10 Gb/s Integrated Tunable Hybrid III-V/Si Laser and Silicon Mach-Zehnder Modulator

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Abstract *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.*

1. Introduction

Silicon photonics is drawing increasing attention due to the promise of fabricating low-cost, compact circuits that integrate photonic and microelectronic elements [1]. Integrated transmitters incorporating lasers and modulators on silicon are of primary importance for all communication applications, and at the same time are the most challenging to fabricate due to the need of hybrid III-V integration. Up to now the only demonstration of such a photonic integrated circuit (PIC) has been reported by A. Alduino *et al*. from Intel [2]. This reported silicon PIC transmitter integrated hybrid III-V/silicon lasers and silicon Mach-Zehnder modulators (MZM) operating in the wavelength window of 1.3 µm. However WDM applications require usually wavelength tunable laser sources. Moreover, tunable transmitter is considered to be an attracting option in optical network terminal transceiver for future access networks. The very large market of access networks provides an opportunity for silicon photonics. In this paper we report for the first time on an integrated tunable laser - MZM (ITLMZ) operating in the wavelength window of 1.5 µm, which incorporates a tunable hybrid III-V/Si laser and a silicon MZ modulator. Our ITLMZ demonstrates several new features: i) wavelength tunability over 9 nm, ii) a silicon modulator with high extinction ratio (ER) between 6 and 10 dB, and 3 dB modulation bandwidth as large as 13 GHz, and iii) excellent bit-error rate (BER) performance.

2. Device Structure and Fabrication

Figure 1 shows a schematic view (left) and a picture (right) of the ITLMZ. 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 etched on silicon waveguides close the laser cavity. The MZM allows modulation of the output light emitted by the hybrid laser.

The fabrication process begins with 200 mm silicon on insulator (SOI) wafers incorporating a 400 nm thick silicon waveguide layer on a 2 µm buried oxide layer. Deep UV 193nm lithography and plasma HBr etching of 180 nm silicon allow the fabrication of rib waveguides for the coupling between the bonded III-V and silicon waveguides. By etching 120 nm in the 220 nm pre-defined level, rib waveguides for modulators are fabricated. Lithography and etching of 100 nm silicon are then carried out to form 220 nm thick stripe waveguides. Next several ion implantation steps are carried out in order to realize p++, p, n and n++ dopings for the modulators. Bragg gratings are then etched on 220 nm stripe waveguides with an etch depth of 50 nm. A HDP silicon oxide deposition on the wafers and chemical-mechanical-polishing are used to planarize the SOI wafers. 2 inch InP wafers containing a quantum well heterostructure are directly bonded onto the planarized SOI wafers after preparation of the surfaces [3]. InP lasers are then processed, and NiCr heaters are defined above the RRs. Metallization steps are performed for contacting the modulators, the heaters and the hybrid III-V/Si lasers [4]. It is to be noted that several tapers are integrated to ensure an efficient mode transfer from the III-V waveguide to silicon rib waveguide [4], and also between the different types of silicon waveguides.

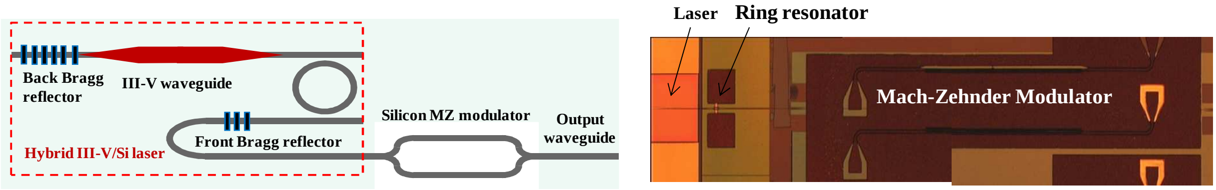

Fig. 1 Schematic view (left), and picture (right) of the ITLMZ chip

3. Tunable laser characteristics

The RR based hybrid laser exhibits a CW threshold current around 41 mA at 20℃ and the output power coupled to the silicon waveguide is around 2.5 mW for an injection current of 100 mA. The maximum output power is around 6.5 mW at 20℃, and the output power is still higher than 1 mW at 60℃. Electrical current injection into the heater allows thermal tuning of the ring resonance wavelength. As a result, the selected cavity mode will jump to another one having the lowest threshold. Figure 2 (left) plots the lasing wavelength as a function of the heating power. One can observe from this figure that a tuning range of 9 nm is achieved. The wavelength tuning is a step by step type, due to the mode jumps with the increase of heating power. This phenomenon is typical of this kind of cavity, and very similar to that observed in classical distributed feedback Bragg lasers made on InP. The heater resistance is in the range of 20-100 Ω, and the thermal tuning efficiency is in the range of 0.15–0.4 nm/mW.

Figure 2 (right) shows an example of the super-imposed optical spectra for 8 values of the heating power. Clearly single mode operation with side mode suppression ratio larger than 30 dB is achieved. The variation of the power level for the dominant lasing mode observed here is due to the periodic modulation created by the MZ modulator. One Fabry-Perot mode between λ_5 and λ_6 was not shown as no BER measurements were performed at this wavelength, which corresponds to the minimum transmission of the MZM.

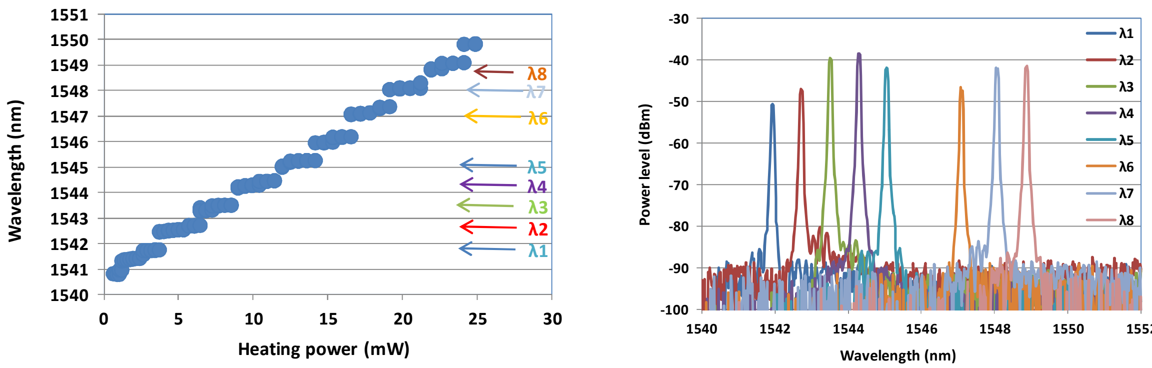

Figure 2: Lasing wavelength as a function of the heating power (left) and super-imposed optical spectra (right)

4. Silicon Mach-Zehnder modulator characteristics

The silicon modulator is a depletion type lateral pn junction modulator as described in [5]. The length of the modulated phase shifters is 3 mm. The arm length difference of the MZM is 150µm, resulting in a free spectral range of around 4.5 nm. The estimated $V_\pi L_\pi$ for the modulator is around 3 V cm. The ER depends on the operation point. Its value is larger than 10 dB when the operation point is close to the minimum transmission, and 6.5 dB close to the maximum for a peak-to-peak voltage swing of 8 V. Thus the average losses are higher for the case of a larger ER. A trade-off between the losses and the ER for the modulator is made in the BER measurements. Moreover, from the power level measurement from a laser alone with the same structure and from the output of the ITLMZ chip, the intrinsic losses of the MZM are estimated to be around 13 dB at its maximum transmission point.

Figure 3 shows the small signal modulation response of the integrated MZM for several values of the applied voltage. One can see that the modulation bandwidth increases with the rising reverse bias voltage of the pn junction. For a reverse bias larger than 2V, the 3 dB modulation bandwidth is larger than 13 GHz. The modulation response decreases very slowly with the modulation frequency. Such a modulation response guarantees operation at 10 Gb/s, and should allow modulation at bit rates up to 25 Gb/s.

5. BER measurement of the ITLMZ

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. 4 (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 2^7-1, 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 λ_2, λ_3, λ_4 and λ_5 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

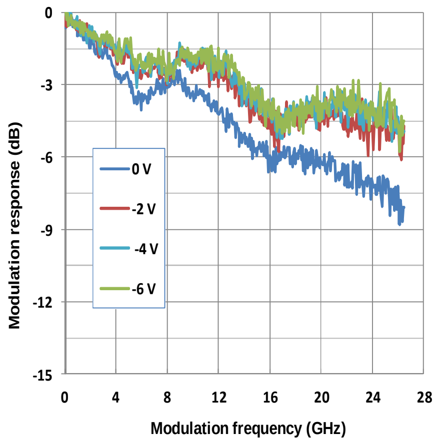

Figure 3 Small signal modulation response of the MZ modulator for different values of the applied voltage

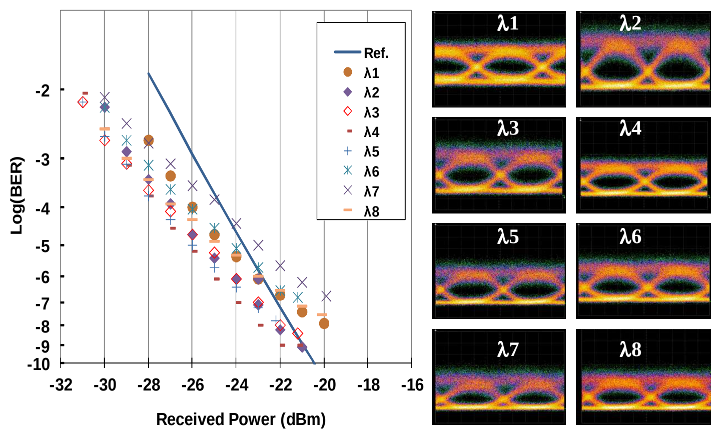

Figure 4 Bit error rate (left) and corresponding eye diagrams for different wavelengths (right)

6. Conclusion

We demonstrate an ITLMZ, incorporating a hybrid III-V/Si laser fabricated on a SOI wafer containing a silicon Mach-Zehnder modulator. This transmitter exhibits 9 nm wavelength tunability, high ER between 6 and 10 dB, and excellent BER performance at 10 Gb/s. We believe that such promising results pave the way to realize large capacity WDM transmitter PICs for communication applications.

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