Compact InP-on-Si DFB Laser Diodes

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Compact InP-on-Si DFB laser diodes with 400 µm length, 1 mW power in the waveguide and 10 GHz 3-dB modulation bandwidth are demonstrated. The lower footprint is achieved by the use of a single-stage taper of 60 µm length. These tapers are four times shorter, leading to two times shorter laser structures than previously demonstrated.

Introduction

Silicon photonics is becoming increasingly popular, for its dense integration of active and passive waveguide circuits, and the possibility of co-integration with electronic circuits. However, silicon itself cannot be used for the implementation of a light source because of its indirect bandgap. A way to integrate light sources on silicon is to heterogeneously integrate and couple III-V waveguides, to an underlying silicon waveguide using adiabatic evanescent coupling.

A lot of work has been done to enhance the bandwidth and modulation speed of such light sources, specifically InP-on-Si DFB laser diodes. In some recent work, the modulation speed demonstrated was 56 Gbps for direct modulation [1], and 2 x 56 Gbps using electro-absorption modulation of both tapers individually [2]. The tapers demonstrated are adiabatic, and are typically 230 µm long. The DFB grating length is typically 300 µm. This makes the device length around 800 µm. In this paper, we aim to shrink the footprint and to demonstrate very compact laser diodes. This is done by a one stage taper of both the III-V and the silicon waveguides. This allows to shrink the tapers down to around 60 µm in length, which is around 4 times shorter. As a result, the device footprint becomes around 2 times shorter.

The taper design was first introduced in [3] for a Fabry-Perot laser. A III-V-on-silicon laser with taper length of 50 µm was demonstrated and around 7.5 mW of optical power was extracted from one facet. We have adapted the design to our laser parameters and structure. We demonstrate very compact InP-on-silicon DFB laser diodes. First, we will show the design parameters used to achieve a good coupling. Then, we will show simulations for different taper lengths. After that, we will report the measurement results of fabricated laser devices. Finally, a small signal experiment is conducted to show the modulation bandwidth of the demonstrated laser devices.

Design and fabrication

The design of the taper is based on [3], in which a taper as short as 40 µm shows around 95% of the light being coupled from the III-V to the silicon. The design shows a silicon taper with a waveguide width varying between 4 µm and 500 nm, sitting below a III-V taper with a width varying between 3 µm and 150 nm. However, making a III-V taper tip of 150 nm requires electron-beam lithography (e-beam). To relax this requirement, and to make the fabrication possible with UV lithography tools, we designed the III-V taper tip to be 550 nm wide.

The 3D view of the laser structure with the single-stage taper design is shown in Fig. 1. The laser cavity consists of a DFB grating of 300 µm, and two single-stage taper structures on both ends. The mesa has a V-shape due to the wet etching, which also is useful for optical mode confinement in the quantum-wells. Finally, metal contacts are used to bias the laser diode.

The simulation results are shown in Fig. 2 (a), where a sweep of different taper lengths vs. the power transmission to the underlying silicon waveguide is shown. This was done for the case of perfect alignment (i.e. the III-V mesa sits exactly in the center of the silicon waveguide below), and with 300 nm misalignment. For 60 µm long taper, around 86% and 78% of the light is coupled for the two cases, respectively. Fig. 2 (b) shows the mode profile while coupling from the III-V to the silicon waveguide for the perfect alignment case.

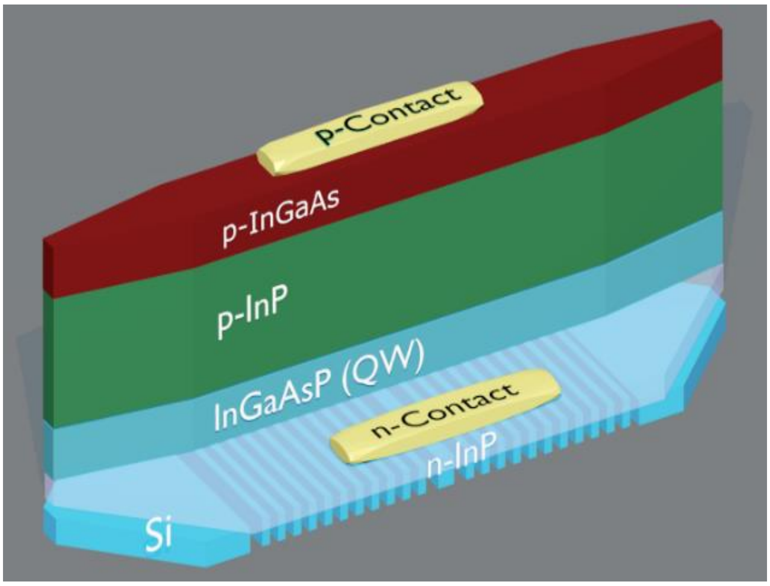

Fig. 1. 3D view of the fabricated laser showing the tapering of both the silicon and the III-V mesa

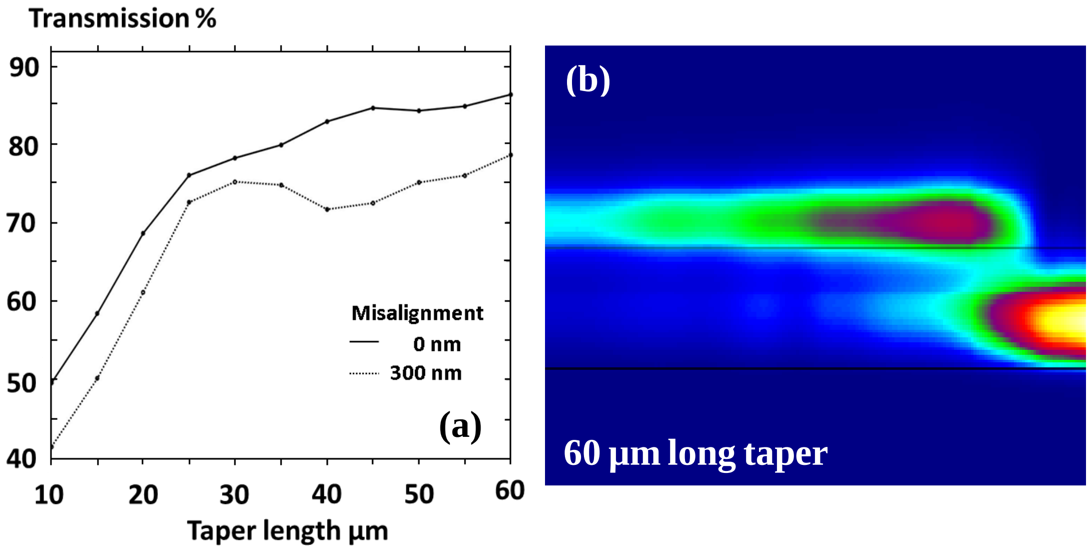

Fig. 2. (a) Simulations show the coupling from the III-V to the silicon from 10 to 60 µm long tapers with perfect alignment of the III-V waveguide on top of the silicon waveguide, and with 300 nm misalignment, (b) the coupling from the III-V to the silicon waveguides with 60 µm long taper and perfect alignment

Ideally, a perfect alignment of the III-V mesa structure on top of the silicon is desired. However, during the mesa definition lithography, a misalignment of 200-300 nm is expected. Fig. 3 (a-b) show how the mesa would be located with respect to the silicon waveguide in case of (a) perfect alignment vs. (b) with a 300 nm misalignment. Since the taper tip width is comparable to the silicon waveguide width, around half of the taper tip will not be on top of the silicon waveguide. And because the coupling region is very short, misalignment is expected to decrease the coupling. This is indeed confirmed by the simulation results in Fig.2 (a).

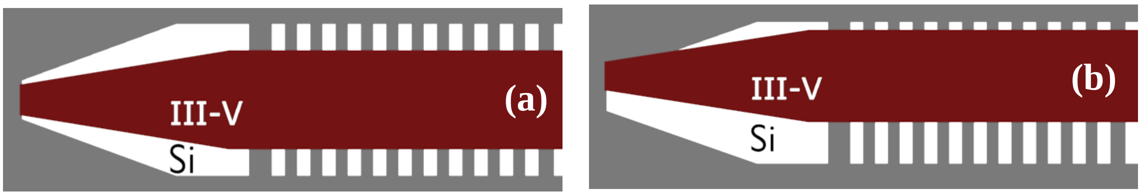

Fig. 3. Top view with (a) a perfect alignment vs. (b) 300 nm misalignment showing the criticality of misalignment

The epitaxial structure used for this device is based on an InAlGaAs active region. The active region consists of 2 InAlGaAs separate confinement heterostructure (SCH) layers (50 nm thick) and 10 InAlGaAs quantum wells (6 nm thick, PL wavelength 1530 nm) separated by 11 InAlGaAs barriers (10 nm thick). The thicknesses of the n-InP, p-InP and p-InGaAs are 150 nm, 1500 nm and 200 nm, respectively. The InP epitaxial structure is bonded on a 400 nm-thick Si waveguide (4 µm wide) that has a 300 µm-long DFB grating. The grating period is 246 nm with a 50% duty cycle, and is etched 180 nm deep. A quarter-wave shift is located in the center of the grating.

Characterization

The optical output power in the waveguide vs. the injected current is shown in Fig. 4 (a). The different taper lengths give similar powers in the output silicon waveguide. The lasers, including the tapers, have around 25 Ω of resistance. The maximum optical power in the waveguide is around 1 mW. This power is about 4 times lower than in lasers with long tapers, which may be due to the limited misalignment tolerance. This could also be due to the higher series resistance compared to the previous demonstrated lasers, which creates heating. Judging from the simulations, a better alignment and a narrower III-V tip should make it possible to enhance the output power to the same levels.

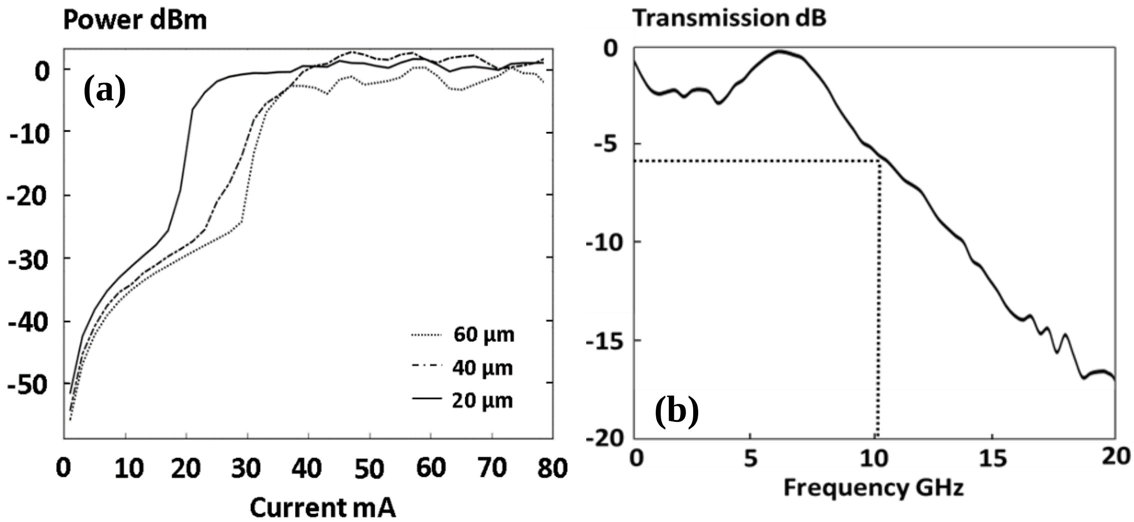

Fig. 4. (a) Power vs. current curve for fabricated lasers with 60, 40 and 20 µm taper lengths, (b) small signal modulation showing 10 GHz 3-dB modulation bandwidth.

A small signal modulation experiment was conducted for the laser with 60 µm long taper. The active section as well as the taper section were modulated using a PNA-X Vector Network Analyzer. A 3-dB modulation bandwidth of 10 GHz is measured, as shown in Fig. 4 (b). The low frequency roll-off is due to the taper. This value is typical of such a DFB laser diode. Further optimization, as in [1] or [2] could enhance the bandwidth further, to obtain both a compact and a high speed laser diode.

Conclusions

Compact InP-on-Si DFB laser diodes were demonstrated. The lasers are around 400 µm long, which is half the footprint of the previously demonstrated lasers. This is achieved by a single-stage taper which is 60 µm long. The optical power in the silicon waveguide is 1 mW, which is lower than in the previously demonstrated lasers due to the alignment intolerance of the design. Using e-beam for the patterning of the laser structure could improve the alignment, which could improve the output power to the levels expected in the simulations. Finally, the measured 3-dB modulation bandwidth is 10 GHz.

References

[1] 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).
[2] A. Abbasi et al., "2x56 Gbps Electroabsorption Modulated III-V-on-silicon DFB Laser," European Conference on Optical Communication (ECOC), (2017).
[3] J. Pu et al., "Heterogeneous Integrated III–V Laser on Thin SOI With Single-Stage Adiabatic Coupler: Device Realization and Performance Analysis," IEEE JSTQE 21(6), (2015).