Proceedings Symposium IEEE Photonics Society Benelux, 2017, Delft, The Netherlands

Towards High Modulation Bandwidth using Two-Section InP-on-Si DFB Laser Diodes

M. Shahin[1, 2, *], A. Abbasi[1, 2], K. Ma[3], G. Roelkens[1, 2], and G. Morthier[1, 2]

[1] Photonics Research Group, Department of Information Technology, Ghent University–IMEC, Belgium
[2] Center for Nano- and Bio-photonics, Ghent University, Belgium
[3] Centre for Optical and Electromagnetic Research, Zhejiang University, Hangzhou, China
[*] Email: mahmoud.shahin@ugent.be

A two-section InP-on-Si DFB laser diode with a high modulation bandwidth of 30 GHz is demonstrated. By modulating one section and controlling the DC-bias in both sections, a modulation speed of 40 Gbps for NRZ is achieved.

Introduction

There is an increasing interest in silicon photonics, mainly due to the advantages of dense integration of active and passive optical functions and the possibility of co-integration with electronics. However, when it comes to light sources, silicon cannot be used on its own due to its indirect bandgap. This motivates research on heterogeneous integration of III-V materials on silicon to create light sources. The basis of this process is bonding III-V material on silicon, and is described in details in [1].

DFB laser diodes are the preferred light sources for many applications, due to their single mode behavior and high Side-Mode-Suppression-Ratio (SMSR). Previous research has already explored different methods to create DFB laser diodes on the InP-on-Si platform for various applications, such as high-speed modulation [2, 3], wavelength tuning [4] and self-pulsations [5].

Recent research has demonstrated the superior performance of high speed modulated DFB laser diodes on the InP-on-Si platform. 56 Gbps directly modulated lasers were demonstrated in [2]. In more recent work [3], electro-absorption modulation of the two laser tapers allowed 2 x 56 Gbps modulation speed.

Further improvement is desired to speed up the transition to 400 Gb/s or Tb/s Ethernet. Though single section InP-on-Si DFB laser diodes are limited by their relaxation oscillation frequency, some design alterations can enhance the modulation bandwidth, e.g., creating an external cavity to exploit a Photon-Photon-Resonance (PPR) which has resulted in a 34 GHz modulation bandwidth [2]. In parallel, there have also been some investigations on two-section DBR [6] and DFB laser diodes [7]. Simulations show that such two-section laser diodes (also referred to as coupled cavities), enhance the modulation bandwidth to values as high as 40 GHz [6, 7].

This paper summarizes the findings obtained from experiments on a two-section DFB laser diode, whereby a small signal modulation resulted in a 3-dB modulation bandwidth of 30 GHz. Judging from the small signal response, it is expected to have error-free transmission for 56 Gbps Non-Return-to-Zero (NRZ) signals, and beyond. However, the highest possible modulation speed that complies with the Forward-Error-Correction (FEC) criteria of 10^{-3} Bit-Error-Rate (BER) is 40 Gbps NRZ. We believe that the limitation is due to the multi-mode behavior of the laser, as the laser was fabricated with minimum bonding thickness resulting in a very high coupling coefficient. Further optimization to obtain a single-mode laser, e.g., by increasing the bonding thickness to decrease the coupling coefficient, promises high modulation bandwidths.

Design and Fabrication

Since the 3-dB modulation bandwidth is determined, among other factors, by the volume of the laser (i.e. the smaller the volume, the higher the modulation bandwidth), narrower sections of 2.5 µm are fabricated compared to the 3.4-µm-wide laser used in [2, 3]. For the same reason, the two sections are designed to have unequal lengths, i.e. a long and a short section, and the short section is chosen to be directly modulated. The top- and side-view of the laser under study is shown in Fig. 1 (a, b). During fabrication, both sections are electrically isolated to control the DC current in each section independently.

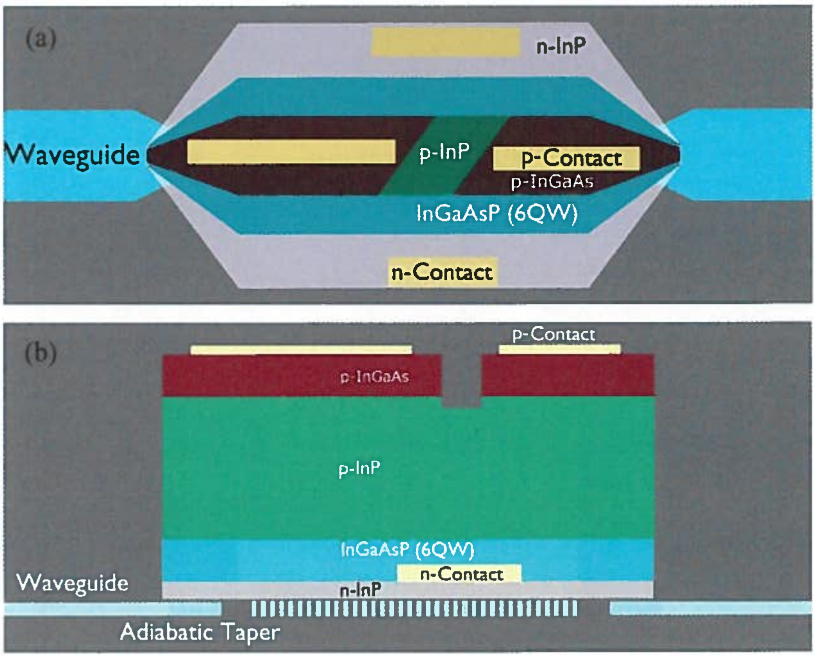

Figure 1. (a) Top- and (b) side-view of the fabricated laser showing two sections that are electrically isolated.

The lengths of the right and left sections are 340 µm and 140 µm, respectively. The silicon DFB grating has a period of 241 nm with a duty cycle of 50%, and λ/4 phase-shift in the middle. The electrical isolation is done by a dry-etch of the top p-InGaAs layer and part of the p-InP. The InP layer-stack is the same as the one reported in [5].

Characterization

Fig. 2 shows the optical spectrum for the bias current combination $I_L = 43$ mA and $I_R = 53$ mA, the current combination at which the best small signal modulation response is obtained. Fig. 3 shows the small signal modulation response amounting to nearly 30 GHz 3-dB modulation bandwidth. The modulation response depends on the injected current combination. As can be seen in Fig. 2, the laser exhibits a multi-mode behavior, with a stop-band of at least 10 nm, from which the coupling coefficient κ can be approximated to be at least 440 cm^{-1}. On the other hand, the single-mode lasers demonstrated in [2, 3] had a coupling coefficient κ of 200 cm^{-1}. This suggests that the multi-mode behavior comes from the high coupling coefficient.

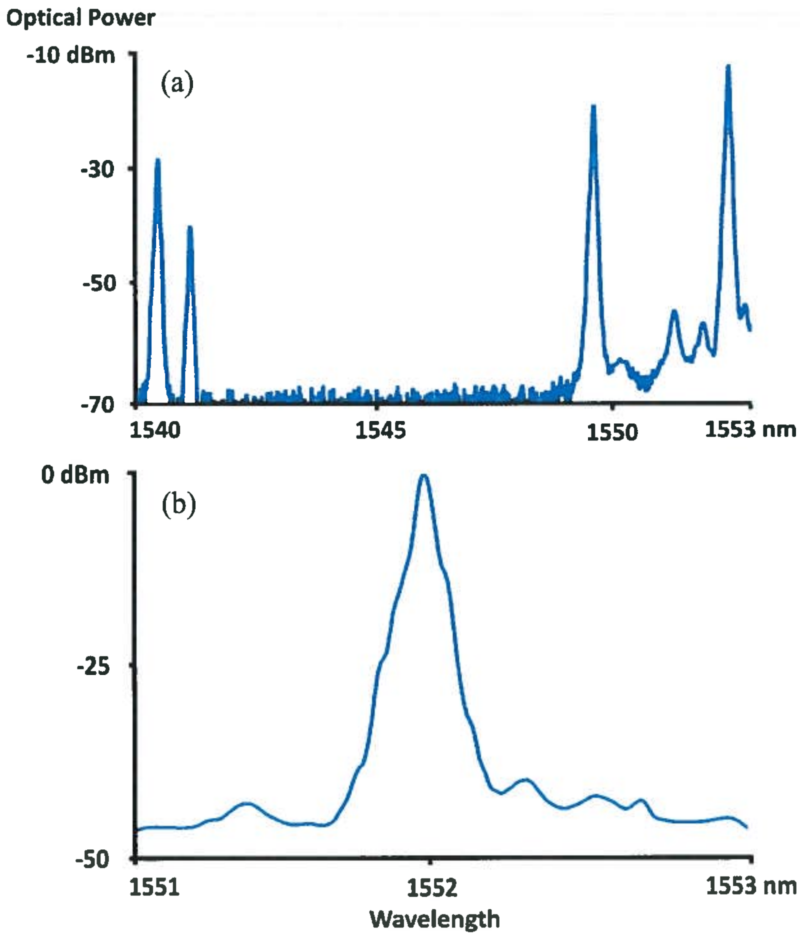

Figure 2. (a) The optical spectrum at $I_L = 43$ mA and $I_R = 53$ mA. The laser exhibits a multi-mode behavior with a stop-band of 10 nm, corresponding to a coupling coefficient κ of 440 cm^{-1}. (b) The optical spectrum of the amplified and filtered signal before the photo-detector.

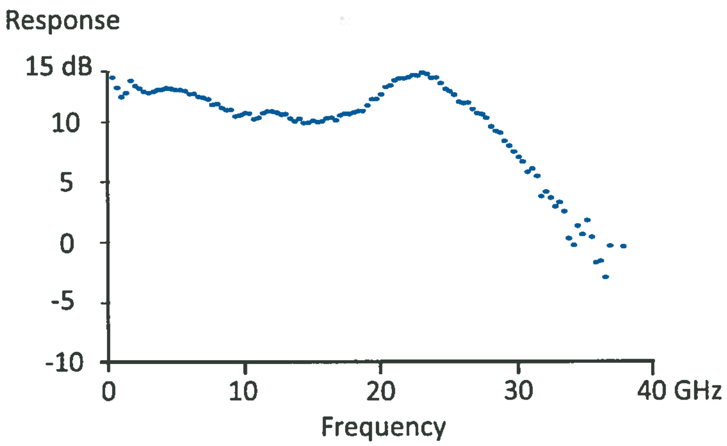

Figure 3. Small signal modulation response of the fabricated laser at $I_L = 43$ mA and $I_R = 53$ mA, which shows 30 GHz 3-dB modulation bandwidth.

To demonstrate the modulation speed of the laser diode, a large signal modulation experiment was conducted. Transmission of a 40 Gbps NRZ signal with a pattern length of 2^7-1 is demonstrated with an open eye-diagram at 20°C. The voltage swing is around 2.2 V_{pp}. Back-to-back configuration, as well as transmission over a 2 km Non-Zero Dispersion-Shifted-Fiber (NZ-DSF) are demonstrated as shown in Fig. 4 (a, b). Fig.4 (c) shows the BER vs. received power measurement result. The transmitted signal has an edge shape of a raised-root-cosine with an alpha factor of 0.2. Looking at the small signal modulation response in Fig. 3, one would expect a modulation speed of at least 56 Gbps. We believe that the modulation speed is limited by the multi-mode behavior of the laser as previously shown in Fig. 2. This is due to the smaller mesa width as compared to the lasers in [2, 3], which pushes the optical mode down closer to the silicon waveguide. This, in turn, increases the coupling coefficient (440 cm^{-1} as opposed to 200 cm^{-1} in [2, 3]) of the laser and causes multi-mode operation.

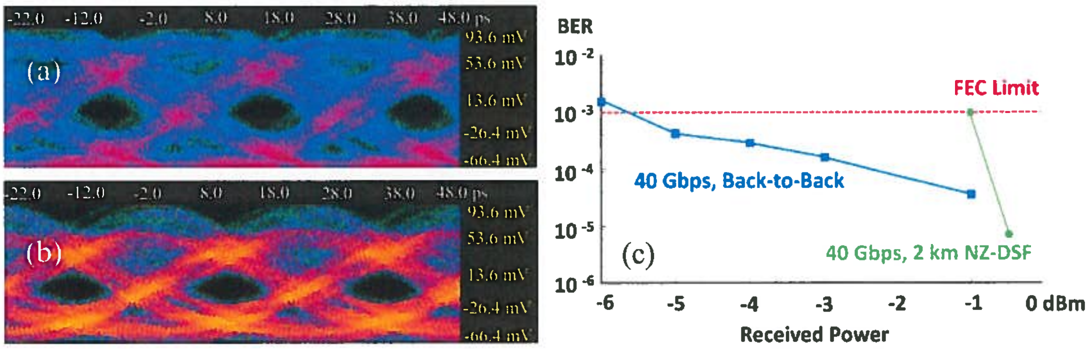

Figure 4. Large signal modulation for 40 Gbps with a pattern length of 2^7-1 is demonstrated with (a) back-to-back and (b) over 2 km of NZ-DSF. (c) Depicts BER vs. received power.

Conclusion

Two-section InP-on-Si DFB laser diodes with high modulation bandwidth were demonstrated. Modulation of one section with a small signal and control of the DC-bias in both sections resulted in a modulation bandwidth of 30 GHz. The laser exhibits a multi-mode behavior assumed to limit the maximum achievable bitrate to 40 Gbps NRZ. Further optimization is being carried out to enable single-mode operation that has the potential to achieve transmission speeds of 56 Gbps NRZ, or beyond.

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, pp. 35-46, 3(1), (2012).

[2] 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).

[3] A. Abbasi et al., "2x56 Gbps Electroabsorption Modulated III-V-on-silicon DFB Laser," accepted for publication in European Conference on Optical Communication (ECOC), (2017).

[4] S. Dhoore et al., "III-V-on-silicon three-section DBR laser with over 12 nm continuous tuning range," Optics Letters, pp. 1121-1124, 42(6), (2017).

[5] K. Ma et al., "Demonstration of InP-on-Si Self-Pulsating DFB Laser Diodes for Optical Microwave Generation," IEEE Photonics Journal, pp. 1504608, 9(4), (2017).

[6] 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).

[7] 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).