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High Speed Modulation of InP Membrane DFB Laser Diodes

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ABSTRACT

Heterogeneously integrated DFB lasers, consisting of thin InP membranes coupled to low loss Si wire waveguides possess several advantages compared to traditional all-InP DFB lasers. The thin membranes give a large optical confinement factor and their small surface area results in relatively small parasitic capacitances. Both properties make these lasers very well suited for high speed direct modulation. The low loss silicon wire waveguides furthermore lend themselves very well for the implementation of low loss external cavities. Coupling membrane DFB lasers to such an external cavity allows exploiting photon-photon resonances in the modulation response.

In this paper we report on the high speed modulation results of our heterogeneously integrated DFB laser diodes. Below we mainly focus on results for on-off-keying, but at the conference we will also present eye diagrams and BER curves for duobinary and PAM-4 modulation formats. We also discuss link experiments done with the lasers and some ideas for further improvement. The excellent large signal modulation and transmission results and the potential to integrate them into WDM modules make the laser diodes particularly suited as transmitters for longer distance optical interconnects inside or between data centers.

Keywords: DFB lasers, direct modulation, short distance links, high bitrate.

1. INTRODUCTION

There is an increasing need for very high speed optical interconnections, a.o. for inter or intra data center interconnects. Maximum distances for intra data center interconnects are around 2km while distances go up to 80 km for inter data center interconnects [1]. Several standards for 100 GbE are based on 4 lanes carrying slightly over 25 Gb/s each, while the emerging 400 GbE will most likely make use of 8 lanes carrying 56 Gb/s each [2]. Moreover, power consumption is very important as present day datacenters consume a lot of power and the networking/interconnect infrastructure is responsible for a significant part of that power consumption [1]. Direct intensity modulation and direct detection normally provide the most cost effective and power efficient solution.

In the past, optical interconnects were preferably implemented using vertical cavity surface emitting lasers (VCSELs) or arrays of such lasers and multimode fiber. However, multimode fibers are getting replaced fast by single mode fibers [3]. Although VCSELs are continuously improving in output power and have recently been demonstrated with 56 Gb/s direct modulation [4], they still have some disadvantages. Their output power, albeit now close to few mW, is not enough to guarantee a large signal to noise ratio at the receiver for longer links. In addition, VCSELs don't lend themselves well for integration with other photonic components, required e.g. to multiplex the output of several VCSELs in wavelength, let alone for co-integration with driver electronics.

InP membrane DFB laser diodes, heterogeneously integrated on silicon-on-insulator (SOI) waveguides, form a good alternative. As will be shown below, such lasers can exhibit high output power and high modulation bandwidth. Their output is coupled to silicon waveguides and the laser diodes therefore lend themselves very well for integration with different kinds of passive waveguide components, which can be implemented in SOI waveguide technology. In principle it is also possible to co-integrate the laser diodes with e.g. BiCMOS driver electronics [5].

Below, we first elaborate on the advantages of the use of InP membrane lasers on silicon for high speed direct modulation. Then we discuss some of the results that have been obtained using this approach. We conclude by giving some considerations on how the laser diodes and their speed can be further improved. We have demonstrated 28 Gb/s direct modulation of heterogeneously integrated DFB laser diodes and transmission over 2 km. In principle four such directly modulated laser diodes could be integrated on SOI and integrated with a wavelength multiplexer in a straightforward way and this would make an ideal transmitter for 100 GbE. We also demonstrated 40 Gb/s PAM-4 and duobinary modulation. Very recently, a laser diode with 34 GHz small signal modulation bandwidth has been fabricated and large signal modulation experiments with that laser will be done in the near future.

2. ADVANTAGES OF HETEROGENEOUS INTEGRATION OF INP MEMBRANES ON SOI

The lasers are fabricated by bonding very thin membranes on top SOI waveguide structures, with a cross section as shown schematically in Fig. 1. The silicon waveguides have very small dimensions (400 nm thickness and width), the bonding layer can be as thin as 10 nm and the InP substrate is removed after bonding. This leads to a laser mode which is very well confined to the active layer of the laser structures, i.e. a high optical confinement factor Γ. Since a high modulation bandwidth requires a high resonance frequency for the relaxation oscillation and since the squared resonance frequency is given by $\Gamma(\mathrm{d}g/\mathrm{d}N)v_g.(I-I_{\mathrm{th}})/qV$, a large confinement factor over active layer volume is advantageous for high speed operation. $\mathrm{d}g/\mathrm{d}N$ is the differential gain and $I-I_{\mathrm{th}}$ is the difference between bias current and threshold current.

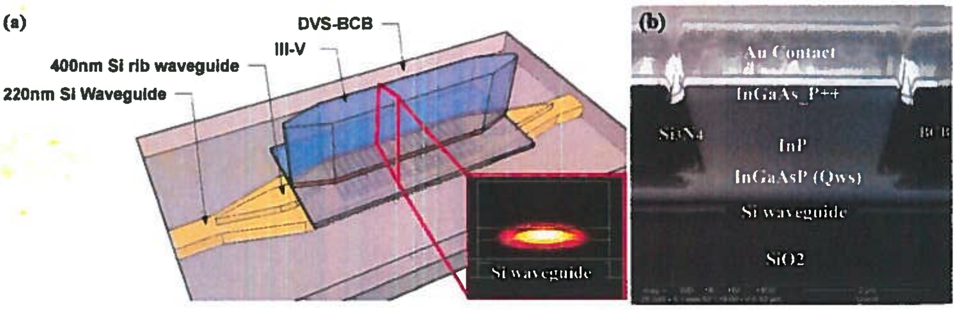

Figure 1: (a) Schematic of the realized device with the lasing mode intensity profile, predominantly confined in the III-V waveguide; (b) cross section of the fabricated hybrid DFB laser.

The Bragg gratings in our approach are implemented in the underlying silicon waveguide and are formed by the very large contrast in refractive index between silicon and BCB. The coupling coefficient of the gratings can be varied by modifying the thickness of the BCB bonding layer. For very thin bonding layers (and they can be as thin as 10nm), very large coupling coefficients κ of over 150 cm^{-1} can be obtained, giving a κL of 4.5 for a 300 μm long grating. Thicker bonding layers lead to smaller coupling coefficients. Large κL values lead to small mirror loss, low threshold gain and low carrier density in the quantum wells. As we used strained layer multi quantum well active layers (both InGaAsP and InAlGaAs), the differential gain increases with decreasing carrier density. Hence, by using thin bonding layers and large κL values we can also get high differential gain. So far, active layers with 6 quantum wells were used, and probably even higher differential gain could be obtained by using a larger number of quantum wells.

A third advantage is related to the fact that the light output from the membrane lasers is coupled to SOI waveguides and that these waveguides have very low loss [6]. It has been shown before [7] that the modulation bandwidth of laser diodes can be extended by using a second resonance caused by the addition of an external cavity and with a resonance frequency determined by the roundtrip time in the compound cavity. However, as shown in [7], this only works well when the loss in the external cavity is small enough. Obviously, because of the low loss of silicon waveguides it is not difficult to connect membrane laser diodes to low loss external cavities. A simulated intensity modulation response for a 2-section DBR laser diode, for various losses in the passive Bragg section, shown in Fig. 2, shows how the modulation bandwidth is increased by the external cavity resonance but only if the loss in the passive section is low enough.

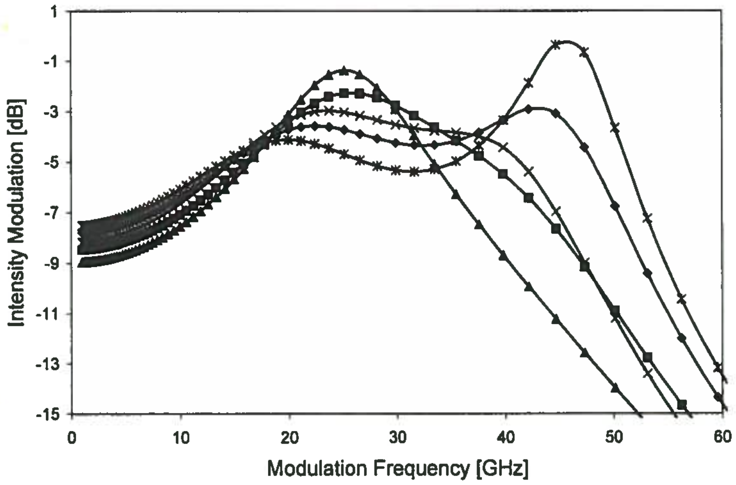

Figure 2. Intensity modulation response (at 150 mA bias current) of the DBR laser with AR-coated facet at the Bragg section and κ= 30 cm^{-1} for α_{int}= 5 (*), 10 (◆), 15 (x), 20 (■) and 25 (▲) cm^{-1}.

3. RESULTS

First fabricated membrane laser diodes were without (intentional) external cavity, using 6 InGaAsP strained layer multi quantum wells, with a coupling coefficient of 135 cm^{-1} and grating length of 300 μm. The light is coupled from the InP membrane to the silicon using tapers and these tapers are pumped as well and act as semiconductor optical amplifiers. The bonding layer thickness was 50 nm. The lasers typically have a threshold current of 17 mA, a series resistance below 10 Ω and an output power (in the Si waveguide) of 6 mW at 100 mA.

Small signal results for these lasers are typically as shown in Fig. 3. The maximum 3 dB bandwidth is 15 GHz. In many small signal responses, there seems to be a low frequency contribution. This could possibly be the result of the modulation of the current injected into the SOAs but it may also be caused by spatial hole burning. Both effects have a cut-off frequency determined by the carrier lifetime, which could be a few GHz. The laser from Figure 3 has then been used to demonstrate 28 Gb/s NRZ on-off-keying (OOK) modulation, as well as 40 Gb/s duobinary and PAM-4 modulation. Eye diagrams for 28 Gb/s NRZ OOK are shown in Fig. 4 for the back-to-back configuration and after transmission through 2 km of NZ_DSSMF fiber. Bit-error-rates were in both cases below the FEC limit [8]. PAM-4 and DB results will be presented at the conference.

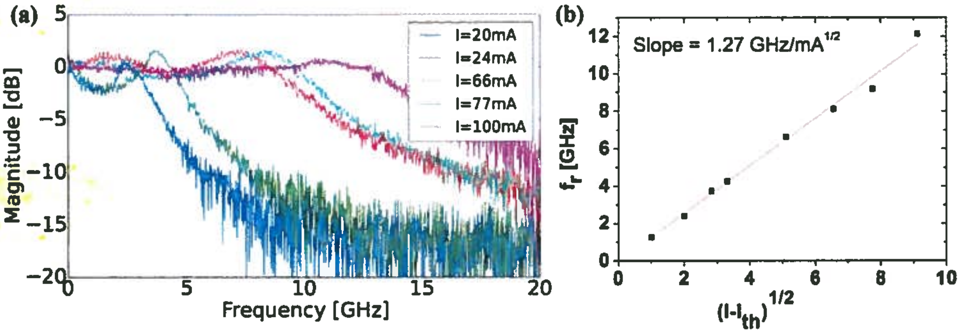

Figure 3: (a) Small signal response at different bias currents; (b) The dependence of relaxation oscillation frequency (f_r) on the driving current.

Figure 4. Eye diagrams for back-to-back (left) and after 2 km NZ_DSSMF fiber transmission (right) at 28 Gb/s using a 2^{11}-1 data pattern length (bias current of 100 mA at 20 ℃).

More recently, membrane DFB laser diodes were fabricated with 6 InAlGaAs strained layer quantum wells. In addition, a thinner bonding layer of 10 nm was used, which increased the coupling coefficient further. The grating couplers, used to couple the light from the Si waveguide to the fiber, provided an external reflection for this laser and formed a compound cavity with a roundtrip time of 5 ps. This resulted in a small signal modulation bandwidth of 34 GHz, enough for OOK modulation beyond 40 Gb/s. Results on the modulation of this laser will be shown during the conference.

4. CONCLUSIONS AND OUTLOOK

We have illustrated how the specific properties of membrane laser diodes, heterogeneously integrated on SOI waveguides can be exploited to obtain very high speed direct modulation. This has so far resulted in a laser diode with a small signal modulation bandwidth of 34 GHz, which can be modulated beyond 40 Gb/s.

Several improvements can still be made to these laser diodes that might possibly increase the maximum bitrate to 56 Gb/s. First, one can be try to increase the relaxation oscillation resonance frequency further by increasing the differential gain and by increasing the output power. Increasing the differential gain will be attempted by using 9 or 12 quantum wells instead of 6. The output power or internal power can be increased for fixed bias current by providing better heat sinking. At present, heat sinking is not very good because of the small surface of the InP membrane and the thick oxide between the silicon substrate and the membrane laser. This can be overcome by providing a metallic connection between the upper silicon and the substrate [10]. A higher first resonance frequency obviously allows shifting the external cavity resonance also to a slightly higher frequency.

A higher relaxation oscillation resonance frequency is in principle also possible by making use of detuned loading. This is typically something which can be implemented with 2 section DBR lasers and allow exploiting the dispersion in the Bragg reflection to increase the relaxation oscillation resonance frequency [7].

ACKNOWLEDGEMENTS

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13:10 Mo.B1.6 Pilot tones based polarization rotation, frequency offset and phase estimation for polarization multiplexed offset-QAM multi-subcarrier coherent optical systems *S.M. Bilal, G. Bosco*					
Lunch break (13:25-15:00)	***Lunch break*** (13:10-14:40)	***Lunch break*** (12:50-14:20)	***Lunch break*** (13:10-14:40)	***Lunch break*** (13:05-14:40)	***Lunch break*** (13:10-14:40)
ICTON II *Chair: **Yaping Zhang*** **(15:00-16:20 Monday, July 11)**	**OWW I** *Chair: **Milorad Cvijetic*** **(14:40-16:10 Monday, July 11)**	**DACINT II** *Chair: **Lech Wosinski*** **(14:20-15:20 Monday, July 11)**	**SWP II** *Chair: **Piotr Nyga*** **(14:40-16:20 Monday, July 11)**	**NAON I** *Chair: **Tomasz Czyszanowski*** **(14:40-16:20 Monday, July 11)**	**ESPC II** *Chair: **Lucio Claudio Andreani*** **(14:40-16:35 Monday, July 11)**
15:00 Mo.C1.1 Space division multiplexing (SDM) transmission and related technologies (***Invited***) ***N. Wada***, *B.J. Puttnam, R.S. Luis, J. Sakaguchi, W. Klaus, J.M.D. Mendinueta, Y. Awaji*	14:40 Mo.C2.1 High-aggregate-capacity guided-wave visible light communication links (***Invited***) ***N. Bamiedakis***, *X. Li, R.V. Penty, I.H. White*	14:20 Mo.C3.1 Single mode optical interconnects for future data centers (***Invited***) ***K. Vyrsokinos***, *M. Moralis-Pegios, C. Vagionas, A. Brimont, A. Zanzi, P. Sanchis, J. Marti, J. Kraft, K. Rohracher, S. Dorrestein, M. Bogdan, N. Pleros*	14:40 Mo.C4.1 Dilute III-PBi and III-SbBi for IR applications (***Invited***) ***Shumin Wang***	14:40 Mo.C5.1 Timing jitter and repetition rate control of a passively mode-locked semiconductor laser by dual optical feedback (***Invited***) *O. Nikiforov, L. Jaurigue, L. Drzewietzki, K. Lüdge,* ***S. Breuer***	14:40 Mo.C6.1 Polarisation singularities in photonic crystal waveguides: How photonic wheels stop turning when light slows down (***Invited***) ***D.M. Beggs***, *B. Lang, A.B. Young, R. Oulton*
15:20 Mo.C1.2 Ultra-dense space division multiplexing technologies towards multi-petabit/s optical transmission (***Invited***) ***M. Suzuki***, *D. Soma, K. Igarashi, Y. Wakayama, K. Takeshima, Y. Kawaguchi, N. Yoshikane, T. Tsuritani, I. Morita*	15:00 Mo.C2.2 New type of VLC communication transmitter based on optical fibers (***Invited***) ***J. Latal***, *J. Vitasek, L. Hajek, A. Vanderka, O. Zboril, D. Pudis, P. Koudelka, V. Vasinek*	14:40 Mo.C3.2 Silicon photonics for switching in next generation data centers (***Invited***) ***L. Pavesi***	15:00 Mo.C4.2 Electrochemical optical actuators: Controlling the light through ions (***Invited***) ***F. Morichetti***, *S. Zanotto, A. Blancato, F. Berkemeier, M. Muñoz Castro, A. Buchheit, H–D. Wiemhöfer, G. Schmitz, C. Klitis, M. Sorel, A. Melloni*	15:00 Mo.C5.2 Evolution of very small lasers (***Invited***) ***Yong–Hee Lee***, *Hoon Jang*	15:00 Mo.C6.2 Slow light enabled wavelength demultiplexing (***Invited***) *Z. Hayran, M. Turduev, M. Botey, R. Herrero, K. Staliunas,* ***H. Kurt***
15:40 Mo.C1.3 Spatial modes-based physical-layer security (***Invited***) ***I.B. Djordjevic***, *Xiaole Sun*	15:20 Mo.C2.3 Non-Hermitian symmetry OFDM for indoor space division multiplexing visible light communications (***Invited***) ***Wen–De Zhong***, *Chen Chen, Dehao Wu*	15:00 Mo.C3.3 Low power consumption receiver on silicon (***Invited***) *L. Virot, D. Marris-Morini, D. Benedikovic, C. Alonso-Ramos, J–M. Hartmann, E. Cassan, P. Crozat X. Le Roux, C. Baudot, F .Boeuf, J–M. Fédéli,* ***L. Vivien***	15:20 Mo.C4.3 Methods of creation and optimization of anisotropic liquid-crystal photonics structures (***Invited***) ***I.A. Goncharenko***, *O.S. Kabanova, E.A. Melnikova, O.G. Romanov, I.I. Rushnova, A.L. Tolstik*	15:20 Mo.C5.3 High speed modulation of InP membrane DFB laser diodes (***Invited***) ***G. Morthier***, *A. Abbasi, M. Shahin, J. Verbist, X. Yin, J. Bauwelinck, G. Roelkens*	15:20 Mo.C6.3 Analysis of the Brownian motion of singly trapped spheres in hollow photonic crystal cavities (***Invited***) *M. Tonin, F. Mor, S. Jeney, L. Forró,* ***R. Houdré***
16:00 Mo.C1.4 Towards multidimensional multiplexing in multicore fiber optical data links (***Invited***) ***R. Llorente***, *A. Macho, D. Garcia-Rodriguez, A. Zainullin, M. Morant, J.L. Corral*	15:40 Mo.C2.4 Adaptive receiver for visible light communication system *A.A. Al–Hameed, A.T. Hussein, M.T. Alresheedi, J.M.H. Elmirghani*		15:40 Mo.C4.4 Optimizing the linear range of FET-based THz detectors (***Invited***) ***F. Bigourdan***, *M.R. Razafindrakoto, D. Felbacq*	15:40 Mo.C5.4 Dilute bismide alloys grown on GaAs and InP substrates for improved near- and mid-infrared semiconductor lasers (***Invited***) *C.A. Broderick, Wanshu Xiong, S.J. Sweeney, E.P. O'Reilly,* ***J.M. Rorison***	15:40 Mo.C6.4 Superconducting photonic crystals with defect structure (***Invited***) ***I. Lyubchanskii***, *Y. Dadoenkova, N. Dadoenkova, A. Zabolotin, M. Krawczyk*
	15:55 Mo.C2.5 Hybrid diffuse IR transmitter supporting VLC systems with imaging receivers *M.T. Alresheedi, A.T. Hussein, J.M.H. Elmirghani*		16:00 Mo.C4.5 Charge-carrier/exciton transfer between two quasi-zero-dimensional nanostructures (***Invited***) ***K. Král***, *M. Menšík*	16:00 Mo.C5.5 Optical injection in semiconductor lasers: Physics and applications (***Invited***) ***A. Bogris***, *D. Syvridis, A. Fragkos, T. Nikas, H. Simos, W. Elsäßer*	16:00 Mo.C6.5 Vanishing gaps in photonic crystals and other periodic potentials (***Invited***) *S. Caffrey,* ***G.V. Morozov***, *D. Macbeath, D.W.L. Sprung*
					16:20 Mo.C6.6 Polarization independent focusing of light by gradually modulated annular photonic structure *B. Tellioğlu, E. Bor, M. Turduev, H. Kurt*
Coffee break (16:20-16:50)	***Coffee break*** (16:10-16:40)	***Coffee break*** (15:20-15:50)	***Coffee break*** (16:20-16:50)	***Coffee break*** (16:20-16:50)	***Coffee break*** (16:35-17:00)
ICTON III *Chair: **Jarmila Müllerová*** **(16:50-18:30 Monday, July 11)**	**OWW II** *Chair: **Goran Djordjevic*** **(16:40-18:10 Monday, July 11)**	**FIWIN5G I** *Chair: **Nikos Pleros*** **(15:50-17:05 Monday, July 11)**	**SWP III** *Chair: **Oksana Shramkova*** **(16:50-18:30 Monday, July 11)**	**NAON II** *Chair: **Judy Rorison*** **(16:50-18:25 Monday, July 11)**	**CTS I** *Chair: **Kira Kastell*** **(17:00-18:40 Monday, July 11)**