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Hybrid III-V/silicon micro-lasers based on resonant cavity reflectors

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We present a novel approach to design compact, single mode, hybrid III-V/silicon micro-lasers. At both ends of the III-V laser cavity, silicon gratings are operated in a resonant regime to allow high reflection over a short distance. We have verified this technique numerically and found that, for a thick bonding layer of 350 nm, more than 93% reflection can be obtained over a distance of less than 20 μm.

Introduction

Over the last decade, Silicon-On-Insulator (SOI) has gained significant momentum as a novel material system for integrated optical circuits. The large refractive index contrast between the silicon waveguide core (3.48 at 1550 nm) and its cladding (1.45 for SiO_2 or 1 for air) results in large optical confinement and allows for ultra-compact waveguide circuits. Furthermore, this CMOS-compatible platform will enable low-cost mass-production and seamless integration of photonic and electronic functionality on the same chip in the future.

Many passive components have been demonstrated with very good performance but due to its indirect bandgap, light emission in silicon is extremely inefficient which makes it virtually impossible to use it as a gain material for lasers in a conventional way. Over the years many possible solutions to this problem have been proposed [1], such as exploiting non-linear effects (e.g. the Raman effect) or epitaxially growing bandgap-engineered materials on top of the silicon substrate. But perhaps the most promising approach is the heterogeneous integration of active materials with silicon. In this approach an active material stack (usually a combination of III-V materials) is glued on top of the SOI substrate using a bonding technique and both the active layer and the silicon are patterned such that a laser cavity arises. This principle has been demonstrated in several different configurations, such as for example linear, grating based lasers and microdisk lasers [1] [2]. In this paper we propose a promising new approach to obtain a compact, efficient and single mode hybrid silicon laser based on so-called cavity enhanced reflectors (CER).

Laser cavity layout

In previously demonstrated linear designs, the laser consists of a silicon waveguide with mirror structures patterned in the silicon on both sides (e.g. Bragg gratings or cleaved facets). Above that silicon wire is a III-V waveguide (including a MQW section and electrical contacts for carrier injection) but both waveguides are designed such that most of the optical power is confined to the silicon waveguide and only the evanescent tail of the optical mode overlaps with the gain layer in the III-V waveguide, yielding long cavities.

In order to decrease the length of the laser, the mode inside the gain section should be confined to the III-V waveguide, this can easily be done by making sure there is no silicon underneath the III-V waveguide along the gain section. At the edges of the gain section, mirrors should provide feedback to establish laser operation. In order to get high reflectivity, Bragg grating reflectors are an obvious choice, but from the point of view of fabrication, it is better to pattern these in the silicon layer. In this case only the evanescent tail of the optical mode, in the III-V layer, will overlap with the grating structure, resulting in longer grating structures to obtain high reflection. it might seem that there is no advantage in confining the optical mode in the III-V layer, because the associated reduction in length is canceled by the longer gratings, but in the next section we will present a novel approach to allow confinement in the III-V layer along with compact grating mirrors defined in the silicon layer.

Cavity Enhanced Reflectors

Consider the hybrid laser scheme in figure 1. The reflector is in essence a dual waveguide system, consisting of a III-V waveguide on top of a silicon grating waveguide. Laser-light is generated in the III-V cavity, so before hitting the grating mirror, only the III-V waveguide is excited. As the light propagates through that waveguide, only a small portion couples to the silicon grating waveguide, because of the considerable distance between both. At first sight, this limited coupling can be neglected, unless the grating waveguide is modified to act as a resonant cavity by adding a phase-shifting section of half a period to the center of the grating. This way the resonant mode can be excited in the silicon grating waveguide and power will build up inside the grating cavity.

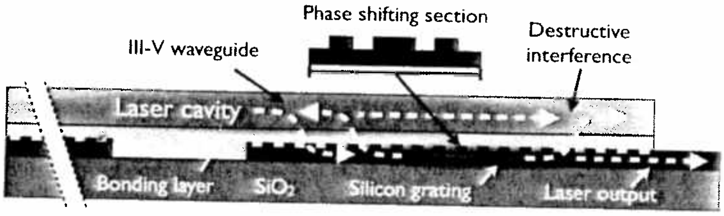

Figure 1: Schematic of hybrid III-V/silicon laser. Both reflectors are identical but only the right one is drawn in detail.

The built-up power in the grating will couple back into the III-V waveguide, both co- and counter-directional to the light coming from the cavity. If the III-V and the silicon waveguides are phase-matched, the co-directionally coupled light will interfere destructively with the incident light resulting in zero transmission in the ideal case. The counter-directionally coupled light propagates back into the cavity, resulting in high reflectivity. This effect has been reported before [3] in the context of narrow-band reflection.

Simulation Results

We have verified the idea of cavity enhanced reflectors using the open-source eigenmode-solver CAMFR. This software package can find the eigenmodes of 1D slab waveguides and calculate the wave propagation through 2D cross-sections. We have used this package to calculate the ground-mode to ground-mode reflection of the 2D cross-section of the right reflector in figure 1. The inherent 3D structure was reduced to this 2D cross-section by using an effective-index approximation. The simulations shown below are for a 1.5*μm* wide and 256 *nm* high InP waveguide on top of a 1.6 *μm* wide and 220 *nm* high silicon waveguide. Both waveguides are separated by a 350 *nm* thick BCB bonding layer. The grating is considered to be etched 70 *nm* deep into the silicon wire, has a period of 300 *nm* (50% duty cycle) and consists of 60 periods. The silicon grating's stopband ranges from 1.54 *μm* to 1.64 *μm* with a Bragg wavelength of 1.59 *μm*. The $\lambda/2$ phase-shifting section is not put exactly in the center of the grating but 4 periods closer to the cavity (so there are 26 periods before the phase-shifting section and 34 after) to counteract the asymmetric optical injection. This increases the overall reflection of the structure.

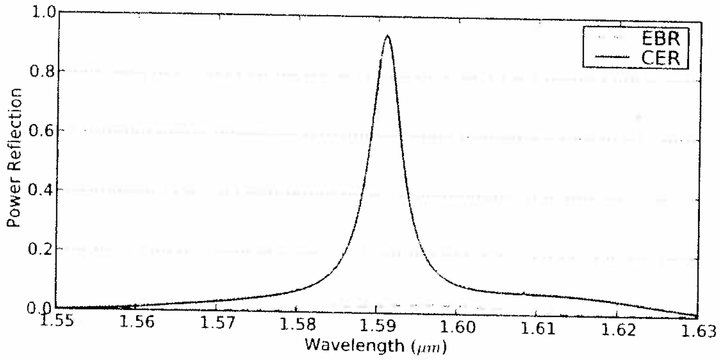

Figure 2: Spectrum of III-V waveguide ground-mode reflection of CER and EBR

Figure 2 shows the power reflection spectrum of the III-V ground-mode using a cavity enhanced reflector (CER - solid line). For reference, the image also depicts the reflection spectrum of the associated evanescent Bragg reflector (EBR - dashed line). This is the exact same structure but without the phase-shifting section. As a consequence of the thick bonding layer, the evanescent Bragg reflection is very weak: around the Bragg wavelength, only 3% of the incoming power is reflected. By adding a phase section, a high reflection peak appears at the Bragg wavelength with a maximum power reflection of 93.7%. The reflection peak is relatively narrow with a FWHM of $\sim 5nm$.

Figure 3 shows the intensity profile along a 2D cut similar to that of figure 1, for both the EBR (without phase-shifting section - top) and CER (with phase-shifting section - bottom) at the Bragg wavelength ($\lambda = 1.591$ *μm*). The silicon grating ranges from z = 1*μm* to z=19*μm*. For clarity, transparent rectangles indicate the location of both waveguides. The III-V waveguide's ground-mode is excited from the left of the simulation area.
In the case of EBR, so without a phase section, the power profile is uniform along the III-V waveguide. As a consequence of the limited Bragg reflection, the standing wave pattern causes a small periodic fluctuation in the spatial power distribution visible at the

far left side of the waveguide. Approximately 3% of the light is reflected where 89% is transmitted. The remaining 7% is lost due to scattering.

The situation changes completely if a phase shifting section is added (CER). In the silicon grating waveguide a field enhancement, centered around the $\lambda/2$ phase shifting section (at $z = 8\mu m$), is clearly visible. In both waveguides a periodic variation in spatial power distribution arises as a result of the standing wave pattern. The plot also shows how the light that couples from the cavity back into the waveguide interferes destructively with the light propagating through the waveguide, resulting in 0.4% power transmission where 93.7 % is reflected. The remaining 6 percent is lost due to scattering and radiation at the edges of the silicon cavity. Note that the color scales differ for both power profile plots, but relative intensities can be compared by referring to the input power of the III-V waveguide.

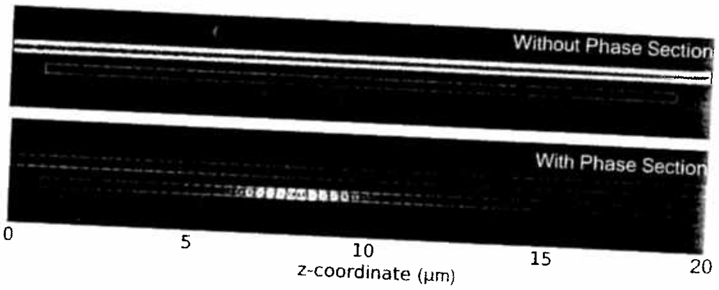

Figure 3: Intensity profile of EBR and CER at Bragg wavelength ($\lambda = 1.591\ \mu m$)

Conclusion

We have presented a novel approach to design compact hybrid III-V/silicon microlasers by operating a silicon grating in a resonant state. A simulation example shows that this technique allows high reflection (> 90 %) over a short distance (< 20 μm), even for thick bonding layers (350 nm).

Acknowledgement

Yannick De Koninck acknowledges Ghent University and the Research Foundation - Flanders (FWO) for a research grant. The author also thanks Shahram Keyvaninia and Martijn Tassaert for the fruitful discussions.

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