Design of an Electrically-Injected Hybrid Silicon Laser with Resonant Mirrors

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Abstract—**Recently we demonstrated a novel type of hybrid silicon laser based on resonant grating cavity mirrors. The first optically-pumped proof-of-principle device measures $2\,\mu m$ by $55\,\mu m$, requires milliWatt-level threshold power and has a side-mode suppression ratio of 39 dB. In this work we discuss the challenges and propose a scheme for porting the concept to an electrically pumped device. The novel implementation combines a high-Q cavity with an advanced III-V waveguide design to reach the same properties as the demonstrated optically pumped laser.**

Index Terms—**Silicon photonics, heterogeneous integration, hybrid lasers**

The last decade silicon photonics has emerged as one of the most important material systems for integrated photonic components and circuits. Unfortunately, silicon has an indirect band gap, making it unsuitable as a laser gain material. The most performant approach to date to integrate laser sources into silicon photonic circuits is the heterogeneous III-V on silicon integration [1]. Recently we presented a new type of hybrid silicon laser based on resonant grating cavity mirrors [2]. This type of laser enables high SMSR single mode devices with mW-level threshold power. This is a highly desirable combination that can not easily be obtained in more conventional hybrid silicon lasers. The proposed laser consists of 3 sections: two mirror sections with a gain section in between, as depicted in figure 1b. The gain section consists of a III-V waveguide with no silicon structures underneath, so the light is fully confined to the III-V waveguide. The III-V waveguide continues into the mirror sections, but in each mirror section there is a silicon cavity underneath the III-V waveguide. The close interaction between the propagating waveguide mode in the III-V waveguide and the resonant mode in the silicon cavity results in high, narrow band reflectivity back into the III-V waveguide, as explained in [2]. A first optically pumped proof-of-principle device was demonstrated recently [3]. The laser measured $55\,\mu m$ long and $2\,\mu m$ wide. The threshold power was around $2\,mW$ and the side-mode suppression ratio was $39\,dB$. However, in practical applications, it is more convenient to pump the laser structure electrically. This work will discuss the challenges associated with migrating the resonant mirror concept to an electrically pumped device and propose a possible solution.

To inject electrical current into the III-V active region, metallic contacts should be attached to the p- and n-doped
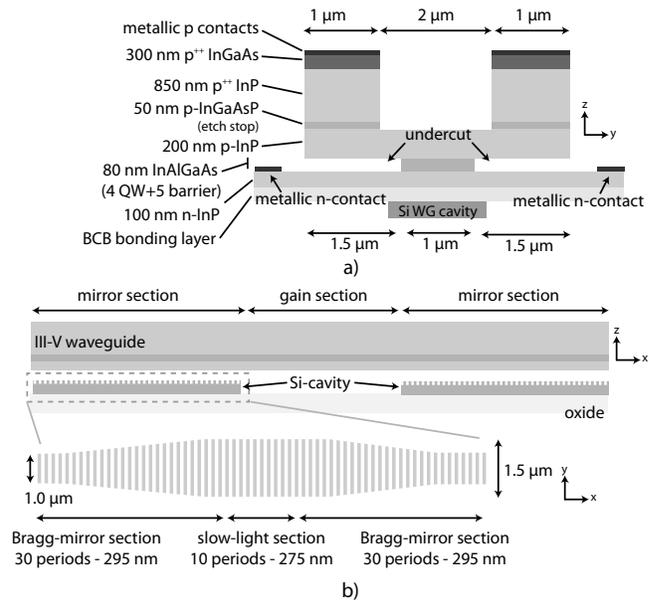

Fig. 1. a) cross-section of the proposed III-V waveguide to accommodate electrical injection. b) layout of the resonant grating cavity mirror

cladding layers. To avoid optical absorption, these metallic contacts should be sufficiently far away from the optical laser-mode. In most hybrid silicon lasers this is accomplished by putting the n-contacts next to the III-V mesa and making the p-cladding sufficiently thick ($>= 1\,\mu m$) to avoid overlap of the III-V fundamental eigenmode with the p-top contact. The thick p-cladding results in a fundamental III-V waveguide eigenmode with a relatively high effective index (typically $n_{eff} > 3.1$). Such a high effective index jeopardises the operation of the resonant mirror because the eigenmodes in the III-V waveguide and the silicon cavity should be approximately phase-matched to ensure sufficient coupling between both layers. In recent years there has been significant research on passive components on a 220 nm thick silicon platform and to ensure compatibility between the laser and these components, the silicon cavities in the laser should also be fabricated in the 220nm technology. But because the effective index of

the silicon eigenmode is much smaller due to the limited waveguide thickness ($n_{eff} = 2.9$ for $220\,nm$ thick silicon), light will couple from the silicon cavity to higher order modes in the III-V waveguide, diminishing the resonant mirror effect.

To establish approximate phase matching between the III-V waveguide and the silicon cavity the size of the III-V waveguide should be reduced in both the lateral and the vertical direction. This is achieved by adopting a cross-section as illustrated in figure 1a. By etching a wide trench in the center of the mesa, the fundamental eigenmode of the III-V waveguide is pushed down. To confine the mode laterally and prevent leakage to the highly doped pillars that provide a path for electrical current injection, the active region, consisting of 4 quantum wells and 5 barriers, is partially undercut. The material in the active region is InAlGaAs with different compositions for the wells and barriers. This material can be etched slowly and selectively with respect to InP using a citric acid and hydrogen peroxide solution [4]. The fundamental eigenmode of the resulting III-V waveguide with dimensions given in figure 1a has an effective index around 2.9, which is much closer to the effective index of the silicon cavity. A more in-depth analysis of such a structure can be found in [5] The silicon cavities that are used in the mirror sections are $220\,nm$ thick silicon waveguides with $70\,nm$ etched grating corrugations. The period of the grating corrugations is varied along the propagation direction of the waveguide. At the outer edges of the waveguide the period is chosen according to the Bragg condition of the desired laser wavelength while in the center the period is slightly shorter to create a resonant defect state at the outer grating's Bragg wavelength. The cavity is wider in the center and narrower at the edges to support coupling between the III-V waveguide and the cavity in the slow-light-part of the cavity and avoid coupling in the Bragg-mirror part. The intrinsic Q-factor of the cavity, without III-V waveguide on top, is around 20.000.

Figure 2 shows the reflection spectrum of a resonant mirror comprising the III-V waveguide structure and silicon cavity described above and depicted in figure 1. The reflection spectrum is calculated using full-vectorial 3D-FDTD by launching the fundamental eigenmode of the III-V waveguide into the resonant mirror section (III-V waveguide with one silicon cavity underneath) and collecting the reflected light. The graph shows that the resonant mirror provides 91.5% of reflection in a narrow $2\,nm$ band.

The resonant mirror laser consists of two resonant mirrors (as described above) with a III-V waveguide in between (figure 1b). The basic laser properties of such a laser structure can be calculated using the reflection spectrum of the resonant mirror in figure 2. The threshold gain required per unit length in the laser can be calculated by considering the mirror reflectivity and the absorption losses of the doped InP cladding layers. The threshold carrier density can be derived from the threshold gain assuming a logarithmic gain model for the InAlGaAs quantum wells and taking into account the confinement factor describing the overlap between the III-V waveguide's fundamental eigenmode with the quantum wells.
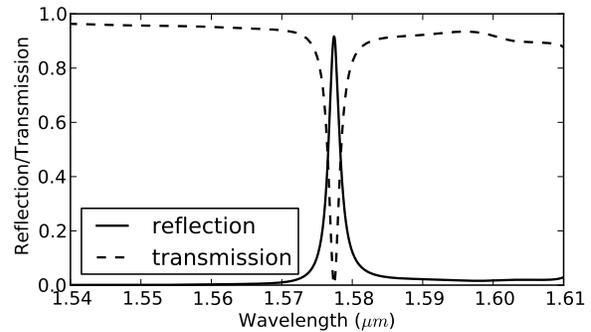

Fig. 2. Calculated reflection and transmission spectrum of a resonant grating cavity mirror with dimensions as indicated in figure 1. The spectrum is calculated using 3D-FDTD by launching the III-V waveguide's fundamental eigenmode into the mirror structure and collecting the reflected and transmitted light.

Finally the threshold current can be calculated using a carrier rate equation including Shockley-Read-Hall recombination, spontaneous recombination and Auger recombination. This approach and the involved material parameters are similar to the treatment in [2]. This calculation yields a threshold current of around 1 mA. The side mode suppression ratio (SMSR) can be estimated at 40 dB.

In this work we presented how our recently demonstrated optically pumped resonant grating cavity mirror laser can be injected electrically. We show how the III-V waveguide geometry should be adapted and what kind of grating cavities can be used. Simulation results of this structure show that the resulting resonant grating cavity mirror laser requires only mW level threshold power and will have a SMSR of 40 dB.

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