28 Gb/s Direct Modulation Heterogeneously Integrated InP/Si DFB Laser

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Abstract We report for the first time the 28 Gb/s direct modulation of heterogeneously integrated III-V-on_Silicon DFB laser. Transmission experiments using 1km of standard single mode fiber were also performed and gave a 4.3 dB penalty at a bitrate of 25 Gb/s.

Introduction

Silicon photonics has received a great deal of attention in the past decade. Its compatibility with CMOS technology as well as the possibility to implement very compact passive optical circuits make it a potential low cost platform for the realization of optical transceivers[1]. While excellent passive components have been demonstrated already some years ago, there has also been significant progress on silicon optical modulators[2] and efficient InP laser diodes heterogeneously integrated on silicon-on-insulator waveguides have been demonstrated as well[3-6].

Direct modulation of laser diodes has significant advantages over the use of external modulators in terms of power consumption[6]. For many applications, a.o. optical interconnects in datacenters, it would thus be desirable to have directly modulated transmitters with high modulation bandwidth, based on hetero-generously integrated laser diodes on SOI.

So far however, only a few results on the high speed direct modulation capabilities of heterogeneously integrated laser diodes have been published. In [7], a hybrid DFB laser was directly modulated up to 12.5 Gb/s with an extinction ratio of 2.8 dB for a 1.5 V voltage swing at that bitrate. In [8], a much higher bitrate of 21.4 Gb/s is demonstrated using a heterogeneously integrated tunable laser, using an external cavity resonance. However, the use of an external cavity resonance requires fine tuning and it thus complicates the control of the laser diodes and increases the power consumption.

This paper reports on the high speed (28 Gb/s) direct modulation of DFB membrane lasers, heterogeneously integrated on and coupled to a SOI waveguide circuit.

Fabrication

The fabrication process begins by adhesive bonding of unprocessed III-V epi on the SOI circuit[9]. DFB gratings are patterned on 400 nm Si rib waveguides in a CMOS pilot line by a 180nm etch. The 400 nm thick Si waveguides are necessary for an efficient coupling between the III-V mesa and the Si rib waveguide by adiabatic taper structures[5]. More details on the III-V processing can be found in [10]. GSG pads are patterned for high speed measurements.

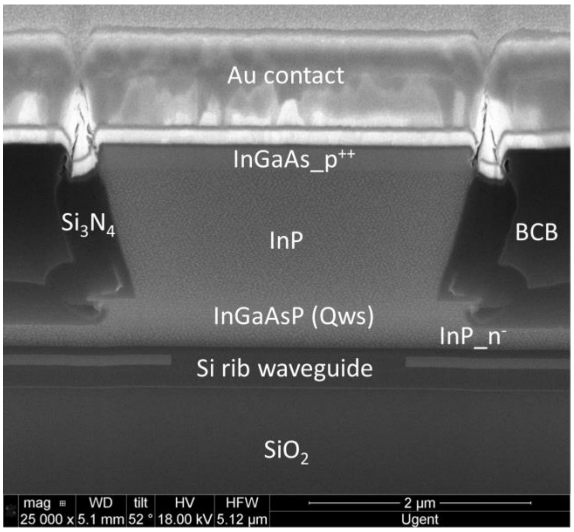

Fig. 1: The cross section of the hybrid DFB laser

The DFB laser length is 340 μm and two tapers of 220 μm each are used to have a lower reflection and a higher coupling between the Si waveguide and the InP mesa. The DFB grating period is 245 nm with 50% duty cycle. In Fig. 1, a cross section of the fabricated device is shown. A V-shaped mesa structure helps to have a large confinement factor in the active section. The III-V epitaxial layer stack that is used consists of a 200 nm thick n-InP contact layer, two 100 nm thick InGaAsP separate confinement heterostructure layers (bandgap wavelength 1.17 μm), 6 InGaAsP quantum wells (6 nm thick, emission wavelength 1.55 μm) surrounded by InGaAsP barriers, a 1.5 μm thick p-InP top cladding and a 300 nm p++ InGaAs contact layer. The passivation stack of PECVD Si_3N_4 and DVS-BCB layers reduces the parasitic capacitance and creates an effective electrical isolation.

Static characteristics

The laser optical spectrum is depicted in Fig. 2. The laser threshold current is around 17 mA and a maximum waveguide coupled optical output power of 5 mW is obtained at a drive current of 100 mA. The SMSR is more than 55 dB. The extracted coupling coefficient in the low gain approximation from the stop-band of the laser spectrum is almost 135 cm^{-1}.

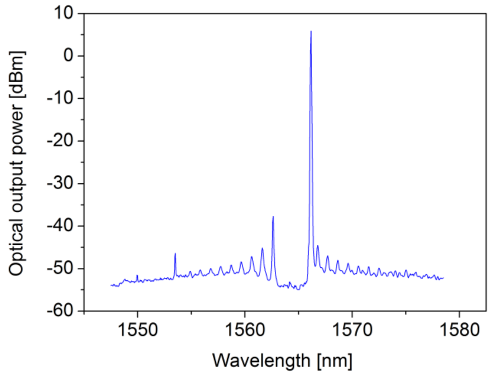

Fig. 2: The optical spectrum of the device with a length of 340 μm for 100 mA bias current.

Dynamic characteristics

A small signal measurement was done with a KEYSIGHT PNA-X 67 GHz network analyzer. The RF signal was combined with a DC current by using a bias-tee, and a GSG probe with 100 μm pitch was used to apply the combined signal to the DFB laser. The small signal response of the device is presented in Fig. 3 for different bias currents.

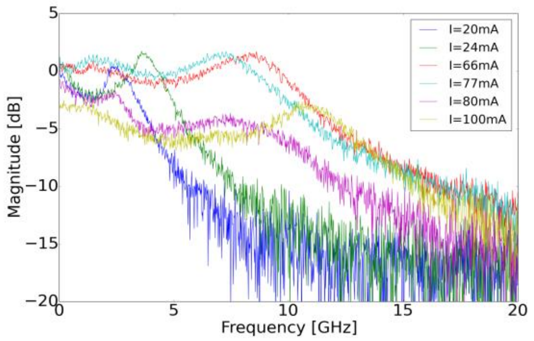

Fig. 3: Small signal response at different bias current

The 3 dB bandwidth is around 15 GHz at 100 mA. Since for the large signal measurement, the data pattern lengths were quite short (2^7-1 and 2^{11}-1), the laser very low frequency response is not considered for the 3 dB bandwidth calculation. A SHF pulse pattern generator (PPG) 12100B was used to do a continuous bitrate sweep with adjustable pattern lengths. The output of the PPG was sent through a RF amplifier. A 1.5 V swing on the laser was used. The modulation response was measured with a Tektronix DSA 8300 sampling oscilloscope with a 30GHz built-in photodetector (PD). This measurement was carried out at 20°C both for back-to-back and with 1 km and 5 km of standard single mode fiber with a 2^{11}-1 non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS) pattern. The result of this large signal modulation, for a bias current of 100 mA, is shown in Fig. 4 (back-to-back). The maximum modulation speed was found to be 28 Gbps with an extinction ratio of 2 dB. To the best of the authors' knowledge, this is the highest direct modulation speed for a membrane DFB laser heterogeneously integrated on and coupled to a SOI waveguide.

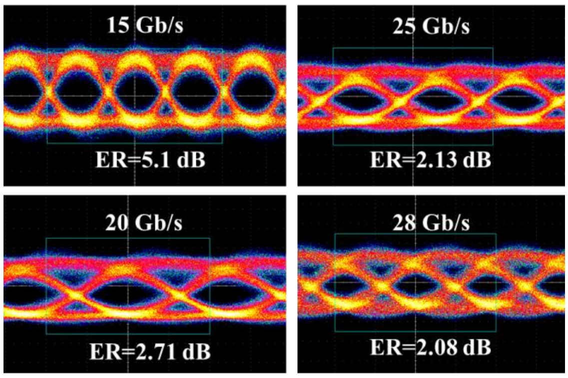

Fig. 4: Eye diagrams for back-to-back operation at 15, 20, 25 and 28 Gbps

In Fig. 5 the eye diagrams for back-to-back and after transmission through 5 km of standard single mode fiber (SSMF) at a rate of 15 Gb/s are shown. The modulated signal is distorted after passing through the fiber because of the inherent chirp of the laser and chromatic dispersion of the fiber.

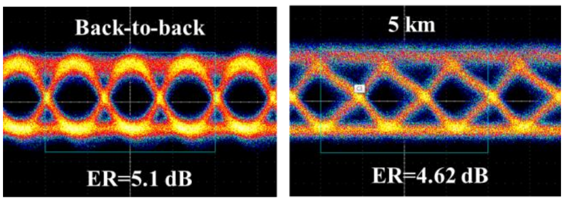

Fig. 5: Eye diagrams for back-to-back (left) and after 5 km fiber transmission (right) at 15 Gbps

BER measurements were done to evaluate the transmitter performance in back-to-back and after transmission through 5 km SMF at a bitrate of 10 and 15 Gb/s. The results are presented in Fig. 6. A PIN photodiode with 40 GHz bandwidth has been used for this measurement. Since this kind of photodiode has a lower sensitivity than avalanche photodiode or photodiodes with integrated TIA, the required received power levels are on the high side.

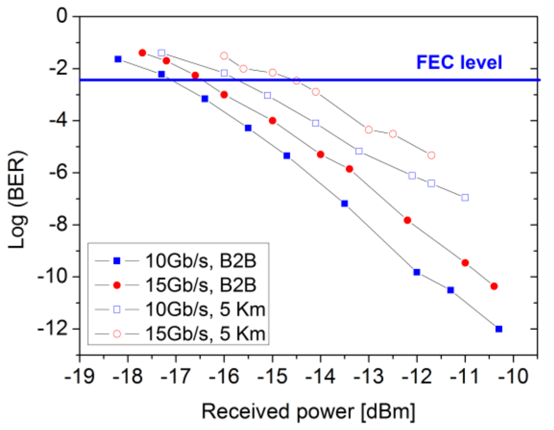

Fig. 6: BER measurements for back-to-back and 5 km single mode fiber configurations.

Assuming 7% hard-decision (HD) forward error correction (FEC), a power penalty of 1.3 dB and 1.7 dB is observed at 10 Gb/s and 15 Gb/s for a BER of 3.8e-3, respectively. For the higher rates, the transient chirp of the modulated laser causes a strong pulse broadening. At 20 and 25 Gb/s modulation speed, the BER measurements were done with 1 km SSMF and a drive voltage of 2 V_{pp} with a 2^7-1 NRZ-PRBS pattern. The results are presented in Fig. 7. The chirp was filtered out for the BER measurement at 25 Gb/s by using a narrow band filter.

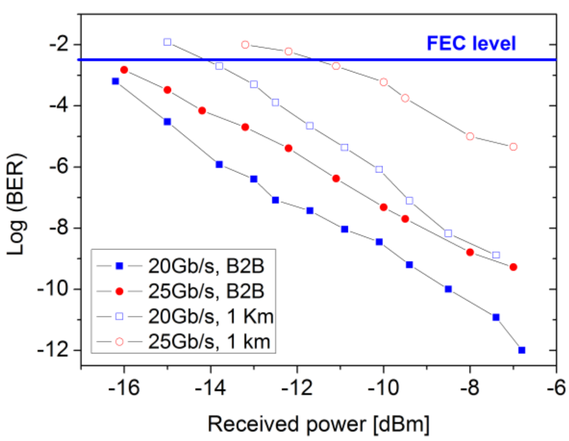

Fig. 7: BER measurements for back-to-back and 1 km single mode fiber configurations.

As shown in Fig. 7, 2.3 dB and 4.3 dB power penalties were measured for a BER of 3.8e-3, respectively. These results show the potential of our DFB lasers for short reach optical interconnect systems at a speed of 25 Gb/s and higher. A coarse WDM configuration, multiplexing an array of four such lasers would be a very suitable 100 Gb/s optical transmitter for short access links or data-center interconnects.

Conclusions

An InP/Si heterogeneously integrated DFB laser for high speed direct modulation has been fabricated. 28 Gb/s direct modulation with 2 dB extinction ratio was demonstrated in a back-to-back configuration. Transmission of 15 Gb/s over 5 km SSMF and of 25 Gb/s over 1 km SSMF was also demonstrated, with power penalties ranging from 1.7 dB to 4.3 dB. Further speed improvement may be possible by wavelength detuning from the gain peak, threshold current reduction, better cooling and an electrically impedance matched design for 50Ω.

Acknowledgements

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