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Co-integrated 1.3µm hybrid III-V/silicon tunable laser and silicon Mach-Zehnder modulator operating at 25Gb/s

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Abstract: In this paper, the 200mm silicon-on-insulator (SOI) platform is used to demonstrate the monolithic co-integration of hybrid III-V/silicon distributed Bragg reflector (DBR) tunable lasers and silicon Mach-Zehnder modulators (MZMs), to achieve fully integrated hybrid transmitters for silicon photonics. The design of each active component, as well as the fabrication process steps of the whole architecture are described in detail. A data transmission rate up to 25Gb/s has been reached for transmitters using MZMs with active lengths of 2mm and 4mm. Extinction ratios of respectively 2.9dB and 4.7dB are obtained by applying drive voltages of 2.5V peak-to-peak on the MZMs. 25Gb/s data transmission is demonstrated at 1303.5nm and 1315.8nm, with the possibility to tune the operating wavelength by up to 8.5nm in each case, by using metallic heaters above the laser Bragg reflectors.

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OCIS codes: (140.5960) Semiconductor lasers; (230.7020) Traveling-wave devices; (250.3140) Integrated optoelectronics circuits; (250.5300) Photonic integrated circuits; (250.7360) Waveguide modulators.

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1. Introduction

For years, the volume of data exchanged across the world increases at a never-ending pace. According to forecasts from Cisco [1], the volume of information transmitted each year via the Internet is now beyond the zettabyte (10^{21}) , and this trend seems unlikely to stop. To manage this amount of information, higher data transmission and processing rates are needed, especially in the data-centers. While copper-based interconnections are still used in high-speed communications for very short reach connections (below 3m), they have been replaced by more efficient photonic links for longer distances. Nevertheless, even though multi-mode vertical cavity surface emitting lasers (MM VCSEL) is the dominant technology up to 300m, photonic modules for longer distances are way more expensive, but also less reliable [2].

In this context, silicon photonics is seen as a way to obtain fully integrated photonic circuits with an expected cost-reduction, due to its compatibility with the Complementary

Metal Oxide Semiconductor (CMOS) fabrication lines. Indeed, fabrication using the wellcontrolled silicon processes offers large production capabilities, with high yield and high device reliability [3]. Moreover, the high index contrast between silicon and its native oxide provides a tight confinement of the optical mode within silicon waveguides, enabling efficient and compact optical designs. Due to a growing interest, silicon photonics has undergone fast developments in the last decade, leading to a specific 'device library', comprising nearly all components needed for the realization of a complete optical link: efficient input/output (I/O) couplers [4], low-loss passive waveguides [5], high-speed modulators [6], low cross-talk (de)multiplexers [7] and high-responsivity photodetectors [8]. All of these components are now fabricated at an industrial level [3], and can also be found in multi-project wafer (MPW) services [9, 10]. However, since silicon is a poor light emitter due to its indirect bandgap, a monolithically integrated optical source on silicon is still missing to form a complete link. To obtain this optical source, different directions have been followed during the last ten years, such as Raman Scattering in silicon [11], strained Germanium [12], and hetero-epitaxy of III-V materials to bring optical gain [13]. While those solutions are all promising, a lot of work is still needed to improve their performances and integration with silicon photonic circuits.

Therefore, early generations of silicon photonics transmitters will likely be based on external sources, such as laser semiconductor diodes flip-chipped on top of the silicon photonic integrated circuit (Si-PIC) [14]. Methods to couple an external light in the Si-PIC have thus been developed, such as near-vertical coupling using integrated lenses [15], ball lenses [16], or edge coupling using spot-size converters in thick silicon [17] or SiON [18]. Nevertheless, flip-chip techniques are expensive and time-consuming, and light coupling from an external source requires additional coupling optics and tight alignment tolerances at the package level which will add optical losses and increase the overall cost. Thus, developing a competitive wafer-level integrated laser source, which would not suffer from these issues, is a major objective for silicon photonics. Currently, the most promising solution to provide light to the Si-PIC at wafer-level is to directly bond III-V stacks on the silicon-on-insulator (SOI) wafer, which will provide the optical gain necessary for a laser. Those stacks can be bonded as wafers or as separate dies [19], using molecular bonding [19– 24], adhesive bonding [25], or even metallic bonding [26]. While the integration of III-V material adds difficulties in the processing of a Si-PIC, it offers several advantages: simplified packaging, reduced alignment issues and more freedom in the laser design. Different laser structures such as Fabry-Perot (FP) [19-21, 26], racetrack [22], Distributed Feed-Back (DFB) [23, 25], or Distributed Bragg Reflector (DBR) [24] can thus be found in the literature.

While these hybrid III-V/silicon lasers have received a lot of attention in the last decade, most demonstrations mainly led to stand-alone lasers, or associated with passive components such as silicon waveguides and waveguide-to-fiber optical couplers. To the best of our knowledge, only two groups demonstrated the co-integration of hybrid III-V/silicon lasers and silicon modulators. Alduino et al. have shown the emission of four different wavelengths fixed in the 1.3μ m range, with modulation rates up to 12.5Gb/s [27]. Duan et al. have demonstrated a tunable laser in the 1.5μ m range, but integrated with a modulator limited at a 10Gb/s modulation rate [28]. Another possibility for a transmitter based on these hybrid lasers would be to use III-V heterostructures brought by bonding for both the lasers and the modulators, and only use the silicon as passive circuitry. By doing so, Park et al. announced a 28Gb/s transmission at four different wavelengths in the 1.3μ m range [29]. However, this approach is not suited to emerging standards in silicon photonics, where the maximum of optical functions are transferred in the silicon.

In this paper, we report on the co-integration of a tunable hybrid III-V/silicon laser emitting in the $1.3\mu m$ range and a silicon modulator, thus forming an integrated transmitter operating at a modulation rate up to 25Gb/s. In the next section, we present the design of the

hybrid III/V-silicon laser. Section 3 includes the design of the silicon modulator, and measurements results of stand-alone devices fabricated to validate their high-speed performance. The fabrication process of the integrated transmitter is detailed in Section 4. The measurements results are shown in section 5, while section 6 provides conclusions on the present work as well as an overview of future developments.

2. Hybrid III-V/silicon laser

2.1 Overall structure

Schematic views of the hybrid III-V/silicon laser can be seen in Fig. 1. III-V material is positioned above the silicon waveguide to provide the optical gain, with a 100nm-thick SiO_2 gap between the two high refractive index media. The III-V active region is 700µm-long, 5um-wide and approximately 2.7um-thick. It is composed of intrinsic InGaAsP multiple quantum wells (MQW) and barriers, surrounded by p- and n-doped InP layers. These MQW are designed to exhibit maximum gain in the 1.3μ m region. The silicon rib waveguide is 500nm-thick, with a 300nm-thick slab section. The rib is narrowed down to 0.6µm below the III-V active region to ensure maximum light confinement in the MQW, but its width increases up to 1.55µm at both ends of the III-V mesa in order to couple light into the silicon waveguide, as shown on Fig. 1(c). This transition is realized over $100\mu m$, using specific mode transformers in the silicon layer designed using the adiabaticity criterion [30]. More details on the mode transformers are given in section 2.2. The device architecture is that of a DBR laser, where silicon Bragg mirrors are located at each end of the III-V active waveguide. In order to provide both high confinement and light extraction in a single direction, the back mirror should exhibit a reflectivity as high as possible, while the front mirror should have a lower reflectivity. These mirrors should also be selective in terms of wavelength to ensure single-mode emission. This DBR structure is chosen for its wavelength tuning capabilities. Indeed, by depositing a metal layer above the gratings, and using it as a heater by injecting current, it is possible to locally increase the silicon refractive index, and thus the selected wavelength. The design of these mirrors is described in section 2.3. Finally, once light is out of the laser cavity, it is transferred from a 500nm-thick rib waveguide with a 300nm-thick slab section into a 300nm-thick rib waveguide with a 150nm-thick slab section, as depicted on Fig. 1(c). This transition is done so the laser can be used with other silicon photonics components designed on a 300nm-thick SOI platform, as detailed in section 2.4.



Fig. 1. Longitudinal (a), transversal (b) and top (c) schematic views of the laser.

2.2 Optical coupling between III-V and silicon

To efficiently couple the light from the III-V into the silicon waveguide, adiabatic coupling is used rather than directional coupling, due to the index difference between III-V materials and silicon, making a perfect phase matching condition difficult to reach. To realize this coupling, the effective indices ratio between the isolated III-V (n_{III-V}) and silicon (n_{si}) waveguides must be inverted along the light propagation direction, as shown on Fig. 2(a). Below the gain region, the condition $n_{III-V}>n_{si}$ must be respected to have maximum light confinement in the MQW, and at both ends of the active region, the condition sare generally achieved by reducing/increasing the width of the silicon waveguide [21,23], III-V waveguide [24] or even both waveguides [25]. However, the effective index of a III-V waveguide with dimensions above 1µm is quite high (typically above 3.2 [19,31]). Thus, if the silicon waveguide is too thin, the conditions for coupling cannot be fulfilled. This can be an issue since components found in most silicon photonics platforms exhibit typical thicknesses below 300nm [3,9,10].



Fig. 2. (a) Schematic view of the light coupling between III-V and silicon waveguides. (b) Effective index of the fundamental TE modes of our III-V waveguide and a silicon slab waveguide (10μ m-wide) versus its thickness, at 1310nm. Both waveguides are cladded with SiO₂.

Figure 2(b) shows the effective index of the fundamental Transverse Electric (TE) mode in a silicon slab waveguide for different thicknesses, with the simulated effective index of the fundamental TE mode in our III-V structure. It can be seen that for 300nm-thick silicon waveguides, the effective index is limited to 3.17, which is too low for coupling. While it might be possible to reduce n_{III-V} by narrowing the III-V waveguide, this solution would be limited by the processing of the thick III-V stack (larger than 2µm). Coupling light from the III-V waveguides to a thin SOI (below 300nm), requires to narrow the III-V waveguide below 200nm [19,32]. However, such narrow III-V tips are difficult to fabricate by conventional lithography. Therefore, the silicon waveguides used for hybrid III-V/lasers have typical thicknesses above 400nm. In our case, 500nm-thick silicon waveguides are used, with a 300nm-thick slab section, for fabrication compatibility with other silicon photonics components.

Once the thickness of the silicon waveguide has been chosen, the mode transformers in the silicon waveguide are designed to transfer light from the III-V region to the silicon waveguide. Light coupling is exclusively realized through those mode transformers, located at both ends of the gain region. The III-V region is not tapered at its ends to ensure robust coupling from III-V to silicon waveguide. To obtain short (100μ m-long) and efficient (coupling efficiency>90%) mode transformers, we used the adiabaticity criterion [30]. The method applied to design those mode transformers is described in our earlier work [23]. The efficiency of a taper designed using this method is displayed on Fig. 3. Figure 3(a) shows the electrical field distribution of the fundamental TE even mode at the center of the III-V region, where the silicon waveguide is narrowest, and the mode overlaps mostly with the

MQW. On Fig. 3(b), the displayed field distribution corresponds to the end of the III-V region, where the silicon waveguide is widest, and the mode overlaps mostly with the silicon waveguide. Figure 3(c) illustrates the power transfer between III-V and silicon waveguides along the propagation direction, while Fig. 3(d) shows the confinement factor in the silicon waveguide and MQW across the entire III-V region. Light confinement in the MQW is simulated to be $\approx 16\%$ at the center, while over 90% of the light is confined in the silicon waveguide at the end of the mode transformers.



Fig. 3. Electric field distribution of the fundamental TE even mode at the center (a), and end (b) of the gain region. (c) Longitudinal view showing the power transfer from the end of the III-V region to the Si waveguide. (d) Confinement factor in the MQW and Si waveguide across the whole III-V region.

The robustness of the mode transformers against fabrication variations is also evaluated by simulating the power confined in the silicon waveguide at the end of the III-V region with different geometrical variations. Figure 4(a) shows the influence of the input and output widths on the coupling efficiency. As one can see, several widths combinations offer a coupling efficiency above 90%, with similar robustness. While the output width is more robust than the input width towards lithographic and etching variations, both remains within the process variations window. The influence of the mode transformer length is displayed on Fig. 4(b). It can be seen that the maximum efficiency is reached at the targeted length of 100 μ m, with reduced variations after this length. The influence of the SiO₂ gap between III-V and silicon is shown on Fig. 4(c). This parameter is the most critical one, since for a ± 30nm variation from the targeted 100nm gap, the efficiency will fall under 70%.



Fig. 4. Power confinement factor in the silicon waveguide at the end of the III -V region versus (a) input and output width of the mode transformer, (b) mode transformer length, and (c) SiO_2 gap between III-V and silicon.

2.3 Bragg reflector design



Fig. 5. Longitudinal (a) and transversal (b) schematic views of the Bragg reflectors.

The cavity of the DBR laser is formed by two Bragg gratings, located in the silicon waveguide, at each side of the III-V region, as shown on Fig. 1. Schematic views of the gratings are shown on Fig. 5. They are patterned in the previously described rib waveguide, with a fixed rib-width of 3μ m, and both have a 0.5 duty cycle. They are mainly defined by their period (Λ), their etching depth (g), and their length (L_{grating}). The influence of these three parameters can be described by using a set of equations derived from the coupled mode theory [33]. First, the peak reflectivity of a Bragg grating is defined by:

$$R = \tan h^2 (\kappa \cdot L_{grating})$$
(1)

The reflectivity increases with $L_{grating}$ and κ , defined as the grating coupling constant. This constant can be evaluated by the following relation:

$$\kappa \approx \frac{2 \cdot \Delta n_{eff}}{\lambda} \tag{2}$$

where Δn_{eff} is the difference between the effective index of the non-etched and etched crosssection of the grating, and λ is the optical wavelength. Δn_{eff} increases with the etching depth, and so does κ and R. Finally, the Bragg wavelength is expressed by:

$$\lambda_g \approx 2 \cdot n_{eff} \cdot \Lambda \tag{3}$$

 n_{eff} , being the average between the effective index of the non-etched and etched crosssection of the grating. Equations (2) and (3) are approximations which can be used for small index difference, which is our case. Indeed, to reach single mode operation, the mirrors must exhibit a reduced optical bandwidth, which decreases with κ [33]. Thus, the study is limited to etching depths around 10nm.



Fig. 6. (a) Reflectivity spectrum for several etching depths. (b) Peak reflectivity versus grating length for several etching depths. The targeted Bragg wavelength is 1310nm.

For a fixed etching depth of 10nm, $n_{eff} \approx 3.34$, and to target operation at 1310nm, the grating period should be 196nm, according to Eq. (3). Therefore, it will be extremely difficult to monitor precisely the etching depth in spacing smaller than 100nm. Figure 6(a) shows the effect of a \pm 4nm variation on the etching depth on the grating reflectivity spectrum, at fixed grating length of 250µm, and a targeted Bragg wavelength of 1310nm. It can be seen that in these conditions, the reflection varies from 65 to 99%. To increase the gratings robustness, the peak reflectivity evolution with the grating length was studied, for different etching depths around 10nm. The results are displayed on Fig. 6(b). For the back mirror, the grating length is fixed at 700µm to ensure a near 100% reflectivity, in case the grating is not sufficiently etched. For the front mirror, the grating length is fixed at 150µm, to obtain a reflectivity between 35% and 85% for \pm 4nm variation on the etching depth.

In order to demonstrate transmitters with different wavelengths, two periods of 195nm and 197nm are chosen, giving - according to Eq. (3) - Bragg wavelengths of 1302.6nm and 1316nm respectively. It can be noticed that according to the same equation, variations on the etching depth also have an influence on the Bragg wavelength. However, this influence is quite reduced because of the small index difference. Thus, according to the simulations, for an etching depth varying between 6 and 14nm, the Bragg wavelength variation is approximately 0.8nm. The characteristics of the chosen reflectors are summarized in Table 1.

Туре	Reflectivity	Length (µm)	Etching depth	Coupling	Period	Bragg
			(nm)	constant (cm ⁻¹)	(nm)	Wavelength (nm)
Front	≈70%	150	10	79	195	1303.3
mirror					197	1315.7
Back	≈100%	700			195	1303.3
mirror					197	1315.7

Table 1. Bragg Reflectors Characteristics

2.4 Silicon thickness transition

As explained in section 2.2, to reach an efficient coupling between III-V and silicon, 500nmthick silicon waveguides are necessary, making them thicker than the waveguides used for other typical silicon photonics components [3, 9,10]. Rather than designing all other components with 500nm-thick silicon waveguides, a transition in the silicon is used, from a 500nm-thick rib waveguide with a 300nm-thick slab section, to a 300nm-thick rib waveguide with a 150nm-thick slab section. This transition is displayed on Fig. 7(a).





Fig. 7. (a) Top view of the transition. (b) Electric field distributions of the fundamental TE mode across the transition.

The transition is 65μ m-long, starts with a 3μ m-wide and 500nm-thick rib waveguide (called waveguide A), and ends with a 500nm-wide and 300nm-thick rib waveguide (called waveguide B). At first, the width of the rib waveguide A is decreased using an exponential taper from 3μ m to 125nm. In the same way, the top 150nm of the slab section is reduced using the same taper shape from 10 μ m to 500nm, to form the rib of the waveguide B. After 65μ m, the 125nm-wide and 200nm-thick silicon tip stops. Figure 7(b) shows electric field distributions of the fundamental TE mode across the transition. As it can be seen by comparing the cross-sections 2 and 3, the mode is well confined in the waveguide B, even with the 125nm-wide and 200-nm-thick silicon tip. This confinement is evaluated at 90% in both cases, while the overall power loss due to this transition is expected to be as low as 1%.

While this solution will permit to use silicon photonics components designed for a 300nm-thick waveguide with the hybrid III-V/silicon laser, it does not change the fact that a thicker SOI must be used. This is an important issue for components planned on thin SOI, since the additional etching processes would induce surface roughness and thickness variations, which in turn would reduce the devices optical performances and reliability. Alternative solutions to locally increase the silicon waveguide thickness for III-V to silicon coupling, without disturbing other silicon photonics components fabricated on thinner SOI have been developed, such as silicon epitaxy [31] or amorphous silicon deposition [34]. However, these solutions are not used for this demonstration, in order to simplify an already complex fabrication process.

3. Silicon modulator

3.1 Design principles

To obtain a high-speed electro-optical (E/O) modulation of the light emitted by the hybrid laser, the use of a silicon device is considered. Since there is no strong electro-optical effect in silicon, the plasma dispersion effect is generally used, i.e. the effect of free charges concentration in silicon on the real and imaginary parts of the refractive index [35]. While carrier injection has a high efficiency, it also suffers from low speed limitations due to minority carrier lifetime, and needs pre-emphasis on the electrical signal to reach high data rates [36]. Devices using carrier accumulation have received a lot of attention for their high efficiency [37], but their fabrication relies on polycrystalline silicon which adds high optical losses, and their speed is limited by a large capacitance. Moreover, very few devices have

been demonstrated up to now. For these reasons, we have developed modulators based on carrier depletion, using a reverse-biased p-n junction, whose efficiency is lower than the previous two, but also leads to less optical losses and higher intrinsic bandwidth [38].

Such devices are commonly implemented as Mach-Zehnder modulator (MZM), or ring modulator (RM). RMs exhibit the advantages of compact footprint, low modulation power and can reach very high data rates [39]. Unfortunately, they also suffer from a significant thermal sensitivity and high dependence on fabrication tolerance [40]. On the other hand, MZMs can offer high modulation speed, and are more tolerant to thermal and fabrication variations. However, due to the relatively weak efficiency achievable via carrier depletion, MZMs generally require millimetre-long sections to reach an acceptable extinction ratio (ER). This may result in an increase of the optical transmission loss and a decrease of the bandwidth due to a large capacitance, if the device is not carefully designed. Finally, the Mach-Zehnder geometry was chosen for its inherent robustness.

Such silicon MZMs are based on a thin SOI layer (300nm). They must be compatible with the laser fabrication process (detailed in section 4), and thus can only use one metal level for its electrodes. They also have to be fast enough to reach a data rate of 25Gb/s in the 1.3μ m region, with few optical losses (to reduce the output power needed from the laser), while maximizing its extinction ratio (ER). Finally, its input voltage must be limited to reasonable levels, such as 2.5V peak-to-peak (2.5Vpp) on each arm.

3.2 P-N junction design

The MZM comprises two parallel silicon rib waveguides, implanted with a p-n junction. The junction is a key element of the device, since it determines its efficiency and optical losses. The waveguides are 300nm-thick and 400nm-wide, while the slab thickness is 150nm, to respect the single mode condition. Different p-n junction profiles have been proposed to enhance the performances of the MZM, such as p-i-p-i-n [41], S-shaped [42], or interdigitated [43], but here a vertical p-n junction is used, to simplify its design and processing.

According to the plasma dispersion formula at 1.31μ m [35], the change of the refractive index real part is more effective by using holes rather than electrons (for concentrations below 10^{20} cm⁻³). Moreover, holes also add less optical losses than electrons. In order to foster the effect of the holes, the junction is located at 100nm from the center of the waveguide (as in the example shown in Fig. 8). The next step is to simulate different doping concentrations to find the best trade-off between phase shift efficiency and optical losses.



Fig. 8. (a) Absolute net doping in the waveguide, simulated with a realistic doping profile. (b) Horizontal cut at $Y = -0.1 \mu m$.

We have modelled the junction behaviour considering a realistic doping profile, displayed on Fig. 8(a), where three successive implantations with different energies are used to ensure uniformity in the vertical direction. A cut of the profile is shown on Fig. 8(b), where the presence of an intrinsic region larger than 100nm can be noticed. In this example, due to the

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n-doping concentration being larger than the *p*-doping concentration, the junction is also slightly shifted of 30nm to the waveguide center.



Fig. 9. Phase shift at 2.5V versus doping related losses at 0V. Each point represents a different combination of acceptor and donor atoms concentrations.

In order to limit the operating voltage of this modulator, its efficiency is studied at 2.5V, as well as its losses at their maximum (0V). Figure 9 shows the evolution of these two parameters, for different combinations of doping concentration. For a junction formed at 100nm from the center, increasing the acceptor doping concentration (N_a) above 4e17cm⁻³ for any donor doping concentration (N_d) will only increase the doping-related losses. On the other hand, increasing N_d seems to increase efficiency and losses for almost all N_a. Finally, the doping concentrations of the p- and n-regions are respectively fixed at 4e17cm⁻³ and 6e17cm⁻³. This *p-n* junction should give a phase shift efficiency of ~21°/mm at 2.5V (equivalent to ~2.14V.cm) and ~0.6dB/mm at 0V. This combination offers a good trade-off, as well as robustness towards doping variations. This junction is implanted into two MZMs with lengths of 2mm to reduce optical losses and 4mm to enhance its efficiency.

3.3 Travelling wave electrodes

Since the MZMs lengths are over 2mm, a lumped model is not suitable for high-speed performances, and a travelling wave design should be considered. In this case, the modulator is seen as a transmission line, and travelling wave electrodes (TWE) must be designed to maximize the bandwidth [44].

The frequency response of a modulator based on TWE is dominated by three main factors [45]. The first one is the velocity mismatch between the optical and RF propagating waves. It can be evaluated by comparing the group index of the optical wave and the effective index of the RF wave. The second one is the impedance mismatch between the modulator, generator and load (which are both fixed at 50Ω in our case). The last ones are the RF losses on the modulator line. By optimizing the trade-off between these three parameters, one can significantly improve the modulator bandwidth.

As explained previously in section 3.1, only one metal level is allowed for the electrodes definition, which limits the design options. The configuration chosen for the electrodes is a coplanar-strip signal-ground-signal (SGS) configuration, where the *p*-*n* junctions in each waveguide are mirrored, as shown in Fig. 10. This configuration has been chosen rather than the commonly used GSGSG configuration for two reasons. First, the SGS configuration increases the characteristic impedance of the device (due to higher inductance and lower capacitance between the electrodes), in order to be closer to 50 Ω . Secondly, unlike in the SGS case, the GSGSG configuration is asymmetric, since the *p*-*n* junction is not located between all electrodes. However, this asymmetry will excite undesired RF modes, and create notches in the frequency response [46]. This issue can be overcome by using metallic



connections from an other metal level between the ground lines, which is not possible here. Therefore, the solution is to use the SGS configuration.



Fig. 10. Transversal view of the silicon MZM.

Several simulations are done to find the best geometry for the electrodes. The previously designed p-n junction doping concentrations and depletion region (for several voltages) are included, with a 800nm-thick buried oxide layer (BOX), a high-resistivity (HR) substrate and a 650nm-thick metal (Aluminium) layer. The aims are to bring the characteristic impedance close to 50 Ω , the RF effective index close to the optical group index (estimated to ≈ 4 given the waveguide dimensions), and to reduce the RF losses. After several simulations with different geometries, the electrodes dimensions are fixed to those shown on Fig. 10. At a 1.25V reverse-bias, a low index mismatch above 10GHz (below 0.2) and a relatively good characteristic impedance of 35Ω are expected, with RF losses of ≈ 2.9 dB/mm at 30GHz. The electrical S-parameters are also evaluated, with a generator and impedance load of 50 Ω . For each length at a 1.25V reverse-bias, the maximum value for the S_{11} parameter is below -10dB, equivalent to reduced reflections. The S₂₁ parameter reaches a -6dB electrical bandwidth of respectively 30GHz and 19GHz for the 2 and 4-mm-long modulators. For the electrical S-parameters, this -6dB electrical bandwidth is the frequency for which the response has fallen to 50% of its reference level. The results of those simulations are displayed in the next section on Fig. 13 and Fig. 14, and compared to measurements.

Moreover, using the simulated characteristic impedance, RF losses, effective index and the model presented in [45], the E/O response of the modulator (m), can also be calculated:

$$m(\omega_m) = \frac{\left(1 + j\omega_0 C_J Z_{Si}\right) V_{avg}\left(\omega_m\right)}{\left(1 + j\omega_m C_J Z_{Si}\right) V_{avg}\left(\omega_0\right)} \tag{4}$$

where ω_m is the frequency of the driving signal, ω_0 is the lowest output frequency of the generator (for normalization), C_J is the capacitance of the *p*-*n* junction, Z_{si} is the series resistance, and V_{avg} is the average voltage between the signal and ground electrodes experienced by a photon as it travels the modulator. This average voltage takes into account the losses and reflections of the electrical signal along the line, as well as the velocity mismatch of optical and RF propagating waves [45]. According to the simulations of the *p*-*n* junction, C_J is estimated to 323fF/mm at 0V, and 235fF/mm at -1.25V, with a series resistance of approximately 9 Ω .mm. For a 1.25V reverse-bias, the expected -3dB E/O bandwidths are respectively 36GHz and 24GHz for the 2 and 4mm-long modulators. For the E/O-measurements, this -3dB E/O bandwidth is the frequency for which the response has fallen to 50% of its reference level. The simulated E/O responses of the modulators are also compared to measurements in the next section, in Fig. 15.

3.4 Stand-alone modulator measurements

In order to validate the design of the modulator for the complete transmitter, stand-alone devices are evaluated on another run, using the same fabrication methods as those described later in section 4, without bonding III-V materials, and adding the deposition and patterning of a metal layer for the electrodes. A view of a 2mm-long modulator under test is shown on Fig. 11. Light comes in and out of the modulator by using two waveguide-to-fiber grating

couplers whose peak wavelengths are centered at $1.3 \,\mu\text{m}$. Light splitting is assured by multimode interferometers (MMIs). There is a $100\mu\text{m}$ length difference between the two waveguides of the MZM to make it asymmetrical. Thus its group index and phase shift with the voltage can be easily determined by shifting the wavelength.



Fig. 11. Top view of the silicon MZM under test.

The raw measurements of the modulators, for different bias voltage are shown in Fig. 12(a) and 12(b). The free spectral range (FSR) of the MZM is approximately 4.2nm, equivalent to a group index of 4. By placing the wavelength at -3dB from the maximum of transmission at 0V (at quadrature), and if both *p*-*n* junctions are alternatively biased at a 2.5V reverse-bias (dual drive configuration), then the static extinction ratios are respectively 6.2dB and 18.5dB for the 2mm and 4mm-long MZM. The total optical losses from fiber to fiber are respectively -15dB and -18dB for the 2mm and 4mm-long MZM. The sources of these losses (estimated from additional measurements on the same wafer) are the following: 4.2dB per grating coupler, 3.4dB from passive routing losses (waveguides and bends), 0.1dB per MMI, and 1.5dB/mm for the doped sections. Since passive waveguide losses are estimated to 0.8dB/mm, the doping-related losses are estimated to be 0.7dB/mm, which is close to the 0.6dB/mm value obtained by simulation. From these measurements, the phase shift efficiency for different voltages can also be extracted, as displayed on Fig. 12(c). The results are quite close to those simulated, which validates the model.



Fig. 12. Transmission spectra under different bias of the device from input fiber to output fiber, for (a) 2mm-long and (b) 4mm-long silicon MZM. (c) Phase shift versus applied voltage, simulations and measurements for both lengths.

The electrical S-parameters of the modulators are measured from 100MHz to 40 GHz through an Agilent vector network analyzer (VNA), using two SG probes with a 100 μ mpitch. The coaxial cables, probes and bias tee are calibrated with a 2-ports short-open-load-through (SOLT) calibration on an impedance standard substrate before the measurements. The results of these measurements for each MZM length are compared to the simulations, and displayed on Fig. 13. For both lengths, the measured S₁₁ parameters show good agreements with the simulations. However, the measured S₂₁ parameter reaches a –6dB electrical bandwidth of respectively 25.5GHz and 14GHz for the 2 and 4mm-long modulators (at a 1.25V reverse-bias), which is lower than predicted in the simulations.



Fig. 13. Measured and simulated S11-parameters for (a) 2mm-long and (b) 4mm-long electrodes. Measured and simulated S21-parameters for (c) 2mm-long and (d) 4mm-long electrodes.

To understand the differences between simulations and measurements, the characteristic impedance, RF losses and RF effective index are extracted from the S-parameters of the 4mm-long MZM, and compared it to the simulations, as depicted on Fig. 14. While the characteristic impedance is relatively close to the simulations, the losses are higher than predicted, which explains the bandwidth reduction. The RF effective index is also lower than expected in the simulations. We assume these differences come from the substrate resistivity, which may have been degraded due to parasitic surface conduction [47], or from the cross-section of the fabricated electrodes.



Fig. 14. Measured and simulated (a) characteristic impedance, (b) RF losses, and (c) effective index of the electrodes.

The electro-optical responses of the modulators are also measured from 100MHz to 40GHz through an Agilent N4373C Lightwave Component Analyzer (LCA). The same SG probes are used, but the probe at the end of the transmission line is terminated with a DC-block and a 50 Ω load. During the measurement, the wavelength is chosen so the modulators are set at quadrature. The measured E/O bandwidths for the different lengths are shown on Fig. 15. The large level of noise beyond 20GHz comes from the low level of signal (no amplification system is used during the measurements). The measured –3dB E/O bandwidths are respectively 28GHz and 23GHz for the 2 and 4mm-long modulators.



Fig. 15. Measured and simulated E/O bandwidth for (a) 2mm-long and (b) 4mm-long electrodes.

Finally, to evaluate the high speed digital performance of the modulator, a 25Gb/s PRBS electrical signal is driven through the devices. The set-up for measurements is depicted in Fig. 16. The electrical driver signals are provided by a M8020A pattern generator associated with a M8061A Multiplexer 2:1 up to 32Gb/s, both from Keysight. Since the modulator works in dual drive configuration, both the DATA and /DATA outputs are used. The electrical signals pass through RF phase shifters, to ensure they are perfectly in opposite phase on the modulators. The signals are then amplified using two paired SHF 806E amplifiers and sent to the modulator via an SGS RF probe. The other end of the modulator is connected to a 50 Ω load. Input light is provided by a laser source with an output power of 13dBm. For all measurements, the laser wavelength is set at quadrature when both arms are biased at 0V. Light at the device output pass through a booster optical amplifier (BOA) and an optical filter, to reduce the noise from the BOA spontaneous emission. Finally, the signal is monitored using the high-speed optical entry of a Keysight 86100D DCA-X Oscilloscope.



Fig. 16. Set-up used during large-signal measurements of the silicon MZM.

While the best option would be not to use the BOA - since it brings a lot of noise to the measurement if its gain is too high – its use was made necessary because of the low sensitivity of the high-speed detector. A compromise is to drive the BOA with a low current, thus the combination of the BOA and the optical filter give a power amplification comprised between + 5 and + 8dB, which is enough to conduct our measurements. Moreover, this measurement set-up needs meter-long RF cables to connect the different components, which degrades the electrical driving signals [see Fig. 17(a)]. To improve PRBS signals at the RF probes output, electrical de-emphasis provided by the multiplexer is necessary. This deemphasis is only used to de-embed the signal degradations caused by cables, and not to

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compensate for the modulator frequency response. An example of signal sent on the RF probes is shown on Fig. 17(b).

The resulting eye diagrams are shown on Fig. 17(c) for the 2mm-long MZM, and on Fig. 17(d) for the 4mm-long MZM. A passive numerical low-pass filter (4th order Butterworth filter) with a 25Ghz cut-off frequency is used to reduce the noise during the measurements. Both eyes are open at 25Gb/s, in a dual drive configuration, with 2.5Vpp send on each arm. Both arms are biased at a 1.25V reverse-bias, thus they receive NRZ signals in opposite phase, switching between 0 and -2.5V. The optical gain provided by the BOA and the optical filter is respectively estimated at + 5.2dB and + 7.7dB for the 2mm and 4mm-long MZMs measurements. The measured extinction ratios are respectively 3.9dB and 7.1dB for the 2mm and 4mm-long MZMs, and their dynamic insertion losses from fiber to fiber are estimated at -16.4dB and -18.6dB. Finally, both MZMs lengths are used for the transmitters.



Fig. 17. 25Gb/s eye diagrams of the (a) input electrical signal sent to the modulator before deemphasis, (b) input electrical signal after de-emphasis. 25Gb/s eye diagrams of the (c) 2mmlong and (d) 4mm-long silicon MZM, both in dual drive configuration with 2.5Vpp applied on each arm.

4. Transmitter architecture and fabrication process



Fig. 18. Layout view of the complete transmitter integrating the hybrid III-V/silicon DBR laser and the silicon MZM (2mm-long).

The layout of the complete hybrid III-V/silicon transmitter is shown on Fig. 18. The transmitter co-integrates the previously described hybrid III-V/silicon DBR laser and the silicon MZM. Lasers with grating periods of 195 and 197nm have been assembled with 2 and 4mm-long MZMs. Light emitted from the laser passes through the MZM, and is collected out of the wafer using a waveguide-to-fiber grating coupler whose peak wavelength is centered

at 1.3 μ m. Moreover, two pairs of heaters have been placed above the Bragg mirrors and undoped waveguides in both MZM arms. The first one is used to control the laser emitting wavelength. For silicon, to raise the temperature results in an increase of its refractive index. Thus, according to Eq. (3), the wavelength can be increased by using this method. The second pair of heaters can set the phase difference between the MZM arms, to set it in a quadrature condition for any wavelength.

The fabrication steps of the hybrid III-V/silicon transmitter are illustrated on Fig. 18. These devices are fabricated on 8" SOI wafers from SOITEC, with a 500nm-thick silicon layer, a 1µm-thick BOX, on a HR handle silicon wafer (750 Ω .cm) [Fig. 19(a)]. At first, the Bragg mirrors are defined using Electron Beam Lithography (EBL), and patterned in the silicon layer using a 10-nm-deep reactive ion etching (RIE). After resist stripping, a 160nmthick SiO₂ hard mask is deposited. Then, 193-nm-deep ultra-violet (DUV) photolithography, followed by hard mask etching, resist stripping, and a 200-nm-deep RIE are performed to define the first waveguide level used for the light coupling between III-V and silicon [Fig. 19(b)]. After resist stripping, a 5-nm oxidation is performed, before realizing the implantations steps for the silicon modulator. Implantations are defined using 248-nm DUV photolithography. Four different levels of implantation are used to form the modulator: two for the junction region (with a targeted doping concentration of 4×10^{17} cm⁻³ for the *p*- and $6x10^{17}$ cm⁻³ for the *n*-doping) and two for the contacts regions (with a targeted doping concentration of 2×10^{19} cm⁻³ for both *p*- and *n*-doping) [Fig. 19(c)]. Multiple-step implantations are employed in all levels (double-step for the contacts and triple-step for the junction) to ensure a uniform doping concentration. Boron and Phosphorus are respectively used for p- and n-type doping. After implantation, a 100nm-thick SiO_2 hard mask is deposited, followed by 193-nm DUV photolithography, hard mask etching, resist stripping, and a 150-nm-deep silicon RIE, to pattern the MZMs waveguides and the waveguide-to-fiber grating couplers. All devices are separated using 248-nm DUV photolithography, and RIE [Fig. 19(d)]. After a rapid thermal annealing (RTA) at 1050°C for 15 s for dopant activation, the highly-doped regions are silicided to reduce contact resistances. The wafer is then encapsulated by 800nm of SiO₂ and planarized by chemical-mechanical polishing (CMP), leaving a planar surface for bonding, with approximately 100 nm of SiO₂ above the 500nmthick silicon waveguides [Fig. 19(e)].



Fig. 19. Fabrication steps of the hybrid III-V/silicon transmitter. (a)-(e) Patterning of the silicon waveguides and MZM implantation steps. (f)-(g) III-V bonding and substrate removal. (h)-(m) III-V patterning and metallization. After step (g), the wafer is downsized from 8" to 3".

2" III-V wafers are used for the bonding. Both the III-V and SOI wafers surfaces are activated by an oxygen plasma, and then bonded at room temperature, followed by a 120 minutes post-bonding annealing at 300°C [Fig. 19(f)]. A top view of the SOI wafer after bonding is shown on Fig. 20(a). After bonding, the InP substrate is removed using HCl/H2O wet etching [Fig. 19(g)], leaving the 2.7µm-thick epitaxial structure detailed on Table 2. To pursue the fabrication, the SOI wafers are downsized from 8" to 3" around the bonded III-V wafers, in order to enable subsequent processing in a standard III-V platform. The p-contact metallic layer is first formed using deposition and lift-off of Pd/Ti/Pt/Au/Pt layers [Fig. 19(h)]. A 400nm-thick SiN layer is deposited and patterned to be used as hard mask. The III-V waveguides are then defined up to the *n*-doped layer using alternatively CH4-H2 dry etching for the InGaAs-based layers, and H3PO4/HCl wet etching for the thick p-doped InP layer. The devices are separated using Br-based wet etching [Fig. 19(i)]. The n-contact metallic layer is also formed using deposition and lift-off of Ti/Pt/Au/Pt layers [Fig. 19(j)]. After a 2µm-thick SiN encapsulation [Fig. 19(k)], the modulator and laser contacts are opened by RIE. Modulator and laser electrodes are then formed by the deposition and lift-off of a 1.3-µm-thick Au layer. To form the heaters, a 250nm layer of NiFe is deposited and patterned by lift-off [Fig. 19(1)]. Finally, the contact pads for the heaters are defined by a deposited 250µm-thick Au layer deposition and lift-off [Fig. 19(m)]. A top view of the downsized SOI wafer is shown at the end of the process on Fig. 20(b). In the same way, a completed hybrid III-V/silicon transmitter with a 2mm-long silicon MZM is displayed on Fig. 20(c). The same figure also show several elements described earlier: a Bragg mirror, a silicon mode transformer, the patterned III-V epitaxy with its metallic contact layers, the end of the transition from thick to thin silicon waveguides, a MMI, the silicon MZM waveguides, and the waveguide-to-fiber grating coupler.



Fig. 20. (a) Top view of the 8" SOI wafer after III-V bonding. (b) Top view of the wafer after downsizing from 8" to 3". (c) Top view of the hybrid III-V/silicon transmitter (with a 2mm-long silicon MZM), and Scanning Electron Microscope (SEM) images of the different components.

Layer	Material	PL Lambda (µm)	Thickness (nm)	Doping (cm ⁻³)
p-doped contact	InGaAs	1.65	200	$2x10^{19}$
Transition	InGaAsP	1.1	50	5x10 ¹⁸
p-doped cladding	InP	0.92	2000	2 to 0.5x10 ¹⁸
SCH	InGaAsP	1.1	100	Undoped
Barriers (x7)	InGaAsP	1.1	10	Undoped
Wells (x8)	InGaAsP	1.29	8	Undoped
SCH	InGaAsP	1.1	100	Undoped
n-doped contact	InP	0.92	110	3×10^{18}
Super-lattice(x2)	InGaAsP	1.1	7.5	$3x10^{18}$
Super-lattice (x2)	InP	0.92	7.5	$3x10^{18}$
Bonding interface	InP	0.92	10	Undoped

Table 2. III-V Epitaxy Layer Structure

5. Transmitter measurements

To evaluate the performances of the hybrid III-V/silicon transmitters, two of them are studied with different Bragg mirrors periods and silicon MZMs lengths. The first transmitter (referred as transmitter 1) includes a DBR laser with a grating period of 195nm and a 4mm-long MZM modulator. The second one (referred as transmitter 2) uses a DBR laser with a grating period of 197nm and a 2mm-long MZM modulator. Both transmitters have been fabricated using the same III-V and SOI wafers.

Static performances of the transmitters are displayed on Fig. 21. During these measurements, the modulator heaters are used to control its phase and set it at maximum transmission. Both lasers have their current thresholds at 48mA. The lasers series resistances are 7.1 Ω for transmitter 1 and 4.5 Ω for transmitter 2. Maximum powers collected in the fiber were respectively 37 and 52 μ W for transmitter 1 and 2. The laser driving currents are limited to those shown on Fig. 21, because for higher values, the lasers are no longer in single-mode regime. This limits the transmitters performance in term of output power. We assume these secondary modes appeared due to defects in the Bragg mirrors fabricated with the EBL.



Fig. 21. Laser voltage and optical power collected in fiber versus laser current for both (a) transmitter 1 and (b) transmitter 2. For these values of current, the lasers were in single-mode regime.

Following these measurements, the hybrid III-V/silicon transmitters are studied with an optical spectrum analyzer (OSA). The effects of the heaters on the modulator phase and lasing wavelength can be seen on Fig. 22. Figure 22(a) shows the effect of the transmitter 1 modulator heater, for a fixed laser drive of 100mA, and at a fixed wavelength. As it can be seen, the laser is single-mode. Moreover, the interferometric spectrum of the modulator can be seen, thanks to the laser spontaneous emission over the wavelength span. By increasing the heating power on one of the silicon MZM arm and changing its phase, its spectrum can be shifted. The shift direction depends on which arm is heated. Thus, it is possible to set the laser wavelength at different working point of the modulator, such as at a maximum of transmission, at quadrature, or at a minimum of transmission. The same operation can be done with transmitter 2. Figure 22(b) shows the effect of the transmitter 2 Bragg mirrors

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heaters, for a fixed laser drive of 150mA, and a fixed modulator phase. As explained is section 4, by increasing the heating power on both mirrors, the laser wavelength can be increased. Here, a large amount of heating power was needed to tune the wavelength, due to the thick SiN layer between the heater and the silicon waveguide, reducing the heating efficiency. Under these conditions, the maximum shift of the laser wavelength is up to 8.5nm for both transmitters. The efficiency of these heaters can be largely improved by optimizing their design, or by using a different heating technology, such as doped silicon heaters [48].



Fig. 22. Spectrum measurements at the optical spectrum analyser of the hybrid III-V/silicon transmitter. (a) Spectrum for a fixed laser wavelength, with different phase between the MZM arms (transmitter 1). (b) Spectrum for a fixed MZM phase, with a tuned laser wavelength (transmitter 2). P_h is the electrical heating power used for both mirrors.

A top view of a hybrid III-V transmitter under test is shown on Fig. 23(a). Due to equipment limitations, it was not possible to use all the heaters at the same time. Thus, only the phase control on the modulator is used -since a single heater is enough - while the lasers are at a fixed wavelength. Nevertheless, more wavelengths could have been used by operating the Bragg mirrors at the same time. To evaluate the high speed digital performance of the transmitters, the set-up depicted in Fig. 23(b) is used. This set-up is nearly identical to the one shown on Fig. 15 to test the silicon modulator. The equipment used to drive the modulator is the same as that described in section 3.4. The difference lies on the optical I/O of the device, since no external light needs to be provided. Instead, two DC-generators are used: one to drive the laser, and one to control the modulator phase difference between its arms. Moreover, due to the output optical power limitation of the transmitters, the BOA is not suited for the measurements due to its noise. Instead, an external photodetector with a better sensitivity than the optical input of our oscilloscope is used. The model is a 1544B photoreicever from New Focus, which has a high internal transimpedance gain, but whose bandwidth is limited at 12GHz, making it limited for 25Gb/s measurements. This photoreicever is DC-coupled, the extinction ratio of the signal can be directly measured. As for the modulator measurements in section 3.4, degradations caused by cables are deembedde using de-emphasis, without compensating for the transmitter frequency response.



Fig. 23. (a) Top view of the hybrid III-V/silicon transmitter (1) under test. (b) Set-up used during large-signal measurements of the hybrid III-V/silicon transmitters.

The resulting eye diagrams are shown on Figs. 24(a) and 24(b) for both transmitters. As for the modulator measurements, a passive numerical low-pass filter (4th order Butterworth filter) with a 25Ghz cut-off frequency is used to reduce the noise during the measurements. Both eyes are open at 25Gb/s, in a dual drive configuration, with 2.5Vpp send on each arm of the silicon MZM. Both arms are biased at a 1.25V reverse-bias, thus they receive NRZ signals in opposite phase, switching between 0 and -2.5V. For both measurements, the modulators are set at quadrature using the phase control heaters. For transmitter 1, the laser drive current is set at 100mA, and its emitting wavelength is 1303.5nm. For transmitter 2, the laser drive current is set at 150mA, and its emitting wavelength is 1315.8nm. The measured extinction ratios are respectively 4.7dB and 2.9dB for the transmitter 1 and 2. By comparing those eye diagrams to the ones of the stand-alone modulator on Fig. 17(c) and 17(d), it can be seen that the rise and fall times are higher, due to the photoreicever bandwidth limitation. This can also explains the reduced extinction ratio of the transmitter, compared to the one of the stand-alone modulator.



Fig. 24. 25Gb/s eye diagrams of the hybrid III-V/silicon transmitters using (a) 4mm-long MZM at 1303.5nm (transmitter 1) and (b) 2mm-long silicon MZM at 1315.8nm (transmitter 2), both in dual drive configuration with 2.5Vpp applied on each arm.

Finally, both transmitters are able to efficiently transmit information at 25Gb/s while operating at two different wavelengths in the O-band, around 1.3μ m. A 1nm difference on the Bragg reflectors period leads to a 6.15nm difference on the laser wavelength. Additionally, since we are able to increase the laser wavelength up to 8.5nm by using the current heaters, the transmitters can emit at any wavelength sufficiently close to the laser gain spectrum, by using a "coarse" tuning with the reflector period, and a "fine" tuning with the heaters. Thus, the transmitters can comply with the fixed wavelengths of communication standards based on wavelength multiplexing, such as 100GBASE-LR4.

6. Conclusion and perspectives

In this paper we have demonstrated the successful co-integration of hybrid III-V/silicon DBR tunable lasers and silicon MZM, forming hybrid III-V/silicon transmitters, able to realize transmissions at 25Gb/s. Two transmitters working at two different wavelengths have been studied, with the possibility to tune the laser wavelength up to 8.5nm. The main components forming this transmitter have been thoroughly described, as well as its fabrication process steps. The transmitters overall performances might be improved further, by reducing the optical losses of the components, improving the Bragg mirror patterning or by a refined heater design.

The next step of our work will consist in integrating these hybrid transmitters on a complete 200-mm-platform, without downsizing the wafers. Various solutions are studied for this purpose, such as amorphous silicon [34], to locally increase the silicon waveguide thickness for III-V to silicon light coupling, or back-side integration [49], to improve the compatibility between hybrid III-V/silicon sources and multi-level planar metal

interconnections. This would also help to improve the design of the silicon modulator, and even higher data rates could thus be reached. Finally, the packaging of these transmitters is also ongoing.

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