High-Speed Directly Modulated Heterogeneously Integrated InP/Si DFB Laser

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Abstract *We discuss how InP membrane laser diodes, heterogeneously integrated on SOI can be designed for high speed operation. This is illustrated with several static and dynamic characteristics of fabricated lasers. We finally report link experiments with the directly modulated lasers.*

Introduction

There is a growing need for high bitrate interconnects, a.o. for intra data center and inter data center interconnects. Standards for 400 GbE are emerging and some companies have even expressed interest in a Terabit Ethernet standard[1]. It is expected that 400 GbE will be based on lane speeds of 25 Gb/s, 50 Gb/s and even 100 Gb/s. Especially for distances of more than 10 km, there is great interest in using either 8 wavelengths, each carrying 50 Gb/s NRZ-OOK, and 4 wavelengths each carrying 100 Gb/s PAM-4 modulation[2].

In the past years many external modulators (both electro-absorption and Mach-Zehnder) have been reported with maximum bitrates of 56 Gb/s or more[3,4]. However, also several DFB laser diodes and VCSELs have been reported at 1300 and 1550 nm that are capable of direct modulation up to 56 Gb/s[5,6]. External modulation is more power consuming than direct modulation[7], results in extra footprint and comes with insertion loss. VCSELs on the other hand are difficult to integrate into a WDM transmitter and may not give enough output power for longer reach links. DFB lasers are much better suited for photonic integration and easily give the required output powers for longer distance interconnects.

In the past years, we have been working on directly modulated InP DFB membrane lasers, heterogeneously integrated onto silicon on insulator (SOI) and we'll discuss the progress in that area below. The fabrication on SOI brings a number of potential advantages. Since SOI is very well suited for the implementation of compact, passive optical components, it is straightforward to integrate arrays of heterogeneously integrated lasers with components such as optical filters or multiplexers. The laser diodes are in principle also more suited for co-integration with driver electronics implemented in BiCMOS[8]. The shorter electrical connections would then allow to avoid impedance controlled interconnects, resulting in lower power consumption and larger electrical bandwidth. Finally, the development of transfer printing techniques make the heterogeneous integration possible with efficient use of the III-V material[9].

Design and fabrication

The laser diodes are realised by integrating the III-V epitaxial structure on top of the SOI waveguides using adhesive bonding and

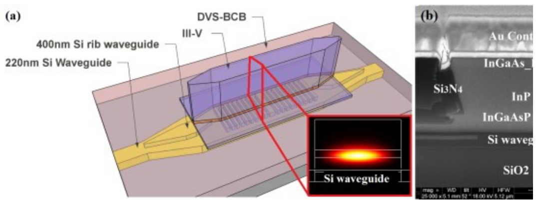

Fig. 1: (a) Schematic of the realized device with the lasing mode intensity profile, predominantly confined in the III-V waveguide; (b) cross section of the fabricated hybrid DFB laser

subsequent processing [10]. Coupling between the InP mesa and the 400nm thick silicon waveguides is obtained by adiabatic tapering of both the InP mesa and the Si waveguides[10]. The Bragg grating is realised in the underlying Si waveguides with an etch of 180nm deep. The bonding layer thickness and InP mesa structure are designed such that the mode has a good overlap with the active layer and the grating. A schematic of the laser structure is shown in Figure 1(a) and a SEM picture of the cross section in Figure 1(b). Very thin bonding layers (as thin as 10 nm) are used to obtain a large coupling coefficient (135 cm^{-1} or higher). The active layer consists of SL-MQW material and both InGaAsP and InAlGaAs SL-MQWs have been used. The large coupling coefficient gives a small cavity loss, which together with the large

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confinement factor for the active layer results in a small threshold gain and a large differential gain. The laser light is coupled from the Si waveguide to single mode fiber using surface grating couplers.

The implementation of the grating in an underlying Si waveguide implies that the lasing mode has to overlap well with both the active layer and the Si waveguide. This compromises the confinement factor (and thus the resonance frequency) somewhat compared to membrane lasers which are bonded on SiO_2/Si substrates[11], but makes the fabrication easier. The tapers required for the coupling between the InP membrane and the Si waveguide were so far always pumped and modulated together with the DFB section. It is however expected that better modulation behaviour can be achieved when the

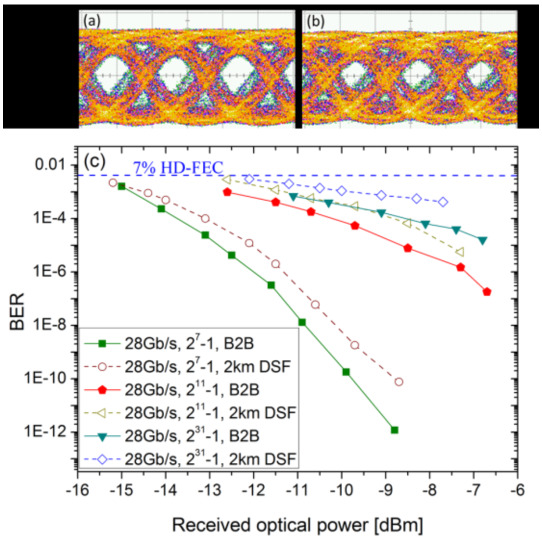

Fig. 2: Eye diagrams for back-to-back (a) and after 2 km NZ-DSF fiber transmission (b) at 28 Gb/s using a 2^{11}-1 data pattern length (bias current of 100 mA at 20℃), BER curves for different PRBS pattern lengths (c).

taper currents are not modulated and results for modulation of the DFB current only will be discussed at the conference.

Results from InGaAsP MQW lasers

The first batch of high speed lasers were fabricated using a III-V layer stack consisting of 6 InGaAsP quantum wells (photoluminescence peak at 1.55 µm) sandwiched between InGaAsP separate confinement heterostructure layers (bandgap wavelength 1.17 µm) and InP cladding layers. The total thickness of the bonding layer (BCB and oxide) is 50 nm. This results in lasers with typical threshold current below 20 mA, a power in the Si waveguide of 6 mW at 100 mA and SMSR of 45 dB at a stage temperature of 20℃. The current is injected into both the laser (above the grating) and the tapers, which act as semiconductor optical amplifer (SOA). The length of the laser is 340 µm and that of the tapers is 220 µm. From the width of the stopband, a coupling coefficient of 135 cm^{-1} was estimated. This laser showed a 3dB small signal modulation

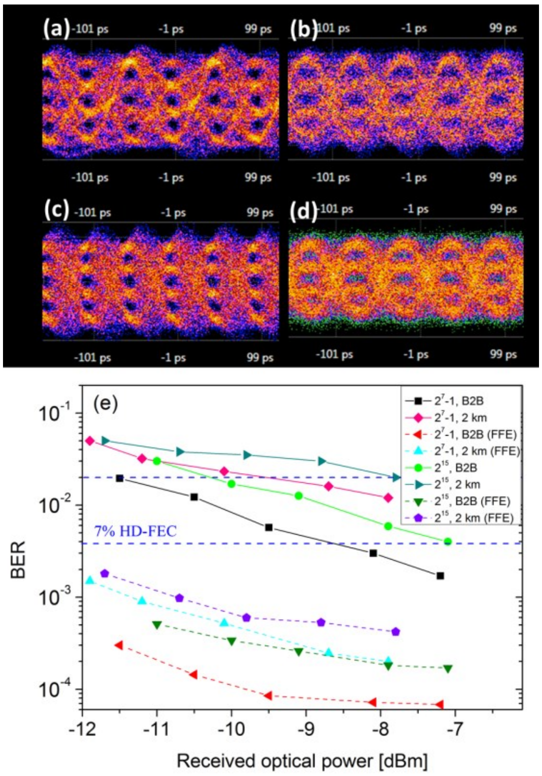

Fig. 3: Eye diagrams for PAM-4 at 20 GBaud in back-to-back configuration and after 2km of transmission over NZ-DSF for a PRBS length of 2^7-1 (a,b) and for a length of 2^{15} (c,d). BER measurements for back-to-back and 2 km NZ-DSF configuration (bottom).

bandwidth of 15 GHz at a 100 mA bias current. NRZ-OOK large signal modulation was demonstrated up to 28 Gb/s, as well as transmission over 2km of NZ-DSF fiber (with dispersion of 4.5 ps/nm.km) with bit error rates (BER) below the 7% HD-FEC limit. Eye diagrams and BERs vs. received power are shown in Figure 2.

This laser was also used for the transmission of 20 Gbaud PAM-4 and DB (duobinary) signals. Eye diagrams and BER vs. received power for the back-to-back configuration and after 2 km of transmission over NZ-DSF fiber are shown in Figure 3. The received data were post-processed off-line for BER estimation with and without equalisation in this case[12].

Results from InAlGaAs MQW lasers

Due to the buried silica, thermal conduction between the InP membrane and the Si substrate is not optimum and our lasers are expected to

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have relatively strong internal heating. As InAGaAs active layers suffer less from high temperatures, we have recently moved to Al-containing active layers with SL-MQWs. The first lasers have been fabricated and first results have been obtained on the modulation.

The small signal modulation response for one of the lasers is shown in Figure 4. When excluding the low-frequency part (which may be due to the modulation of the tapers acting as SOAs, or due to spatial hole burning), we find a 3dB modulation bandwidth of 34 GHz. This high bandwidth is achieved thanks to an external cavity resonance at around 30 GHz[13]. The external cavity is formed by the grating couplers, which reflect about 4% and are separated by about 1000 μm. Several other lasers with similar modulation response were obtained from the same fabrication run.

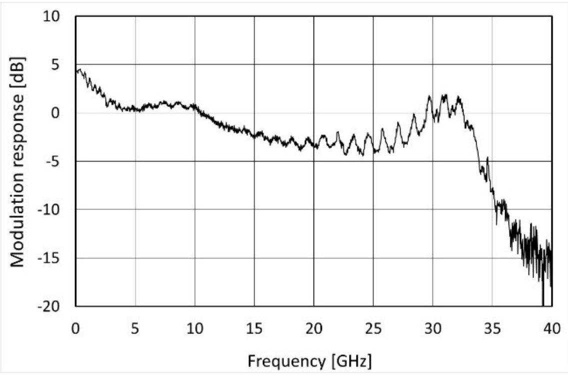

Fig. 4: Small signal modulation response of an InAlGaAs membrane DFB laser diode with external cavity formed by the grating couplers.

Large signal experiments are currently being performed with these laser diodes and will be discussed during the presentation.

Conclusions

InP membrane laser diodes, heterogeneously integrated on SOI, are well suited for high-speed modulation and have potential for modulation above 50 Gb/s. They are moreover ideally suited for integration into WDM sources and for co-integration with driver electronics.

Further improvements are expected by further optimisation of the active layer, by modulating only the laser section and not the tapers and by reducing the laser section length further.

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