A novel electrically pumped III-V on silicon micro-laser

Y. De Koninck, M. Tassaert, G. Roelkens and R. Baets
Photonics Research Group – Ghent University / imec
Center for Nano- and Biophotonics
Ghent - Belgium
yannick.dekoninck@intec.ugent.be

A. Bazin and F. Raineri
Laboratoire de Photonique et de Nanostructures
CNRS-UPR20
Marcoussis - France

Abstract—**In this article we present a numerical study of a new electrically pumped heterogeneously integrated III-V on silicon micro-laser. The novelty in our design lies in the fact that we use resonant silicon grating cavities to serve as reflectors. The proposed structure is simulated using a 3D FDTD simulator and we provide some preliminary experimental results.**

Keywords: lasers; heterogeneous integration; silicon photonics; III-V; FDTD; gratings

I. Introduction

In the last decade, Silicon on Insulator (SOI) has proven to be the one of the most important material systems available for integrated photonics because it builds on the maturity of CMOS technology. Its high refractive index contrast allows for high optical confinement and enables sub-micrometer scale photonic components and unprecedented integration of complex optical functionality. Unfortunately, silicon has an indirect bandgap, making it a very inefficient light emitter, hence it is virtually impossible to use it as a gain material for a laser. Over the years, research groups around the world have proposed a number of solutions such as epitaxial growth of an active material on top of the SOI stack or exploiting non-linear optical effects in the silicon itself to generate new frequencies. But probably the most established approach is the heterogeneous integration of a III-V epitaxial stack onto the SOI platform. A III-V substrate containing an epitaxial layer stack on top is bonded upside-down onto the already patterned SOI circuit. After removing the III-V substrate, a series of lithography and etching steps are performed to create the necessary topography that, combined with the underlying silicon structures, forms a laser. Using this technology, a number of devices have been demonstrated, ranging from linear DFB lasers to micro-disk lasers [1]. Unfortunately, these devices are either very large (consuming a lot of silicon real-estate and power) or it is difficult to control the operating wavelength (e.g. in micro-disks tiny variations in disk radius, caused during fabrication or due to heating, can shift the operating wavelength dramatically).

II. Resonant Mirrors

Because the operating wavelength of micro-disk/ring lasers has an inherent sensitivity to small disk radius variations, it is sensible to look into the direction of linear, grating based laser cavities, where the operating wavelength can be determined precisely by the grating period and the waveguide's effective index. Here we face a trade-off that is seemingly intrinsic to heterogeneous integration: to optimize the optical gain, the laser mode should be confined to the III-V waveguide. On the other hand, to assure strong reflection over a short distance, the laser mode should be confined to the silicon layer, where the mature CMOS fabrication technology can provide the nanometer scale features that are required to fabricate first order Bragg gratings in the telecom wavelength range.

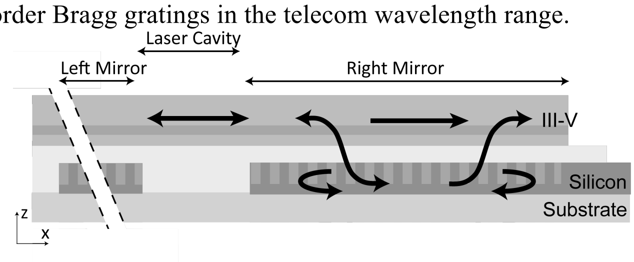

Figure 1: schematic view of resonant mirror

We propose an approach that can potentially provide high reflectivity over a short distance in a clearly defined, narrow, wavelength range and offers an elegant way to couple the generated laser light into a silicon waveguide [2]. The laser consists of a III-V wire with silicon grating structures underneath both ends (see Figure 1). In the center of the laser cavity, the laser mode is completely confined to the III-V cavity, to maximize modal gain. The novelty of this device is in the mirror design: underneath both ends of the III-V waveguide lies a silicon waveguide with a grating corrugation. Both sides are identical, so the following discussion holds for both. Near the edge of the III-V waveguide, a small part of the light couples to the silicon waveguide. The III-V mesa and the underlying silicon grating waveguide are phase-matched at a wavelength that corresponds to one of the two edges of the silicon grating's stop-band. At these edges, the silicon grating waveguide supports so-called resonant band-edge modes. This means that the light coupling from the III-V waveguide into the silicon grating waveguide will start to resonate. After power has built up in that silicon grating cavity, light will start to couple back into the III-V waveguide. The light coupling

Y. De Koninck acknowledges the Research Foundation – Flanders (FWO) for a research grant and IWT-SBO GlucoSens for additional funding

back co-directionally to the incoming light will interfere destructively with the latter and cancel all transmitted light. The light coupling back in the reverse direction is fed back into the laser cavity and provides the required optical feedback, hence the entire structure works as a mirror. Because of the resonant nature of this mechanism, it will only work in a narrow wavelength range, providing good control over the lasing wavelength. Finally, the silicon cavity can be tweaked to leak a small amount of the optical power into an external silicon waveguide to output the generated laser light.

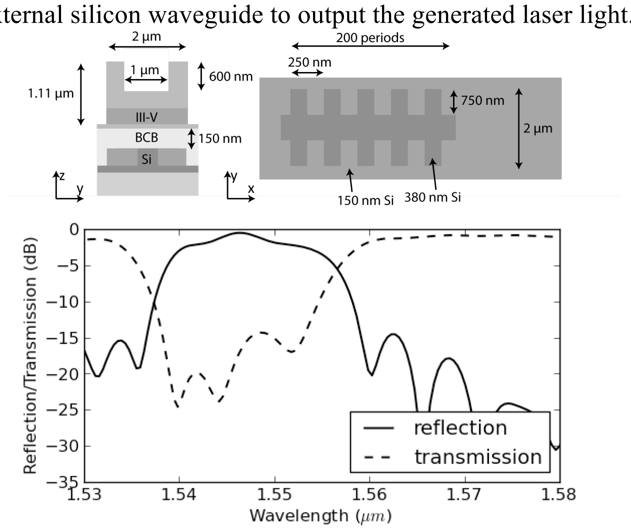

Figure 2: Reflection and transmission spectrum of proposed resonant mirror

The most difficult aspect of this approach is to make sure that the III-V waveguide and silicon grating waveguide are phase matched at the edge of the silicon grating's stop-band. To be able to put electrical contacts for current injection on top, the III-V mesa has to be sufficiently thick such that the metal does not absorb the optical mode inside the mesa. This inevitably leads to a high effective index, which cannot be matched with our silicon platform that offers silicon waveguides up to only 380nm thick. The solution we propose is to etch a slit into the III-V waveguide that pushes the optical mode down and lowers its effective index while still providing a path for the electrical current to flow. In the following sections we provide both optical and electrical simulations to prove that this concept can work.

III. SIMULATIONS

Using a full-vectorial 3D FDTD solver [3] we calculated the reflection and transmission spectrum of the mirror by launching the zeroth order eigenmode of the III-V waveguide and retrieving the reflected and transmitted power fluxes in the III-V mesa. Figure 2 shows the result of these calculations and a detailed description of the structure we simulated. The III-V stack consists of 150 nm n-InP, 4 InGaAs QW's + barriers (120 nm total) and 840nm p-InP. We consider a bonding thickness of 150 nm, which is very feasible [4].

In this particular case, the reflection spectrum is relatively broad (almost 20 nm) because it is the superposition of 3 band-edge resonances in the silicon waveguide (3 distinct dips in the transmission curve). By using a defect mode instead of a band-edge mode, the reflection bandwidth can be narrowed to below 5 nm [2]. The peak reflectivity is 89.2% at $\lambda = 1546$ nm. Outside the reflection band the reflectivity of the structure is below 14.5 dB everywhere. Using Silvaco Atlas [5] we verified that the etched slit does not jeopardize the current injection.

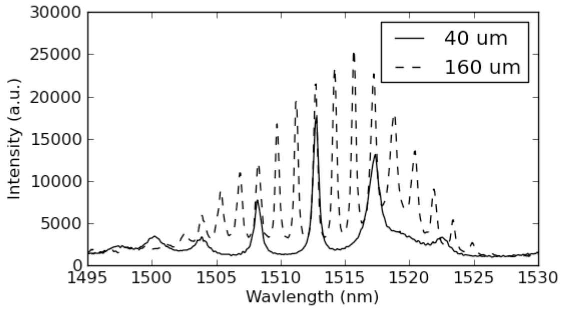

Figure 3: Measured spectrum of ASE in optically pumped sample for 2 different laser cavity lengths (40 μm and 160 μm)

IV. PRELIMINARY EXPERIMENTAL RESULTS

To test the concept of resonant mirrors, a first prototype was fabricated using a thin slab of III-V material that can be pumped optically (similar to [2]) instead of the more advanced etched-slit approach proposed here. The peak of the active material's gain curve we used was centered on 1450 nm while these particular mirrors were designed for wavelengths ranging from 1510 nm to 1580 nm. Nevertheless, we were able to measure amplified spontaneous emission (ASE) in clearly distinguishable longitudinal modes with an FSR consistent with the corresponding device lengths (see Figure 3). Moreover, for different grating periods, the spectral position of the longitudinal resonances shifts accordingly. These observations are strong indications that the proposed concept indeed works.

V. CONCLUSION

We have introduced a novel concept for electrically pumped heterogeneously integrated III-V on silicon lasers based on resonant mirrors. We provide a solution for solving the phase-matching problem and show by means of 3D FDTD simulations that this approach yields high reflection. Finally we offer preliminary experimental results that give a strong indication that our concept works.

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