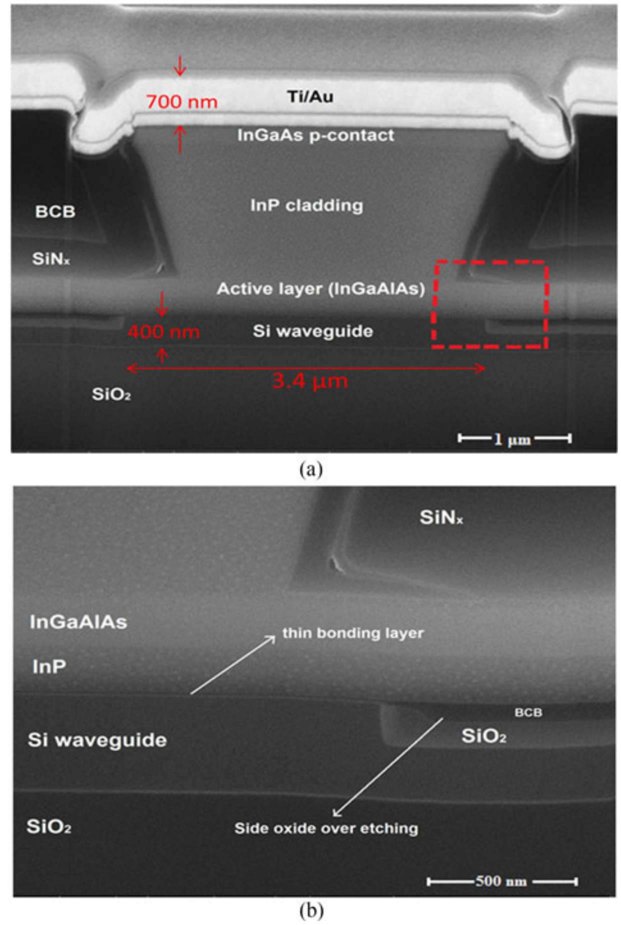

Fig. 2. (a) SEM image of the DFB laser cross-section with an ultra-thin bonding thickness. (b) The zoom-in image shows an over-etching of the SiO_2 in the waveguide trench.

The laser light is coupled from the Si waveguide to a single mode fiber using surface grating couplers. GSG pads were defined at the final stage of the metallization for high-speed measurements.

III. Direct Modulation

The DFB laser is used to do direct modulation experiments. The device under test has a 6 Ω series resistance, is single mode (emission wavelength of 1570 nm) and couples more than 6 mW output power in the Si rib waveguide for a bias current of 110 mA. The threshold current is 32 mA. Previously realized DFB lasers based on this technology had limited modulation

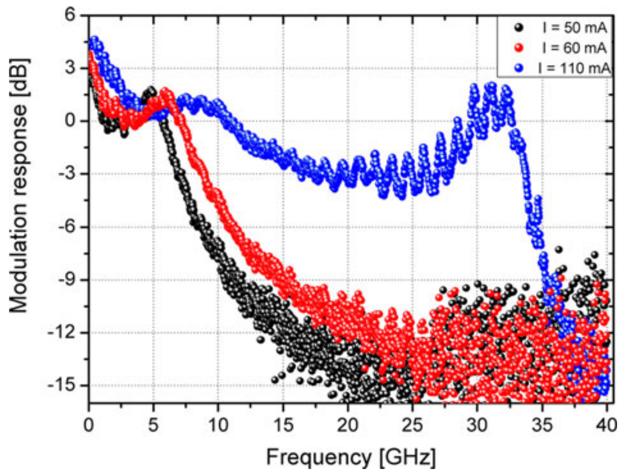

Fig. 3. Small-signal modulation response of the InAlGaAs membrane DFB laser diode with the enhanced modulation bandwidth due to the photon-photon resonance.

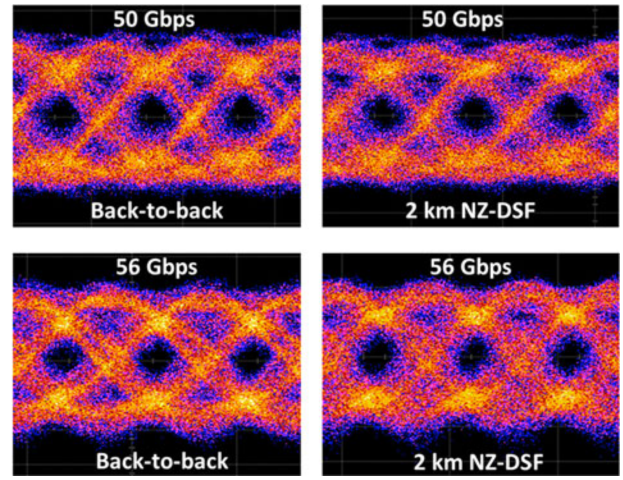

Fig. 4. Eye diagrams for 50 and 56 Gbps for the back-to-back case (left eyes) and after transmission over 2 km of NZ-DSF fiber (right eyes).

bandwidth (15 GHz) due to their low relaxation oscillation frequency [12], [13]. In the literature several techniques have been introduced to increase the modulation bandwidth of current modulated lasers such as injection locking [14], detuned loading [15] and the photon-photon resonance effect (PPR) [16], [17]. Injection locking requires an extra master laser with normally a high output power. Detuned loading has been studied and demonstrated for distributed Bragg reflector (DBR) lasers where the lasing wavelength can be tuned over the DBR spectrum in order to set it on the long wavelength side slope, but for DFB lasers it is not trivial to do the same. The reason for this is that it is difficult to adjust the round trip phase without changing the DFB reflection spectrum.

The photon-photon resonance effect has been theoretically explained in [16] and also experimentally demonstrated in [17], [18] and uses an external reflector to create a compound laser cavity. Using this technique for a DFB laser monolithically integrated with a passive InP waveguide, 34 GHz modulation bandwidth was achieved [19]. The PPR effect occurs when one of the signal modulation sidebands is close in wavelength to a side mode of the compound cavity laser and thereby is resonantly amplified by the optical cavity. The modulation bandwidth was further increased to 55 GHz for an InP short-cavity distributed reflector (DR) laser recently [20]. The heterogeneous integration of DFB lasers on Si waveguide circuits enables creating a very low loss external cavity for the DFB laser that can enhance the photon-photon effect [16]. Moreover it obviously allows the co-integration with high-performance multiplexers, which makes WDM integration feasible. Therefore, in this paper we realize wide bandwidth directly modulated DFB lasers on a silicon photonics platform by implementing an external cavity in the silicon waveguide layer. In this case, the external cavity is formed by the grating couplers, which reflect about 4% and are separated by about 1000 μm.

First, small-signal measurements were done with a KEYSIGHT PNA-X 67 GHz network analyzer (Fig. 3). As the laser bias current increases, both the relaxation oscillation resonance frequency and the modulation bandwidth of the laser keep rising. As one can see, there is a low frequency roll off due to the modulation of the tapers, which act as SOAs, and due to spatial hole burning in the laser cavity. When excluding the low-frequency part, we measured a 3 dB modulation bandwidth of 34 GHz at 110 mA, clearly enabled by this photon-photon resonance (Fig. 3). However, this value drops to 3 GHz when including the low frequency part.

The large signal measurements were performed using a Keysight M8195A arbitrary waveform generator (AWG) at different bitrates. An RF-voltage of 1 V_{pp} from the AWG was applied to the laser to realize large signal modulation while the laser was biased at 110 mA. Using a Root Raised Cosine (RRC) filter with $\alpha = 0.7$ at the output of the AWG helps to open the bandwidth limited electrical eye. A pseudo-random bit sequence (PRBS) pattern of 2^7-1 was used in these experiments. An Erbium Doped Fiber Amplifier (EDFA) is used to compensate for the grating coupler loss and boost the optical signal. An optical filter (0.2 nm bandwidth) is used to suppress the amplified spontaneous emission of the EDFA. Measurements were done both in a back-to-back configuration as well as using a 2 km span of NZ-DSF fiber with a dispersion of 4.5–6 ps/nm.km at the laser wavelength of 1570 nm. This signal is directly detected by a commercial photodiode and trans-impedance amplifier (TIA) with a bandwidth of 32 GHz. The output of the TIA is connected to a real time oscilloscope (Keysight DSA-Z63).

Fig. 4 shows the eye diagrams at 50 and 56 Gbps both in back-to-back and 2 km fiber span configuration. The BER curves for the back-to-back case and after transmission over the 2 km of NZ-DSF fiber are given in Fig. 5. In all cases a raw bit error rate below 3.8×10^{-3} can be obtained, enabling error free operation using HD-FEC. The power penalty for transmission over 2 km of optical fiber is approximately 0.5 dB.

IV. External Modulation

An alternative approach is to externally modulate the light generated by the III-V-on-Si DFB laser, using the III-V taper

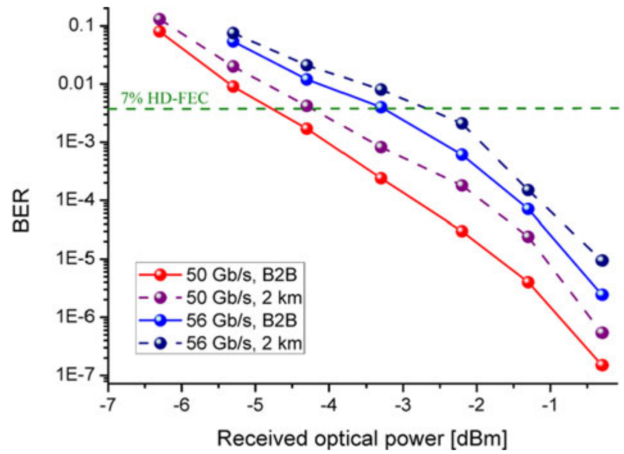

Fig. 5. BER vs received optical power for 50 and 56 Gbps for the back-to-back case and after transmission over 2 km of NZ-DSF fiber.

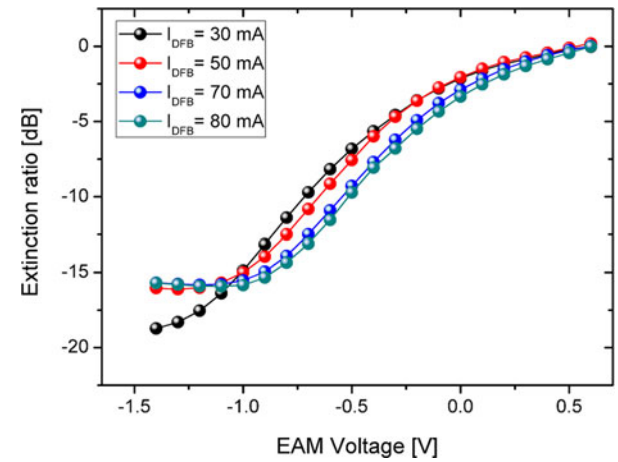

Fig. 7. Normalized CW output power versus reverse bias on the taper.

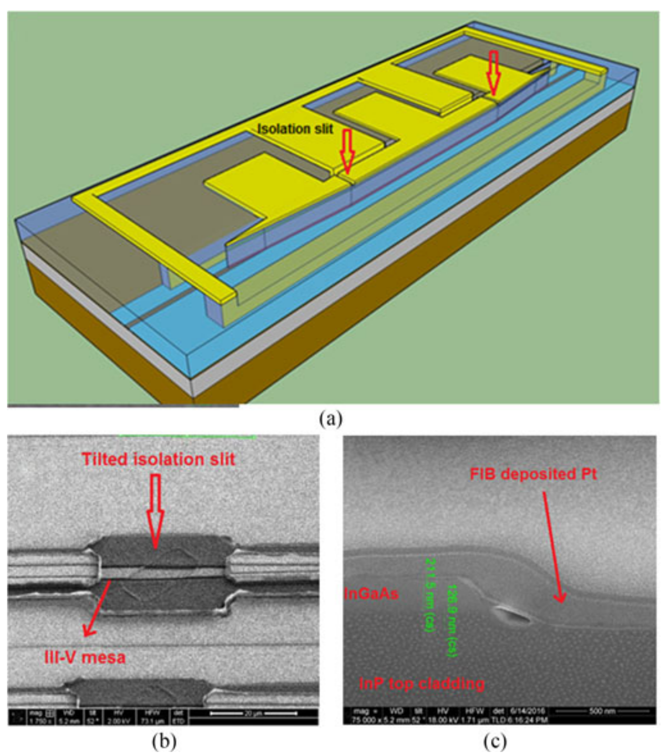

Fig. 6. Schematic of the DFB laser with electrically isolated tapers (a), SEM image of the isolation area (b), and the cross section at the isolation area (c).

structures that connect the laser to the silicon waveguide circuit. By reversely biasing these structures, which share the same active layer structure as the laser, electro-absorption modulation is obtained. At the same time this removes the low-frequency roll-off observed in the directly modulated case, as in this case the tapers do not act as modulated SOAs. To individually bias the tapers they should be electrically isolated from the DFB laser (Fig. 6(a)). Apart from this isolation, the devices discussed in this section are fabricated identically as the devices from the previous section, using the same passive Si circuit and the same MQW epitaxial stack. Following the optical lithography to define the isolation slits, the top 200 nm p-contact InGaAs layer and 130 nm of the p-InP film is etched using inductively coupled plasma (Fig. 6(b) and (c)). This etching provides a 3 kΩ electrical isolation. The two 200 μm long InP tapers on either side of the DFB lasers can be separately biased and modulated but for our measurement we have focused on a single side. The DFB lasers' static characteristics were similar to those of the directly modulated laser. Threshold currents at room temperature of 20 mA, output powers in the silicon waveguide above 3 mW at 100 mA, and a series resistance of 7 Ω were measured for the lasers. In order to be able to have efficient electro-absorption modulation (in terms of extinction ratio and insertion loss) using an identical MQW structure for both the laser and the EAM, the wavelength of the laser should be close to the effective band edge of the MQW active layer [21]. A laser with an emission wavelength of 1572 nm was used for this purpose.

The bias current to the DFB was fixed to 50 mA and 0.3 V reverse bias was applied on the taper connecting the DFB to the single mode fiber (via a grating coupler in the SOI). The lower bias current and the insertion loss of the electro-absorption structure reduced the CW output power to 0.6 mW. Since the output power of the DFB laser cannot be measured directly without the taper section and the transparency point of the taper section is not evident, the exact value of the EAM insertion loss is not clear. Fig. 7 shows the normalized output power versus the reverse bias applied to the taper for 4 different bias currents of the DFB laser. An extinction ratio of 15 dB is obtained for a voltage swing of 1.5 V and there is little dependence on the laser bias current, indicating that absorption saturation is not occurring.

The small signal characteristics, measured at 50 mA and 80 mA bias currents to the DFB laser and for two bias voltages on the taper are shown in Fig. 8. For negative bias voltages on the taper, a 3 dB bandwidth of around 25 GHz is found, limited by the RC time constant. At the high bias current (80 mA), there is a slight change in the modulation frequency response that may be related to the EAM saturation at high power. For the forward bias (as is the case in the directly modulated laser) of

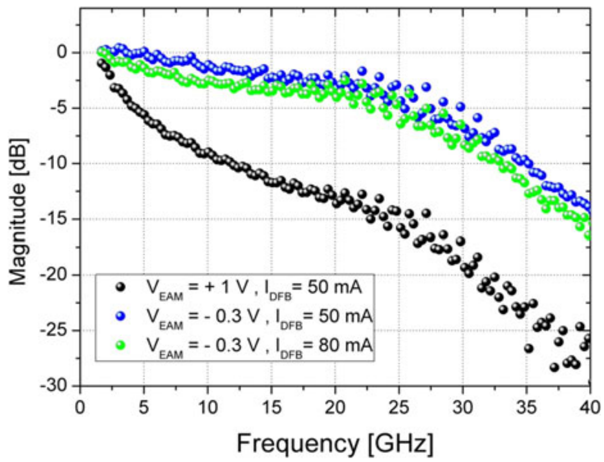

Fig. 8. Small signal modulation characteristics for different bias voltages applied to the taper and for 50 mA and 80 mA bias currents to the DFB laser.

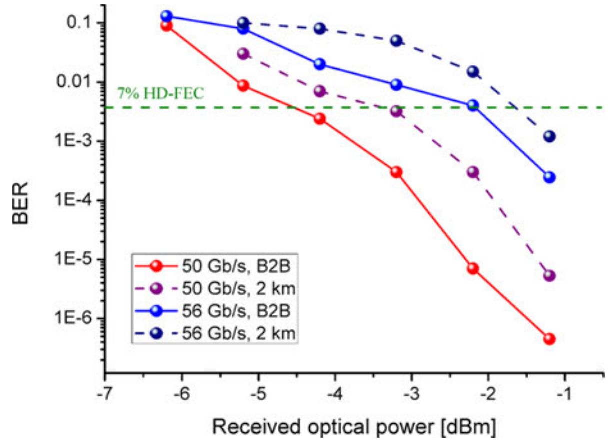

Fig. 10. BER vs received optical power for 50 and 56 Gbps for the back to back case and after transmission over 2 km of NZ-DSF fiber.

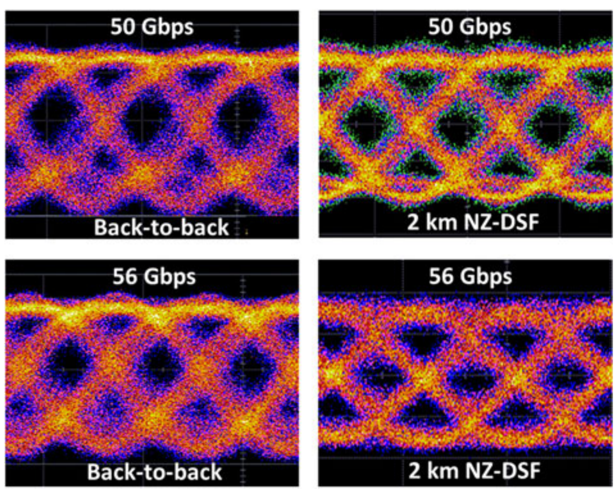

Fig. 9. Eye diagrams for 50 and 56 Gbps for the back-to-back case (left eyes) and after transmission over 2 km of NZ-DSF fiber (right eyes).

1 V, the taper acts as a semiconductor optical amplifier (SOA), and the modulation bandwidth is determined by the inverse carrier lifetime and is very small. Careful observation of the low frequency characteristics of the taper under forward bias reveals the low frequency roll-off behavior of the DFB laser in the previous section. As we mentioned in the previous section, this SOA characteristic of the taper is superimposed on the DFB laser response and makes it non-flat (Fig. 3).

Using a Keysight M8195A AWG, large signal modulation at different bitrates was performed with a voltage swing of just 0.8 V_{pp}. The DFB laser was again biased at 50 mA and −0.3 V reverse bias was applied to the taper as well. These values were the optimum bias current and voltage in order to measure open eyes. Both back-to-back characterization and transmission over 2 km of NZ-DSF was investigated. Open eyes were obtained up to 56 Gbps, both for the back-to-back case and after transmission over 2 km NZ-DSF fiber. Fig. 9 shows the eye diagrams at 50 and 56 Gbps for a pattern length of 2^7-1. The BER curves for the back-to-back case and after transmission over the 2 km of NZ-DSF fiber are given in Fig. 10. The bit error rate reaches below the 7% HD-FEC limit in all cases. The better performance of the directly modulated DFB laser compared with the EAM modulator is attributed to the high output power of the DML transmitter. However, the latter structure might be attractive to reduce power consumption of the transmitter, including the driver electronics.

As the EAM modulator is an RC-limited device, the bandwidth can be further increased by decreasing the taper length. Our simulation shows that even a 50% reduction in the taper length would still guarantee a high III-V-to-silicon coupling efficiency, while it would increase the modulation bandwidth significantly.

V. Conclusion

In summary, we investigated the 50 and 56 Gbps modulation of heterogeneously integrated InP-on-Si DFB laser diodes, either by direct modulation of the DFB laser itself or by electroabsorption modulation in the tapers. For the directly modulated DFB laser, the photon-photon resonance effect is exploited to enhance the modulation bandwidth beyond its relaxation oscillation frequency limit to 34 GHz. 56 Gbps direct modulation was achieved without any equalization and transmission over 2 km of nonzero dispersion shifted fiber was demonstrated as well at this bitrate. For the integrated EAM modulator the same bit rate was achieved with 0.3 V bias voltage and 0.8 V_{pp} drive voltage on the modulator.

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