45 Gbps Direct Modulation of Two-Section InP-on-Si DFB Laser Diodes

M. Shahin, K. Ma, A. Abbasi, G. Roelkens, and G. Morthier

***Abstract*— Two-section heterogeneously integrated InP-on-Si DFB laser diodes are demonstrated. In the modulation response, the relaxation oscillation frequency of 10 GHz is followed by a second resonance to achieve nearly 25 GHz 3-dB modulation bandwidth and 45 Gbps NRZ-OOK transmission.**

***Index Terms*— InP-on-Si, Distributed Feedback Lasers, Direct Modulation, Silicon Photonics, Semiconductor Laser Diodes, Two-Section Laser Diodes.**

I. Introduction

Silicon has been motivating many photonics researchers over the past decades to investigate active and passive optical components. Typically known as silicon photonics, the platform is attractive for two main reasons: a dense integration potential, and the possibility to use the mature CMOS electronics fabrication technology. The drawback of silicon lies in its indirect bandgap, making it challenging to be used for light sources. With the help of direct bandgap materials, such as III-V semiconductors, this drawback can be overcome. The heterogeneous integration of III-V semiconductors on silicon can be realized using die-to-wafer bonding [1]. In that case, the III-V material is bonded on silicon with the help of an adhesive material, typically divinylsiloxane-bis-benzocyclobutene (DVS-BCB), or using molecular bonding.

For many applications, DFB laser diodes are preferred as light sources due to their single mode behavior with large Side-Mode-Suppression-Ratio (SMSR). The fabrication of such lasers in the III-V-on-silicon platform is promising and has high potential for different applications. For example, for radio-over-fiber applications, self-pulsating laser diodes with controlled frequency between 10 and 40 GHz were demonstrated using two-section DFB laser diodes [2]. For data communication applications, high-speed directly modulated DFB laser diodes were recently demonstrated at 56 Gbps [3]. A detailed report about other advances on this platform is given by [4].

Classical single section InP-on-Si DFB laser diodes are limited by their relaxation oscillation frequency. Fortunately, there are some advanced laser designs that improve the modulation bandwidth substantially. For example, an external cavity that exploits the Photon-Photon-Resonance (PPR) effect improved the modulation bandwidth from its relaxation oscillation frequency peak at 8 GHz, to a second resonance peak around 30 GHz [3]. This improved the achieved 3-dB modulation bandwidth to 34 GHz. An alternative laser design that will be investigated in this paper is referred to as a two-section laser, or coupled cavity laser [5, 6]. Simulations show that such designs can enhance the modulation bandwidth to values as high as 50 GHz due to the beating between the main mode and a closely-located side mode. An actual device utilizing this concept was fabricated and measured in [7], in which a monolithic InP DFB laser demonstrated a modulation speed of 112 Gbps. Here, the beating between the DBR and DFB modes, which are separated by 50 GHz, gives the modulation enhancement at 50 GHz.

In this paper, a two-section laser diode is demonstrated on the InP-on-Si platform. First, the design and fabrication are discussed. Then, a small signal modulation bandwidth of 25 GHz is demonstrated. Third, data transmission experiments are conducted, and transmission at 45 Gbps is verified at bit error ratios that are substantially below the Forward-Error-Correction (FEC) threshold after propagation over 2 km of non-zero dispersion shifted fiber.

II. Design and Fabrication

The laser structure was used previously to demonstrate self-pulsating laser diodes [2]. The two sections are designed to have different mesa width to obtain a difference in effective index, and thereby to control the spacing of the stop bands. This, in turn, allows beating between two modes and produces self-pulsations. However, two-section laser diodes can also be useful in improving the modulation bandwidth. If beating happens between a main mode and a sufficiently weaker side mode, then the modulation bandwidth is enhanced at the beating frequency, as in [7]. The 3D-view and top-view of the laser structure are shown in Fig. 1 (a, b). During fabrication, the two laser sections are electrically isolated using dry-etching to control the DC current injected in each section independently. Each section is 250 µm-long. The left and right sections are 4 and 2 µm wide, respectively. The effective index difference is 0.0073, which spaces the stop-band of both sections by 3.5 nm. This creates self-pulsations with frequency that is controlled by the injected currents [2]. Adiabatic taper structures are used to couple to the silicon waveguide layer [4]. The right section is modulated while the left laser output is considered. The active region consists of 2 InGaAsP separate confinement heterostructure (SCH) layers (100 nm thick, PL wavelength of

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1170 nm) and 6 InGaAsP quantum wells (7 nm thick, PL wavelength 1550 nm) separated by 7 InGaAsP barriers (9 nm thick, PL wavelength of 1170 nm). The thicknesses of the n-InP, p-InP and p-InGaAs are 190 nm, 1500 nm and 220 nm, respectively. The InP epitaxial structure is bonded on a 400 nm-thick Si waveguide (3.5 µm wide) that has a 500 µm-long DFB grating etched 180 nm deep, with a period of 241 nm and duty cycle of 50%. A quarter-wave shifted section is located in the center of the grating.

Fig. 2 shows a Focused-Ion-Beam (FIB) cross section image of the laser structure near the taper tip. The DVS-BCB bonding layer thickness is less than 10 nm. The laser is encapsulated in Si_3N_4 and BCB for planarization.

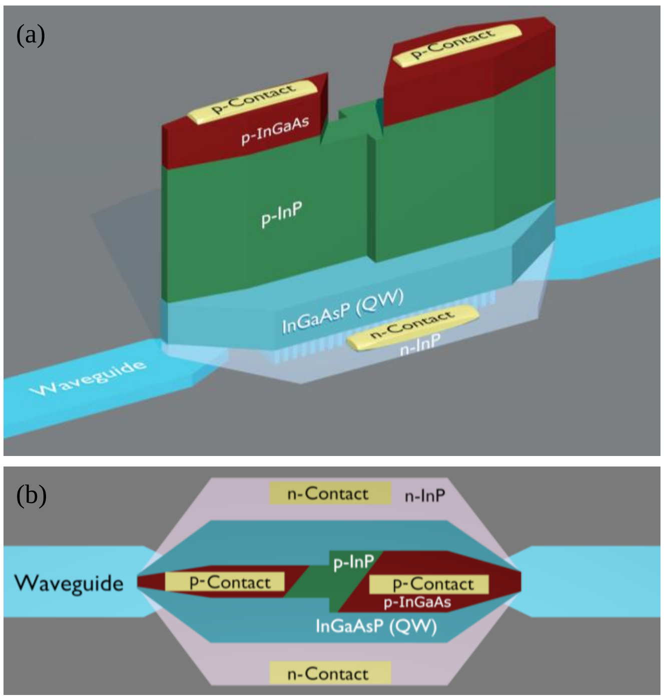

Figure 1. (a) 3D-view and (b) top-view of the fabricated InP-on-Si device showing electrically-isolated laser sections for independent current control.

III. Characterization

The power vs. current behavior for the device was similar to the device demonstrated in [2]. Generally, the power increases while increasing the current, until a point in which a roll-off happens at a high current due to heating. Fig. 3 and 4 show the optical spectrum when the bias currents are I_L = 48 mA and I_R = 60 mA, which produces the highest small signal 3-dB modulation bandwidth. As the bonding layer thickness is very small (less than 10 nm), the silicon grating coupling is strong. The stop-band of each laser section is not clearly identified, but from characterization it is expected that each section has as stopband of around 5 nm [2] with the extracted coupling coefficient κ being ~ 150 cm^{-1}. This high coupling coefficient is the source of the multimode behavior observed in the spectrum. A possible solution to eliminate such modes is to lower the coupling coefficient (i.e. by increasing the bonding thickness) which in turn reduces the stop-band of each section and excites less modes. Alternatively, making the two sections shorter reduces spatial hole burning and multimode behavior.

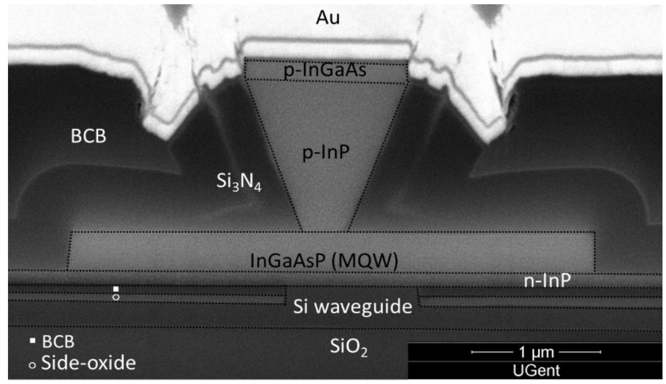

Figure 2. FIB cross-section image of a fabricated device showing the laser structure encapsulated in Si_3N_4 and BCB on top of a silicon waveguide.

An Erbium Doped Fiber Amplifier (EDFA) was used to boost the optical signal and compensate for any losses in the optical link. For example, the loss from the grating coupler is about 5 dB. The amplifier is followed by an optical tunable filter with a bandwidth of 1 nm to suppress the amplified spontaneous emission from the EDFA. Moreover, the optical tunable filter also serves to eliminate the other modes, which improves the quality of the eye diagram at the receiver side. An alternative could be to integrate an on-chip optical filter. Making this device single-mode (e.g. by reducing the coupling coefficient) and having high output power (e.g. less grating coupler losses) removes the necessity for the amplifier and the filter.

For bandwidth characterization, the laser peak at 1555 nm is filtered out. A small signal modulation bandwidth close to 25 GHz can be observed in Fig. 5 at I_L = 46 mA and I_R = 60 mA. Next to the relaxation oscillation frequency around 9 GHz a second resonance around 20 GHz is obtained, which improves the total 3-dB modulation bandwidth by more than a factor of 2. The resonance at 20 GHz results from the beating between the main peak and the side-mode in Fig. 4, which are separated by around 20 GHz (≈ 0.15 nm). If both modes are of similar strengths, there will be beating around the frequency difference [2]. As a result, the second resonance would be too strong and would lead to too strong distortion. Therefore, the side-mode should be sufficiently weaker than the main mode, for the second resonance to be within the 3-dB small signal modulation range. As shown in [2], it is possible to tune the separation between the peaks, which controls the frequency at which the second resonance occurs, to fine tune the small signal modulation.

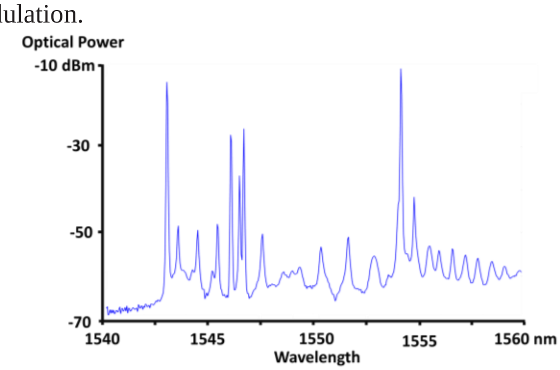

Figure 3. Optical spectrum of the laser at I_L = 48 mA and I_R = 60 mA. The right laser peak is filtered out at the receiver side.

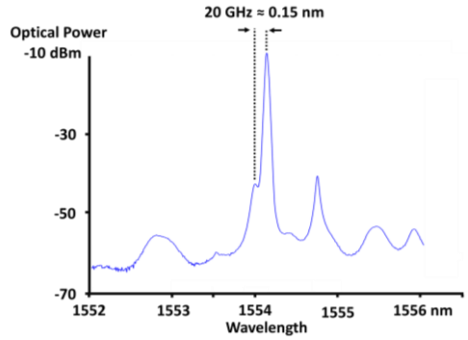

Figure 4. The filtered laser peak at the receiver side. The spacing between the main mode and the side mode is about 0.15 nm, which corresponds to 20 GHz.

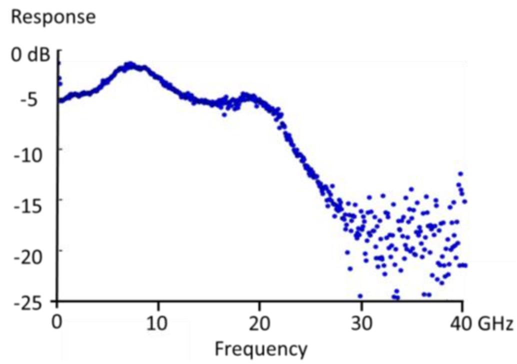

Figure 5. Small signal response showing nearly 25 GHz 3-dB modulation bandwidth at I_L = 46 mA and I_R = 60 mA.

Data transmission experiments were conducted to investigate the large signal modulation of the laser. Transmission of 45 Gbps non-return-to-zero data that has a pattern length of 2^7-1 shows an open eye-diagram. The voltage swing applied to the right section of the laser is about 2.2 V_{pp}. Bias conditions of I_L = 46 mA and I_R = 50 mA were used, resulting in -5 dBm output power in single mode fiber. The difference between IR in the small and large signal experiment is because small signal measurements only give an indication for the device performance, as the device behavior can be different for small and large signal modulation.

A root-raised-cosine filter with an alpha factor of 0.5 is used to shape the eye diagrams. Fig. 6 shows the eye diagram for a back-to-back configuration, followed by the eye diagram after transmission over a 2-km-long Non-Zero Dispersion-Shifted-Fiber (NZ-DSF).

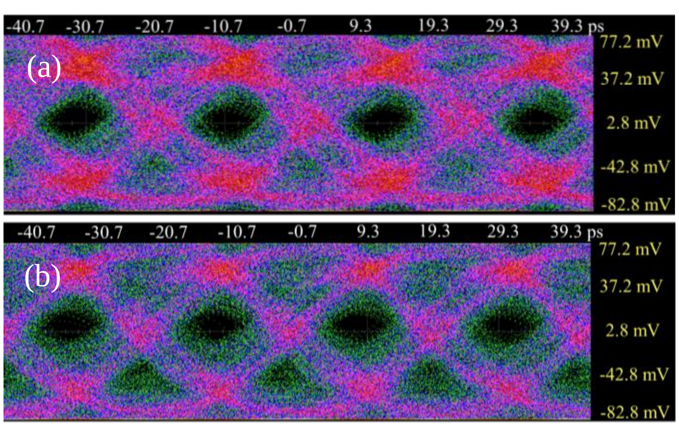

Figure 6. 45 Gbps sub-HD-FEC transmission (a) back-to-back and (b) with 2 km NZ-DSF, for a pattern length of 2^7-1.

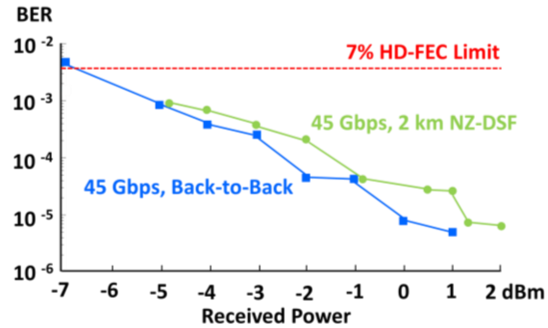

Figure 7. Received power vs. bit-error-rate showing sub-HD-FEC operation for a received power as low as -7 dBm.

The BER vs. received power measurement for this laser is shown in Fig. 7. 45 Gbps transmission with a BER lower than the 7% Hard Decision (HD) FEC limit is possible for a received signal power above -7 dBm.

IV. Conclusions

Two-section InP-on-Si DFB laser diodes with enhanced modulation bandwidth were demonstrated. The modulation bandwidth is estimated to be around 25 GHz, allowing data transmission at 45 Gbps both for a back-to-back configuration and for transmission over 2 km non-zero dispersion-shifted fiber.

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VI. References

[1] S. Keyvaninia et al., “Ultra-thin DVS-BCB adhesive bonding of III-V wafers, dies and multiple dies to a patterned silicon-on-insulator substrate,” Optical Materials Express, 3(1), pp. 35-46, (2012).
[2] K. Ma et al., “Demonstration of InP-on-Si Self-Pulsating DFB Laser Diodes for Optical Microwave Generation,” IEEE Photonics Journal, 9(4), pp. 1504608, (2017).
[3] A. Abbasi et al., “Direct and electro-absorption modulation of a III-V-on-silicon DFB laser at 56 Gbps,” IEEE Journal of Selected Topics in Quantum Electronics, 23(6), pp. 1501307, (2017).
[4] G. Roelkens et al., “III-V-on-Silicon Photonic Devices for Optical Communication and Sensing,” Photonics (3), pp. 969-1004, (2015).
[5] P. Bardella et al., “Design and Analysis of Enhanced Modulation Response in Integrated Coupled Cavities DBR Lasers Using Photon-Photon Resonance,” Photonics 3(1), (2016).
[6] T. Numai et al., “High Resonance Frequency in a Coupled Cavity DFB-LD with Phase- Shifted/Uniform Gratings by Photon-Photon Resonance,” proceedings in International Conference of Numerical Simulation of Optoelectronic Devices (NUSOD), pp. 35-36, (2017).
[7] Y. Matsui et al., “55 GHz Bandwidth Distributed Reflector Laser,” Journal of lightwave technology, 35(3), pp. 397-403, (2017).