Integrated Hybrid III-V/Si Laser and Transmitter

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***Abstract* — This paper reports on recent advances on integrated hybrid InP/SOI lasers and transmitters. Based on a molecular wafer bonding technique, we develop hybrid III-V/Si lasers exhibiting new features: narrow III-V waveguide width of less than 3 µm, tapered III-V and silicon waveguides for mode transfer. These new features lead to good laser performances: a lasing threshold as low as 30mA and an output power of more than 10 mW at room temperature in continuous wave operation regime from a single facet. Continuous wave lasing up to 70°C is obtained. Moreover, hybrid III-V/Si lasers, integrating two intra-cavity ring resonators, are fabricated. Such lasers achieve a thermal tuning range of 45 nm, with a side mode suppression ratio higher than 40 dB. More recently we demonstrate a tunable transmitter, integrating a hybrid III-V/Si laser fabricated by wafer bonding and a silicon Mach-Zehnder modulator. The integrated transmitter exhibits 9 nm wavelength tunability by heating an intra-cavity ring resonator, high extinction ratio from 6 to 10 dB, and excellent bit-error-rate performance at 10 Gb/s.**

***Index Terms* — Hybrid integrated circuits, silicon laser, silicon-on-insulator (SOI) technology, adiabatic taper.**

I. Introduction

Silicon photonics is drawing increasing attention due to the promise of fabricating low-cost, compact circuits that integrate photonic and microelectronic elements [1]. It can address a wide range of applications from short distance data communication to long haul optical transmission. Today, practical Si-based light sources are still missing, despite the recent demonstration of an electrically pumped germanium laser [2]. This situation has driven research to the heterogeneous integration of III-V semiconductors on silicon. In order to densely integrate the III-V semiconductors with the silicon waveguide circuits, mainly DVS-BCB adhesive wafer bonding and molecular bonding techniques are used and are actively reported in state-of-the-art hybrid lasers [3-7]. In these approaches, unstructured InP dies are bonded, epitaxial layers down, on a SOI waveguide circuit wafer, after which the InP growth substrate is removed and the III-V epitaxial film is processed. The design space for hybrid InP/SOI lasers is large and in particular the coupling between the optical mode in the top active III-V waveguide and that in the bottom passive SOI waveguide plays an important role.

This paper reports on recent advances on integrated hybrid InP/SOI lasers and transmitters [8-11]. Based on a molecular wafer bonding technique, we developed hybrid III-V/Si lasers exhibiting new features. For instance, III-V waveguides have a narrow width of less than 3 µm, reducing the power consumption of the devices. In order to make the mode coupling efficient, both the III-V waveguide and silicon waveguide are tapered, with a tip width for the III-V waveguide down to 300 nm for some devices. These new features lead to good laser performances. Moreover, hybrid III-V/SI lasers, integrating two intra-cavity ring resonators, are fabricated. Such lasers achieve a thermal tuning range of 45 nm, with side mode suppression ratio higher than 40 dB. More recently we demonstrate a tunable transmitter, integrating a hybrid III-V/Si laser fabricated by wafer bonding and a silicon Mach-Zehnder modulator. The integrated transmitter exhibits 9 nm wavelength tunability by heating an intra-cavity ring resonator, high extinction ratio from 6 to 10 dB, and excellent bit-error-rate performance at 10 Gb/s.

II. III-V/Si Laser Structure and Fabrication

We developed a new type of hybrid III-V/Si lasers, as shown in Fig. 1. The laser structure can be divided into three parts. In the center of the device the optical mode is confined to the narrow III-V waveguide, which provides the gain. At both sides of this section there is a coupling region that couples light from the III-V waveguide to the underlying silicon waveguide. After the coupling region the light is guided by a silicon waveguide without III-V on top.

The III-V region consists of a p-InGaAs contact layer, a p-InP cladding layer, InGaAsP quantum wells surrounded by two InGaAsP separate confinement heterostructure (SCH) layers, and an n-InP layer. The SOI substrate (200mm wafer manufactured by SOITEC) is composed of a mono-crystalline silicon layer on top of a 2µm thick buried oxide layer on a silicon substrate. The silicon rib waveguides have a height of 400nm, an etch depth of 180nm and a width of 1µm. The III-V epitaxial layers are transferred to the patterned SOI wafer through DVS-BCB adhesive bonding. The bonding layer thickness is around 80nm.

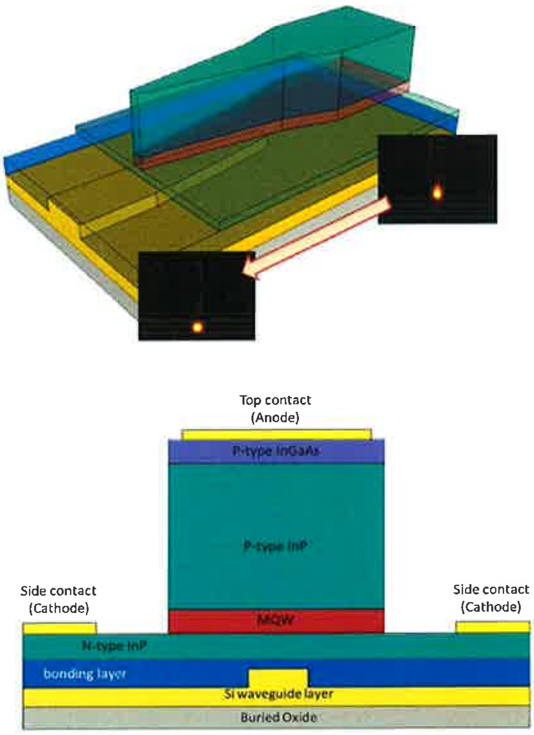

Figure 1 (up) 3D view of the coupling structure of the hybrid laser with representative mode profiles in two cross-sections, (down) the detailed cross-sectional view of the center of the hybrid laser

The active waveguide structure and the guided mode profile are illustrated in Fig. 1 (up). The straight active waveguide has a typical width of 1.7µm. The mode profiles are calculated using the mode matching method. The calculated optical confinement in the MQW is typically around 10%. To achieve index matching between the two waveguides a deep ridge III-V waveguide is used in the double taper region. As shown in Fig. 1(up), a double taper structure is used to allow the efficient coupling of light from the III-V waveguide to the silicon waveguide [8,9]. In the double taper region, the silicon waveguide tapers from 350nm to 1µm, while the III-V waveguide taper has two linear parts: the first part of 30µm long with a decrease of width from 1.7 to 1.0 µm, and the second part of 150 µm long starting with a III-V waveguide width of 1.0 µm and ending at 500nm.

After wafer bonding and InP substrate removal, an SiO_2 hard mask was defined using 248nm UV lithography. ICP etching was used to etch through the InGaAs layer and partly through the InP p-doped layer. The InP p-doped layer etching was completed by chemical selective etching. The MQW layer was etched by CH_4:H_2 RIE. The active waveguide is encapsulated with DVS-BCB. A Ti/Pt/Au alloy was used for metallisation on both p and n sides. Finally, the III-V/silicon wafer is cleaved, to form a Fabry-Perot laser cavity.

The devices are mounted on a temperature controller set to different temperatures. An example of the L-I curves is shown in figure 2 for a hybrid laser with a III-V waveguide width of 1.7µm. The length of the straight III-V waveguide section is 490µm. The coupling section length is 230µm. The overall cavity length is 1700µm, including the passive silicon waveguide. The device has a threshold current of 35mA and a maximum single facet continuous wave output power of 5mW at 20°C. At 60°C the laser still exhibits an output power of more than 1mW. The series resistance is 5 Ohms, while the slope efficiency is 0.043 W/A.

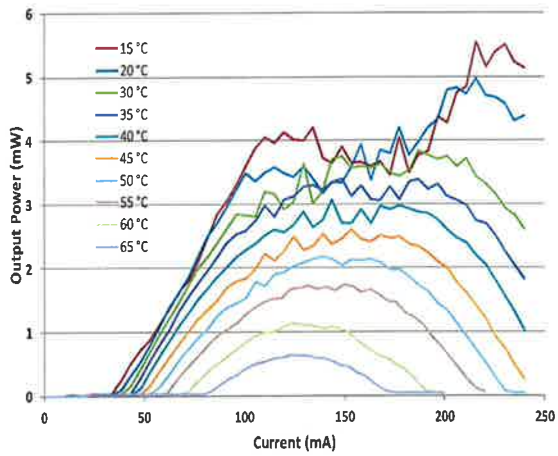

Figure 2: Continuous wave single facet laser power as a function of drive current at different stage temperatures.

III. Widely tunable hybrid III-V/Si lasers

The tunable laser, as schematically shown on figure 3 (up), consists of an InP based amplification section, tapers for the modal transfer between III-V and Si waveguides, two ring resonators (RRs) for single mode selection, metal heaters on top of the rings for the thermal wavelength tuning and Bragg gratings providing reflection and output fibre coupling [10].

The straight III-V waveguide has a width of 1.7 μm and a length of 500 μm. Both silicon and III-V waveguides are tapered over a length of 200 μm to allow an efficient adiabatic mode transfer between those two waveguides [10]. In the silicon sections, ring resonators 1 (R1) and 2 (R2) have free spectral range (FSR) of 650 and 590 GHz, respectively. The slight difference between these two values allows taking advantage of the Vernier effect for the wavelength tuning. Moreover, the bandwidth of the double ring filter is designed to select only one Fabry-Perot mode of the cavity. The Bragg reflectors are made by partially etching the silicon waveguide. The two Bragg reflectors, each with a pitch of 290 nm and 60 periods, are designed to have a reflectivity of more than 90%, and a 3 dB bandwidth larger than 100 nm. Figure 3 (bottom) shows a picture of the fabricated tunable lasers [10].

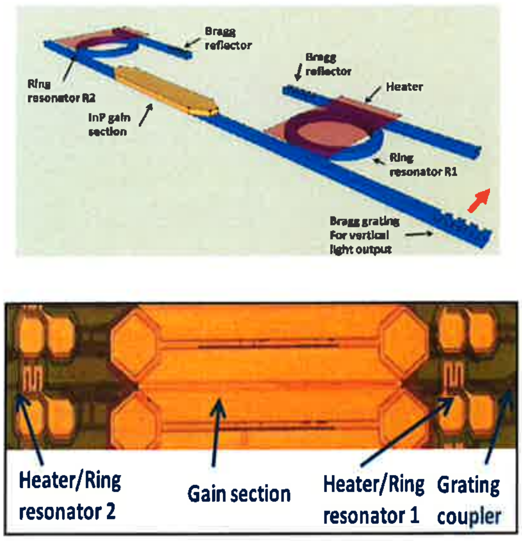

Figure 3: Schematic view (up) and picture (down) of the widely tunable single mode hybrid laser

The lasers are tested on wafers with vertical Bragg gratings coupling the output light into a cleaved single mode fiber. The coupling losses were measured to be around 10 dB. At 20°, the laser has a threshold current of 21mA. Figure 4 shows the super-imposed laser emission spectra by changing heating power levels to the two RRs. On the backgrounds of those spectra curves, one can observe transmission peaks created by R2 and the transmission dips created by R1. With less than 400mW of combined power in both heaters, a high SMSR (>40dB) wavelength range over 45nm is achieved. For wavelength setting, both ring power must be adjusted so that one transmission peak of R1 matches one of R2 at a desired wavelength. The wavelength tuning range is currently limited by the too large difference in the FSR between the two RRs. An optimized design should allow covering the whole gain bandwidth of the III-V active material.

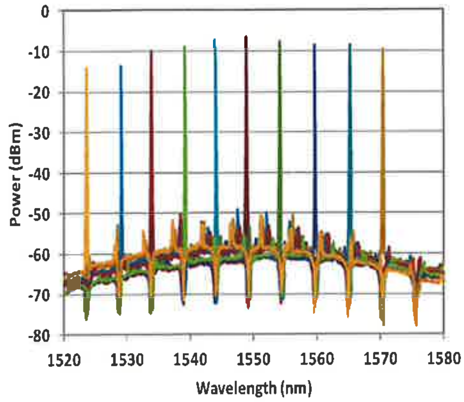

Figure 4 Super-imposed laser spectra of the tunable laser

IV. Tunable Hybrid III-V/Si Transmitter

Figure 5 shows a schematic view (up) and a picture (down) of an Integrated Tunable laser – Mach Zehnder Modulator (ITLMZ) [11]. The ITLMZ chip consists of a single mode hybrid III-V/silicon laser, a silicon MZM and an optical output coupler. The single-mode hybrid laser includes an InP waveguide providing light amplification, and a ring resonator (RR) allowing single mode operation. Two Bragg reflectors are etched on silicon waveguides in order to close the laser cavity. The MZM allows modulation of the output light emitted by the hybrid laser [12].

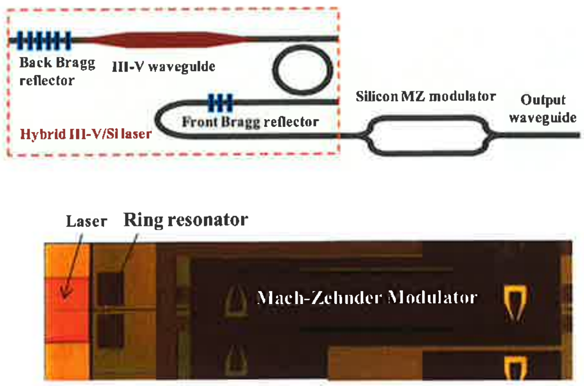

Figure 5. Schematic view (up), and picture (down) of the ITLMZ chip

The output of the ITLMZ chip is coupled to a lensed fiber, amplified by an erbium doped fiber amplifier and then filtered out. One arm of the MZM is modulated with a voltage swing of around 7 V, at 10 Gb/s using a pseudo-random binary sequence (PRBS).The BER measurement is performed for 8 different wavelengths by changing the power dissipated in the RR heater. Fig. 6 (left) shows the BER curves for all the wavelengths and also a reference curve for a directly modulated laser, measured using a high sensitivity receiver including an avalanche photodiode. The PRBS length is 27-1, limited by the photo-receiver used in this experiment. Fig. 4 (right) shows the corresponding eye diagram for all those channels, independent of the length of PRBS in the range from 2^7-1 to 2^{31}-1. The ER of all those wavelengths varies from 6 to 10 dB, while the ER for the reference is only 4 dB. One can see from Fig. 4 (left) that all channels have better BER performance than the reference for received power levels lower than -25 dBm, due to the higher ER of the ITLMZ compared to that of the reference. For power levels higher than -25 dBm, channels λ2, λ3, λ4 and λ5 behave slightly better than the reference, achieving error free operation with BER < 10-9. Other channels have minimum BER between 10-7 and 10-8, mainly limited by the optical signal to noise ratio (OSNR) due to the high coupling losses between the ITLMZ output waveguide and the used lensed fiber. The power level difference to achieve the same BER among all channels is around 4 dB, explained by the difference in OSNR and the achieved ER among those channels. Finally the smaller slopes for all wavelength channels compared to that of the reference in the BER curves is attributed to their lower OSNR

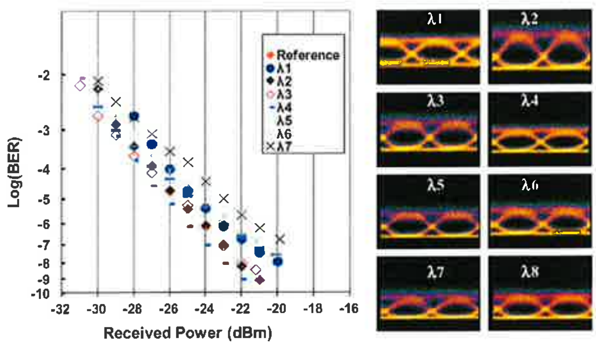

Figure 4 Bit error rate (left) and corresponding eye diagrams for different wavelengths (right)

V. Conclusion

This paper reports on recent advances on hybrid III-V/Si lasers and transmitters. The performance of hybrid III-V/Si lasers approaches that of monolithically integrated InP lasers. Moreover, high quality silicon waveguides offer new design possibilities to make for example high performance and robust tunable lasers. We demonstrate also the integrated transmitter by incorporating hybrid tunable III-V/Si lasers and silicon modulators. We believe that the integrated hybrid III-V/Si transmitters will have important applications for WDM transmission for both short range and long haul optical transmission.

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Monday Aug. 27
1:30 PM – 3:00 PM

Mo 1C: Hybrid Integration

Room: University Center Harbor Room
Session Chair:

1:30 Mo-1C.1
Compact InP-based 1Ã × 2 MMI Splitter on Si Substrate with BCB Wafer Bonding for Membrane Photonic Circuits
J. Lee, Y. Yamahara, Y. Atsumi, T. Shindo, N. Nishiyama, and S. Arai, Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo, Japan

1:45 Mo-1C.2
Reflection-Assisted Unidirectional Hybrid-Silicon Microring Lasers
D. Liang, S. Srinivasan, D. A. Fattal, M. Fiorentino, Z. Huang, D. T. Spencer, J. E. Bowers, R. G. Beausoleil, Intelligence and Infrastructure Lab, HP Labs, Palo Alto, CA, USA

2:00 Mo-1C.3
Integrated Hybrid III-V/Si Laser and Transmitter (Invited)
Guang-Hua Duan, III-V Lab

2:30 Mo-1C.4
Hybrid InP-Polymer 30 nm tunable DBR Laser for 10 Gbit/s direct Modulation in the C-Band
H. Klein, C. Wagner, W. Brinker, F. Soares, D. Felipe, Z. Zhang, C. Zawadzki, N. Keil and M. Moehrle, Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institute, Berlin, Germany

2:45 Mo-1C.5
High-Speed Optical Phased Array Using High-Contrast Grating All-Pass Filters
W. Yang, T. Sun, Y. Rao, M. Megens, T. Chan, B. W. Yoo1, D. A. Horsley, M. C. Wu1, and C. J. Chang-Hasnain, Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, Berkeley, California, USA

3:00 PM – 3:30 PM Coffee Break in Lagoon Plaza

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