100-Gb/s Electro-Absorptive Duobinary Modulation of an InP-on-Si DFB Laser

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***Abstract*— 100-Gb/s single-channel optical data communication transceivers can provide a compact and cost-effective solution for the exponentially growing data-center traffic. One of the enabling technologies is electro-absorption-modulated single-mode lasers which are very compact, efficient, and fast. In this letter, such a transmitter integrated on a silicon photonics platform is demonstrated. While low loss and high contrast waveguides are provided by Si photonics, the gain and efficient electro-absorption are provided by the InP-based multi-quantum-well structure. A lumped electro-absorption modulator integrated with a distributed feedback laser is designed and fabricated in this platform. The epitaxial stack is identical for the laser and the modulator, which eases the fabrication process considerably. In this way, we successfully demonstrate 100-Gb/s single-channel electrical duobinary optical data transport over ~100 m of fiber with a bit error rate of 1.6e-3.**

***Index Terms*— Electro-absorption, DFB lasers, heterogeneous integration, silicon photonics.**

I. Introduction

Data traffic is increasing exponentially owing to the rapid growth of cloud services and wireless applications. As a result, the required Ethernet transceiver capacity is increasing rapidly. 100-gigabit Ethernet (100GbE) was standardized by IEEE in 2010 [1] specifying four 25 Gb/s non-return-to-zero on-off keying (NRZ-OOK) channels. The four lanes are allocated on a local area network wavelength division multiplexing (LAN-WDM) grid with 800-GHz spacing at 1.3 μm. For 400GbE, similar standards are emerging using 50 Gbaud PAM-4. However, the use of these advanced modulation formats puts stringent requirements on the electronics (linearity) and optical channel (signal to noise ratio). This will impact the cost of such transceivers, which is of paramount importance for intra-datacenter links. Therefore there is an interest in transceivers that allow for 100Gbit/s operation per wavelength using simpler modulation formats.

Previously, several 100 Gb/s single-lane transmission demonstrations have been realized using four level pulse amplitude modulation (PAM-4) [2]–[5] and discrete multi-tone (DMT) [6]. However, many of these experiments still rely on complex digital signal processing (DSP) at the RX and/or TX-side, typically done offline. On the other hand, 100 Gb/s NRZ-OOK modulation requires a very high modulation bandwidth (>50 GHz). The 100-Gb/s NRZ-OOK operation of a traveling-wave type electro-absorption modulator integrated with a distributed feedback laser (TW-EADFB laser) has been reported [7], [8]. The transmission line design of the TW-EADFB laser slightly increases the overall device size when compared to a lumped modulator and it also needs a power-consuming 50 Ω termination. The impact of this power and size increase should however be viewed in the context of the entire packaged module, as other factors (fiber coupling loss, EAM insertion loss, DFB efficiency, temperature control) can overshadow these savings. The combination of state-of-the-art SiGe electro-absorption (EA) modulators on a silicon photonics platform with state-of-the-art modulator drivers has resulted in a first real-time serial 100 Gb/s NRZ-OOK transmission [9], [10]. However, in this demonstration the laser source was not integrated on the photonic integrated circuit.

Electrical duo-binary (EDB) modulation is an intensity modulation format that relaxes the bandwidth requirements on the optical components and still offers a simple demodulation scheme. EDB was used to demonstrate real time 100 Gb/s transmission based on an InP travelling-wave electro-absorption modulator with integrated DFB laser [9]. However, as mentioned earlier, the 50 Ω termination for such a transmission line structure increases the power consumption. Using a silicon-organic Mach-Zehnder modulator 100 Gb/s electrical duobinary transmission was demonstrated [11] at the cost of large footprint and 50 Ω termination. Also, in this case the laser source was not integrated. In this letter, we present

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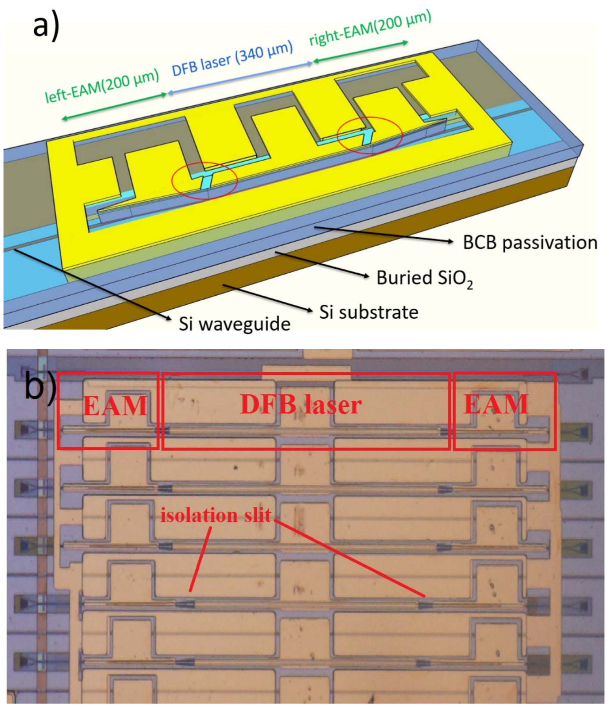

Fig. 1. (a) Schematic of the heterogeneously integrated InP-on-Si externally modulated laser (tilted isolation slits' position is indicated by red circles); b) Microscope image of the fabricated device showing the central DFB laser and the EAMs implemented in the tapers.

the first demonstration of the transmission of a 100 Gb/s electrical duobinary signal using a heterogeneously integrated InP-on-Si externally modulated DFB laser (EML) combined with an in-house designed transmitter (TX-IC) chipset in SiGe BiCMOS technology, without the need for any digital signal processing (DSP). A bit error rate (BER) of 1.6e-3 is obtained for transmission over ˜100m of single mode fiber, which is below the hard decision forward error coding limit with 7% overhead of 3.8e-3.

II. Heterogeneously Integrated Transmitter

The transmitter is a heterogeneously integrated III-V-on-Si electro-absorption DFB laser. The EML was realized through adhesive die-to-wafer bonding on a silicon photonic integrated circuit, schematically illustrated in Fig. 1(a). The EAM is implemented in the III-V taper, which is used to couple the light between the InP and the Si waveguide. In our devices the active layer for the DFB laser and the EA modulators (or tapers) is identical which eases the fabrication process [12], [13]. The active region consists of 8 InAlGaAs quantum wells with a bandgap wavelength around 1570 nm. The EAM taper is electrically isolated from the laser mesa by etching the InGaAs contact layer (200 nm) and part of the p-InP cladding layer (125 nm). 8 kΩ electrical isolation is obtained. The realized devices are shown in Fig. 1(b). Each row consists of one DFB laser (340 μm long) and two EAMs (200 μm long) coupled to a silicon waveguide. The output power of the EML can be collected using a grating coupler on each side.

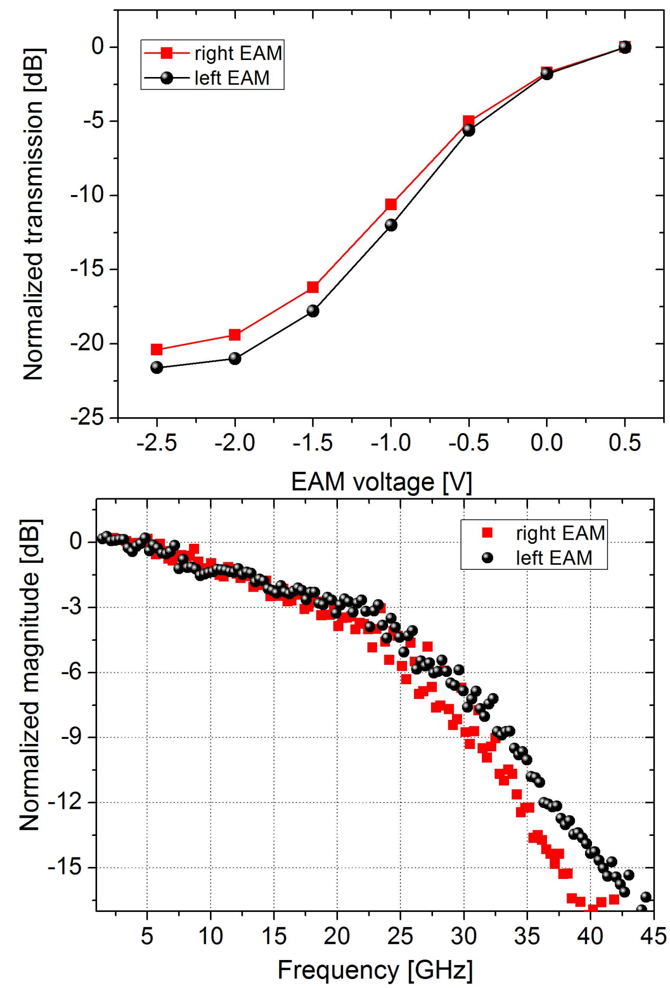

Fig. 2. Normalized output power versus the reverse (DC) bias applied to the EAM (top); small signal modulation characteristics for −0.8 V bias on the EAM and 80 mA bias current to the DFB laser (bottom), T = 20 °C.

The EML was placed on a temperature-controlled stage during the static and dynamic measurements at the fixed temperature of 20 °C, while the laser was contacted using electrical probe needles. Threshold currents at room temperature of 20 mA, output powers in the silicon waveguide above 3 mW at 100 mA bias current, and a series resistance of 7 Ω were measured for the lasers. Single mode emission at 1567 nm with 40 dB side mode suppression ratio is obtained. Further optimization of the layer structure is required to enable semi-cooled operation of the transmitter at 40-50 °C. In order to reduce the insertion loss and increases the extinction ratio of the EAM, lasers operating on the long wavelength side of the gain spectrum are used. These EAMs are fabricated using the same active region as the lasers.

In Fig. 2-(top) the normalized output power of the EML is shown versus the reverse (DC) bias applied to the EAM. For a voltage swing of 1.5 V, an extinction ratio of 15 dB is obtained. This measurement was done at different DFB laser bias currents and we observed that there is little dependence on the laser bias current, indicating that absorption saturation is not occurring. In order to measure the device modulation bandwidth, the small signal characterization of the two

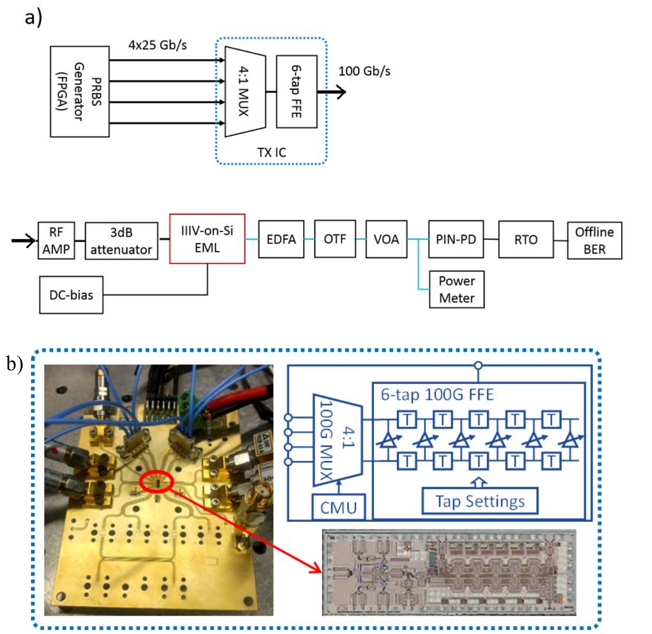

Fig. 3. Schematic of the measurement setup, (a) the image of the electronic 100 Gb/s transmitter and (b) its high level block diagram.

EAMs is performed at 80 mA bias current of the DFB laser (Fig. 2-(bottom). An RC-limited 3 dB bandwidth of around 20 GHz is obtained with a slow roll-off at higher frequencies.

The left-hand and right-hand side EAM are designed to be identical. From the measurement, this is the case for the small signal response as it is shown in this figure. The two EAMs integrated with a single laser enables to further improve the compactness of the transmitter in case a parallel single mode fiber solution is pursued, where both outputs connect to a separate optical fiber. The laser is emitting from both sides with almost the same output power.

III. Link Demonstration

The large signal performance is performed using the setup shown in Fig. 3. The first stage of the transmitter is A XilinX FPGA-board which generates four 25 Gb/s binary data streams with 2^7-1 long pseudo-random bit sequences (PRBS). These signals are multiplexed on the TX-IC with the required delays to form a 2^7-1 long PRBS at 100 Gb/s. Next, a six-tap analog feed forward equalizer (FFE) is used to compensate the frequency roll-off of the components in the link. The TX-IC consumes less than 0.9W. An RF amplifier with integrated bias-T delivers the signal with a swing of $\sim$ 2.5 Vpp to the EML via an RF-probe. During bit-error rate (BER) measurements the laser was biased at 80 mA and the EAM was biased at -0.8 V.

An erbium-doped fiber amplifier (EDFA) is used to boost the signal power to ~9 dBm before entering a commercial PIN-photodiode (BW=45 GHz). The ASE of the EDFA is filtered out using an optical tunable filter. The received signal by a 63 GHz 160 GSa/s real-time oscilloscope (RTO) is resampled offline to determine the BER.

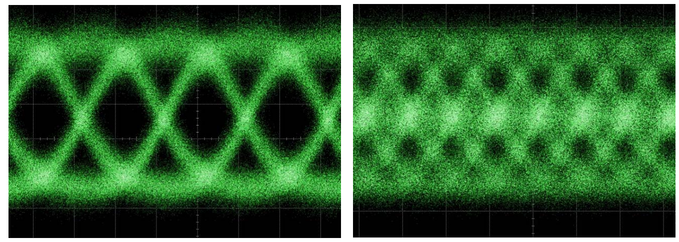

Fig. 4. eye diagrams at 50 Gb/s NRZ-OOK (left) and 100 Gb/s EDB (right), the DFB laser is biased at 80 mA and the EAM at -0.8 V, T = 20 °C.

The optimal sampling point is determined by visual inspection of the eye diagram.

No off-line equalization or other digital signal processing is used. The eye diagrams at 50 Gb/s NRZ-OOK and 100 Gb/s EDB are shown in Fig. 4. At 100 Gb/s, a BER of 1.6e-3 was measured for transmission over ˜100m of single mode fiber (for 9dBm optical input power to the receiver) which is below the hard decision forward error coding limit with 7% overhead of 3.8e-3.

IV. Conclusion

In summary, we demonstrated the generation and transmission of a 100 Gb/s electrical duobinary signal using a heterogeneously integrated InP-on-Si externally modulated DFB laser without having to rely on any digital signal processing. Since the device consists of two identical EAMs on each side, the device potentially can be used to generate 2 independent 100 Gb/s EDB data streams resulting in a single laser 200 Gb/s transmitter. Combining two of these devices could be a low-cost and compact option for a parallel single mode 400 GbE transmitter. The fabrication of high performance integrated EA-DFB lasers on Si photonic circuits enables also the integration of 100Gbps receivers on the same photonic integrated circuit [14].

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