Design of an electronically tunable laser diode integrated on the SOI platform

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Fast tunable laser diodes are expected to play a crucial role in future optical packet-switched data center and metro networks. We propose a heterogeneously integrated laser diode for fast and wide wavelength tuning. The laser structure consists of III-V tunable twin-guide (TTG) membrane that is adhesively bonded on sampled-grating-containing SOI structures. In this paper, we will present a detailed design analysis of the suggested laser structure. Emphasis is put on the optimisation of the modal gain, tuning efficiency and grating coupling constant. Simulations of an adiabatic tapered coupler to efficiently couple the light from the III-V waveguide to the underlying silicon device layer are presented as well.

Introduction

With the evolution towards cloud computing in the Internet, an increasing amount of applications are hosted in data centers. Due to the packet or burst nature of the data being routed in such data centers, there has been a renewed interest in optical packet or burst switching [1]. New flexible bandwidth optical network architectures that can dynamically increase the number of links between hot spots in a data center core network make for instance use of this optical switching [2]. Optical packet switching systems for employment in metro networks have furthermore known a remarkable growth as well [3]. Implementations of optical switches or cross connects used for this purpose, require very fast widely tunable laser diodes with high power efficiency [4].
In this paper we propose a heterogeneously integrated tunable III-V/SOI laser that will address the aforementioned needs. Through carrier injection in the tuning layer of the III-V membrane, the effective index of the III-V/SOI waveguide mode can be modified, in turn modifying the lasing wavelength. Due to the electronic tuning nature, tuning speeds may be very high, with switching times on the order of nanoseconds. Sampled gratings are defined in the SOI waveguide. These are used to obtain comb-like reflection spectra and can enhance the wavelength tuning range through exploitation of the Vernier effect.

Device layout

The general III-V/SOI layout of the proposed laser is shown in Figure 1. The III-V TTG membrane comprises a p^{++}-type InGaAs top contact layer, a p-type InP top cladding layer, a MQW region (with 6 InGaAsP-based QWs and 5 barriers, $Q = 1.55$) sandwiched between 2 SCH layers, an n-type InP middle cladding layer, an InGaAsP ($Q = 1.4$) tuning layer, a p-type InP bottom cladding layer and a p^{+}-type InGaAsP ($Q = 1.3$) bottom contact layer. The SOI waveguide has a total silicon thickness of 400 nm with a 180 nm

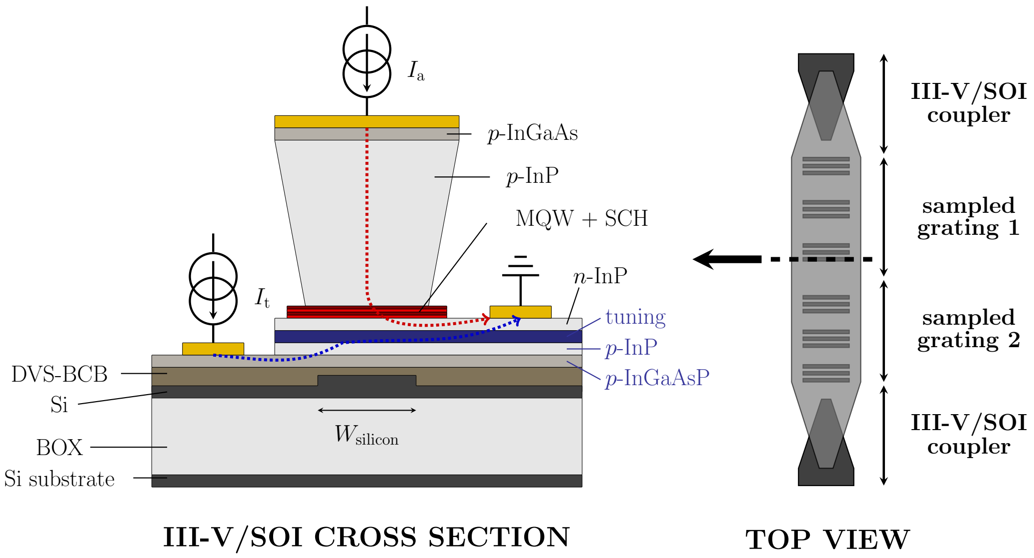


Figure 1: Layout of the proposed III-V/SOI TTG laser diode. I_a and I_t represent the active and tuning current respectively.

etch depth. The BOX layer is 2 μm thick. A thin DVS-BCB adhesive layer is used to bond the III-V stack on top of the SOI waveguide.

III-V/SOI cross section design

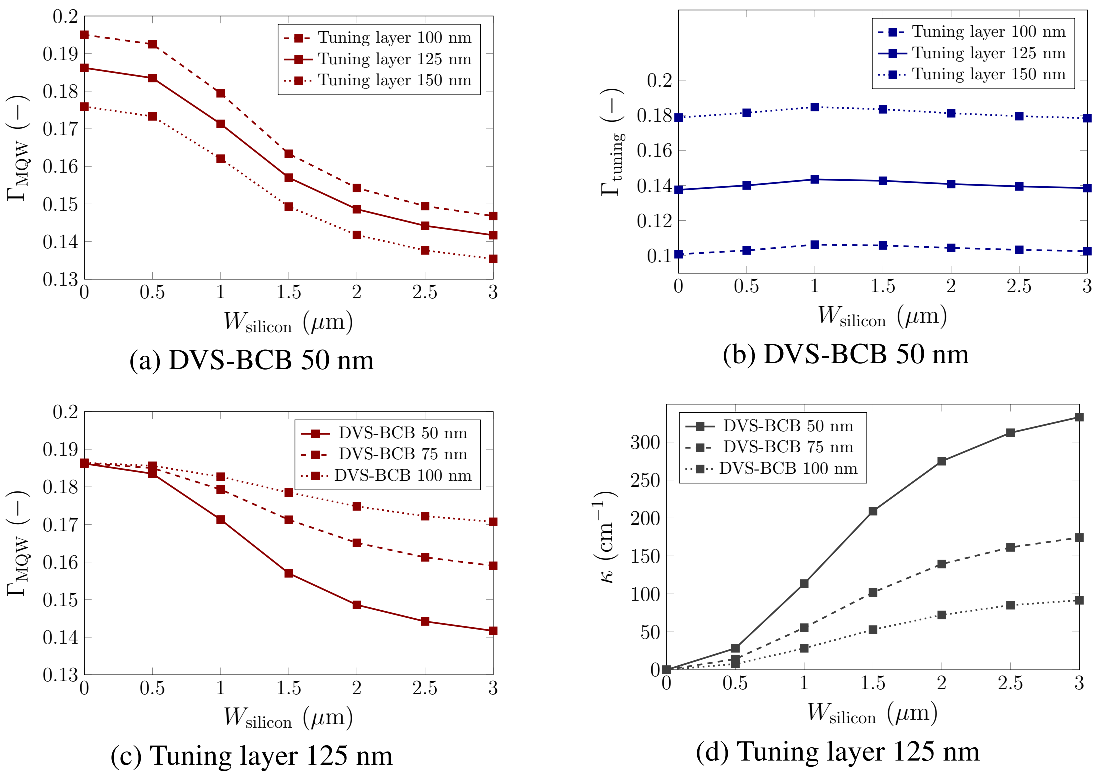
As a main design goal the overlap of the optical mode with the MQWs has to be maximised so to lower the lasing threshold and maximise the output power. At the same time the mode should have sufficient overlap with the tuning layer and silicon waveguide to ensure efficient tuning and sufficient distributed feedback respectively. Optical properties of the device were studied using Fimmwave, a commercial mode solver from Photon Design. Fundamental TE modes and confinement factors were calculated for different values of the tuning layer thickness, DVS-BCB thickness and silicon waveguide width. Because of thermal and electrical considerations the width of the III-V mesa was kept fixed at 3 μm. Wavelength tuning is achieved by modifying the refractive index through carrier injection in the tuning layer, thereby exploiting the free-carrier plasma dispersion effect. The tuning efficiency may be calculated from

$$\frac{\Delta\lambda_B}{\Delta N} = \Gamma_{\text{tuning}} \frac{\lambda_B}{n_g} \frac{\mathrm{d}n_{\text{tuning}}}{\mathrm{d}N}, \tag{1}$$

where n_g is the group index, λ_B is the Bragg wavelength and ΔN the change in carrier density upon carrier injection. The tuning efficiency is directly proportional to Γ_{tuning}, which represents the confinement factor in the tuning layer. Figures 2 (a) and (b) show the confinement factor in the MQW and tuning region versus silicon waveguide width, for different thicknesses of the tuning layer. It is clear that Γ_{MQW} quickly decreases with increasing silicon waveguide width. Γ_{tuning} is only slightly affected by the width of the silicon waveguide, with a weak maximum around 1 μm. As expected the thickness of the tuning layer has a much larger influence on Γ_{tuning}. A thickness of 125 nm is chosen as tradeoff between a large Γ_{MQW} and Γ_{tuning}. The Bragg grating coupling strength is evaluated through the grating coupling constant κ, which is for uniform gratings given by

$$\kappa = 2 \cdot \left(\frac{n_{\text{eff, Si}} - n_{\text{eff, no Si}}}{\lambda_B} \right) \sin\left(m\pi \, \mathrm{DC}\right). \tag{2}$$

Hereby $n_{\text{eff, Si}}$ and $n_{\text{eff, no Si}}$ are the effective indices of the optical mode simulated with and without underlying silicon waveguide respectively. DC is the grating duty cycle, which is set to 50% under the assumption of rectangular first order gratings. Figures 2 (c) and (d) show the confinement factor in the MQW region and grating coupling constant versus silicon waveguide width, for different thicknesses of the DVS-BCB bonding layer. As expected a thicker bonding layer yields a higher overlap of the optical mode with the MQW region. However, thick bonding layers significantly decrease κ and deteriorate the III-V to SOI coupling. Therefore the aim is to keep the bonding layer as thin as possible. It is furthermore clear that a silicon waveguide width ≥ 1.5 μm ensures a κ above 50 cm^{-1}, even for thick bonding layers. However, for silicon waveguide widths $\geq$ 2.5 μm the grating coupling constant becomes very high, which will lead to spatial hole burning and low optical output powers. For sampled gratings a spatially averaged grating coupling constant can be defined as the product of the sampling duty cycle and the grating coupling constant for uniform gratings. A sampling duty cycle of 10 to 15% is typically chosen to obtain a sufficiently flat comb-like reflection spectrum. This implies a larger silicon waveguide width of 2 or 2.5 μm is necessary in order to provide sufficient distributed feedback and to somewhat limit the overall device footprint.



(a) DVS-BCB 50 nm

(b) DVS-BCB 50 nm

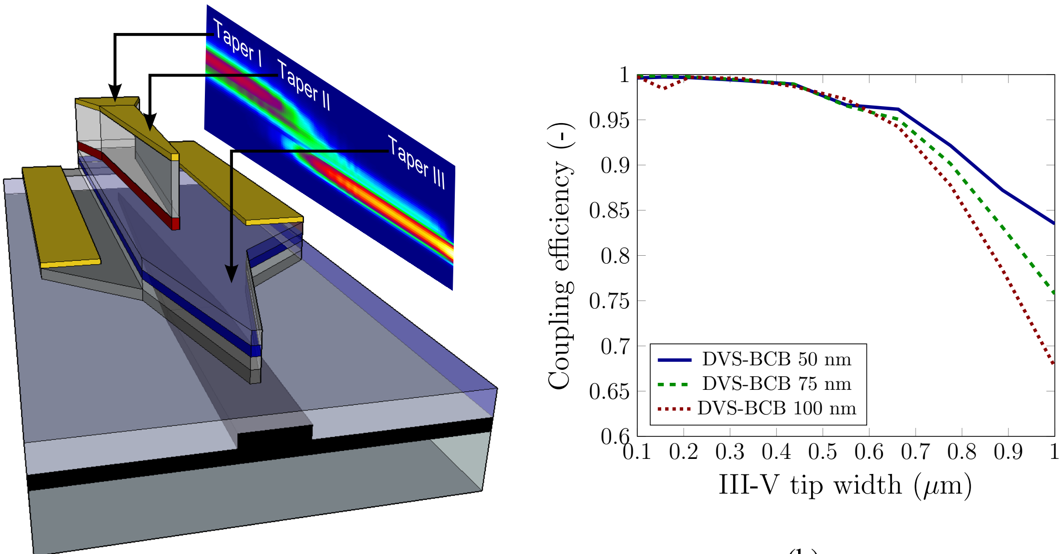
(c) Tuning layer 125 nm

(d) Tuning layer 125 nm

Figure 2: Fundamental mode confinement factors dependence on DVS-BCB thickness, tuning layer thickness and silicon waveguide width.

Adiabatic tapered III-V/SOI coupler design

In order to efficiently couple the light between the III-V TTG membrane and the underlying silicon waveguide layer an adiabatic coupling structure is employed. A schematic is shown in Figure 3 (a). The coupler is piecewise linear and consists of three parts: Taper I has a length of 50 μm and decreases the active III-V waveguide width from 3 μm to 1.5 μm. In the second part (Taper II) the actual III-V-to-silicon coupling takes place through gradual tapering of both the III-V and silicon waveguide. Finally a short taper (Taper III) of 20 μm is employed to taper out the tuning and bottom cladding layers. Figure 3 (b) shows the influence of the III-V taper tip on the overall coupling efficiency. III-V taper tips smaller than 800 nm already ensure a coupling efficiency above 90%, even for a bonding layer thickness of 100 nm. The coupler has a total length of 250 μm, which provides some robustness with respect to lateral misalignment during contact lithography.



(a) (b)

Figure 3: Adiabatic tapered III-V/SOI coupler. (a) Schematic; (b) Influence of the III-V tip width on the coupling efficiency.

Conclusion

We have proposed a III-V/SOI laser structure for fast and wide wavelength tuning. Device simulations of both the III-V/SOI cross section and an adiabatic tapered coupler have been presented. Currently effort is put in the optimisation of the fabrication process of the laser.

References

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