

# 100 Gb/s Duobinary Electro-Absorption Modulation of a Heterogeneously Integrated InP-on-Si DFB Laser Diode

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## ABSTRACT

We demonstrate for the first time a serial 100 Gb/s transmission with a heterogeneously integrated InP/Si DFB laser by operating the InP tapers – used to couple to the underlying silicon waveguide- as electro-absorption modulators. An in-house developed driver IC, fabricated in a 0.13 $\mu\text{m}$  SiGe BiCMOS technology, employing a 4x1 multiplexer and an analog six tap feedforward equalizer was used to generate a duobinary modulated signal at 100 Gb/s on the tapers, requiring no power-consuming digital signal processing (DSP) or digital-to-analog converters (DAC). With these devices, open eyes and a bit-error ratio (BER) down to 1.6E-3 at 100 Gb/s electrical duobinary are obtained. As the DFB consists of 2 independent tapers and emits light from both ends, this laser can be used to generate 2x 100 Gb/s data streams from a single transmitter, leading to a reduction in area, power and packaging cost over a 2-laser approach. Such a transmitter would be an attractive solution for 200 GbE and 400 GbE transceivers in short-reach optical interconnects.

**Keywords:** Semiconductor Lasers, IIIV-on-Si, Silicon Photonics, Electro-absorption modulation, Optical Interconnects

## 1. INTRODUCTION

The increasing growth of internet traffic driven by high-definition video-streaming and cloud computing pushes the requirements on inter and intra-datacenter optical interconnects. The use of lower line rates (e.g., 25 or 50 Gb/s) requires a relatively large number of lanes to achieve 400GbE transceivers and beyond, making integrated transmitters for high aggregate bit rates more complex, which impacts the cost. While bit rates per wavelength beyond 100 Gb/s are very well possible using quadrature amplitude modulation (QAM), coherent transmission is considered less viable for intra-datacenter links. Therefore there is an interest in transceivers that allow for 100Gbit/s operation per wavelength using an intensity modulation / direct detect format.

Electrical duobinary (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 [1]. However, the 50  $\Omega$  termination for this transmission line structure increases the power consumption. Using a silicon-organic Mach-Zehnder modulator (MZM) 100 Gb/s electrical duobinary transmission was demonstrated [2]. The combination of state-of-the-art SiGe electro-absorption (EA) modulators

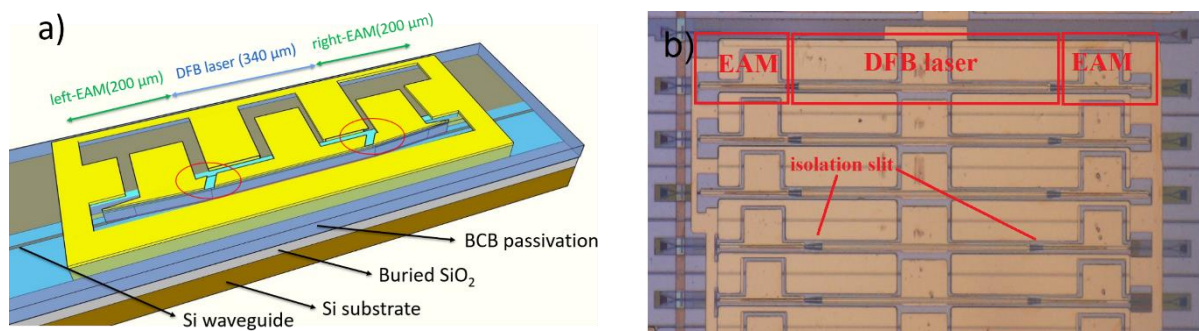


Figure 1. a) Schematic of the heterogeneously integrated InP-on-Si externally modulated laser (tilted isolation slits' position are indicated by red circles); b) Microscope image of the fabricated device showing the DFB laser in the middle and the tapers used as EAMs.

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 on a silicon platform without any DSP, DAC or power-hungry travelling wave structures [3]. At the same time, both direct and EA modulation of heterogeneously integrated InP-on-Si lasers were shown up to 56 Gb/s [4,5].

Here we present the first demonstration of the generation and 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 a SiGe BiCMOS technology, without the need for any digital signal processing (DSP).

## 2. DEVICE STRUCTURE, STATIC AND SMALL-SIGNAL CHARACTERISTICS

The EML was realized through adhesive die-to-wafer bonding on a silicon photonic integrated circuit, schematically illustrated in Fig. 1(a). A DFB laser structure, with the grating defined in the silicon waveguide layer, is coupled to the silicon waveguide using a III-V/Si taper structure. The EAMs are implemented in this taper structure. In our devices, the active layer for the DFB laser and the EA modulators (or tapers) is identical, which eases the fabrication process. The active region consists of 8 InAlGaAs quantum wells emitting in the C-band. The taper is electrically isolated from the laser by etching the InGaAs contact layer (200 nm) and part of the p-InP cladding layer (125 nm). 8 k $\Omega$  electrical isolation between both is obtained. The realized devices are shown in Fig. 1(b). Each row consists of one DFB laser (340  $\mu\text{m}$  long) and two EAMs (200  $\mu\text{m}$  long) coupled to a silicon waveguide. The output power of the laser can be collected using two grating couplers on each side. The structure is identical to the heterogeneously integrated DFB lasers that have been discussed in [5].

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  $\Omega$  were measured for the lasers. Single mode emission at 1567 nm with 40 dB side mode suppression ratio is obtained. Lasers operating on the long wavelength side of the gain spectrum are used as this reduces the insertion loss of the EAM, which uses the same active region as mentioned before. Fig. 2(a) shows the normalized output power versus the reverse (DC) bias applied to the EAM. An extinction ratio of 15 dB is obtained for a voltage swing of 1.5 V. This measurement was done at the 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. The small signal characteristics, measured at 80 mA bias current to the DFB laser and for a bias voltage of -0.8 V to the EAMs, are shown in Fig. 2(b). An RC-limited 3 dB bandwidth of around 20 GHz is obtained with a slow roll-off at higher frequencies.

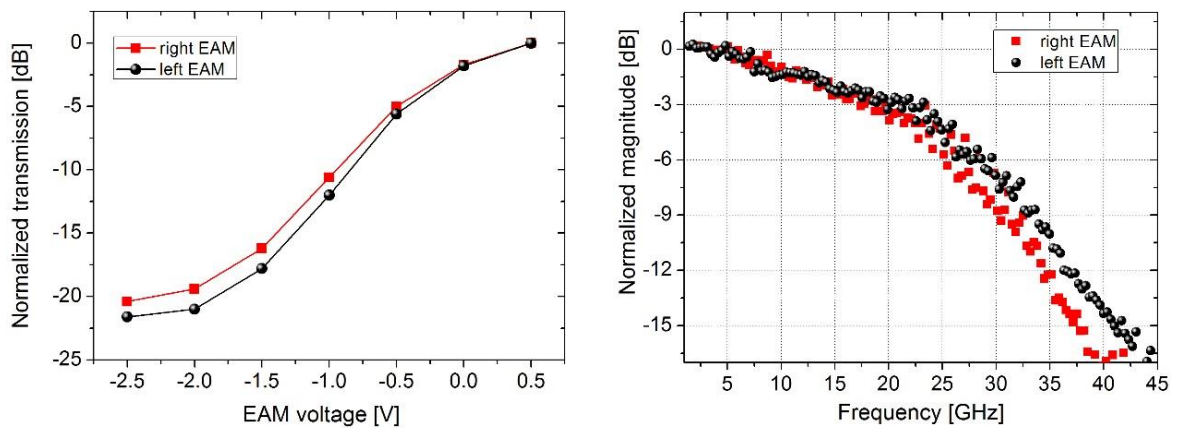


Figure 2. Normalized output power versus the reverse (DC) bias applied to the EAM (left); small signal modulation characteristics for a bias voltage of -0.8V to the EAMs and 80 mA bias current to the DFB laser (right).

## 3. LARGE SIGNAL MODULATION CHARACTERISTICS AND TRANSMISSION EXPERIMENT

To characterize the device's large signal performance the setup shown in Fig. 3 is used. A Xilinx FPGA-board generates four 25 Gb/s binary data streams with  $2^7-1$  long pseudo-random bit sequences (PRBS), which are multiplexed on the TX-IC with the required delays to again form a  $2^7-1$  long PRBS at 100 Gb/s. Next, a six tap analog feed forward equalizer (FFE) is used to compensate frequency roll-off of the following components in

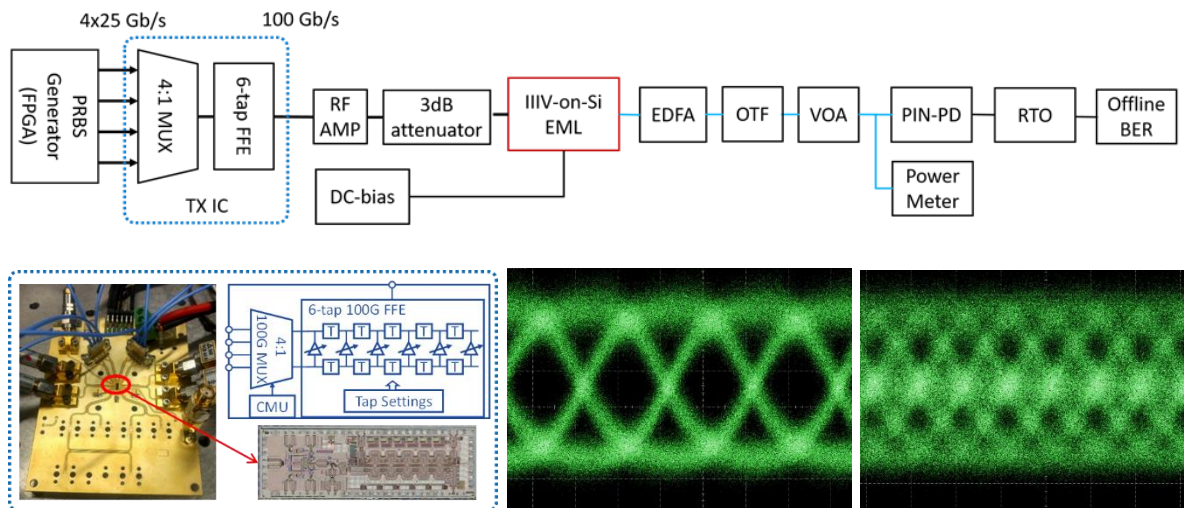


Figure 3. Schematic of the measurement setup (top), schematic and die micrograph of the TX-IC (bottom left); eye diagrams at 50 Gb/s NRZ-OOK (bottom middle) and 100 Gb/s EDB (bottom right), the DFB laser is biased at 80 mA and the EAM at -0.8 V.

the link. The TX-IC consumes less than 0.9W. An RF amplifier with bias-T delivers the signal with a swing of  $\sim 2.5$  Vpp to the EML via an RF-probe. To reduce back reflection to the RF amplifier, a 3 dB attenuator is placed at the output of the RF AMP. During bit-error rate (BER) measurements the laser was biased at 80 mA and the EAM was biased at -0.8 V. As no high-speed transimpedance amplifier was available during testing, an erbium-doped fiber amplifier (EDFA) had to be used to increase the signal power to  $\sim 9$  dBm before entering a commercial PIN-photodiode (BW=45 GHz). An optical tunable filter is used to minimize the EDFA-noise. Finally, the signal is captured by a 63 GHz 160 GSa/s real-time oscilloscope (RTO). The BER is determined offline by resampling the captured signal. The optimal sampling point is determined by visual inspection of the eye diagram, no equalization or other DSP is used. For more than 100,000 symbols a BER of  $1.6\text{E-}3$  was measured which is below the hard decision forward error coding limit with 7% overhead ( $3.8\text{E-}3$ ).

#### 4. CONCLUSIONS

We demonstrated for the first time the generation 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 DSP. Since the device consists of two identical EAMs on each side, we can use each side to generate 2 independent 100 Gb/s EDB data streams resulting in a single laser 200 Gb/s transmitter [4]. Combining two of these devices could be low-cost and compact option for 400 GbE transceivers for short-reach optical interconnects.

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